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Simulation of a Mesoscale Cyclone over the Mediterranean Sea

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I. Introduction

A rare tropical-like storm with winds near its center approaching hurricane force formed over the Mediterranean Sea in January 1982. The system first appeared immediately ahead of the axis of an upper-level cold trough, in a region characterized by light to moderate winds aloft and relatively weak thermal gradients. A strong, moderately baroclinic subtropical jet lay to its south and east. During the first phase of its development, when the system was of small synoptic-scale size, the low deepened nearly 20 mb in 48 hours, as it moved northward from a position midway between the Libyan coast and Sicily, to the coastal waters off Sicily's southeastern tip. Subsequently, the low made a small loop and headed eastward to the Ionian Sea (see Fig.1), where it did a second small loop before traveling again eastward between the Greek Peloponnesus and Crete, to the vicinity of Rhodes, where it dissipated. During this second phase, the low-pressure system shrank in size, shedding its outer isobars, and assumed the appearance of a convective vortex or tropical-like storm. Satellite imagery exhibited a comma or doughnut-shaped cloud pattern with a distinct eye during this later phase (Fig.2). A synthetic sounding (not shown), based on the surface temperature and dew point from a ship caught in the storm, and based on upper-air temperatures interpolated from surrounding land stations, revealed that the vortex was situated in an environment that was highly unstable to upright convection.

A simulation of this storm using an earlier version of the Penn State - NCAR mesoscale

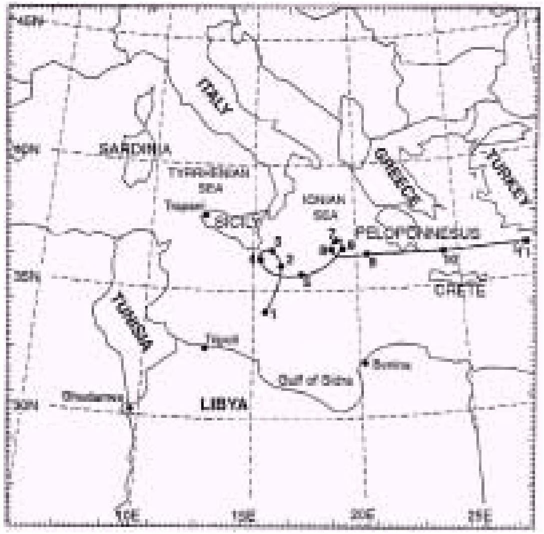

Fig. 1. Model domain, geographical locations and storm track. Dots show low positions at 12-h intervals (1: represents 1200 UTC 23 Jan).

Fig. 2. NOAA 7 infrared satellite image at 1232 UTC 26 January. Reproduced from Billing et al. (1983).

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model, MM5, by Reed et al. (2001) was met with mixed success. The 20-km MM5, initialized at 0000 UTC 23 January 1982, failed to predict the contraction of the storm from subsynoptic-scale to mesoscale dimension. Also, the predicted cyclone track deviated substantially from the observed track. In this paper, we present results from an improved simulation of this case, using the latest version of MM5 with improved model physical parameterization, grid resolution, and model initial condition. With a successful simulation, we then examine the structure of this mesoscale cyclone and study the physical processes responsible for its development.

2. Experiment Design

Following Reed et al. (2001), we began our simulation at 0000 UTC 23 January. A major shortcoming of the earlier simulation was the poor quality of the model initial condition over the Mediterranean Sea. For example, the satellite image at 0144 UTC 23 January showed a well-organized cloud band (Fig. 3) that was associated with the incipient cyclone. However, this cloud band was not reflected in either the temperature or the humidity analysis. In order to improve the model initial condition, we performed a subjective analysis of sea level pressure, and temperature and relative humidity in the lower troposphere (from surface to 500 mb). We then digitized the analysis at 1-degree intervals, and incorporated the digitized supplementary data into the objective analysis. Figure 4 is the moisture analysis at 850 mb with the supplementary data included, which shows saturation over regions where the cloud band was located.

In this paper, we report results from four numerical experiments. We first conducted a big-domain (BD) experiment, using the Penn State - NCAR mesoscale model MM5, with triply nested (81/27/9 km) grids. The model was initialized at 0000 UTC 23 January 1982, using the ECMWF ERA-15 analysis, which incorporated both the traditional surface and upper-air observations, together with the supplementary data derived from the subjective analysis. This version of MM5 used the following physics options: Betts-Miller cumulus parameterization, Reisner-I mixed-phase microphysics, Blackadar planetary boundary layer (PBL) scheme, and Dudhia radiation scheme. The domain of the various grids is shown in Fig. 5.

Fig. 3. Same as Fig. 2, except at 0144 UTC 23 January 1982.

Fig. 4. Subject analysis of relative humidity at 850 mb at 0000 UTC 23 January 1982.

The next three experiments are single domain experiments, with a grid size of 3 km, nested within the 9-km grid of the big-domain experiment. In the full-physics (FP) experiment, we used physics options identical to those of the BD experiment, with the exception that the subgrid-scale cumulus parameterization was turned off. To assess the importance of surface energy fluxes, we deactivated surface latent and sensible heat fluxes in Experiment NF (no-flux). Experiment F10 was similar to FP, except that we limited the wind speed to 10 m/s in the calculation of surface energy and momentum fluxes. This prevents the positive feedback between the cyclone and the surface energy fluxes, as the calculation of the fluxes are restricted to that associated with the wind speed of 10 m/s.

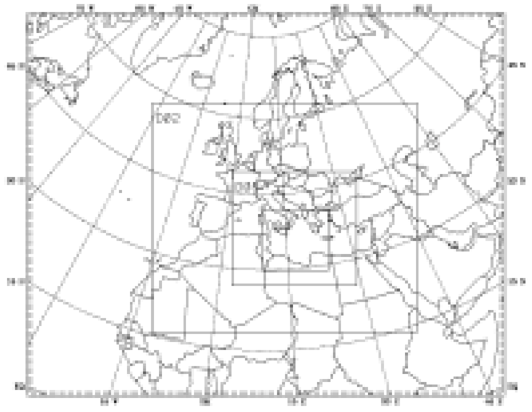

Fig. 5. Domains of the numerical experiments. D01, D02, D03, and D04 are 81, 27, 9, and 3 km grids, respectively.

3. Evolution of Full-Physics Simulation

The full-physics experiment was very successful in simulating the outbreak of convection, with the initial condition enhanced by the subjectively prepared supplementary data set. Within a few hours, a cloud band (Fig. 6a) developed with the shape, size and location consistent with the satellite image (Fig. 3). The incipient surface cyclone had a central pressure of 1012 mb in the model initial condition. Despite active convection, there was very little intensification during the first 9 h of the simulation. At 0900 UTC 23 January, several small-scale, weak, low centers were found on the southern periphery of the rainband, with values ranging from 1010 mb to 1012 mb, and no apparent cyclonic circulation (not shown).

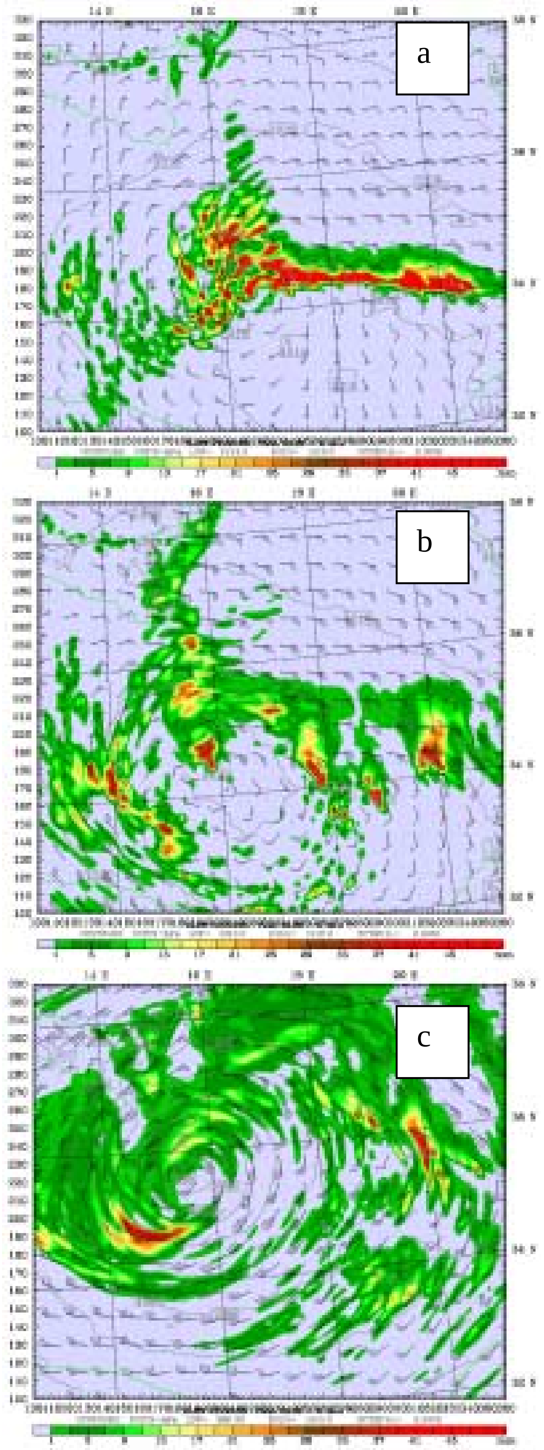

Fig. 6. Sea-level pressure and 3-h accumulated rainfall for the full-physics (FP) experiment at 6-h, 12-h, and 36-h forecast.

By 1200 UTC 23 January, one mesoscale convective system, associated with high potential vorticity, began to deepen and form a mesoscale cyclone (Fig. 6b). Rapid deepening took place in the next 24-h, bringing the central pressure from 1010 mb to 996 mb. At 1200 UTC 24 January (Fig. 6c), the Mediterranean Sea cyclone was well developed, and was located to the southeast of Sicily with nearly perfect positioning and intensity. The distribution of wind and sea-level pressure contours compare favorably with the observations (see Fig. 5 of Reed et al. 2001). The wind field at 1 km elevation indicated maximum speed exceeding 55 kts at approximately 50 km to the northwest of the low center. This is also consistent with available observations.

Subsequently, the surface cyclone deepened further to 992 mb by 2100 UTC 24 January (45-h forecast), and maintained this intensity through 0900 UTC 25 January (57-h forecast), while making a loop to the west, then south and then eastward. Admittedly, the loop described by the model cyclone was considerably larger that the observed loop. This caused the model cyclone to move to the Gulf of Sidra by the end of the 72-h forecast. Though this is by no means perfect, it is quite encouraging, as the previous simulation failed to make a loop. At 0000 UTC 26 January, the cyclone was weakened to 997 mb and had shrunk considerably in size (not shown). The reduction in the size of the cyclone is also consistent with the observation.

Although it has long been suspected that this type of subsynoptic-scale cyclone is likely to pose a warm core similar to that of a tropical cyclone, such structure has not been documented in the literature for this type of storm. This is due to the lack of mesoscale observations over the Mediterranean sea, and the difficulties encountered in past numerical simulations of these storms (Billing et al. 1983; Reed et al. 2001). Figure 7 shows the evolution of temperature at 925 mb. At 0000 UTC 23 January (model initial condition), the temperature distribution took the shape of a

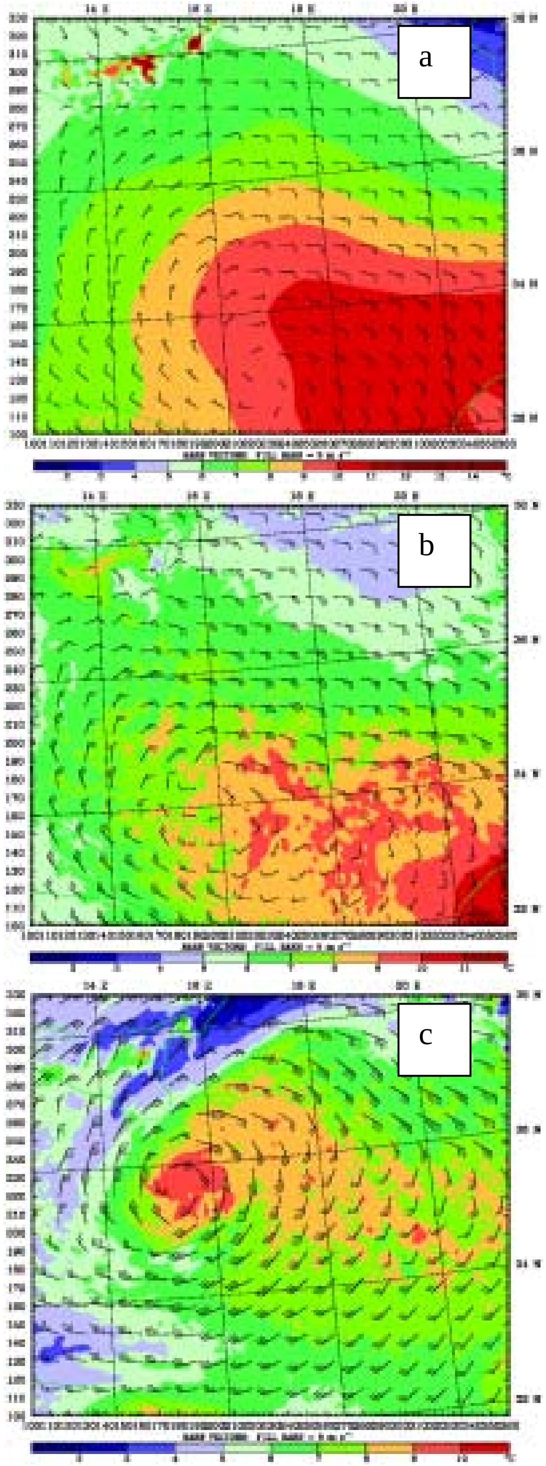

Fig. 7. 925 mb temperature and winds for the full-physics (FP) experiment at 6-h, 12-h, and 37-h forecast.

thermal wave, with a well-defined warm sector located to the southeast of the surface cyclone (Fig. 7c). As convection developed, this warm sector was quickly “chewed up”; the warm, moist air was lifted from the boundary layer by convection. By 1200 UTC 23 January 1982, the warm sector seen in the initial condition, was largely consumed (Fig. 7b). There was no warm core at the center of the developing mesoscale cyclone at 34.5 N, 15.5 W. As the mesoscale cyclone began to develop and grew in scale, it began to form a warm, dry core. By 1300 UTC 24 January (37-h forecast), a well-defined warm core had emerged at the center of the storm, with temperatures 6~8 warmer than the cold air to the northwest of the storm. The relative humidity fields indicated that the warm core was also drier than its surrounding air, indicating a structure similar to that of a hurricane (not shown). Analysis of the model simulation revealed that this warm, dry core was not a shallow feature, as it extended up to 400 mb.

4. Effects of Surface Energy Fluxes

Emanuel (1986) hypothesized that the intensification and maintenance of tropical cyclones depends exclusively on self-induced heat transfer from the ocean. He argued that the development of tropical storms might result from a finite amplitude air-sea interaction instability, rather than from a linear instability involving ambient potential buoyancy (e.g., conditional instability). Later, Rotunno and Emanuel (1987) performed numerical experiments using a nonhydrostatic, axisymmetric model and showed that a hurricane-like vortex may indeed amplify in an atmosphere that is neutral to cumulus convection, through a finite amplitude air-sea interaction instability. Given the similarity of the Mediterranean Sea cyclone to a tropical cyclone, it would be of interest to examine the effects of surface energy fluxes on the development of the storm.

Indeed, when we turned off the surface energy fluxes, the mesoscale cyclogenesis seen in the full-physics experiment did not take place. Figure 8 shows the 36-h prediction of sea-level pressure and 1-km wind from the NF experiment valid at 1200 UTC 24 January. The no-flux experiment simulated a weak surface cyclone of 1010 mb, and there was no intense mesoscale cyclone found within the subsynoptic-scale surface low. Also, the temperature in the vicinity of the low center was about 5^{o}C colder than that in the full-physics, and the warm core was absent in the NF experiment.

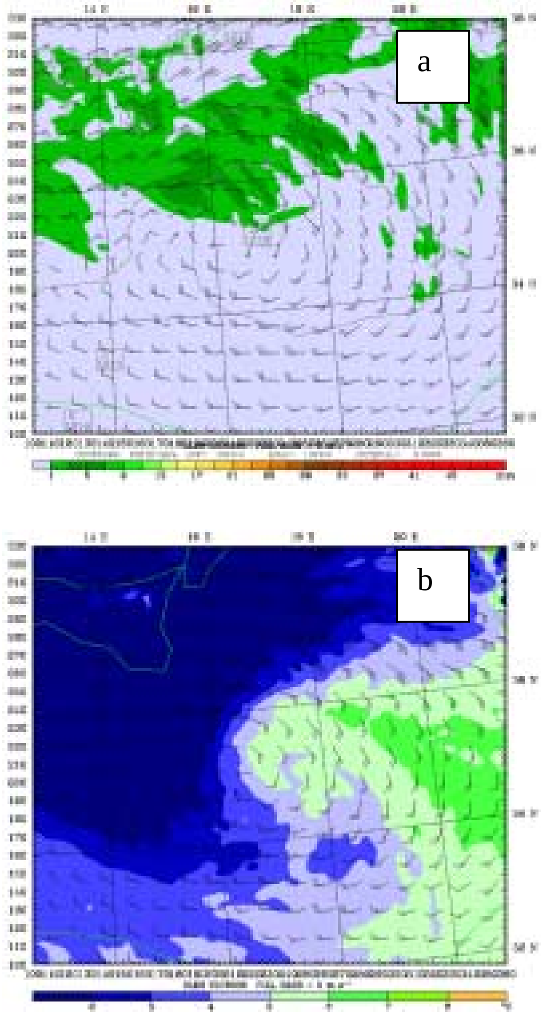

Fig. 8. 36-h forecast of sea-level pressure and 1-km wind (a) and 925 mb temperature by the no-flux (NF) experiment valid at 1200 UTC 24 January 1982.

It is clear that the surface energy fluxes are crucial for the development of the storm, consistent with the air-sea interaction instability theory proposed by Emanuel (1986) and Rotunno and Emanuel (1987).

At the heart of the air-sea interaction instability advocated by Emanuel (1986) is the interaction between the vortex and the ocean, with cumulus convection rapidly redistributing heat and moisture acquired at the oceanic surface upward and outward to the upper troposphere. In particular, as the storm develops, the wind speed increases causing enhanced surface energy fluxes, which in turn provides additional fuel to support the storm's development. Given this, it would be interesting to examine the role of vortex-ocean interaction in storm development, as we did in experiment F10, in which the wind speed used in the calculation of the surface fluxes of heat, moisture and momentum was limited to 10 m/s regardless of the actual predicted value of wind speed. This placed a cap on the surface energy fluxes, and reduced the nonlinear interaction between the surface energy fluxes and the vortex circulation. Of course, this did not completely cut off the nonlinear interaction, because even though the wind speed was limited to 10 m/s, greater air-sea temperature and specific humidity differences developed and increased the surface fluxes (even with the wind speed limited to 10 m/s). Nevertheless, experiment F10 offered a way to study the cyclone development with reduced surface energy fluxes.

We found that limiting the surface energy fluxes produced subtle but interesting differences in the storm evolution. Throughout the simulation, the differences in central pressure caused by flux reduction rarely exceeded 2 mb. However, by restricting the maximum wind speed to 10 m/s in the flux calculation, it affected the amount of surface energy fluxes primarily near the center of the storm while having little or no impact over the broader outer circulation (as the winds over the outer regions rarely exceeded 10 m/s). As a result, the precipitation near the center of the storm was weakened and a weaker pressure gradient was found in the vicinity of the low (Fig 9a). Moreover, the warm core took longer to organize (Fig. 9b).

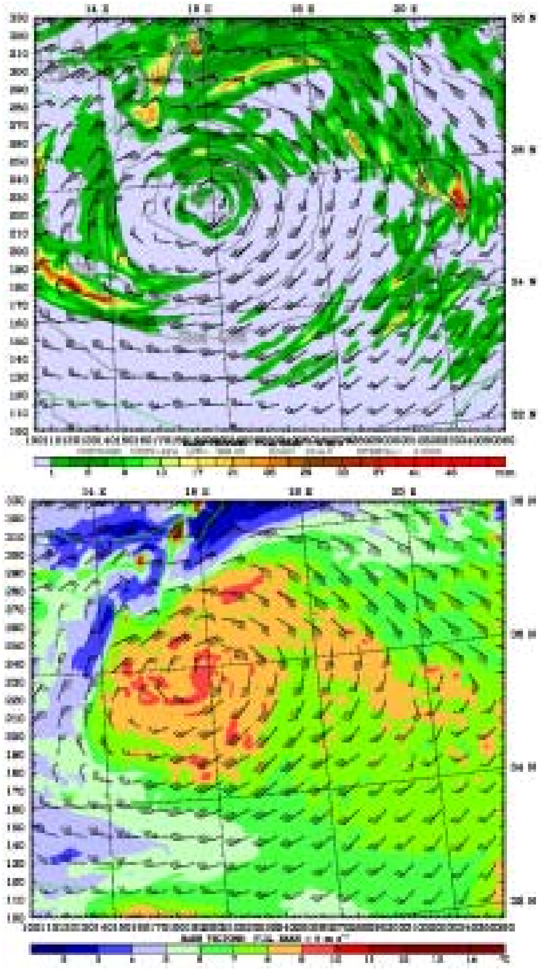

Fig. 9. (a) Sea-level pressure and 1-km wind at 36-h forecast and (b) 925 mb temperature at 37-h forecast by the limited flux experiment (F10).

By the end of the 72-h simulation, a storm with reduced fluxes had a much larger horizontal scale than that in the full-physics experiment. The tight coil of pressure contours near the center of the storm was absent. The difference in horizontal scale is also quite evident in the 925-mb potential vorticity fields (Fig. 10). It appears that the nonlinear interaction between the vortex and the ocean through the wind-speed-surface-fluxes feedback process was important for the storm to develop a mesoscale inner core. Such interaction also affected the size of the storm and the size of its warm core.

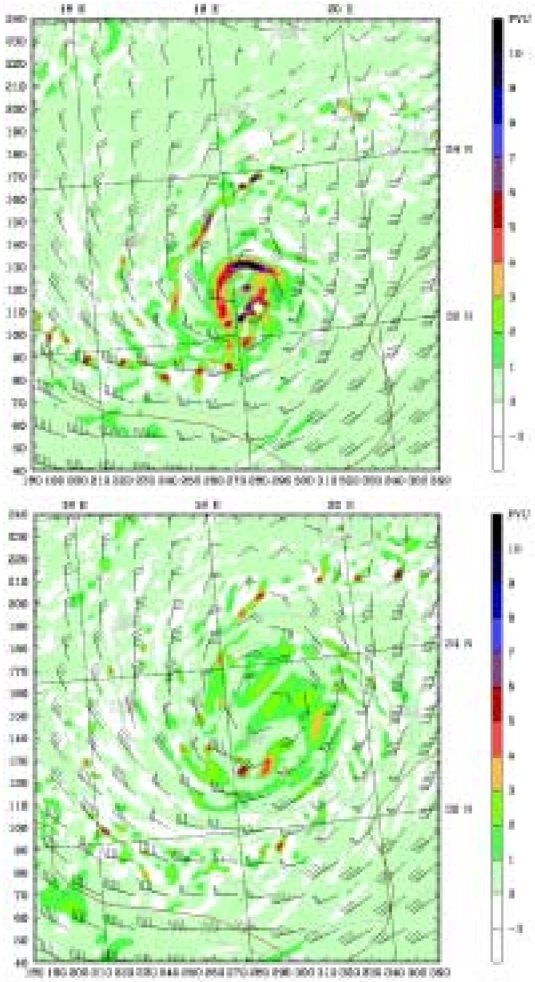

Fig. 10. Sea-level pressure and 925 mb potential vorticity and wind vectors at 72-h forecast valid at 0000 UTC 26 January 1982, (a) full-physics experiment and (b) reduced flux (F10) experiment.

Summary

In this paper we performed a high-resolution simulation of a hurricane-like mesoscale cyclone over the Mediterranean Sea. We reached the following conclusions:

(1) The 3-km MM5 initialized with ECMWRF ERA-15 global analysis augmented by routine observation and a supplementary data set was able to successfully simulated the development of the convective rainband, the mesoscale cyclogenesis, and the up-scale growth of the mesoscale cyclone.

(2) The simulated cyclone possessed a warm, dry core, which extended to 400 mb, with a structure similar to that of a tropical cyclone.

(3) The surface energy fluxes are found to be crucial for the mesoscale cyclogenesis. The Mediterranean Sea cyclone did not develop when the surface energy fluxes were shut off.

(4) The vortex-ocean interaction was found to be very important for the cyclone to develop a mesoscale inner core. When wind speed was limited to 10 m/s in the flux calculation, a storm with a much larger scale developed. Such a storm did not possess the tight mesoscale coil of pressure contour in its center.

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