4.13 FRONTAL INTERACTION WITH ISOLATED OROGRAPHY

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1 INTRODUCTION

In recent years several studies of orographic cyclogenesis in relation to the interaction of mountains with fronts have appeared in the literature (e.g. Schär, 1990; Li et al., 1996). The work by Orlanski and Gross (1994) examined the development of the orographic modifications to a mature baroclinic cyclone in the encounter with an elongated mountain, discussing the effects of mountains of varying length. The consideration of a finite amplitude wave, or an intense front, puts those studies outside the scope of the normal mode theory of orographic cyclogenesis (Speranza et al., 1995) which deals with orographically modified baroclinic modes growing from infinitesimal amplitude. The question of how fast, if ever, a given initial condition of arbitrary amplitude reduces to the normal mode picture is relevant to the applicability of the latter in real world situations.

It is our intention to examine a developing orographic perturbation in the presence of a finite amplitude primary wave, and relate it to the environmental parameters characterizing the incoming cyclone. For this purpose we formulated a semi-geostrophic model which represents analytically an Eady wave of any amplitude, with its associated front, and integrates numerically the perturbation generated when it encounters a mountain of small amplitude. As it is well known, when the equations of motion in the geostrophic momentum approximation are written in geostrophic coordinates (see e.g. Hoskins, 1975) an Eady model can be formulated whose bidimensional linear solutions are also finite amplitude solutions, and they are able to represent a realistic frontal structure in physical space.

To take full advantage of this feature we need to linearize the equations for the mountain-induced perturbation, so that there is no orographic modification of the Eady base state. Linearization is also needed to make the mountain location in geostrophic space dependent only on the known Eady wave and not on the orographic perturbation itself. However, the solutions presented in the next section are transformed back in physical space by means of the full (Eady + mountain) geostrophic wind.

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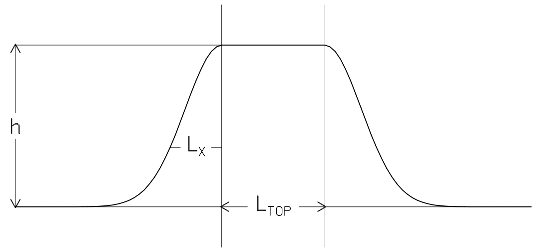

Figure 1: Mountain profile, made of two half gaussians joined by a flat plateau

A detailed description of the model is given in Fantini and Davolio (1999), together with a discussion of its drawbacks, including the continued exponential growth of the 2-D Eady wave, which therefore reaches the limits of validity of the coordinate transformation sooner than desirable; and, most importantly, a small inconsistency of the linearized mountain boundary condition, which generates a spurious flux of potential vorticity into the interior flow. To summarize the argument here: we are inverting an elliptical operator with flux boundary conditions, which therefore need to integrate to zero over the boundaries. In the nonlinear formulation of the problem the streamlines follow the rigid boundaries and the consistency condition is satisfied. In the linearized version the integral at the lower boundary is performed on the flat bottom surface, across streamlines, leaving a small residual when the orographically induced vertical velocity is not symmetrically distributed.

2 RESULTS

All the results presented here were obtained with a 5,000 km primary Eady wave, 500 Pa deep at the initial time, and a mountain height of 1,500 m. The profile of the mountain is given in Fig. 1. The half width was chosen as L_X = 500 km in both the zonal and the meridional directions, while the mountain is elongated in the zonal direction with a value L_{TOP} = 2,000 km. Contours of mountain height are also shown in all the remaining figures. The initial phase of the primary wave is chosen so that the front, colocated with the minimum surface pressure, touches the 500 m topographic con-

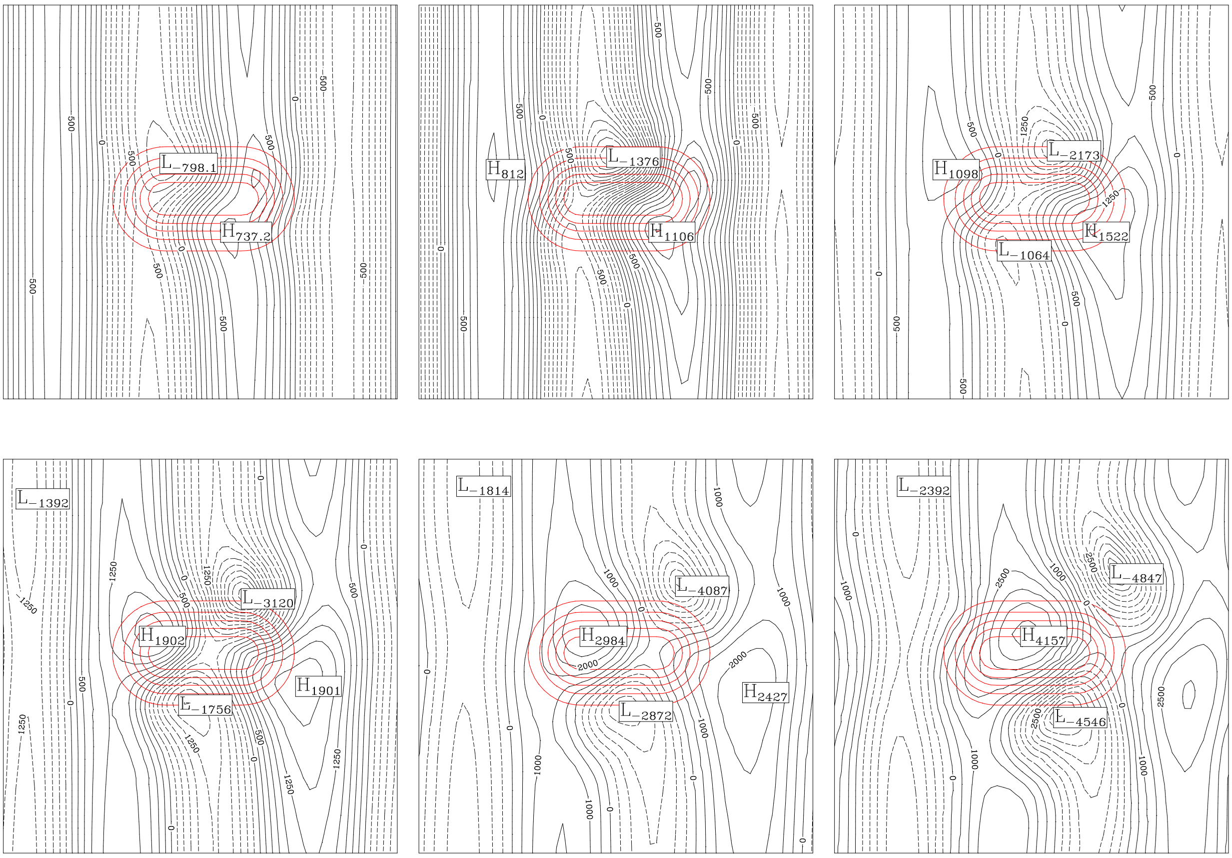

Figure 2: Surface pressure in Pa at times $6 \cdot 10^4$ s (a), $12 \cdot 10^4$ s (b), $18 \cdot 10^4$ s (c), $24 \cdot 10^4$ s (d), $30 \cdot 10^4$ s (e), $36 \cdot 10^4$ s (a). The mountain contours start from 250 m and are repeated every 250 m.

tour on the western side.

We show in Fig.2 the evolution of surface pressure in Pa and in Fig.3 potential temperature in K, every $6 \cdot 10^4$ s. A distinct low pressure area forms first on the north side of the mountain, growing while being advected by the zonal mean wind (also see Fig.s 4 and 5 below). The growth of the northern low stops at about the time of the 4th panel in Fig.s 2 and 3, after which time it begins to detach from the mountain, is advected northeastward and will eventually rejoin the primary wave. The southern low appears later in time, and follows the same path along the southern mountain slopes. Only when it reaches the southeast corner of the mountain it overtakes in amplitude the northern low which by this time is beginning to fill.

The evolution of the thermal perturbation starts with a dipolar anomaly, warm on the western side and cold on the east, on the mountain's top. The warm bubble slides away to the north east, joining the northern low pressure area. At a later time the cold air associated with the primary wave crosses the mountain in a NW-SE direction, and contributes to the creation of a very intense front on the south slope, where it encounters the warm air advected by the southern orographic low. In the later stages of evolution a descent of cold air is also seen on the western side of the mountain in coincidence with the flow associated with a orographic high to the north.

We also show in Fig.4 the evolution of minimum pressure for the northern and southern orographic lows, normalized with the depth of the Eady wave at the same time. Only the orographic perturbation was considered in Fig. 4, i.e. the difference between the run displayed in the previous figures and the primary Eady wave at the same time. The difference fields (not shown) make clearer the uniformity of evolution and displacement of the perturbations, which is partly hidden by its superposition with the primary wave. Fig.5 shows the location of the centers of the northern and southern orographic lows during the evolution (thick lines) compared with the locations observed in Fig. 2 above (thin lines). The northern minimum appears accelerated in the early displacement from the primary low to the more advanced orographic one as the latter grows, while the opposite

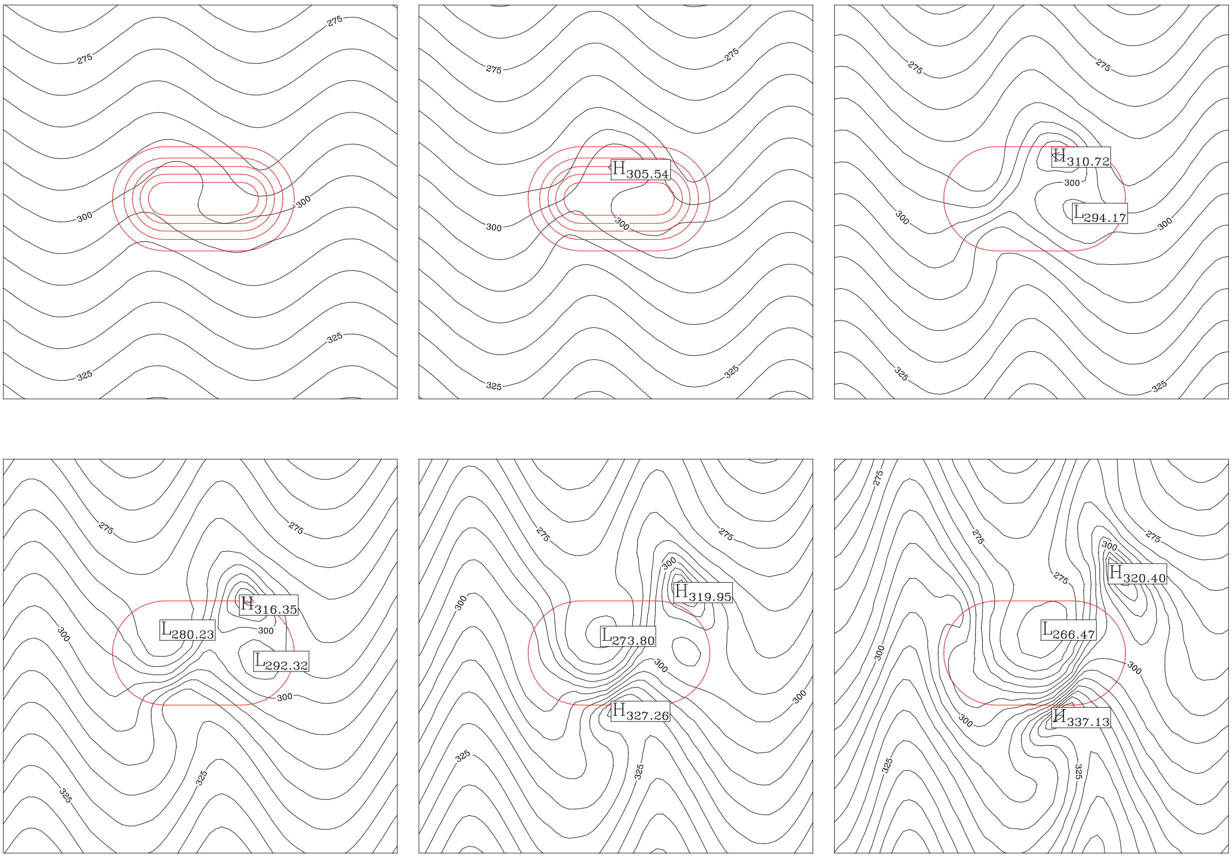

Figure 3: Same as Fig.2 but for potential temperature at the surface in K.

is true of the southern one which superposes with the Eady wave in the opposite phase. Both orographic lows are advected uniformly by the mean wind, as it was to be expected, since they are forced by the Eady wave computed analytically, and evolve according to linearized equations.

3 DISCUSSION

The results of the previous section were obtained for an Eady-like mean state, with wind vanishing at the ground, and a linearized mountain, which does not modify the mean state nor interact with it. The interaction of the incoming flow with the orography is here provided only by the finite amplitude baroclinic wave. Therefore we are not in the position to directly compare this work with studies in which the mountain does generate a stationary perturbation (e.g. Schär, 1990).

In comparison with previous work by other authors (e.g. Orlanski and Gross, 1994; Gross, 1994) the lack of flow blocking due to the application of a linearized mountain boundary condition on the flat bottom surface distorts the evolution especially of the thermal field. This effect could only be included in the model with the use of terrain following coordinates, but their application in the semigeostrophic environment would require an implicit redefinition at every time step, since the locations of the topographic grid points change with the solution itself. The use of the full solution in the transformation to physical space, after performing the integration in geostrophic space, can partially account for the nonlinear deformation of the southern front, which is intensified both by cold air flowing from the north across the mountain top and by warm air advected by the orographic perturbation. We expect that, were the large scale flow forced to go around the obstacle, rather than over, the convergence line would be located more to the south and west of the location displayed in Fig. 3f.

We started this work with two main objectives: (i) to relate the development of orographic perturbations to the environmental and geometrical parameters of the incoming primary cyclone and mountain and (ii) possibly to extend the normal mode theory of orographic cyclogenesis (Speranza et al., 1985; Buzzi et al., 1986) with the inclusion of a finite size initial condition, which

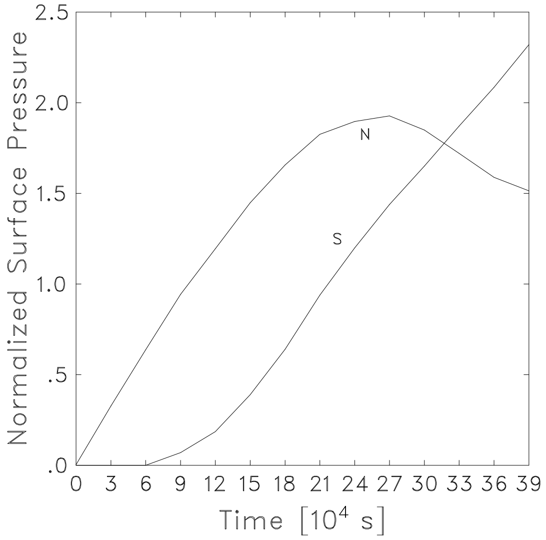

Figure 4: Minimum surface pressure for northern and southern orographic lows, normalized with the amplitude of the primary wave at the same time, vs time.

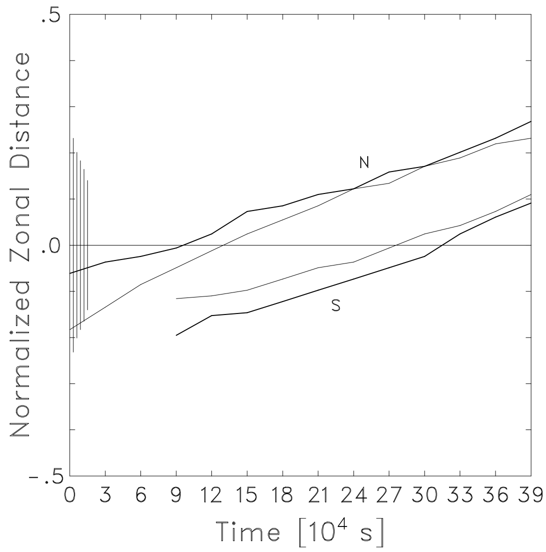

Figure 5: Location of minimum surface pressure, for the northern and southern orographic lows, vs time. The zonal coordinate is normalized with the domain size (10,000 km) so that the tick marks represent 1,000 km distance, and centered at the mountain center. The thick lines refer to orographic perturbation only and the thin lines to the total surface pressure (Eady wave plus perturbation). The five thin lines on the left edge show the length of the mountain at the heights of the contours in Fig.s 2 and 3, i.e. 250, 500, 750, 1000 and 1250 m.

could well represent the situation advocated by Smith (1984) of a turning of the mean wind above the mountain. This sought for extension should be able to provide information on how fast an initial condition of given, not infinitesimal, amplitude it is able to project on the orographic normal modes. In this preliminary work we showed that the model is able to represent an orographic perturbation with reasonable relation to the observed phenomenon. On the other hand, shortcomings of the model's formulation were identified which may lead to question its appropriateness for the proposed task.

Acknowledgements

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