Atmospheric Research 123 (2013) 400–411

Contents lists available at SciVerse ScienceDirect

Atmospheric Research

journal homepage: www.elsevier.com/locate/atmos

Surface heat fluxes influence on medicane trajectories and intensification

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ARTICLE INFO

Article history:
Received 17 January 2012
Received in revised form 4 May 2012
Accepted 28 May 2012

Keywords:
Medicanes
Mediterranean
Air–sea interaction
Surface heat fluxes

ABSTRACT

A few tropical-like cyclones have developed over the Mediterranean Sea during the last decades according to the inventory of images provided by Meteosat satellite. These extreme small-scale warm-core storms, also called "medicanes", operate on the thermodynamical disequilibrium between the sea and the atmosphere, and sometimes attain hurricane intensity and threaten the islands and coastal regions.

Despite their small size, mesoscale model runs at moderate horizontal resolutions (7.5 km) made with MM5 are able to simulate the formation of a subsynoptic cyclone and the general trajectory of the disturbance, and for most of the cases a warm-core axi-symmetrical structure becomes evident in the simulations. The timing and precise details of the storm trajectories are shown to be more problematic when compared against the satellite images available for the events. It is hypothesized that the small size of the systems and the crucial role of moist microphysics, deep convection and boundary layer parameterizations are the main factors behind these errors. On the other hand, a sensitivity analysis examining the role of the sea surface heat fluxes is conducted: latent and sensible heat fluxes from the Mediterranean are switched off at the beginning of the simulations to explore the effects of these factors on the medicane trajectories and deepening rate.

Results show different roles of the surface heat fluxes on medicane properties (intensification and track) depending on their magnitude and spatial distribution over the Mediterranean Sea. In this way, three distinct patterns have been identified using a database of twelve events.

1. Introduction

The Mediterranean basin is recognized as one of the main cyclogenetic areas in the world (Pettersen, 1956; Hoskins and Hodges, 2002; Wernli and Schwierz, 2006) with an average of 1817 cyclone centers per year (Campins et al., 2011), typically lee baroclinic disturbances. The spatial distribution of these cyclones is not uniform and there are two preferred regions for cyclogenesis: Cyprus area and the gulf of Genoa (Alpert et al., 1990; Campins et al., 2011).

In spite of the high frequency of cyclones over the Mediterranean Sea, there is a kind of cyclones that are not always well represented in automatic detection methods due to their small size and evolution over the sea, where the observations are highly sparse and, consequently, it is more problematic to represent the features of meteorological fields. Some studies have shown that these storms exhibit some physical similarities with tropical cyclones (Rasmussen and Zick, 1987; Laugovardos et al., 1999; Pytharoulis et al., 2000; Homar et al., 2003), revealing the presence and primary role of the deep convection released around the cyclone core and an equally strong influence of surface heat fluxes. In satellite images, these events present a continuous cloud cover with axisymmetric shape around a cyclone eye that becomes evident during some phases of its life. Furthermore, some measurements made at meteorological stations close to these cyclone tracks show a quick and pronounced surface pressure drop (e.g. Fig. 1). For these reasons, since a while now, this parallelism is accepted by meteorological community and the name used to call these special Mediterranean cylones is "medicanes" (MEDIterranean hurriCANES).

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doi:10.1016/j.atmosres.2012.05.022

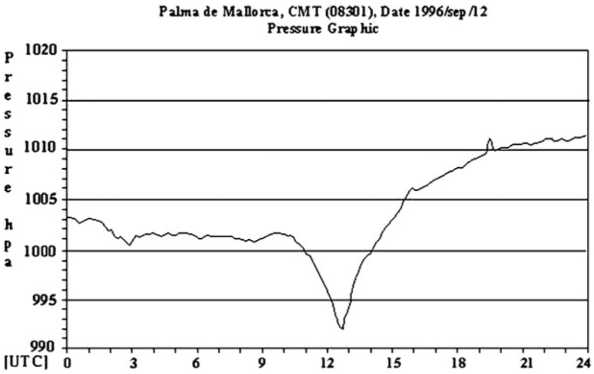

Fig. 1. Pressure record in Palma de Mallorca during the passage of the medicane of 12th September 1996.
Courtesy of A. Jansà, AEMET.

As shown by Tous and Romero (2012), past detected medicanes are located in the Central and Western parts of the Mediterranean basin and are more frequent in winter and autumn. Although it was not possible in the same study to establish clear boundaries for the large-scale meteorological parameters that would help to discriminate medicanes environments from the conditions for genesis of other intense Mediterranean cyclones, the diabatic contribution to low level equivalent potential temperature and the sea surface temperature were shown to play an important role in their development. This fact is also coherent with the background knowledge that the thermodynamical disequilibrium between the sea and the atmosphere is the physical root of the tropical cyclones (and also medicanes) development.

Once assumed the importance of sea surface heat fluxes on particular medicane events (e.g. Homar et al., 2003), we would like to assess whether a common pattern is found for the generality of medicanes. For this reason, the study here presented will evaluate quantitatively the effects of these fluxes on medicane properties, more specifically on their trajectories and intensification, including if they are a necessary condition for the medicane genesis itself. Then, a collection of control simulations has been made in the first place to evaluate the ability of a mesoscale model to reproduce medicane events (Section 3.1) as a necessary requirement to use the methodology here planned (Section 3.2). After that, the sensitivity analysis aimed at determining what is the specific role of surface heat fluxes on medicane characteristics has been carried out (Sections 3.2 and 3.3) including a qualitative interpretation based on the spatial distribution over the Mediterranean of the enthalpy fluxes during the episodes (Section 3.4).

2. Methodology

The collection of twelve medicanes detected subjectively from a satellite based climatology using IR Meteosat channel (Tous and Romero, 2012) is used as a database in this study. The restrictive selection criteria applied to identify these events in the satellite images were based on the detailed cloud structure, size and lifetime of the systems. These cyclones are located in the central and western Mediterranean, and are more frequent during the cold seasons (winter and autumn), although they also occur in spring, in contrast to real tropical cyclones that tend to occur during a few fixed months of the year (for example, from June to November in the Atlantic area).

A set of numerical simulations (hereafter, CTR) was run in order to determine if the model physical parameterizations, other chosen parameters (simulation period, domain, resolution, etc.) and the input initial and boundary conditions are suitable to reproduce successfully the medicane events (Table 1). The model used in this study is the non-hydrostatic version of the Fifth-Generation NCAR/Penn State Mesoscale Model MM5v3 (Dudhia, 1993; Grell et al., 1995). Each simulation lasts 48 h, starting about 24 h before the mature phase of the observed medicane, and the forecast output is recorded every 3 h during all the period to be sure to include the formation phase of the storms. The simulation domain spans a grid of 196 × 196 points spaced 7.5 km in the zonal and meridional directions and in each case it is centered at the location of the observed mature phase, too. In the vertical, 31 terrain-following σ levels were used with enhanced resolution in the lower troposphere. The diabatic heating associated with the latent heat released in the convective cloud systems developed during the simulation is particularly relevant in this study. The Kain and Fritsch (1990) convective parameterization scheme was used here. The microphysics scheme Reisner graupel, based on a mixed-phase scheme but adding graupel and ice number concentration prediction equations, was used for the resolved-scale moist processes. For boundary-layer processes, a modified version of the (Hong and Pan, 1996) PBL scheme, also called MRF, was applied which uses a countergradient term and K profile for diffusion processes.

Meteorological grid analysis data from the ECMWF were used for the initialization and boundary forcing of the simulations. The best possible horizontal resolution of these analysis was considered, which depends on the year but is about 85 km, and they are available every 6 h (at 00, 06, 12 and 18 UTC). Observations from soundings and surface stations stored in the Global Telecommunication System (GTS) archive were also ingested to improve the fields according to the initialization scheme explained in detail in Grell et al. (1995), and in this case, the availability is every 6 h for surface data (like analysis data) and 12 h for other levels (at 00 and 12 UTC).

An additional set of simulations (hereafter, NOFLX) has been performed to confirm the important role of air–sea interaction in medicane development. In these simulations surface sensible and latent heat fluxes (SurFlux) are explicitly

Table 1
Code, date, starting simulation time (UTC) and geographical coordinates of domain center.

Code	Date	Time (UTC)	Lat (°N)	Lon (°E)
M01	1983-Sep-28	00	41.1	6.8
M02	1984-Apr-06	12	36.4	19.2
M03	1984-Dec-29	12	35.4	11.6
M04	1985-Dec-13	12	35.5	17.6
M05	1991-Dec-04	12	36.2	16.7
M06	1995-Jan-14	00	37.4	19.1
M07	1996-Sep-11	12	39.4	2.8
M08	1996-Oct-05	12	37.2	3.9
M09	1996-Dec-09	00	40.3	3.7
M10	1998-Jan-25	12	36.7	17.9
M11	1999-Mar-18	00	38.5	19.6
M12	2003-May-26	00	40.1	2.8

set to zero in the MRF boundary layer parametrization. By comparing both types of simulations, we can establish how important is the SurFlux in the development and intensification of medicanes. But not only it is possible to examine if the surface heat fluxes are an essential factor for their formation, it is also possible to assess if different patterns of behavior arise depending on how the SurFlux spatial distributions evolve in relation to the medicane trajectory, from genesis to mature state. For that purpose, as surrogates of SurFlux maps, we determined from CTR outputs the moist enthalpy differences over the Mediterranean between the sea surface level (SST level) and a near atmospheric level (2 m):

$$\begin{aligned} &\mathrm{SurFlux} = K^{\star}_{\mathrm{SST}} - K_{2\mathrm{m}} \\ &\text{where, } K = \left(C_{\mathrm{pd}} + r_t C_{\mathrm{l}}\right)T + L_{\mathrm{v}} r \end{aligned} \tag{1}$$

In the expression, the star ($\star$) indicates saturation conditions at SST. SurFlux has J/kg units, and the total water mixing ratio (r_t), in this case, can be approximated to r, the vapor mixing ratio. It should be reminded that the moist enthalpy surface fluxes, largely regulated by the difference expressed in Eq. (1), become a key ingredient in the air–sea interaction theory of tropical cyclones (Emanuel, 1986).

Furthermore, the distribution of trophospheric precipitable water (PRWA, in mm) close to medicane environment will be beared in mind during the analysis. This meteorological variable is closely related with SurFlux, specifically with the evaporation from the Mediterranean.

3. Results

3.1. Capability of the MM5 model to simulate medicane events

Medicanes are deep cyclones with a low-mid tropospheric warm core. In order to assess if the model simulates a medicane, it would be expected to find a quasi-symmetric intense low-pressure center at sea level with an isolated warm-core structure aloft (in our case, evaluated at 700 hPa level), the typical structure found in tropical cyclones.

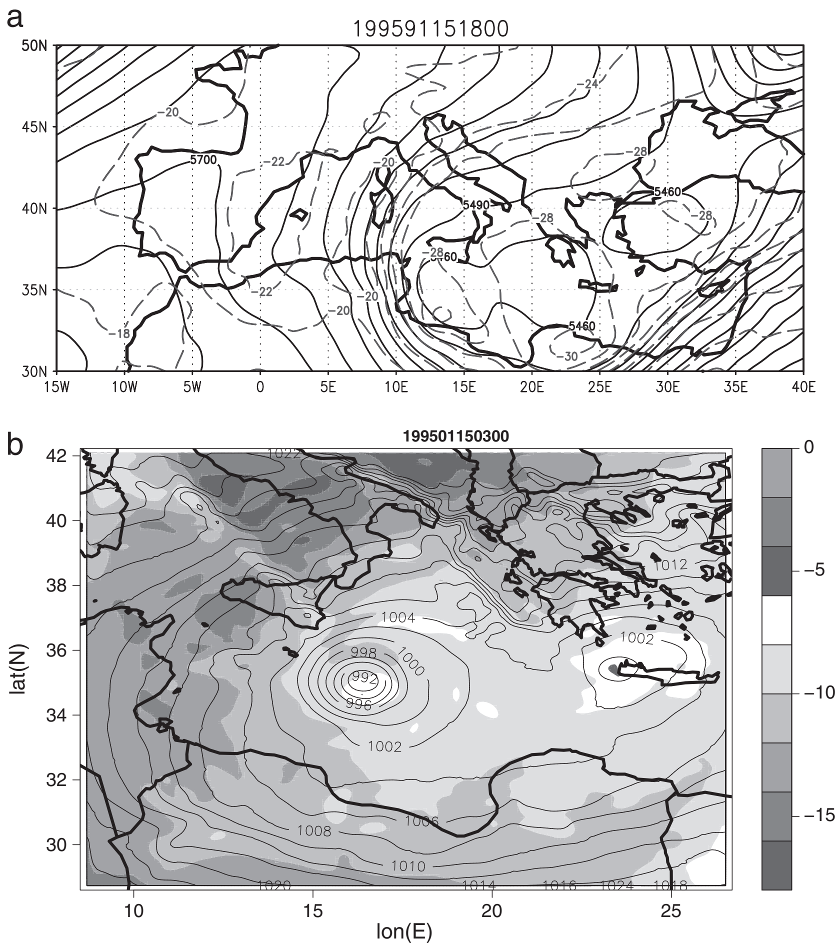

Fig. 2. M06 event. a) Geopotential height (gpm, continuous lines) and temperature (°C, dashed lines) at 500 hPa on January 15th 1995 at 18 UTC. Simulation domain is represented as the thick square; b) simulated sea level pressure (every 2 hPa, continuous lines) and temperature at 700 hPa level (°C, filled contours according to scale) by the CTR simulation on January 15th at 03 UTC.

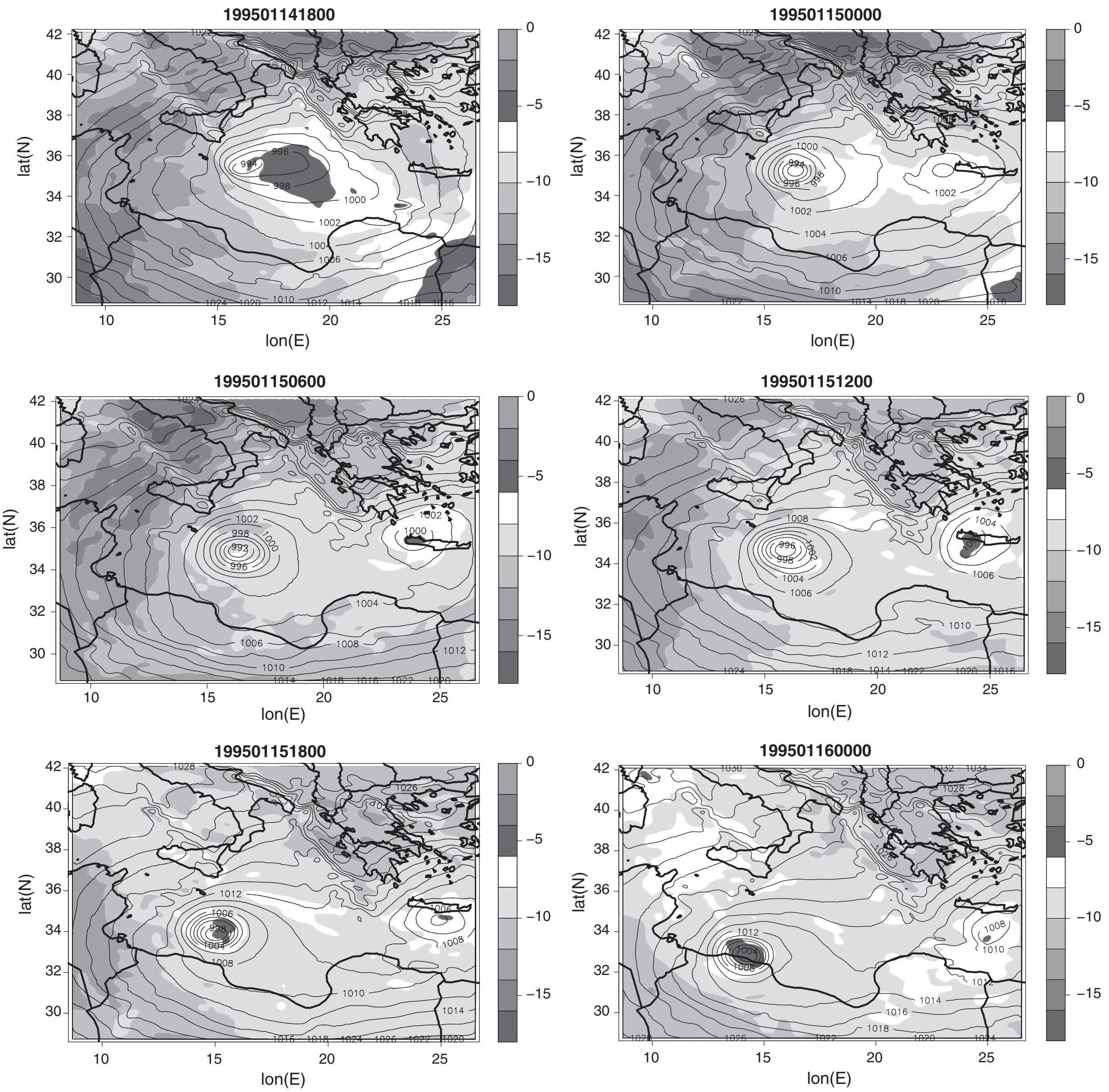

Fig. 3. M06 event. Simulated sea level pressure (every 2 hPa, continuous lines) and temperature at 700 hPa level (°C, filled contours according to scale) by the CTR experiment.

Our input synoptic-scale analyses for an illustrative example (Fig. 2a) tend to confirm the hypothesis made by some authors (e.g. Pytharoulis et al., 2000; Homar et al., 2003; Emanuel, 2005) that medicanes are not fully isolated structures of the atmospheric circulation. They require a large-scale baroclinic disturbance evolving over the Mediterranean and only during the mature or late stages of this parent cyclonic storm, a medicane might develop. They almost always develop under deep, or cut-off, cold core cyclones present in the upper and middle troposphere, usually formed as a result of the “breaking” of a synoptic scale Rossby wave. As (Emanuel, 2005) showed through his numerical experiments using an axisymmetric, cloud-resolving nonhydrostatic model, these conditions are indeed ideal incubators for surface flux-driven, small-scale, warm-core cyclones.

Although from the previous figure it would not be possible to anticipate a medicane developement, the CTR mesoscale simulation (Fig. 2b) evidences the development of a tropical-like cyclone during the simulation period. In this case, thetime shown is 03 UTC on January 15th, 1995. A symmetric intense cyclone (with a pressure gradient of 13.82 hPa in 142.5 km) and a warm core is clearly developed to the east of Sicily. The

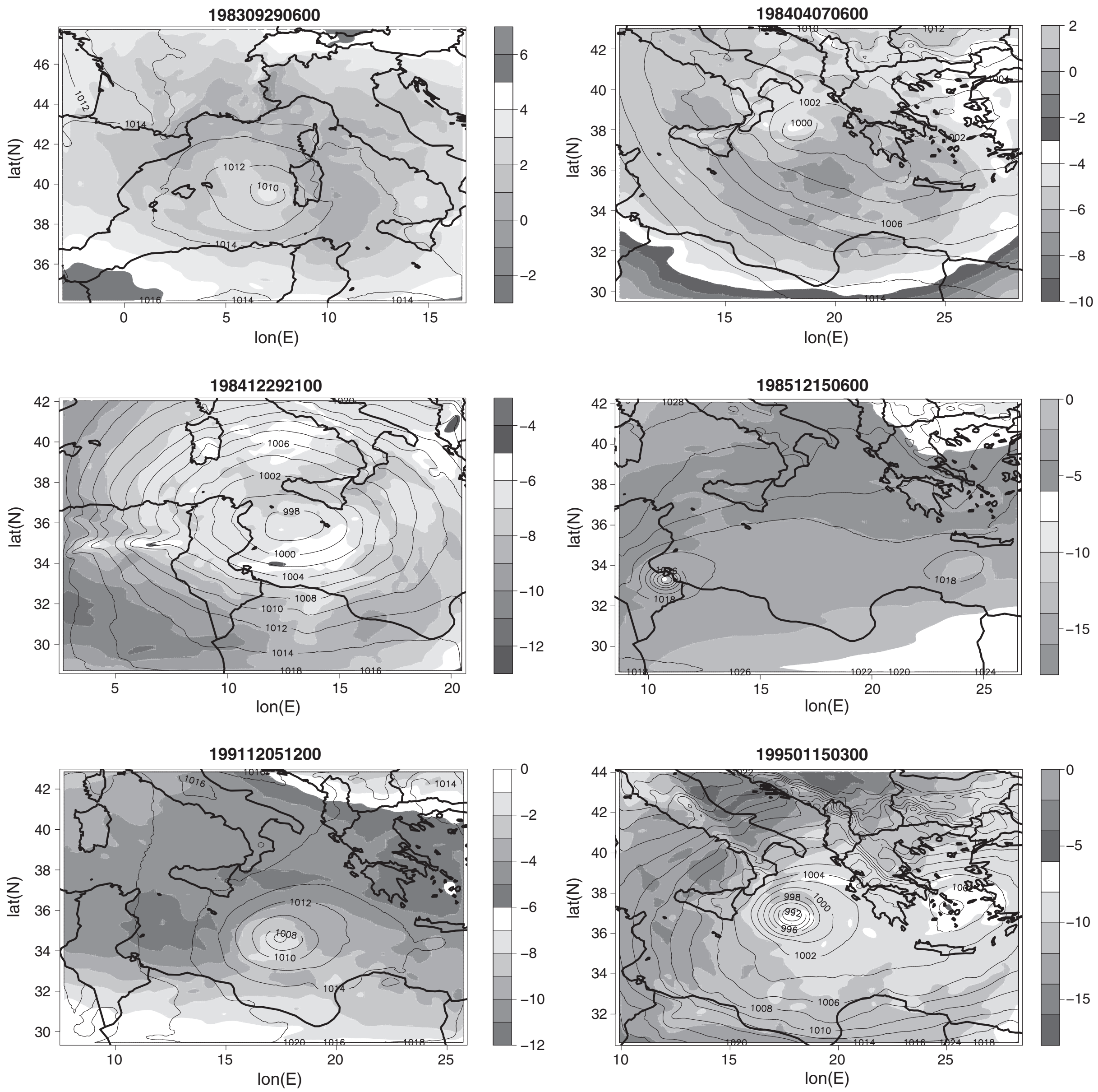

Fig. 4. As in Fig. 3 but for representative times of M01–M06 CTR simulations (from left to right and from up to down, respectively).

last steps of the simulation period (here every 3 h) are shown in Fig. 3. After its genesis during the late hours of January 14th, the low becomes intense and keeps its symmetry and warm core during the rest of the simulation. The lifetime of this long-lasting medicane was 78 h according to satellite archive, then it is logical that, at the end of the simulation, the cyclone is still quite intense.

Since there is not a clear definition of what is already a medicane just looking at the meteorological fields, it is not practical to determine precisely the first moment the cyclone can be classified as medicane in our simulations. Some authors use the cyclone phase evolution in the diagrams developed by Hart (2003). These diagrams permit to classify the cyclones as symmetrical or asymmetrical, and as cold or warm cores structures. In the study here presented, we do not use this method because its parameters were adjusted for much bigger cyclones (in the order of tropical cyclones) than medicanes, and also on the basis of lower-resolution grid data. Furthermore, it is not the goal of this study to catalogue the transition phase from a regular cyclone to a medicane; a mere qualitative assessment of the capability of the model to simulate the medicane is enough for our purposes. Even so, after looking at the simulation of the present case, we will consider that the medicane has been fully developed at 00 UTC January 15th

(Fig. 3). This simulation goes ahead on time of the true event, because satellite images show that the mature phase is reached at 18 UTC the same day.

Figs. 4 and 5 exemplify the ability of the model to simulate medicane-like storms. Most of the cases are well represented, especially M04, M05, M06, M09 and M12. Even though cases M01, M02, M07, M08, M10, M11 become less intense, a small cyclone with a warm-core is still simulated, so the model configuration is considered adequate here, too. Just M03 does not evolve into a medicane or a similar structure. M07 and M08 simulated storms have a very short lifetime (significantly less than real events), not enough to properly follow their characteristics. For these reasons, M03, M07 and M08 are discarded for the next steps of the study here presented.

3.2. Surface heat fluxes influence on medicane trajectories

In this section, NOFLX simulatons are compared with CTR ones. Apart from possible temporal shifts, three main responses can be examined: 1) changes in the track position (i.e. medicanes do not follow the same trajectories); 2) in medicane speed (i.e. for the same time, the translation of their centers between two or more time steps differs); and 3) in the lifetime of the cyclone.

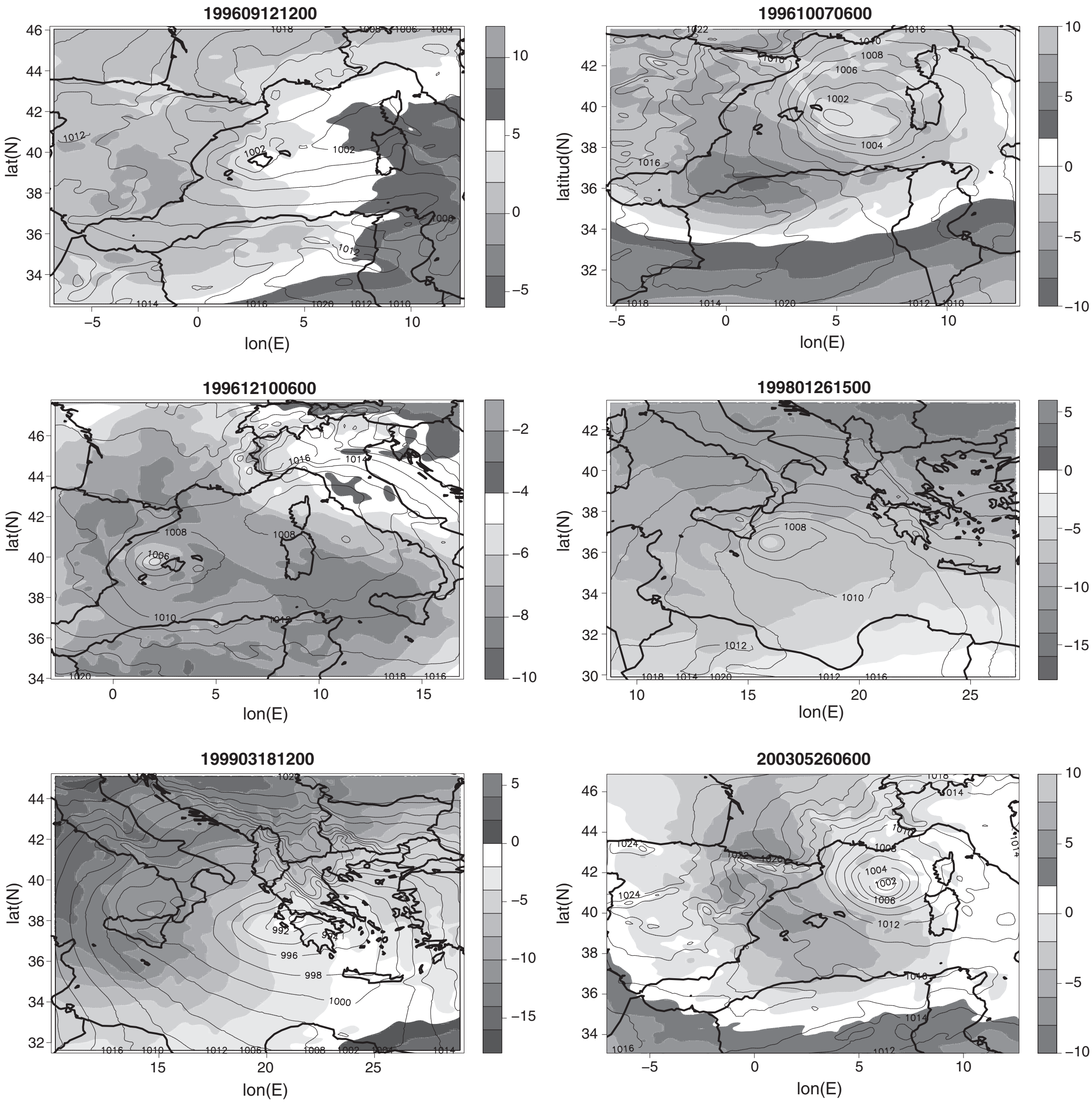

Fig. 5. As in Fig. 3 but for representative times of M07–M12 CTR simulations (from left to right and from up to down, respectively).

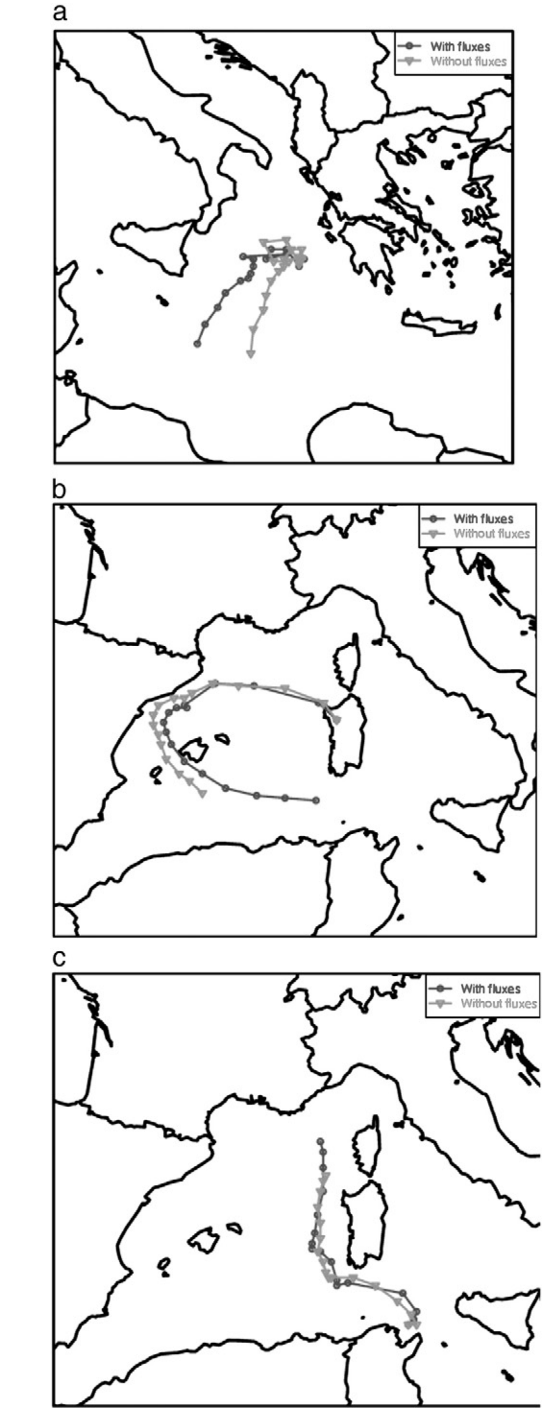

Fig. 6. Examples of how the surface heat fluxes influence the cyclone trajectories: a) M06 event (TR1, location influenced); b) M09 event (TR2, speed and/or lifetime influenced); and c) M01 event (TR0, no significantly influenced).

The events have been grouped in three different classes depending on which kind of SurFlux influence they exhibit: track location influenced (TR1), speed and/or lifetime influenced (TR2) and no significantly influenced (TR0). As TR1 we would include M04, M06 and M10; as TR2 we find M02, M05, M09 and M12; and as TR0 the cases M01 and M11. For the sake of brevity, only one example of each category is described in detail: M06, M09 and M01, respectively (Fig. 6).

- *TR1*. Already at the first simulation steps, CTR and NOFLX simulations differ in trajectories for M06 (Fig. 6a). NOFLX simulation trajectory lies on the eastern side of the CTR one. This also happens in M04 but not inM10, where the relative positions of the tracks are on the other way around (i.e. westward from CTR). Going back to M06, we can observe a shift between trajectories of about 160 km. This distance is kept approximately constant during most part of the evolution. Furthermore, keeping in mind that the diameter of this medicane is up to 300 km (Fig. 3), this spatial shift is considerable.
- *TR2*. This group also exhibits some spatial shifts in the medicane tracks (Fig. 6b), but this difference is much lower than in TR1, while the main effects in this case come from the medicane speed and/or lifetime. Accordingly, both trajectories accumulate a difference in length of 330 km at the end of the simulation. In two cases (M02 and M05), NOFLX simulated cyclone vanishes before CTR (these lifetime differences are 9 and 6 h, respectively). Despite this,taking as reference the last common timestep, there is also a significant difference in track lengths between both simulations. These differences in the storm speed are specially notable towards the end of the track (see Fig. 6b).
- *TR0*. Finally, the TR0 group (Fig. 6c) exemplifies a non significant difference between CTR and NOFLX simulations, i.e. a small effect of surface heat fluxes on medicane trajectory.

3.3. Surface heat fluxes influence on medicane intensification

To analyze the surface heat fluxes influence on medicane intensification, the central minimum sea level pressure of the simulated cyclones is considered. Therefore, this value is tracked along the full cyclone trajectory whenever it is possible to recognize a cyclonic structure, not necessarily with pure medicane characteristics.

The results confirm the cyclogenetic action of the surface heat fluxes on this kind of storms (Fig. 7). As in the previous section, it is possible to recognize three distinct kinds of influences. The first one consists of small differences in pressure values at the beginning of the development (although CTR simulations have lower values), followed by a big drop just in CTR and a slight recovery (or filling of the disturbance) but not reaching NOFLX higher values (IN1). The second kind of influence (IN2) is a growing difference between minimum pressures during the full cyclone lifetime. This difference can be higher or lower depending on the event, but at the end of the simulations, there is noticeable disparity in cyclone intensity. Finally, the last group comprises the low influence cases (IN0). The same events used to explain the influences on trajectory (M06, M09 and M01) are also useful in this section.

- *IN1*. M06 CTR simulation is shown in Fig. 7a, as an example of IN1, presenting much lower values than NOFLX during

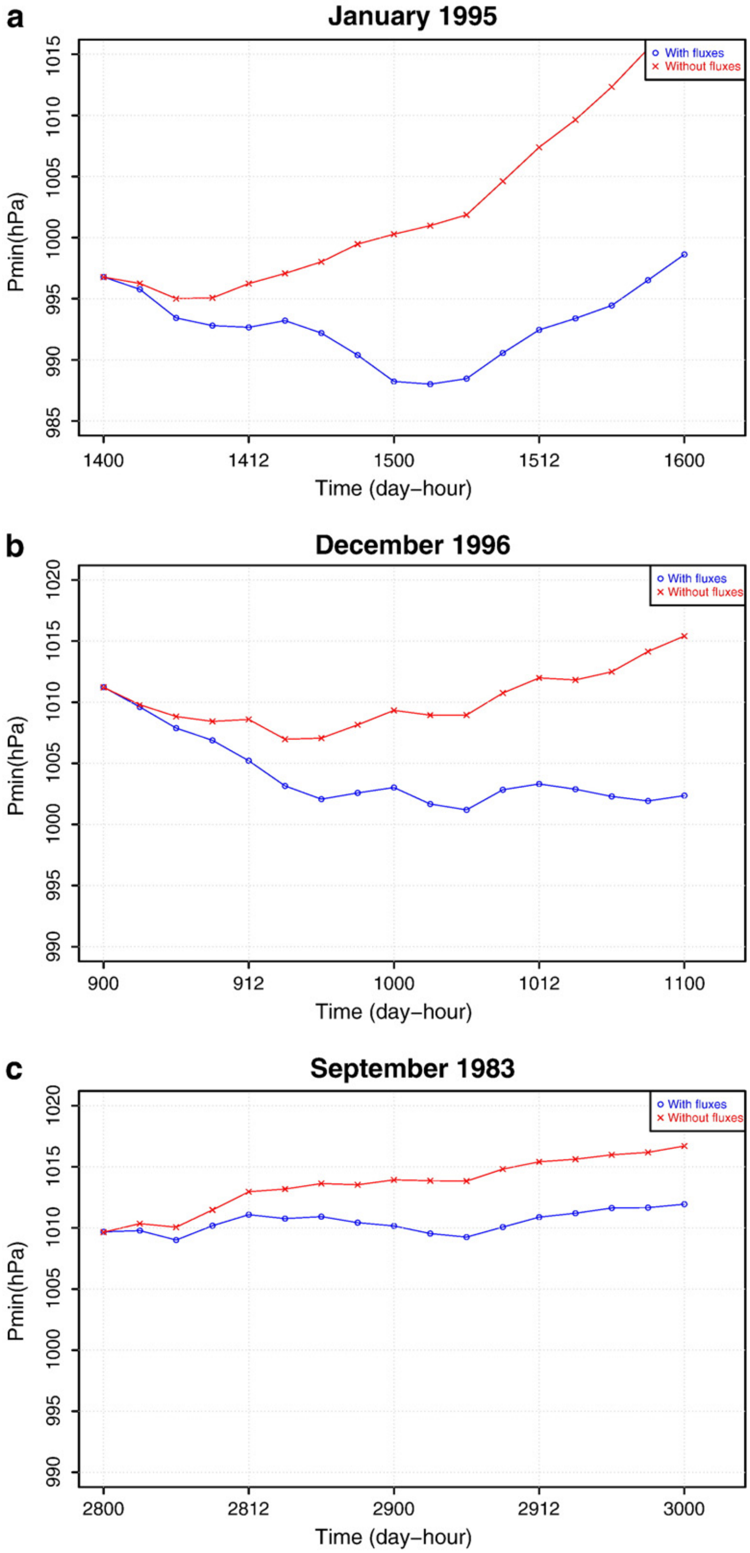

Fig. 7. Examples of how the surface heat fluxes influence the cyclone intensification: a) M06 event (IN1, big drop just in CTR); b) M09 event (IN2, growing difference); and c) M01 event (IN0, low influence).

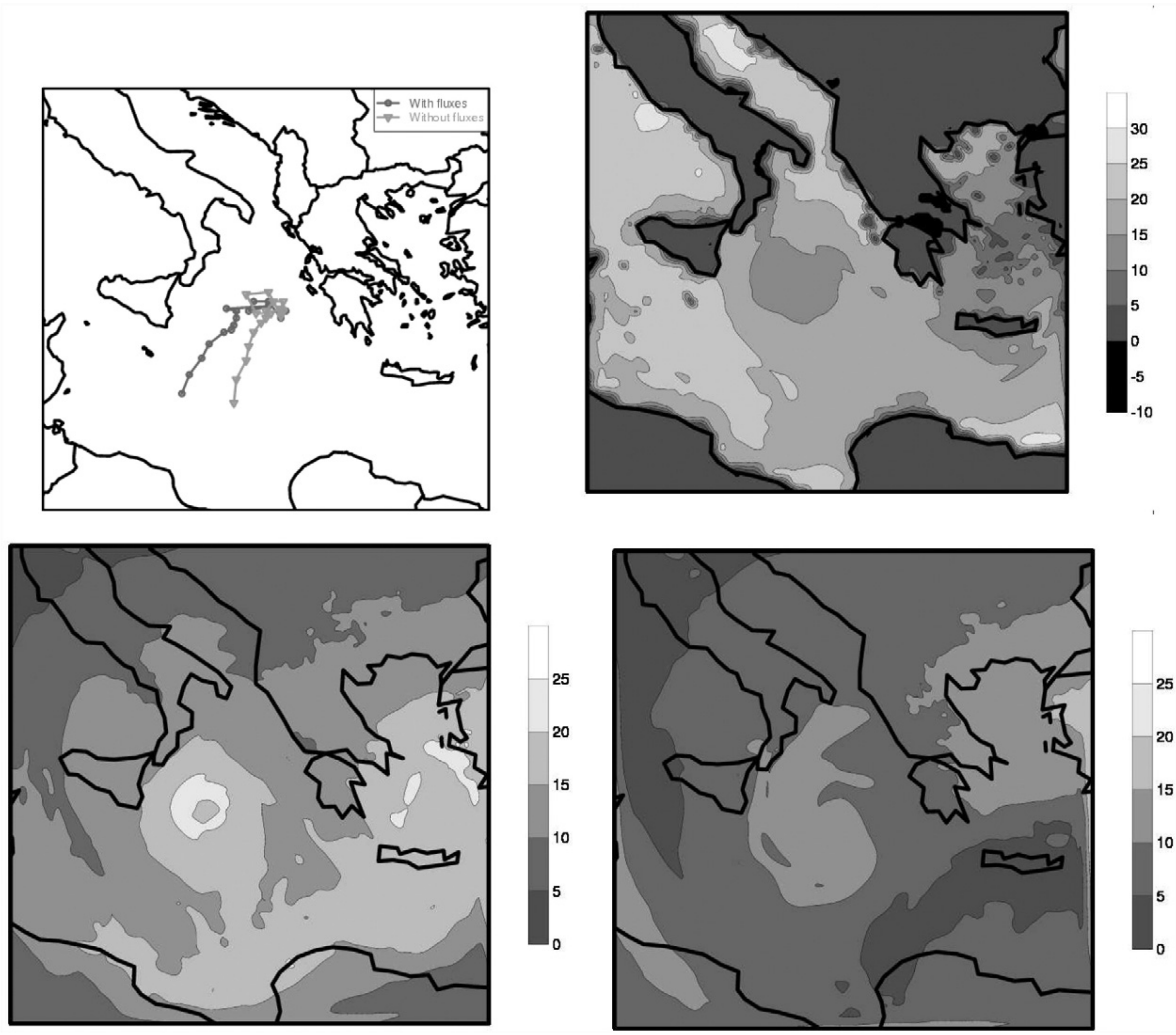

Fig. 8. M06 event (on January 15th 1995 at 12 UTC), representative of TR1 and IN1 classes. Top left: trajectories with and without fluxes (dark and light gray, respectively). Top right: SurFlux potential (filled contours, in 10^3 J/kg). Bottomleft: PRWA in CTR simulation (filled contours, in mm). Bottom right: PRWA in a NOFLX simulation (filled contours, in mm).

all the period. The high deepening rate in CTR starts on January 14th at 15 UTC, leading to a minimum central pressure of 988 hPa on January 15th, at 03 UTC, and it is not until 15 UTC that the system has filled and the initial values are restored. The minimum central pressure value in NOFLX is reached at the third time step of the simulation, so it can be seen that the system is ineffective in gaining intensity during the simulation. On Jan. 15th at 03 UTC, the central value is 1001 hPa, 13 hPa higher than in CTR.

- *IN2*. A case of growing difference between the cyclone pressure minima can be seen in Fig. 7b. At the moment when CTR medicane has its minimum value (that is on Dec. 10th at 06 UTC), there is a gap of 7.2 hPa with respect to the NOFLX weaker cyclone. At the end of the simulation, this difference grows up to 13.0 hPa.
- *IN0*. Lastly, simulations as M01 (Fig. 7c), do not present a notable difference between simulated central pressures, just slight changes (it is logical to understand that cyclone intensification is positively related with heat fluxes, although this dependence is not as crucial in this case). In CTR simulation it is possible to determine two minima: the first one, as it happened before, occurs during the first time steps, so it will be not considered because the system isstill under the influence of the spinup process of the model; and the second one, occurring on September 29th at 06 UTC, is taken as representative of the medicane. In this case, the central pressure does not drop too much, and the minimum value isfixed at 1009.2 hPa. At the same time, NOFLX has a central pressure of 1013.8 hPa. At the end of the forecast period, when the difference between the two simulations is maximum, it is of 4.8 hPa. As it has been noted, these values are weaker than in the other cases.

3.4. Interpretation in terms of precipitable water and surface heat fluxes influences distributions

Once confirmed the different types of SurFlux influences on medicane properties, it is time to analyze the connection

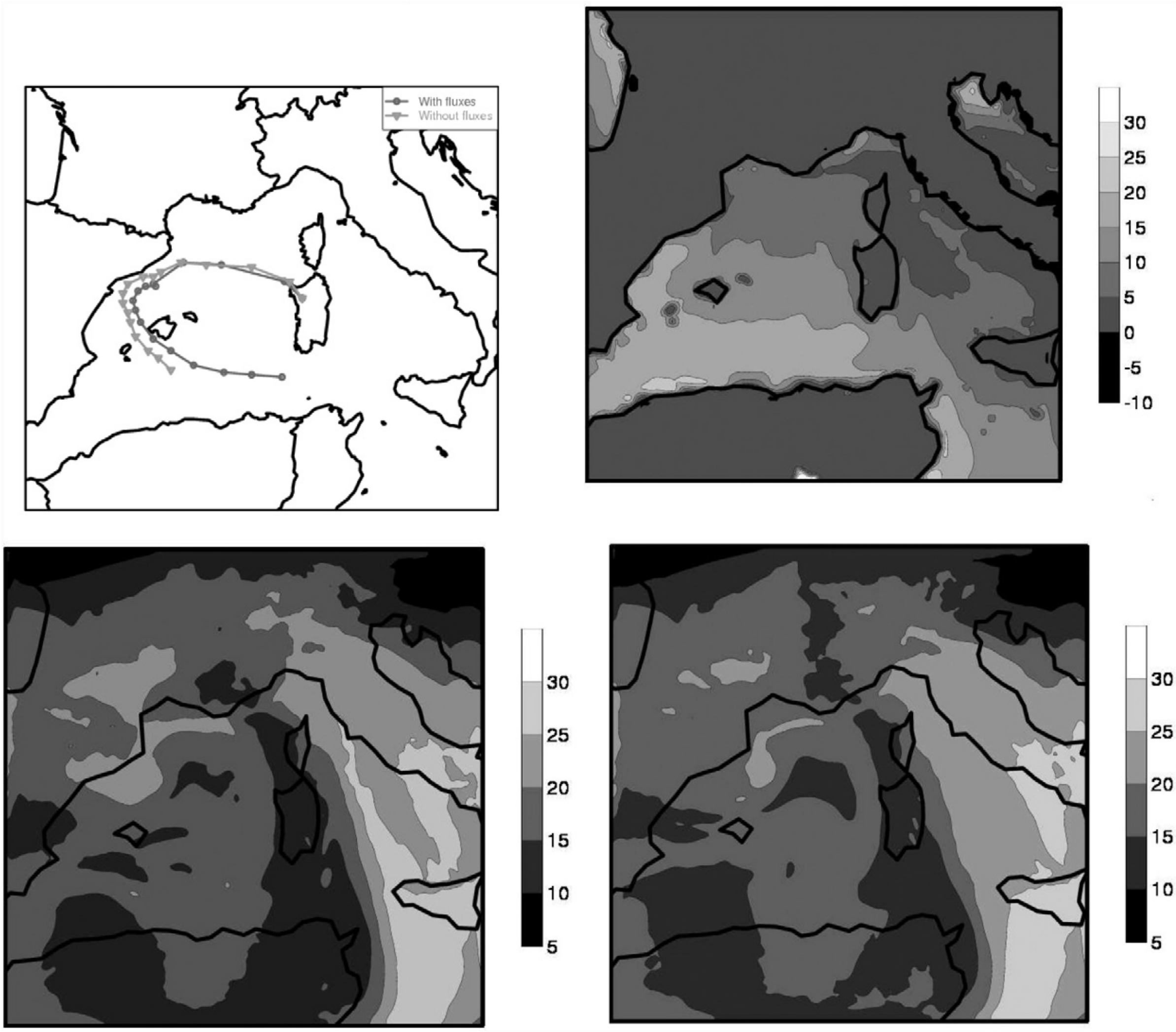

Fig. 9. M09 event (on December 10th 1996 at 12 UTC), representative of TR1 and IN1 classes. Top left: trajectories with and without fluxes (dark and light gray, respectively). Top right: SurFlux potential (filled contours, in 10^3 J/kg). Bottom left: PRWA in CTR simulation (filled contours, in mm). Bottom right: PRWA in a NOFLX simulation (filled contours, in mm).

with the spatial patterns of the physical variables. To this end, the SurFlux potential distribution via Eq. (1) is compared with precipitable water maps in CTR and NOFLUX simulations. The same events used in previous sections are also studied here (Figs. 8–10).

At the beginning of the M06 CTR simulation, low values of SurFlux occur where the parent cyclone is developing. Upper level dynamical forcing drives the cyclone to the west, where there are higher values of SurFlux, especially the latent flux contribution (not shown). Consequently, the convection increases. Faster surface winds are present, and this stimulates further the evaporation. Very high values of PRWA are concentrated in the environment around the cyclone center. The central pressure decreasesand it becomes a deep small warm-core cyclone or medicane (Fig. 8). After a while, when the fluxes become lower around the cyclone position and the neighboring regions, the intensification stops, and the cyclone dynamics is determined by the large-scale circulation. In the NOFLX simulation, PRWA values are lower than in CTR one during all the simulated period, so the moist convection is less promoted and latent heat release in the troposphere is more limited. Consequently,a weaker cyclone largely influenced by the general circulation is developing in these circumstances.

In M09 case, surface potential fluxes are lower than in M06 CTR and quite uniform in distribution along the medicane path (Fig. 9). Due to this fact the evaporation from the Mediterranean is lower and the resulting convection is not so powerful. PRWA has lower values than in the previous event, too. For these reasons, it is not possible for the cyclone to become as intense as in M06. Nevertheless, fluxes are still significant and higher values occur in the cyclone environment when it migrates

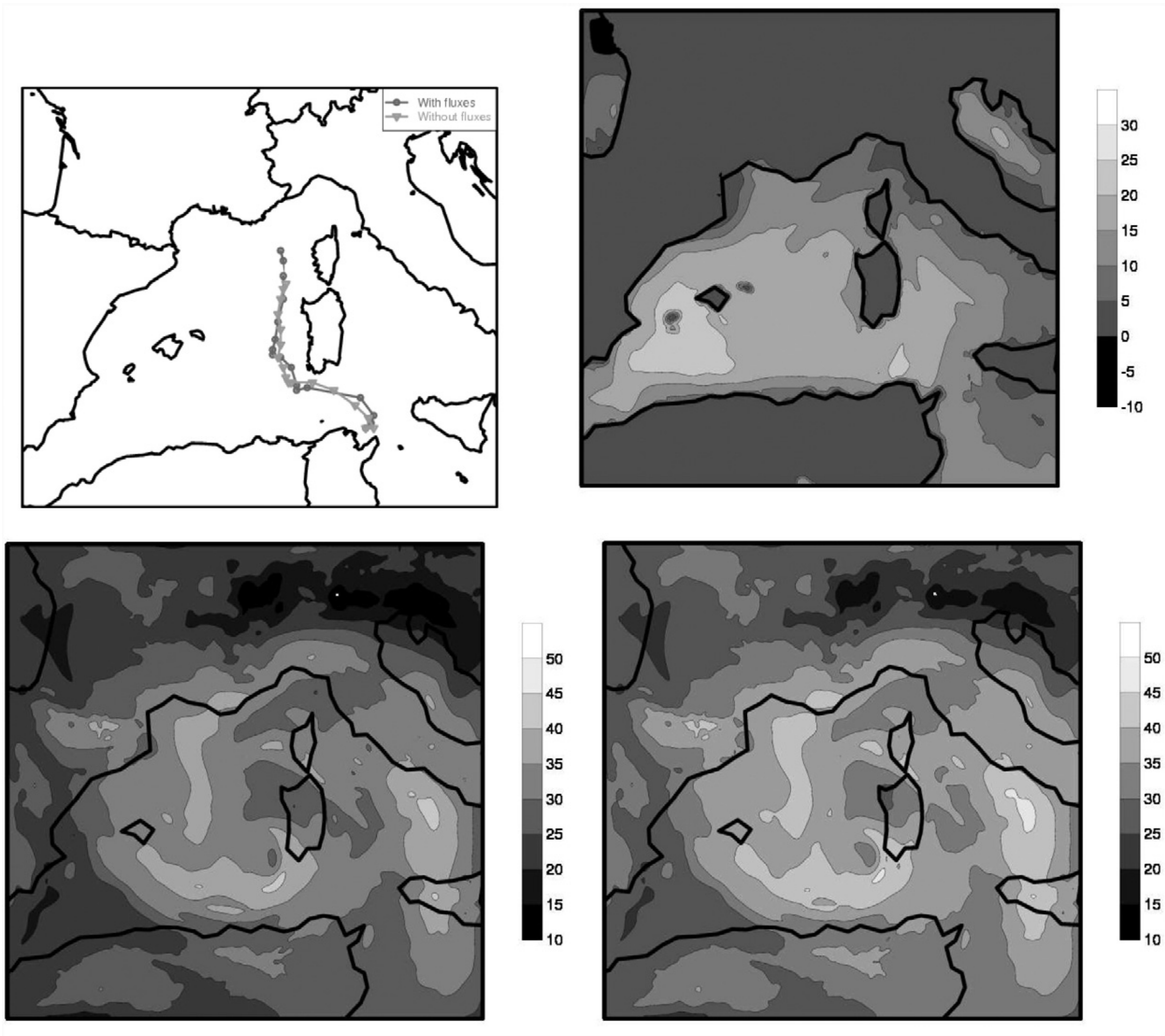

Fig. 10. M01 event (on September 29th 1983 at 00 UTC), representative of TR1 and IN1 classes. Top left: trajectories with and without fluxes (dark and light gray, respectively). Top right: SurFlux potential (filled contours, in 10^3 J/kg). Bottom left: PRWA in CTR simulation (filled contours, in mm). Bottom right: PRWA in a NOFLX simulation (filled contours, in mm).

southwards towards the end of the simulation, coinciding with the time period when the differences between CTR and NOFLX simulations are the largest. PRWA values are quite similar in CTR and NOFLX along the cyclone track.

In M01 CTR, higher values of SurFlux potential are found between the Iberian peninsula and the Balearic islands, far from cyclone track (Fig. 10). Therefore, the cyclone properties are less influenced by the air–sea interaction mechanism. Close to the Corsica and Sardinia coasts, along which the cyclone is evolving, field values are lower than in previously considered events, and the spatial distribution is quite uniform. Only during the first timesteps, SurFlux values along the cyclone path are noticeable, so it is when higher differences in cyclone intensity, although not too large, are built (recall Fig. 7c). After that initial period, departures in medicane properties between the two simulations remain nearly constant.

4. Conclusions and further work

MM5 simulations with a horizontal resolution of 7.5 km seem to be appropiate to characterize medicane precursor situations. Most of the simulated cases show the development of an axi-symmetrical intense cyclone with a warm core. These experiments have permitted us to examine in some detail the physical mechanism involved in their development and dynamical properties, as well as to make a sensitivity analysis to test and describe the air–sea interaction mechanism operating on them.

Surface heat fluxes and tropospheric precipitable water magnitudes and distributions influence medicane tracks, speed or lifetime. This influence can be on just one of these characteristics or on a combination of them, although occasionally it is almost indistinguishable, especially in those cases insufficiently matured in the simulations. The intensification of

Table 2
Summary of sensitivity test. Influence on medicane trajectory: light, moderate and dark shaded circles indicate, respectively, TR1, TR2, TR0 type results (see text). Influence on medicane intensity: light, moderate and dark shaded backgrounds indicate, respectively, IN1, IN2 and IN0 type results (see text). White boxes indicate the three medicane events that produced inadequate CTR simulations.

M01	M02	M03	M04
M05	M06	M07	M08
M09	M10	M11	M12

central pressure gradient in medicanes is also shown to be positively influenced by surface heat fluxes and precipitable water when the cyclone moves over areas with high sea–atmosphere moist enthalpy differences. A schematic summary of the sensitivity tests is included in Table 2. In general, there is a tendency for the surface heat fluxes to exert the same degree of influence (low, medium or high) on both the medicane trajectory and medicane intensity, although with some exceptions.

These results reinforce the idea of an important role of air–sea interaction for medicane development, but a crucial factor for this special type of mid-latitude warm-core cyclone seems to come from the synoptic-scale dynamical forcing. New numerical experiments with weakened (or strengthened) upper-level PV anomalies are underway to test and quantify this hypothesis.

Acknowledgments

This research has been supported by MEDICANES project (CGL2008-01271/CLI) and PhD grant BES-2009-022616 from the Spanish “Ministerio de Ciencia e Innovación” and “Ministerio de Educación y Ciencia”, respectively.

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