Genesis and maintenance of "Mediterranean hurricanes"

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Abstract. Cyclonic storms that closely resemble tropical cyclones in satellite images occasionally form over the Mediterranean Sea. Synoptic and mesoscale analyses of such storms show small, warm-core structure and surface winds sometimes exceeding 25 ms^{-1} over small areas. These analyses, together with numerical simulations, reveal that in their mature stages, such storms intensify and are maintained by a feedback between surface enthalpy fluxes and wind, and as such are isomorphic with tropical cyclones. In this paper, I demonstrate that a cold, upper low over the Mediterranean can produce strong cyclogenesis in an axisymmetric model, thereby showing that baroclinic instability is not necessary during the mature stages of Mediterranean hurricanes.

1 Introduction

The Mediterranean Sea is a favored location for the development of cyclonic storms (Petterssen, 1956). Most of these are of synoptic scale and baroclinic in origin, sometimes aided by the peculiar nature of flow around the Alps and Pyrenees (Buzzi and Tibaldi, 1978). But once in awhile, intense mesoscale vortices develop whose structure, as revealed by satellite images, closely resembles tropical cyclones, having a clear, circular eye surrounded by an eyewall and a roughly axisymmetric cloud pattern (Mayengon, 1984). Experiments with full-physics, three-dimensional models (Pytharoulis et al., 2000) demonstrate that, at least in their mature phase, such storms are maintained the same way as tropical cyclones, by inducing large enthalpy fluxes from the sea.

In this paper, I review one well-observed Mediterranean hurricane, and model its development using a nonhydrostatic, axisymmetric, convection-resolving model, to show that standard baroclinic processes need not be called on to explain the final development, though they are probably necessary in the early stages. I conclude with a brief theoretical treatment of the problem.

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2 An example

A well-studied example of a Mediterranean hurricane occurred in mid January, 1995. As shown in Fig. 1, this storm looks very much like a small hurricane in satellite images. It developed directly underneath an unusually deep, cut-off low at upper levels, and on the west side of a larger-scale surface cyclone (Fig. 2). Mediterranean hurricanes usually, and perhaps always, develop under deep upper tropospheric troughs, in regions of small baroclinicity but large air-sea thermodynamic disequilibrium owing to the unusually deep, cold air associated with the trough. (This is also true of "polar lows"; Rasmussen et al., 1992.) Soundings near the surface cyclone reveal very large instability to ascent of surface air saturated at sea surface temperature (Pytharoulis et al., 2000), a measure of potential intensity (Bister and Emanuel, 2002). At the same time, the air is nearly saturated through a deep layer, owing to its having been lifted (and thereby cooled) on the approach of the upper low, as dictated by inversion of the upper potential vorticity anomaly (Hoskins and Robertson, 1985). As we shall see in the next section, the atmosphere over the relatively warm Mediterranean and under a deep, cutoff cold low is an ideal embryo in which to gestate a hurricane.

3 A numerical simulation

To demonstrate that upper cold lows over warm seas are conducive to tropical cyclone development, I use a modified version of the axisymmetric, nonhydrostatic, cloud-resolving model of Rotunno and Emanuel (1987). The model has been modified to ensure global energy conservation, including dissipative heating. Any development in such a model must occur owing to Wind-Induced Surface Heat Exchange

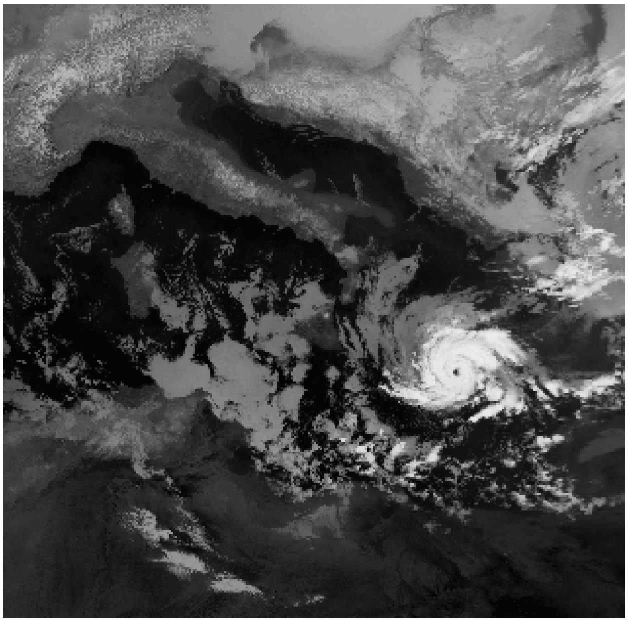

Fig. 1. Mediterranean Hurricane on 15 January 1995.

(WISHE), since baroclinic instability is absent in axisymmetric geometry. I run the model with a radial grid size of 3.75 km and vertical level separation of 300 m. The model is initialized with an ambient sounding characteristic of radiative equilibrium over a sea surface of temperature 24°C, but in this integration the sea surface temperature is reduced to 22°C. (The sounding as produced by running the same model into a state of convective neutrality, as described in Rotunno and Emanuel, 1987.) This has the effect of greatly reducing the potential intensity, to reflect the low climatological potential intensity over the Mediterranean in January. Into this state I insert an upper cold low with maximum wind amplitude at 10 km altitude, decaying linearly to zero at the surface and also decaying upward into the stratosphere. The maximum wind of 20 ms^{-1} of this initial cold low is at a radius of 300 km; thermal wind balance then gives a minimum temperature perturbation of −4°C at about 9 km altitude. Near the center of this initial cold upper low, there is considerable potential intensity. The initial wind and pressure fields are in gradient and hydrostatic balance. Small perturbations are introduced into the surface fluxes to initiate convection and development.

Figure 3 shows the evolution of the azimuthal wind component with time. After two days, a shallow, low-level, warm-core cyclone has developed and by the third day has maximum winds of about 24 ms^{-1} at a radius of around 20 km. If allowed to persist for several more days, this storm extends upward and develops to hurricane strength (∼35 ms^{-1}), and in large measure destroys the upper cold low in the process. This development proceeds somewhat faster than most tropical cyclones do, owing to its small scale and the relatively large value of the Coriolis parameter.

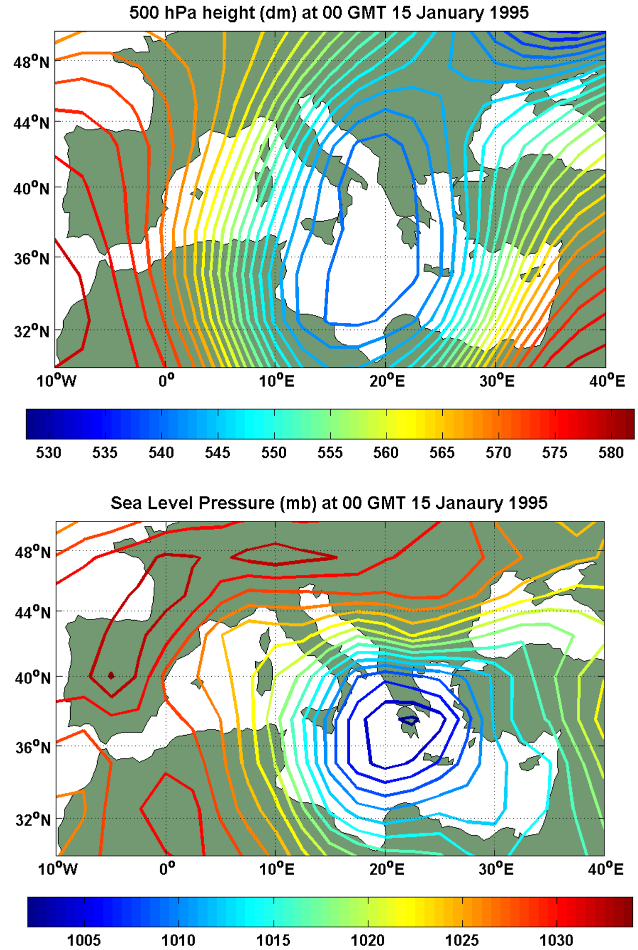

Fig. 2. 500 hPa geopotential height (dm, top) and sea level pressure (hPa, bottom), at 00:00 GMT on 15 January 1995. Analyses from NCAR/NCEP 2.5 degree re-analysis data.

There is increasing evidence that real tropical cyclones also develop inside cold core cyclones, though these are mesoscale features that arise in association with mesoscale convective complexes (Bister and Emanuel, 1997). The cyclonic vorticity together with the downdraft-suppressing humidified air is highly conducive to tropical cyclogenesis. The simulations described here show that the moist, cold air found underneath deep upper cold lows over warm seas, such as the Mediterranean, are likewise nearly ideal incubators for hurricane-like developments.

4 Theory of cyclone development under upper cold lows

Consider first a horizontally homogeneous atmosphere overlying an ocean surface of constant temperature in a state of radiative-moist convective equilibrium. I will approximate the temperature lapse rate in the troposphere as moist adiabatic, having a constant value of the saturation moist static energy, h^*, defined

$$h^* \equiv c_p T + gz + L_v q^*, \tag{1}$$

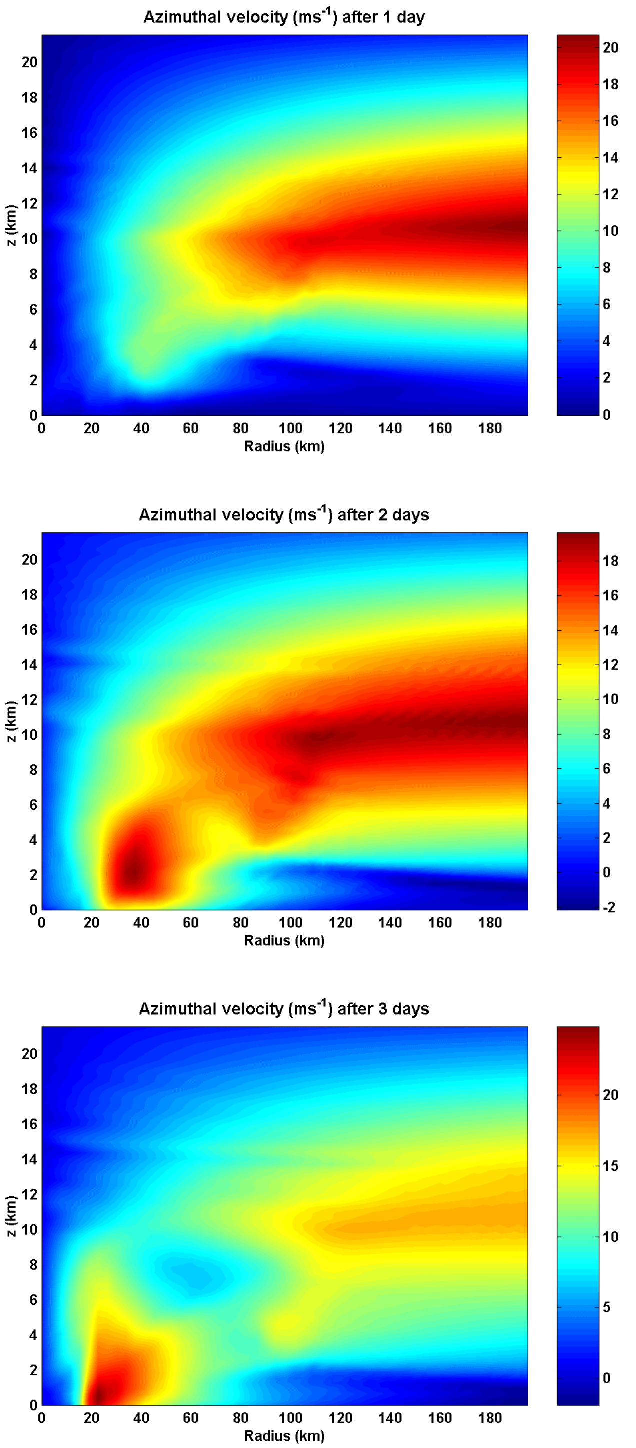

Fig. 3. Azimuthal velocity (ms^{-1}) in the axisymmetric, nonhydrostatic model, after 1 day (top), 2 days (middle), and three days (bottom) of integration.

where c_p is the heat capacity at constant pressure, T is the absolute temperature, g is the acceleration of gravity, z is the altitude, L_v is the latent heat of vaporization, and q^* is the saturation specific humidity. Then the potential maximum

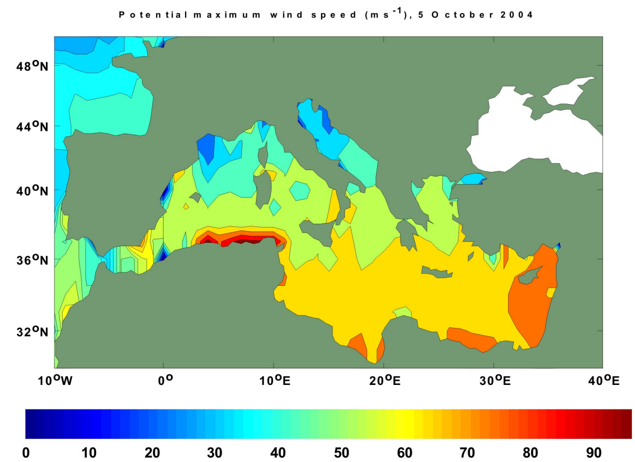

Fig. 4. Potential maximum wind speed (ms^{-1}) over the Mediterranean Sea at 12:00 GMT on 5 October 2004, from the NCEP analysis on a 1 degree grid.

wind speed squared is given by (Bister and Emanuel, 1998) :

$$V_p^2 = \frac{C_k}{C_D}\frac{T_s - T_o}{T_o}\left(h_s^* - h^*\right), \tag{2}$$

where C_k and C_D are the surface exchange coefficients for enthalpy and momentum, T_s and T_o are the sea surface and entropy-weighted outflow temperatures, and h_s^* is the saturation moist static energy of air at sea level at sea surface temperature. Usually, over the Mediterranean, V_p is too small to support tropical cyclones, but it can be large in the fall (Fig. 4). Moreover, the air over the Mediterranean is usually far too dry to allow tropical cyclones to develop.

Now suppose a synoptic scale, upper cold low is advected into this environment. As the low approaches, the air mass is lifted, decreasing the temperature aloft and increasing convective instability. I shall suppose that convection occurs and holds the lapse rate at a moist adiabatic value. Hydrostatic equilibrium gives

$$\left(\frac{\partial\phi}{\partial p}\right)' = -\alpha' = -\left(\frac{\partial\alpha}{\partial h^*}\right)' h^{*\prime} = -\left(\frac{\partial \ln T}{\partial p}\right)_{h^*} h^{*\prime}, \tag{3}$$

where ϕ is the geopotential, α is the specific volume, the primes represent departures from the background state along surfaces of constant pressure, and I have used one of Maxwell's relations (Emanuel, 1986). I can now integrate this through the depth of the troposphere, to relate the perturbation of h^* at the center of the cold low to the perturbation of ϕ associated with cold low at the tropopause:

$$h^{*\prime} = \frac{\phi'_{cl} - \phi'_s}{\ln\left(\frac{T_s}{T_o}\right)} \simeq \frac{T_o\left(\phi'_{cl} - \phi'_s\right)}{T_s - T_o}, \tag{4}$$

where "cl" stands for "cold low", I have assumed that the tropopause temperature is also T_o, and I have expanded the logarithm assuming that T_s and T_o are not too different. Substituting this perturbation of the saturation moist static energy into (2), I obtain an expression for the modified potential intensity at the core of the cold low aloft:

$$V_{mod}^2 = V_p^2 - \frac{C_k}{C_D}\left(\phi'_{cl} - \phi'_s\right) \tag{5}$$

Since ϕ' will be more negative in a cold upper low than at the surface underneath it, this will give an increase of potential intensity. Note that in evaluating (3), the ambient potential intensity, V_p^2, may very well be negative if the atmosphere is stable to the lifting of a parcel saturated at sea surface temperature. Examining Fig. 2, I note that the center of the cutoff low aloft, $\phi'_{cl} \simeq -4000\,\mathrm{m^2 s^{-2}}$, while in the synoptic-scale surface low underneath, $\phi'_s \simeq -2500\,\mathrm{m^2 s^{-2}}$. Even if the ambient potential intensity (i.e. in the absence of the cold low) is zero, this gives a maximum wind speed of around $40\,\mathrm{ms^{-1}}$, assuming that the exchange coefficients are equal.

5 Conclusions

The climatological potential intensity over the Mediterranean Sea is usually only marginal for tropical cyclone formation, and the atmosphere is usually far too dry to permit development. But when a deep, upper-level cutoff low moves over the region, the air mass must ascend and cool to maintain balance. Thus the air under such an upper low is unusually cold and humid. Its low temperature, in combination with the relative warmth of the underlying sea, and its high relative humidity provide an ideal incubator for hurricane-like development. A simulation with an axisymmetric, nonhydrostatic, cloud-resolving model shows rapid development under these circumstances. Calculations of potential intensity over the Mediterranean using daily re-analysis data are underway; these should enable an assessment of the overall risk of hurricanes in the Mediterranean region.

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