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Orographic cyclogenesis in a saturated atmosphere and intense precipitation: baroclinic modal solutions under the joint action of localized mountains and humidity

Roberto Benzi ([1]), Maurizio Fantini ([2]), Roberta Mantovani ([3]) and Antonio Speranza ([4])
([1]) *Dipartimento di Fisica, II Università di Roma, Italy*
([2]) *CNR-FISBAT, Bologna, Italy*
([3]) *Dipartimento di Scienze Geologiche, III Università di Roma, Italy*
([4]) *Dipartimento di Fisica, Università di Camerino, Italy*

Abstract
In this paper we analyse the nature of orographic cyclogenesis in a saturated atmosphere by means of a simplified model based on the analysis of linear modal solutions. The space structure of fastest growing modal solutions suggests that three different scales of axtratropical atmospheric motion may simultaneously be activated in a single, growing, unstable mode: the orographic modulation of growing baroclinic modes extending, as we know from the classical modal theory of orographic cyclogenesis, from the scale typical of the primary, extratropical cyclone to the scale of the secondary, orographic cyclone, is also characterized by the (smaller) scale associated with strong ascending motion in a saturated atmosphere. Since ascending motion can be associated with intense precipitation, this result is important in view of its potential consequences both on the ability to achieve a good forecast of intense precipitation events in the Mediterranean and on the refinement of the theory of orographic cyclogenesis.

Key words *wide precipitation area – orographic cyclogenesis – moist cyclogenesis – intense precipitation*

1. Introduction

On the basis of the experience accumulated over more than two decades of intensive study of orographic cyclogenesis it can be asserted, with reasonable confidence, that:

– The influence of localized, steep orography on growing extratropical cyclones extends in space up to scales comparable with the size of the entire primary cyclone.

– The large-scale structure of secondary, orographic cyclones, in the course of the onset-phase, can be adequately computed by means of a linear, modal theory, provided orography (particularly if steep) is correctly represented in the boundary conditions.

– The above conclusions, originally drawn for the Alpine case, apply to similar phenomenologies in many other areas of the world.

For extensive discussion of all the observational, analytical and numerical aspects of the problem see Tibaldi *et al.* (1990) and literature therein.

Several important aspects of the problem of secondary, orographic cyclogenesis are,

Mailing address: Dr. Roberto Benzi, Dipartimento di Fisica, II Università di Roma, Via Orazio Raimondo, 00173 Roma, Italy.

though, still essentially open. In particular:

– The mechanisms of growth and finite-amplitude-stabilization of the secondary cyclone.

– The role of atmospheric dynamical processes different from interaction with orography (sensible and latent heat exchanges with the ocean, dynamical effects of atmospheric water, frontal dynamics, etc.) which were considered in the above referred studies as «weak modulating factors» in the onset-phase.

Orographic cyclogenesis is still an important scientific subject in itself; however, the renewal of interest in the problem is essentially due to practical reasons connected with the need for civil protection alert on the occurrence of intense precipitations in the Mediterranean area: it is quite evident from the configuration of hydrographic basins upset by frequent, catastrophic flooding that the highest potential for an improvement of operational forecasting and warning, still resides in a bettering of the synoptic scale, hydrometeorological forecast. This, in turn, requires a deeper understanding of some key processes typical of synoptic and subsynoptic atmospheric dynamics, starting from secondary, orographic cyclogenesis itself.

In this paper we anticipate a first result obtained from systematic study of secondary cyclogenesis which provides a potential contribution to the practical problem of forecasting intense precipitation, but may also provide a better basis to the theory of onset of secondary, orographic cyclogenesis: we find that, under conditions similar to those assumed by Emanuel *et al.* (1987), the orographic modulation of growing baroclinic modes can simultaneously extend from the scale typical of the primary, extratropical cyclone, not only to the scale of the secondary, orographic cyclone (as in classical modal theory of orographic cyclogenesis), but even further to the (smaller) scale of «wide precipitation areas» (according to the definition of Browning, 1990) associated with intense ascending motion in a saturated atmosphere.

In section 2 we formulate the physical problem and the mathematical formalism, in section 3 the results of our analysis and in section 4 we draw our conclusions.

2. Physical problem and mathematical formalism

As to the formulation of the dynamics of moist cyclogenesis we adopt the parameterization introduced by Fantini (1995) which, in turn, is a quasigeostrophic version of the model proposed by Emanuel *et al.* (1987).

The basic elements of Fantini's formulation can be summarized as follows:

– In the vertical motion ascending air is saturated, while descending air can be treated as being dry, since condensation of water vapor never occurs.

– Due to the rapid motion of air, we can neglect any exchange of heat with the environment: as a consequence, potential temperature is conserved in the descending region (dry) and equivalent potential temperature is conserved in the ascending region (moist).

– The ascending region is characterized by the condition of neutrality with respect to moist, symmetric instability.

For further details see the above cited literature. We note that, at present, we do not have complete evidence that the parameterization in question is adequate for the Mediterranean area: the slantwise convective neutrality characterizing the ascent regions of baroclinic cyclones has its observational evidence only in the United States (for an extended description of the experiments, see Emanuel, 1988). In the Mediterranean area we have observational evidence of the important role played by «banded» precipitation structures, similar to those investigated by Emanuel, in flooding events (see, for example, Sénési *et al.*, 1996; Tudurì and Ramis, 1997), but not a specific study of their dynamical nature.

From the above assumptions Fantini (1995) derived the following equations for motion in a saturated atmosphere:

$$\left\{\frac{\partial}{\partial t}+\frac{\partial\psi}{\partial x}\frac{\partial}{\partial y}-\frac{\partial\psi}{\partial y}\frac{\partial}{\partial x}\right\}\frac{\partial\psi}{\partial z}+n^2 w=0, \quad (2.1)$$

$$\left\{\frac{\partial}{\partial t}+\frac{\partial\psi}{\partial x}\frac{\partial}{\partial y}-\frac{\partial\psi}{\partial y}\frac{\partial}{\partial x}\right\}\nabla_H^2\,\psi=w_z, \quad (2.2)$$

where ψ is the nondimensional (see below) geopotential,

$$\nabla_H^2 = \frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial y^2},$$

and

$$n^2 = \begin{cases} 1 & \text{for} \quad w<0 \\ r<1 & \textit{for} \quad w>0 \end{cases}; \tag{2.3}$$

eq. (2.1) is the thermodynamic equation and eq. (2.2) is the vorticity equation. The above equations are nondimensional and, conventionally, the dimensional quantities are characterized by the presence of an asterisk while the nondimensional ones are represented with the usual notation.

From eq. (2.3) we argue that the proposed parameterization of the process of latent-heat-release simply consists in using a dry static stability for all descending motions and a smaller moist static stability for ascending motions. The coefficient r that appears in eq. (2.3) is defined as

$$r = \frac{1}{R_i} = R^2,$$

where R_i is a Richardson-number, R is a Rossby-number and the second equality comes from having chosen the Rossby-radius as the length scale. For further details see Fantini (1995).

For the solution of the mathematical problem (2.1)-(2.2) with a coefficient n^2, piecewise defined as in eq. (2.3), we need to know w at each time-step and at each grid-point. For this purpose we combine the thermodynamic eq. (2.1) with the vorticity eq. (2.2) to obtain a diagnostic equation for w

$$\nabla_H^2(n^2 w) + w_{zz} = 2\,(\psi_{xz}\partial_y - \psi_{yz}\partial_x)\,\nabla_H^2\psi. \tag{2.4}$$

At this point we proceed as follows: eq. (2.2) is integrated forward in time with a leap-frog scheme and eq. (2.4) is solved at each time-step with a relaxation method so that we know w for the next time-step. Assuming as boundary conditions a double periodicity in the horizontal directions, we can obtain the geopotential by inverting $\nabla_H^2\,\psi$ with a double Fourier transform. For an extended description of the procedure see Fantini (1995).

We introduce orography as a boundary condition at the bottom of the integration domain, *i.e.*:

$$w = \frac{dh'}{dt} = \frac{\partial h'}{\partial t} + u\frac{\partial h'}{\partial x} + v\frac{\partial h'}{\partial y} \quad \text{for } z = 0, \tag{2.5}$$

where h' is a function describing the surface profile. At the top boundary we have the following condition:

$$w = 0 \quad \text{for} \quad z = 1. \tag{2.6}$$

Condition (2.5) can be exactly applied in the case of small mountains, however, in considering the finite height of orography we do not introduce substantial modifications in the structure of the solutions of the orographic problem, as shown by Buzzi and Speranza (1986).

The orography is represented by an infinite ridge, located in the center of the domain along the meridional direction and with its axis lying in the zonal direction. In so doing we introduce the fundamental asymmetry characterizing orographic cyclogenesis which consists in the different sign of $\partial h'/\partial y$ on the two sides of the ridge (see Speranza *et al.*, 1985).

The bottom-boundary condition becomes

$$w = v\frac{\partial h'}{\partial y} = \psi_x\frac{\partial h'}{\partial y}. \tag{2.7}$$

In scaling the quantities connected with the mountain, we start from the dimensional quantity

$$w_* = v_*\frac{\partial h_*}{\partial y_*},$$

which becomes, in nondimensional form,

$$w = \frac{1}{R}\,\psi_x\,\frac{\partial h}{\partial y},$$

where R is the Rossby-number and h is the nondimensional mountain profile. Consequently

$$h' = \frac{h}{R}.$$

With such an assumption, a nondimensional height $h' = 1$ corresponds to a dimensional mountain height $h_* = 1$ km.

We have chosen for the width of the mountain the value $Y/10$ (*e.g.*, 850 km, if $Y = 6$), where Y is the length of the periodicity domain in the meridional direction and for the height of the mountain the value $h' = 1$ (1 km), so that the mountain is high enough to cause slow deflections on the scale of the Rossby-deformation-radius, but, at the same time, the slope of the mountain is small enough to allow a quasi-geostrophic approach to the dynamics of orographic cyclogenesis.

As to the problem of meridional confinement of the perturbation, we adopt periodicity conditions at the latitudinal boundaries and produce latitudinal wave confinement by introducing a basic state with a jet-like meridional structure, having the same mean baroclinicity as the Eady basic state:

$$U = z\,(1 + 0.25 \cos \frac{2\pi}{Y} y). \tag{2.8}$$

Under such conditions, we expect the same type of latitudinal confinement as with vertical walls at the latitudinal boundaries (Malguzzi *et al.*, 1987).

Linearizing the problem (2.2)-(2.4) around the basic state (2.8) we obtain finally for the complete problem of onset of orographic cyclogenesis in a saturated atmosphere:

$$\left(\frac{\partial}{\partial t} + U \frac{\partial}{\partial x}\right) \nabla_H^2 \phi - U_{yy}\, \phi_x - w_z = 0, \tag{2.9}$$

$$\nabla_H^2 (n^2 w) + w_{zz} - 2U_z \nabla_H^2 \phi_x + 2U_{yy} \phi_{xz} = 0. \tag{2.10}$$

We use a finite-difference-scheme, with 64 grid-points in both horizontal directions; along the vertical we have 11 levels for ϕ, each of which is intermediate between two w-levels.

3. Orographic cyclogenesis in a saturated atmosphere

Before considering the coupled effect of moisture and orography, we separately analyze some aspects of the theories of moist cyclogenesis and orographic cyclogenesis which play a basic role in our theory of jointly moist and orographic cyclogenesis.

We illustrate moist cyclogenesis with a numerical experiment initialized with an Eady-wave, with zonal and meridional wavelengths respectively $X = 4.0$ and $Y = 4.0$ (coincident with the dimensions of the periodicity domain in both the horizontal directions). The basic state of this experiment is the same as in the Eady-problem, since here we do not need to confine the perturbation in latitude. The bottom-boundary condition is

$$w = 0, \qquad z = 0.$$

We have integrated up to $t = 10$ ($t_* \approx 5$ days).

The main results of this numerical experiment are as follows:

– Moist solutions have the same modal structure(*) already characterizing the Eady-problem solutions: this may be argued from the stabilization of the growth-rate *versus* time of integration shown in fig. 1a.

– Moisture has the effect of accelerating the wave amplification since the growth-rate of the baroclinic wave is greater than in the analogous dry case (see fig. 1a,b); phase-velocity is, instead, the same as in Eady-model: this is not shown and may be inferred from the fact that subtracting 0.5 (the phase-velocity of the Eady-vawe) from the phase-velocity of the moist solution propagation disappears.

(*) We have a modal structure when the solution is of the form

$$\mathrm{Re}\left\{e^{kc_i t}\, e^{ik(x - c_r t)} f(y, z)\right\}.$$

We define growth-rate of the modal solution the constant quantity

$$\sigma = kc_i.$$

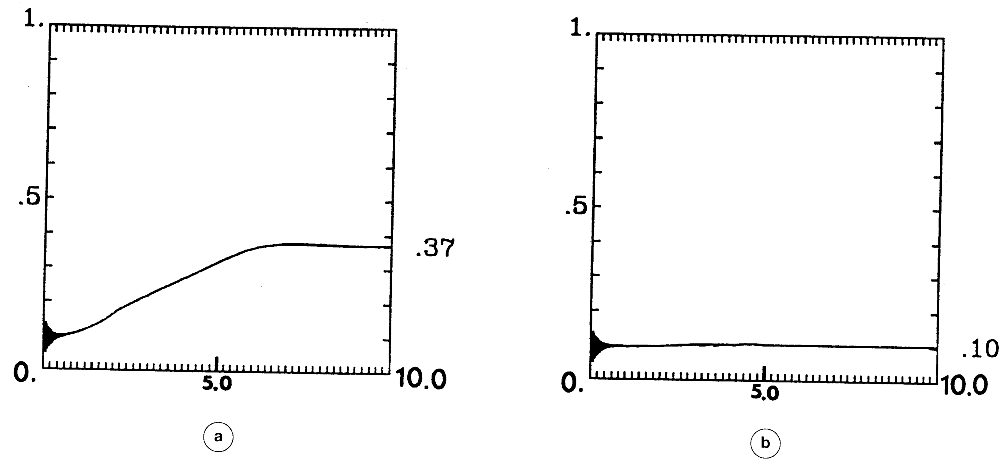

Fig. 1a,b. a) Growth-rate *versus* time (up to $t = 10.0$) for the moist experiment; b) as in fig. 1a but for the dry experiment. Flat bottom case.

– The wave spatial structure changes with respect to the dry case: there is a localization along the zonal direction together with an intesification of the upward vertical velocity and of the northward meridional velocity (see fig. 2a,b and in particular for the latter field see zonal ϕ-gradient shown in fig. 2a); the presence of regions of intensified upward velocity together with strong northward advection suggests the possibility of identifying such regions with «wide precipitation areas» or similar phenomenological structures described, for example, by Browning (1990) as characterized by saturated air aloft in the absence of extensive convective activity.

For further details see Fantini (1995).

In order to study orographic cyclogenesis we restore now the jet-like basic state introduced in section 2 and examine the dry case in which

$$n^2 = 1, \quad \text{always}.$$

We compare two cases: the orographic one (where $w = v(\partial h'/\partial y)$ for $z = 0$) and the one with a flat bottom (where $w = 0$ for $z = 0$). For this purpose, we show in fig. 3a-d the geopotential-field in these two different situations and the geopotential difference-field. In the same figure the growth-rate *versus* time (up to $t = 30.0$) is reported for both the cases with and without orography. Both experiments are initialized with an Eady baroclinic wave without meridional structure and with zonal wavelength $X = 6.0$. The meridional and zonal range of the periodicity domain are $X = 6.0$ and $Y = 6.0$, respectively. The total time of the integration is $t = 30.0$ ($t_* \approx 15$ days). The main results are as follows:

– Orographic solutions preserve the modal structure distinctive of the Eady-problem (as may be inferred from the stabilization of the growth-rate *versus* time shown in fig. 3d).

– The mountain induces a slight decrease in the wave amplification (see growth-rates in fig. 3d) as expected from the theory of orographic cyclogenesis, since the peculiarity of this phenomenon is to cause a local intensification in the perturbation field, but, at the same time, a global reduction of the baroclinic mode-efficiency. Also the phase-velocity is reduced by the introduction of orography. The latter result is not shown: it can be deduced from plots of the position of geopotential minimum *versus* time; we have for the flat bottom case $c_r = 0.58$ ($c_{r*} = 18.01$ m/s) and for the orographic one $c_r = 0.52$ ($c_{r*} = 16.43$ m/s).

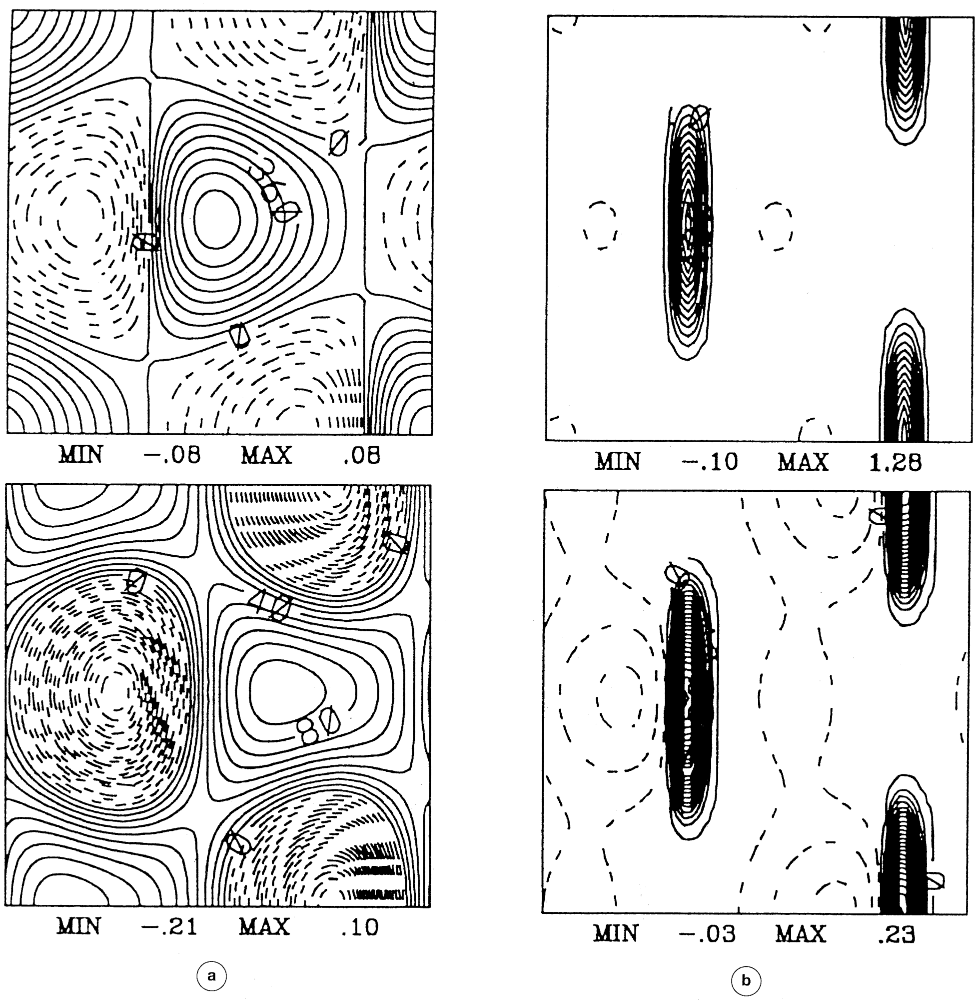

Fig. 2a,b. a) Horizontal section of geopotential ϕ; b) horizontal section of vertical velocity w. For each field there are two distinct levels: the lowest one ($z = 0.045$) and the middle one ($z = 0.5$) from bottom to top, respectively. Continuous lines represent positive values, while dashed lines are negative values. Each situations refers to the instant $t = 10.0$. All the figures have the same horizontal and vertical range: respectively $x = (0., 4.0)$ and $y = (0., 4.0)$.

– There is a typical modification in the spatial wave-structure: the geopotential difference-field shows a high-low dipole with a north-south orientation, with consequent intensification of the low south of the mountain (see fig. 3a,c); this behaviour is observed at the surface as well as in the interior of the atmosphere. Again it is known from the theory of orographic cyclogenesis that orographic effects extend well outside the mountain range.

We finally turn our attention to the combined effect of moisture and orography: we have no *a priori* knowledge of the nature of the interaction between these two modifying

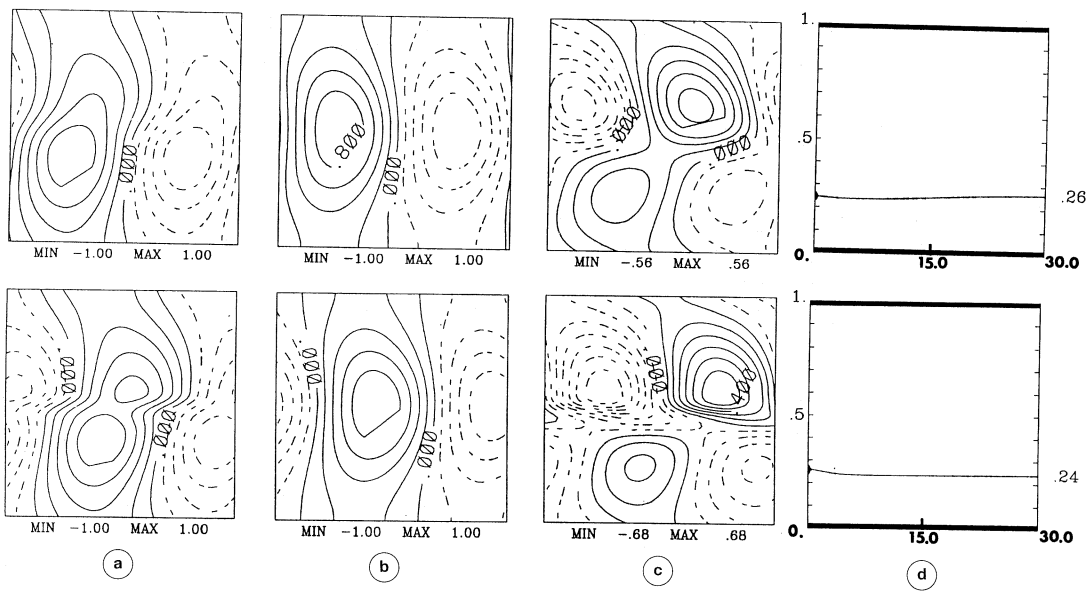

Fig. 3a-d. a) Horizontal section of geopotential ϕ, for the orographic case; b) horizontal section of geopotential ϕ, for the case without orography; c) geopotential difference-field. For each field there are two distinct levels as in fig. 2a,b. Each situations refers to the instant $t = 30.0$ and all the figures have the same horizontal and vertical range: respectively $x = (0., 6.0)$ and $y = (0., 6.0)$. d) Growth-rate *versus* time up to $t = 30.0$, for the orographic case and for the one without orography from bottom to top, respectively. Dry case.

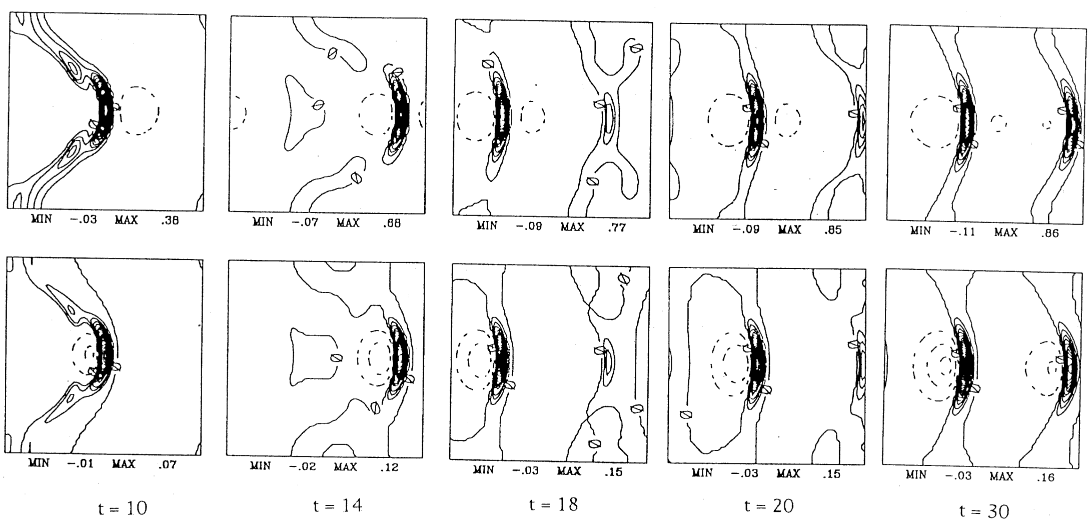

Fig. 4. Horizontal section of vertical velocity w at different istants, for the moist experiment without orography. At each time we have two distinct levels as in fig. 2a,b. We look at the development of a second region of upward motion, and at the time $t = 30.0$ the solution has reached stabilization. All the figures have the same horizontal and vertical range: respectively $x = (0., 6.0)$ and $y = (0., 6.0)$.

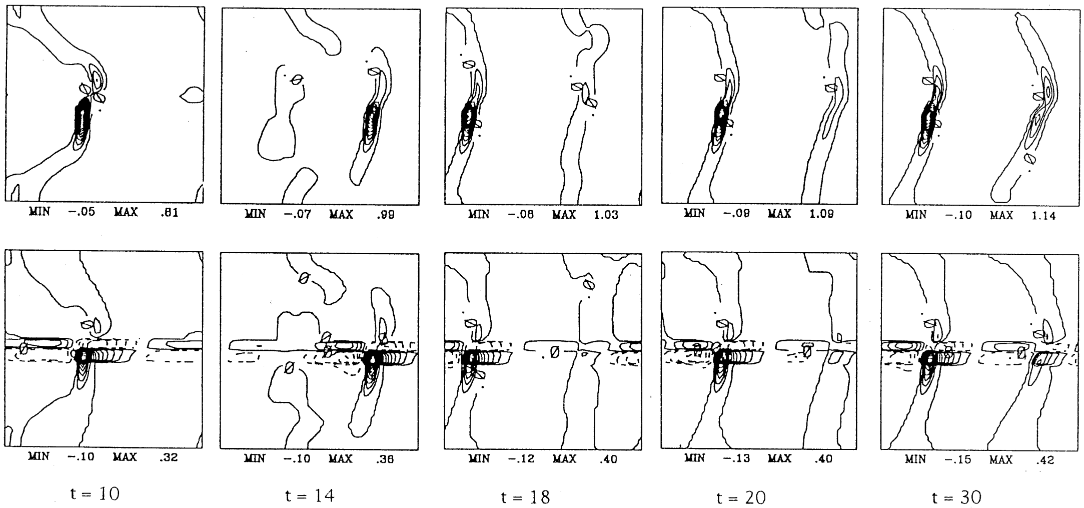

Fig. 5. As in fig. 4 but for the moist experiment with orography. At the time $t = 30.0$ the solution has not reached stabilization and the second region of upward motion is still developing.

agents of baroclinic instability; even the mere existence of modal solutions is not *a priori* certain.

Also in this case we compare the results of the moist experiment without orography with those of the moist experiment with orography. The initialization and the basic state are the same as in the dry case with orography just described.

In fig. 4 we show the time-evolution (up to stabilization) of the numerical experiment without orography: for each time indicated we show a horizontal view of the vertical velocity w at two different levels. The introduction of a jet-like basic state leads to the development of two bands of increased vertical and meridional velocity (see, for comparison, fig. 2b where the basic state was the Eady basic state). This phenomenon may be justified in terms of the latitudinal folding introduced by the meridional structure of the zonal wind causing separation of the extreme regions of the initial band which finally merge into a second band.

In fig. 5 we see the same evolution shown in fig. 4 (though, in this case, the solution does not reach stabilization) for the orographic experiment; fig. 6a,b shows growth-rate *versus* time (up to $t = 30.0$) for the orographic case and for the one without orography; in fig. 7a-c we show the geopotential-field for these two different cases along with the geopotential difference-field. We summarize the results obtained as follows:

– Moist, orographic solutions preserve the modal structure characterizing respectively moist and orographic solution (this may be argued by the existence of a constant growth-rate as shown in fig. 6a).

– There is a slight decrease in the amplification of the wave (see growth-rates shown in fig. 6a,b) and a reduction of the phase-velocity with respect to the moist case without orography. This last result is not shown and was obtained with the same procedure described for the dry case: for the flat bottom case $c_r = 0.63$ ($c_{r*} = 19.91$ m/s) and for the orographic one $c_r = 0.58$ ($c_{r*} = 18.33$ m/s).

– There is an evident increment in the growth-rate of the moist, orographic solution with respect to that of the dry, orographic solution (see for comparison the growth-rate shown at bottom of fig. 3d): an orographic perturbation in moist conditions grows faster than in

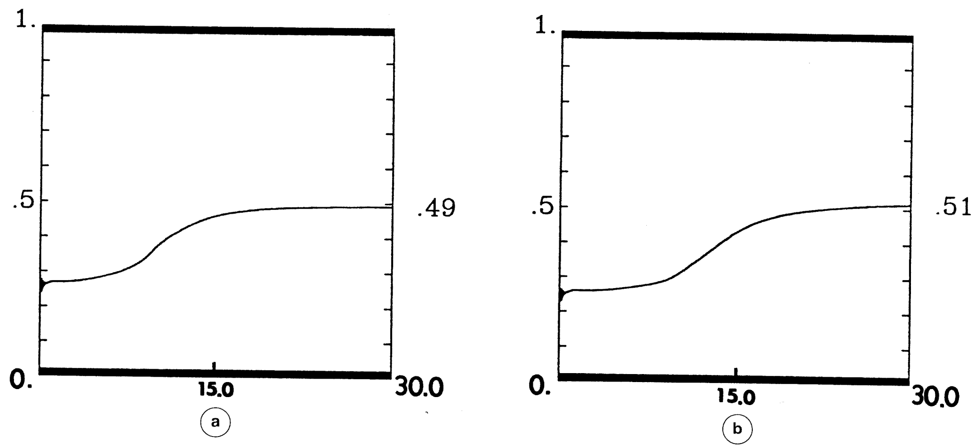

Fig. 6a,b. a) Growth-rate *versus* time (up to $t = 30.0$) for the moist case with orography; b) as in fig. 6a but for the moist case without orography.

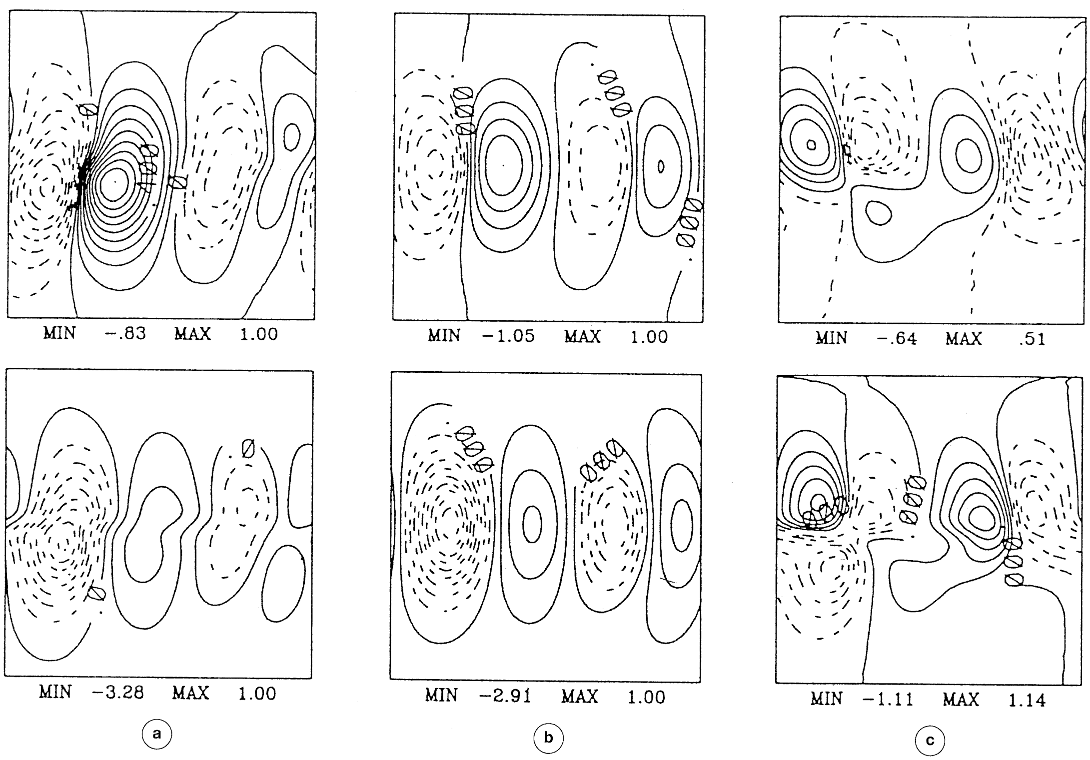

Fig. 7a-c. a) Horizontal section of geopotential ϕ in the orographic case; b) horizontal section of geopotential ϕ in the case without orography; c) geopotential difference-field. For each field we have two distinct levels as in fig. 2a,b. Situations refer to the instant $t = 30.0$. Moist case. All the figures have the same horizontal and vertical range: respectively $x = (0., 6.0)$ and $y = (0., 6.0)$.

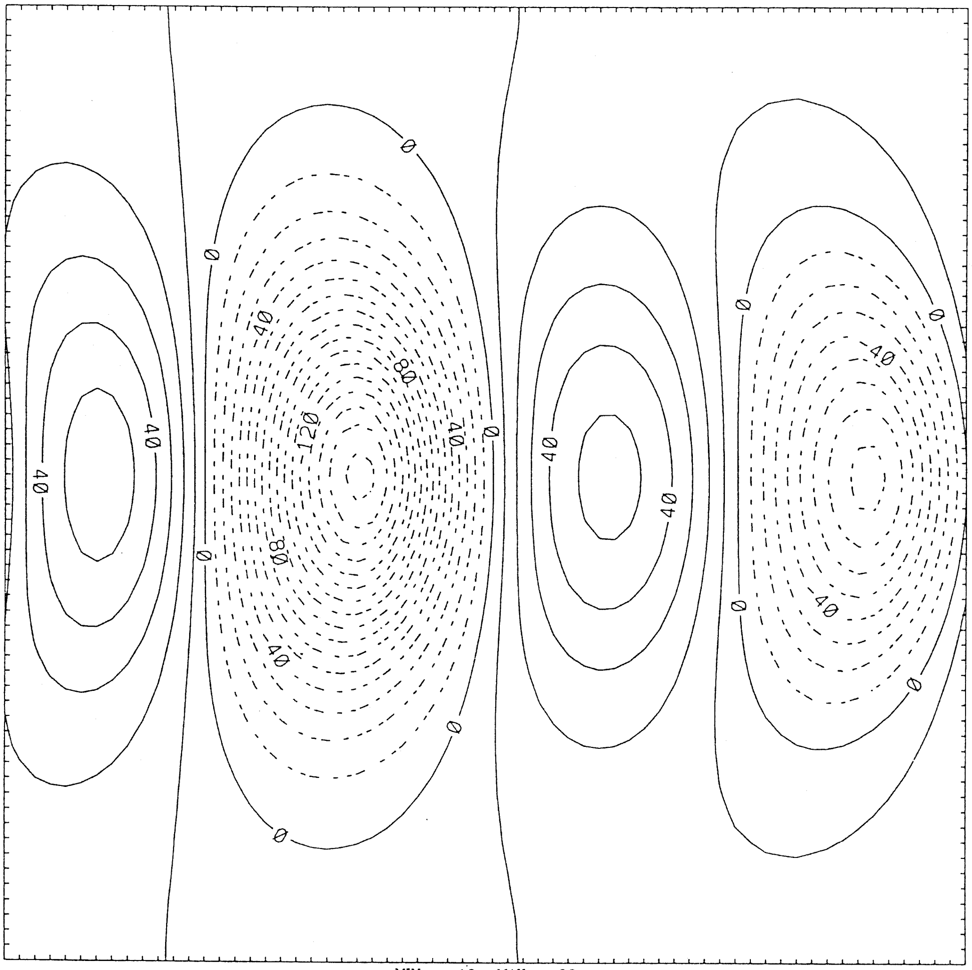

Fig. 8. Blow-up of the geopotential-field at the surface, already shown in fig. 7b.

dry conditions. As to the phase-velocity, instead, moisture does not introduce substantial modifications.

– The moist ascent-belts are still present in the experiment (fig. 5).

– There is a better structured orographic cyclogenesis then in the dry case (see fig. 7a and for comparison with the dry case see fig. 3a): a more localized perturbation appears south of the mountain; this may be due to the intensification of the northward meridional velocity field, caused by moisture, and to the major role played by this field in the orographic cyclogenesis, as it can be deduced from the boundary condition (2.7). Furthermore, the disturbance is more localized near the mountain than in the dry case.

– There is a strengthening of the intensification and a localization south of the mountain, with respect to the moist case without orography, of the fields that characterize the moist ascent-belts (*i.e.*, upward vertical velocity field

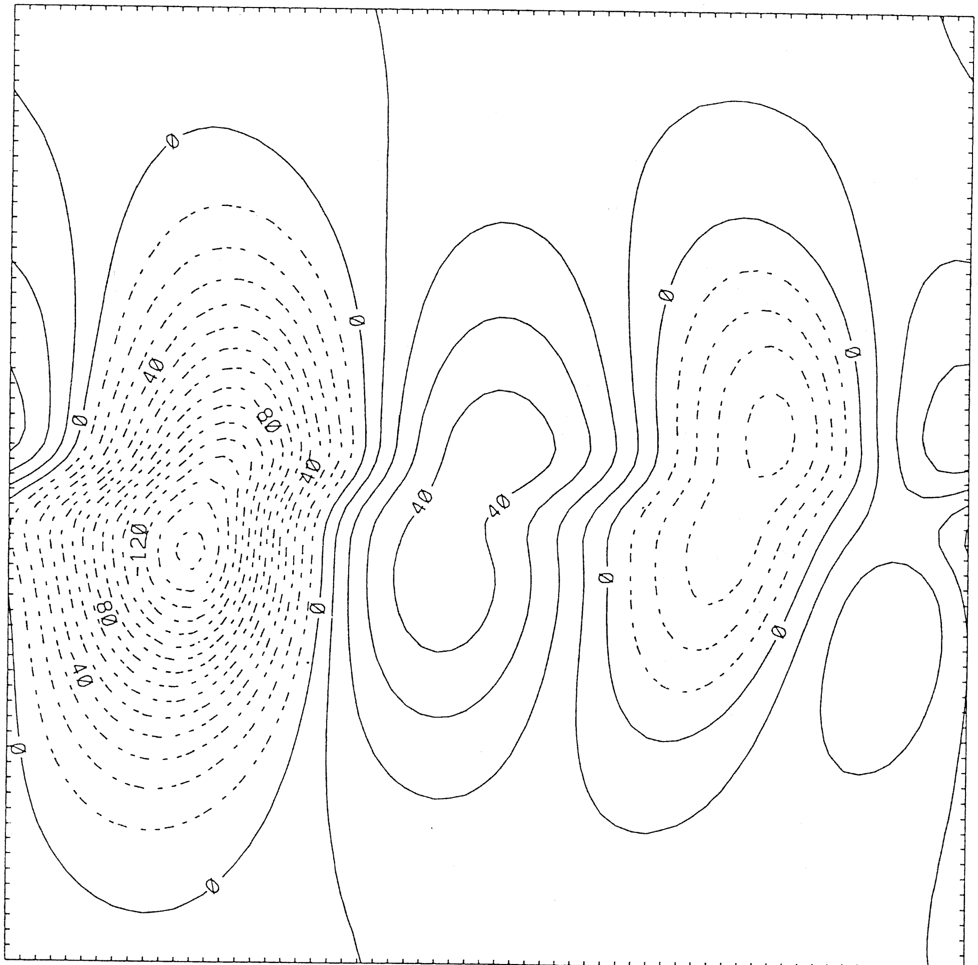

Fig. 9. Blow-up of the geopotential-field at the surface, already shown in fig. 7a.

and northward meridional velocity field). Such spatial modifications are observed at the surface as well as aloft: deepening of the disturbance throughout the whole atmospheric depth is a classical orographic effect. The intensification and localization of the northward meridional velocity field may be deduced from the geopotential zonal gradient: for this purpose figs. 8 and 9 show a magnification of the geopotential-field at the surface respectively for the flat case and the orographic one.

4. Conclusions

The main purpose of this paper is to show, by means of a specific example, that three different scales of extratropical atmospheric motion may simultaneously be activated *in the same modal structure* on occurrence of orographic cyclogenesis in a saturated atmosphere. The practical implications in forecasting intense precipitations may be relevant: for example, what are the consequences of inadequate resolution and/or initialization of one of the scales of motion (as is usually the case in operating LAM in the Mediterranean area) on numerical forecasting?

Theoretical implications are also potentially relevant with respect to problems connected with the refinement of the theory of orographic cyclogenesis: the action of water vapor turns out in our study to be as strong as that of orography on cyclogenesis.

We do not intend to claim that the phenomenology taken into consideration in this paper is fully appropriate for the Mediterranean area: observational analysis in support of the hypothesis postulated by Emanuel *et al.* (1987) and further theoretical studies of the involved processes are still needed. However, even at this preliminary stage the theory presented in this paper poses important guidelines for further research and application. In particular we need phenomenological characterization of banded precipitation areas, improvement of the observational technology (most of the dynamical processes of interest take place over the ocean), further development of the theory, specifically for finite-amplitude-stabilization of symmetric instability.

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