Torrential Rains on the Spanish Mediterranean Coast: Modeling the Effects of the Sea Surface Temperature

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ABSTRACT

Torrential rains are a frequent meteorological risk in the Mediterranean Basin, and the work reported here is part of a long-term study that includes the analysis of the synoptic conditions involved in their genesis. This paper studies the role of SST in torrential rain development. Two episodes were selected for simulation with the Regional Atmospheric Modeling System. Three runs of each were performed by progressively improving the SST input data sources: from monthly climatological averages, to data from the International Satellite Land Surface Climatology Project, to near-to-real-time data derived from National Oceanic and Atmospheric Administration (NOAA) satellite images. For the first episode, the maximum total precipitations calculated were 242, 301, and 496 mm, respectively, versus more than 550 mm measured. For the second event, the maxima were 316, 349, and 378 mm, respectively, versus more than 450 mm measured. The conclusion is that significant improvements in the modeling of peak precipitation can be expected when using SST derived from NOAA satellite data.

1. Introduction and background

Intense rain events in the western Mediterranean Basin can occur from late summer to winter, and in the last few decades they have caused numerous catastrophic floods in several countries, with human casualties. On the east coast of the Iberian Peninsula, the Valencia region, shown in Fig. 1, is one of the most affected areas. Figure 2 shows the frequency and annual distribution of torrential rain events in this region during the last 27 years, including 48 severe episodes. Damages could be reduced by the proper forecasting of the meteorological situations leading to these events; some efforts have already been made to this effect (Codina et al. 1997).

Our framework for the study of these events has been the back door (cold) front concept (Huschke 1959; Bluestein 1993), in which the cold front is generated by the northerly, northeasterly, or easterly flow of colder continental air over the warmer Mediterranean. Most of the precipitation events have been observed to occur directly over the sea, and the torrential rains over eastern Spain appear to be the result of a two-step process. The formation of a potentially unstable air mass through the advection of the colder continental air over the warmer sea is the first step; here the temperature difference between the advected air and the sea surface temperature (SST) plays the key role in the recharge of moisture. The second step is the easterly transport of the potentially unstable air mass toward the coastal regions where orographic lift can trigger the precipitations.

We studied 32 torrential rain events for which the western Mediterranean SST could be retrieved from National Oceanic and Atmospheric Administration (NOAA) satellite images. These images were processed with an algorithm developed by Badañas et al. (1997), which obtains the SST with an error of less than 0.5°C. Our analysis of the NOAA images and the trajectories of the surface air masses indicated that the Mediterranean SST along their path drops by 3°C ± 5°C with respect to values previous to the event. Because the SST, as a long-term-varying parameter, did not show significant changes during the days previous to the event, our assumptions were 1) that the drop in the observed SST after the event was mainly the result of vigorous evaporative cooling along the back door (cold) front and thus 2) that the warmer areas of the Mediterranean acted as a source of moisture for the torrential episodes (Millán et al. 1995). Other works have also confirmed the relevance of SST on the development of torrential rains on the Spanish Mediterranean coast (Fernández et al. 1995, 1997).

The objective of this work was to study further the importance of SST data quality in the quantitative simulation of precipitation amounts. For this purpose, the tool used was the Regional Atmospheric Modeling System (RAMS), which was adapted to the specific conditions in the western Mediterranean by including more accurate regional topography, as well as better land use...
data and grid-size selection, and by testing the outputs against field data from the study of forest fires (Gómez-Tejedor et al. 1999) and air pollution dynamics in the region (Salvador et al. 1999, Millán et al. 2000). Through this process, results from previous studies were incorporated to improve the model.

2. Modeling

a. The model

The numerical mesoscale model used for this work (RAMS) was developed at Colorado State University by merging different mesoscale and cloud models (Piel-
ke et al. 1992; Walko et al. 1995a). The RAMS model is built around the full set of primitive dynamical equations, which describe atmospheric motions, supplemented with optional parameterizations for different meteorological magnitudes. It was fundamentally developed as a limited-area model for regional mesoscale studies.

RAMS uses the Arakawa C grid (Messinger and Arakawa 1976), in which all the thermodynamic and moisture variables are defined in the center of a grid volume with the velocity components staggered by one-half of a grid space in their normal direction. This procedure has several advantages, including the isotropy of the velocity component locations relative to the thermodynamic variables, which is very important for mass and flux conservation.

Detailed descriptions of the microphysics and moisture schemes used by RAMS can be found in Walko et al. (1995b) and Meyers et al. (1996). In the case of convection, the RAMS model uses a simplified Kuo (1974) parameterization as described by Molinari (1985). For this work, the explicit microphysics options of RAMS—cumulus parameterization and cloud hail and rain microphysics—were activated (for all three grids). These options facilitate the diagnosis of the number concentration of different species of liquid or ice from a mean diameter specified from a default value in the code and the forecasted mixing ratio.

Properties of bare soil are calculated in RAMS with a multilayer soil model described by Tremback and Kessler (1985). This model calculates prognostic equations for the soil surface temperature and water content. Soil moisture content is initialized in the model simulations by a parameter specified in the model before the execution of the simulations. The values of this parameter range from 0.0 (totally dry soil) to 1.0 (fully saturated soil) and represent the percentage of total water capacity that the soil can hold; in our case we have chosen a value of 0.3 for each soil level.

Our simulation uses three interactive nested grids shown in Fig. 1. Grid 1, with a 1600 km by 960 km domain, links with the synoptic systems. The Valencia region is covered by grid 2, with a 400 km by 480 km domain; grid 3 with a 120 km by 120 km domain, is intended to resolve the small-scale phenomena. The mesh resolutions for each grid are shown in Table 1. The ratio between the second and third mesh sizes is 8:1, which is greater than normally used. It represents a compromise between our computing capabilities and the spatial resolution desired, and it was selected after trying different configurations for the grids. All three grids span 32 vertical levels, with their tops reaching 15 km.

**b. Methodology**

Two cases have been selected for which the NOAA datasets were of excellent quality. The first, from 4 to 7 September 1989, was one of the strongest episodes in the last 10 years, and the second, from 28 September to 1 October 1986, can be considered to be a more “average” event.

The methodology followed was to run three RAMS simulations of each event to detect model output variations as the SST data input was changed. The first simulations were run with the RAMS-distributed SST files and are considered the “control” runs. The second simulation used SST data obtained during the International Satellite Land Surface Climatology Project (ISLSCP), and the third simulation used the SST data derived from the closest available NOAA images previous to the event. In each event, therefore, the initial meteorological parameters remained unchanged for each of the three simulations, and the only changes introduced in each new initialization were the sea surface temperature data.

The model has been initialized with a three-dimensional grid of atmospheric data provided by European Centre for Medium-Range Weather Forecasts analysis, using the analysed datasets with 2.5° × 2.5° and 1° × 1° horizontal spacing for the 10 standard pressure levels. These datasets are ingested by the model Data Preparation Package and converted to the RAMS format. The Isentropic Analysis package is used to create the initialization variable fields, which the model utilizes in two different ways. The first way is that, when a simulation is begun, the model fields are initialized directly from the first initialization file.
The second way is that the initialization files (obtained every 6 h) are used to supply a time series of observational data for the model to assimilate during execution. These (verification) data files are obtained by a linear time interpolation between the two initialization files that bracket the current time of simulation. The modeled fields are then nudged toward the interpolated values according to parameters that are specific to the model (default mode); the interpolated values can also be used as inputs to the model. In this work the default parameters were used.

Last, because of the need for avoiding initial value and boundary condition problems, the calculation time was extended at both the beginning and the end of each event (−2 and +2 days).

3. Episode of 4–7 September 1989
a. Meteorological sequence

Figure 3 shows a selection of surface and 500-hPa synoptic maps covering the 28 August–7 September
Fig. 4. Formation of a maritime–Mediterranean air mass along easterly trajectories crossing the western Mediterranean Basin for the rain event of 28 Aug 1989: (a) SST and back trajectories and (b) interpolated moisture mixing ratio for three stations located along the trajectories (Trapani, Italy, and Palma and Murcia, Spain).
The days previous to the event were typical of summer conditions, with thermal lows forming over the Iberian Peninsula and a marked breeze cycle developing in the Valencia region. During the last days of August, a ridge of high pressure extended toward central Europe, pushing, along its leading edge, a mass of maritime polar air (mP) across north-central Europe and through the Rhone Valley toward the western Mediterranean (Fig. 3a). By the time it reached the sea, its surface temperature was still some 6°–10°C lower than the Mediterranean SST. The southerly transport along the surface was accompanied by the displacement of a trough of cold air aloft, and both resulted in the development of a Genoa depression, as shown in Figs. 3a, b, which produced generalized storms over central Italy. The trailing edge of this moist air mass was also driven toward the Spanish coast by a combination of the general synoptic flow and the Iberian thermal low, and it favored the formation of storms in the Valencia coastal mountains on 30–31 August.

By the beginning of September, the Azores high stretched farther toward the east, and, by 3 September and the following days, it extended over central Europe, leaving the western Mediterranean within its return (easterly) flow. From this position, the anticyclone pushed the moist (Mediterranean) air mass toward the west and kept forcing colder eastern European air over a warmer central basin (Fig. 3c). Between 3 and 4 September, a low finally developed over northern Africa. All of this led to the right conditions for the onset of the episode which started late on 3 September. Along with the surface developments, cooler air aloft also moved southward through western Europe and formed a strong upper trough (cold pool of air aloft) over the whole of Spain and the Gulf of Cadiz area by 5–6 September (Fig. 3c,d), that is, just after the first peak of precipitation on 5 September. This situation remained, essentially, until 8 September, and the episode concluded on 9 September.

Figure 4 shows the SST over the western Mediterranean Basin on 27 August 1989, the isobaric trajectories for the air masses arriving at Valencia at 1200 UTC 7 September, and a cross section of the water vapor mixing ratios at 1200 UTC 5 September, obtained from the soundings at Trapani, Italy; Palma, Majorca; and Murcia, Spain. The two back trajectories have been obtained from the surface pressure fields starting 72 h preceding the episode and have been calculated every 6 h. One of them (A) is considered to represent the geostrophic winds between 1000 and 1500 m, and the ageostrophic (near surface) trajectory (B) was determined by backing the winds 30° in the direction of the pressure gradient to account for surface drag effects.

The cross section with the mixing ratios is intended to illustrate the modification of the surface air mass as it is advected over the warmer sea. At the time shown, the air mass below the 9 g kg⁻¹ isoline extends from Trapani to Palma, but it has not yet reached Murcia; it is approximately 1400 m deep over Trapani and nearly 2500 m deep over Palma.

b. Simulations

The three RAMS simulations performed for this event started at 0000 UTC 2 September and lasted for 210 h, finishing at 1800 UTC 10 September; while the rain event took place from 4 to 7 September. Figure 5 shows the spatial distribution for the total precipitation recorded during the event. Within grid 3, the pattern is almost semicircular and is centered, essentially, over the coastline near the city of Gandía. The 250- and 200-mm isolines extend farther inland in a less regular manner. The measured precipitations over the Gandía station were 105, 143, 99, and 173 mm, respectively, for 4–7 September, and the modeled results presented below are for the days with precipitation maxima, that is, 5 and 7 September, and for the total amount during the event.

1) CONTROL RUN

The RAMS-distributed SST files for September are shown in Fig. 6a; they come originally from the U.S. Navy and are given in a 1° × 1° grid from 30-yr monthly
Fig. 6. SST analysis for the three RAMS simulations of the Sep 1989 event: (a) control, (b) ISLSCP, and (c) satellite simulations (retrieved from the 28 Aug 1989 NOAA satellite image).

averages (from about 1950 to 1980). They show the SST to be above 20°C over the whole western Mediterranean Basin, and they also show a 3°F gradient between the southern French coast and the Balearic Islands. From the Valencia coast to North Africa, the SST stays almost constantly above 23°C.

Figures 7a and 8a show, respectively, the simulated amount of rain for 5 and 7 September, and Fig. 9a shows the simulated total accumulated precipitation during the event. Only the grid-3 results are shown, in order to resolve the smallest scale in the area with the strongest precipitations. Comparison with Fig. 5 shows the location of the simulated maximum rainfall area as displaced south and inland, that is, toward the mountains. However, the main disagreement between the model results and the precipitation data is in the amount of rain, which is off by at least a factor of one-half, or less, in most parts of the grid. The maximum precipitation from RAMS-distributed SST results is 242 mm, but more than 550 mm were recorded at some stations during the event.

2) ISLSCP RUN

This second simulation used the ISLSCP sea surface temperature data, obtained through an initiative by several scientific meteorological institutions to collect a dataset for input and initialization in the field of land–atmosphere modeling. For this work, the ISLSCP Initiative I datasets were used. These files cover 24 months (1987–88) and are a global 1° × 1° grid of monthly climatic averages in the case of SST.

The ISLSCP SST field used is shown in Fig. 6b. It has a similar structure to the one from the RAMS-distributed files but has slightly increased values. In the southern half of the western Mediterranean Basin, they reach temperatures higher than 24°C; in the control simulation they are 1° lower. It is also important to point out the presence of a warmer zone, 25°C, just offshore from the Valencia coast.

The modeled precipitation is shown in Figs. 7b and 8b, for 5 and 7 September, respectively, and in Fig. 9b for the total during the event. In this simulation, the total precipitation shows an increase of approximately 50 mm versus the control simulation, and the maximum value modeled is 301 mm. With regard to the spatial distribution, the simulated rainfall is slightly greater than in the control run, and the maximum rainfall is located roughly over the same place, that is, displaced south and inland from the measured field. The 200-mm isoline, however, is located closer to the city of Gandía.

3) SATELLITE DATA RUN

For this simulation the SST data have been obtained from the NOAA satellite images of 28 August 1989 (shown in Figs. 4a and 6c). These had the clearest picture (cloudless sky) and widest coverage over this area. Although the retrieval of the SST employs an algorithm based on the split-window technique (Bádenas et al. 1997), which avoids errors caused by clouds, we preferred to reduce the risk of inexact SST estimation by choosing a cloudless day. The resulting data are given on a grid with a 0.5° × 0.5° distance between data points and an accuracy of ±0.5°C. Because of numerical modeling requirements, it was necessary to merge these data with the ISLSCP SST data outside the largest grid of the modeling domain.

In Fig. 6c, major differences can be noted between the SST values used for this simulation and the previous ones. The satellite-derived SST values are higher over
the whole western Mediterranean Basin, that is, greater than 24°C (the highest value in the ISLSCP simulation). They are more irregular, and values above 28°C can be observed over a broad zone extending from the Valencia coast to the south of Sardinia and from the Balearic Islands to the African coast.

The results of this simulation are shown in Figs. 7c, 8c, and 9c, for the precipitation on 5 and 7 September, and for the total during the event, respectively. The most important difference with respect to the previous two is that the maximum gridpoint simulated value reaches 496 mm, that is, more than 2 times the values obtained from the control simulation. The affected area is also closer to the real one, and the 200-mm isoline covers a greater area, ranging from the south to some distance north of Gandía; in the control and ISLSCP simulations the 200-mm isoline was located to the south of Gandía. However, as Fig. 5 shows, the modeled maximum is still displaced to the south and farther inland, that is, toward the mountains.

Figure 10 shows two cross sections of the water vapor mixing ratio obtained by the model for each simulation.
4. Episode of 28 September–1 October 1986

a. Meteorological sequence

Figure 11 shows a selection of the 1200 UTC surface and 500-hPa synoptic maps covering the 23–30 September 1986 period. The meteorological conditions on the days previous to the event were typical of late summer, with a ridge of high pressure extending zonally across western Europe and, as shown in Fig. 11a, the diurnal Iberian thermal low forming over Spain. On 24 September, a high pressure ridge started to develop, and by 25 September a ridge of high pressure extended meridionally from the central Atlantic to Iceland (Fig. 11b), which sent a wave of cold(er) mP air southward across Europe. Along with the surface developments, an isolated pool of cold upper air also moved eastward from the central Atlantic toward southern France, and both resulted in the formation of a Genoa depression west of Italy, in a way similar to the previous case.

By 27 September, the ridge of high pressure began to stretch farther toward the east, and by 28 September and following days, as Figs. 11c,d show, it extended over central Europe, leaving the western Mediterranean within its return (easterly) flow. From this position the anticyclone pushed the moist maritime (Mediterranean) air mass over the western Mediterranean toward the Spanish east coast, leading to the right conditions for the onset of the episode, which started on 28 September. Along with the surface developments, the trough of colder air aloft stretched southwestward and eventually broke off from the upper flow by 29 September, creating an isolated pool of cold air aloft over the north African Atlas region, which coincided with the formation of a short-lived (2 day) surface depression over the same area (Fig. 11d).

Figure 12 shows the SST over the western Mediterranean Basin on 27 September 1986, the isobaric trajectories for the air masses arriving at Valencia at 1200 UTC on 29 September, and a cross section of the water vapor mixing ratios at 1200 on 29 September, obtained from the soundings at Ajaccio, Italy, and Palma and Murcia, Spain. The back trajectories were calculated as per Fig. 4, and the cross section of the mixing ratios shows an air mass below the 4g kg$^{-1}$ isoline that extends from Ajaccio to Palma, which is not noticeable in Murcia. At the time shown, the air mass is approximately 2600 m deep over Ajaccio and nearly 2800 m deep over Palma. Comparison of the temperature scales with Fig. 4 also shows that the SST in this event (September) is, on the average, 3°C cooler than in the previous case (in August).

b. Simulations

The simulations run for this event start at 0000 UTC 26 September and finish at 1800 UTC 2 October, last-
ing for 162 h, and the rainfall occurred from 28
September to 1 October. The measured precipitation
amounts over the Gandía station were 20, 157, 72, and
6 mm, respectively, for 28–30 September and 1 Oc-
tober 1986. Figure 13 shows the spatial distribution
and total precipitation recorded during this event. Sev-
eral features can be distinguished in an east-to-west
direction. The first area extends from the coast inland
and includes the Cape of La Nao, is enclosed by the
400-mm isoline, and has two maxima of 450 mm lo-
cated over the coastal mountains. The second feature
is enclosed by the 350-mm isoline, extends from the
coast inland, and, besides the previous area, encloses
another maximum of 400 mm located approximately
in the middle of the left half of grid 3. The third is the
area enclosed by a second 350-mm isoline, farther in-
land, which includes another (small) maximum of 400
mm. Last, a fourth isolated area can be observed north-
west of Gandía, marked by a 300-mm isoline enclosing
a 350-mm maximum.

1) CONTROL RUN

The RAMS-distributed sea surface temperature files
for September (Fig. 14a) are the same shown in Fig.
6a, and the same comments apply as in section 3b(1).
Figure 15a shows the total accumulated precipitation
simulated for the event. Comparison with Fig. 13 shows
that the spatial distribution of the modeled rainfall fails
near the coast and improves with distance inland. The
best agreement is observed at the western edges of grid
3 where the 250-mm isoline almost coincides with the
350-mm area of the observed data. Another modeled
peak of precipitation near the center of grid 3 (200 mm)
also coincides in location, but not in amount, with a region of observed maxima (i.e., 400 mm) inland. The maximum precipitation from RAMS-distributed SST data yields 316 mm at the western edge of grid 3, but more than 400 mm were recorded at some stations during the event.

2) ISLSCP Run

This second simulation used the ISLSCP sea surface temperature data for September (Fig. 14b), that is, the same as in Fig. 6b, and the same comments also apply as in section 3b(2). The modeled precipitation total is shown in Fig. 15b. With regard to the control run, the distribution improves near the coast, by extending the 100-mm isoline toward the Cape of La Nao and by increasing the area of precipitation within the second and third areas mentioned above (section 4b). The total simulated precipitation shows an increase of approximately 33 mm versus the control simulation, and a maximum value of 349 mm is reached at the western edge of grid 3.
Fig. 12. Formation of a maritime–Mediterranean air mass along easterly trajectories crossing the western Mediterranean Basin for the rain event of 27 Sep 1986: (a) SST and back trajectories and (b) interpolated moisture mixing ratio for three stations located along the trajectories (Ajaccio, Corsica, and Palma and Murcia, Spain).
3) SATELLITE RUN

For this simulation the SST data have been obtained from the NOAA satellite images of 27 September 1986 and are shown in Fig. 14c (as well as in Fig. 12a). Again, the NOAA-derived field is much lumpier than the monthly averaged values. In this case, however, the NOAA-derived SST field near the study area is more similar to the ISLSCP temperature field, except that the pool of water at 25°C near the coast is more than 3 times as large and extends farther to the south and east. As in the previous case, because of numerical modeling requirements, it was necessary to merge these data with the ISLSCP SST data outside the largest grid of the modeling domain.

The results of this simulation are shown in Fig. 15c, and the spatial patterns are essentially the same as for the ISLSCP simulation. In comparison with Fig. 13, however, further improvements appear in the enlargement of the rain area near the coast, the expansion of the 100-mm isoline toward the sea, in particular, and the closure of a 125-mm isoline over the Cape of La Nao. Another area within a 125-mm isoline appears west of Gandía and corresponds to the fourth area (300-mm contour) mentioned in Fig. 13. The simulated maximum for this case was 378 mm, at the western edge of grid 3.

Figure 16 shows the cross sections of the water vapor mixing ratios obtained for each simulation. Again, the data for the cross section at 36°54′N (Murcia sounding) are shown in Figs. 16a–c, and those for 39°N are shown in Figs. 16d–f. In this case, no significant differences can be found between the model results for the three simulations, because the initial conditions for SST do not show large differences as compared with the 1989 event. Only in the case of the satellite simulation at 39°N (Fig. 16f) can an area with slightly higher values...
Fig. 15. Total precipitation calculated by RAMS for the Sep–Oct 1986 event: (a) control, (b) ISLSCP, and (c) satellite simulations.

be noticed from the surface up to a height of 1000 m. In comparison with Fig. 12b, the simulated water vapor mixing ratios are higher than those observed, particularly at the latitude of Murcia.

5. Conclusions

Two torrential rain events have been studied with RAMS to determine the relevance of the sea surface temperature in the development of torrential rains in the Valencia region, and several conclusions can be derived from the analysis of the results.

The first is that SST is shown to be a key factor in the development of such events in the western Mediterranean Basin. The best agreement between the modeled results and the data recorded during the event, both in peak amounts and in spatial distribution of rainfall, has been found when the SST data input to the model was derived from the NOAA satellite image of a few days previous to the event. The simulations using climatological monthly averages for the SST were less accurate in the location of the spatial distribution and in the simulation of the maximum amounts. However, although the main rainfall amounts calculated by the RAMS model with the satellite data are closer to reality, they still remain lower than the actual precipitation.

A further point to notice is that the peak amount of precipitation appears to be related to the average temperature within the basin, or along the trajectories, as shown in Figs. 4 and 11: that is, higher precipitations are recorded in the August event than in September. This result requires further verification with more case studies. In both cases, most of the simulated rain came from the resolved clouds rather than from the convective parameterization, and the precipitation in the larger grids showed results consistent with the ones shown in this paper (for grid 3).

However, it must also be pointed out that, despite the fairly good model results regarding the grouping, that is, the structural distribution of the rain areas in the two cases simulated, these are displaced toward the mountain regions inland. This may be due to the impact of orography and land use on the model results. It also leads us to believe that the orographic trigger mechanism is favored by the RAMS model in its current configuration, whereas other mechanisms may also be important when the interface between the sea and the orography is abrupt. For example, in the study area there are 400- to 700-m-high cliffs and mountains near the sea, and there are mountain ridges taller than 1500 m at less than 15 km from the coast. Thus, the possible effect of displacement flows enhancing vertical lift before the moist air masses reach the coast may have to be considered. Further work is in progress to improve this part.

Another conclusion relates to the numerical forecasting of meteorological hazards. Our working hypothesis is that the SST has a major influence on torrential rains in this region, and the results show that an accurate input of real-time data has greatly improved the results of a numerical model, in particular the peak precipitation levels. The only way to obtain reliable real-time SST values was to use estimations from satellite images, and thus the authors conclude that further development in numerical modeling should concentrate more on the gathering of real-time data and improving their assimilation (input) procedures into the model. The
authors also believe that this approach, combined with an analysis of the synoptic sequences, could improve the operative forecasting of meteorological hazards, especially for the very specific characteristics of the Mediterranean Basin.

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Fig. 16. Water vapor mixing ratio cross sections from model results: (a) control, (b) ISLSCP, and (c) satellite simulations at 36°54′ N lat, and (d) control, (e) ISLSCP, and (f) satellite simulations at 39° N lat.


