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Physical modelling of baroclinic development in the lee of the Alps

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Abstract
When baroclinic development is triggered by an obstacle, like an extended mountain range, the so-called lee, or secondary cyclogenesis can develop. The presence of the obstacle exerts a blocking effect on the lower layers of the impinging airflow, forcing them to go round its borders and reach the lee region with a delay. Blocking and delay are both responsible for the initial pressure decrease downwind of the mountain and for the subsequent proper downstream baroclinic development. According to this rather simple scheme, a cyclogenesis episode in the lee of the Alps was simulated in a hydraulic turntable. The results of these experiments showed a good agreement, both from a qualitative and quantitative point of view, with the analysis of an episode of lee cyclogenesis coupled to a cold outbreak in the Mediterranean, which actually occured in Southern Europe downstream of the Alps.

Key words *baroclinic instability – orographic cyclogenesis – laboratory modelling*

1. Introduction

On the Earth, cyclogenesis is mainly observed at mid-latitudes, where the baroclinic structure of the synoptic airflow, connected to the typical increase of the westerly winds with height, allows cyclones to form and intensify.

The process of cyclogenesis, which is generally referred to as a development of synoptic scale weather disturbances (Buzzi and Tibaldi, 1978; Egger, 1972; Radinovic, 1965), can be regarded as an infinitesimal perturbation superposed on an unstable zonal current. For this infinitesimal perturbation to amplify, the basic flow must provide potential and kinematic energy to the perturbation (Atkinson, 1981a) through the so-called baroclinic instability development.

Lee cyclogenesis is a peculiar secondary cyclogenetic process occurring when baroclinic unstable zonal currents interact with topographical features, like the Alps or Pyrenees. It has been suggested that, under well specific conditions, the obstacle can act as a trigger for this secondary cyclogenetic development (Buzzi and Tibaldi, 1978; Boyer *et al.*, 1987).

This means that the mountain can induce a cyclogenetic process which is intensified and locked in the region downwind of the obstacle.

Alpine lee cyclogenesis is induced by the interaction with the mountain of a primary growing baroclinic wave embedded in a mean westerly shear flow. The shape and the loca-

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tion of the Alps are necessary conditions (Egger, 1972) for the strong cyclogenetic activity on the Mediterranean (*boundary condition*), from the Gulf of Genoa to the Po Valley and thence to the north of the Adriatic Sea.

Cold outbreaks into the Mediterranean basin from the north or the northwest are very favourable for the formation of cyclones (*initial condition*) (Egger, 1972).

The Alps can be considered as a wall blocking the normal flow in the lowest layers: the following two processes seem to be responsible for the initial pressure fall in the lee (Buzzi and Tibaldi, 1978):

1) Horizontal advection, which varies in the vertical because of the blocking effect of the mountain.

2) Horizontal deformation of the thermal field, which is induced by differential advection in the horizontal.

The theoretical model of this process, which can be summarised as an *advection-retardation* effect due to the orographic influence, has been described in detail by many authors and will not be discussed here. The reader is particularly referred to the textbooks of Holton (1992), Bluestein (1993) and Atkinson (1981b).

We shall only recall the basic steps of this theory, based on the concept of primary and secondary pressure waves (Egger, 1972; Bluestein, 1993):

1) At higher levels, the primary wave of pressure fall, caused by differential cyclonic vorticity advection processes, crosses the Alps without hindrance and makes the surface pressure fall downstream of it (Atkinson, 1981b).

2) The approach of the cold front is connected with divergence in higher levels.

3) The compensating flow from the cold to the warm region in lower layers is hampered by the mountains.

4) The effect of the primary wave is isolated in the lee of the Alps and secondary cyclogenesis has to be expected there. Then, a proper downstream baroclinic development, triggered at low level by the frontal readjustment process and sustained aloft by the deepening of the large-scale trough, takes place accounting for the subsequent stage of the cyclone life. This also explains why the cyclone of the Gulf of Genoa is considered a «secondary» cyclone, as opposed to the already existing «primary» parent cyclone, north of the Alps.

5) Finally, the cyclone increases its horizontal scale to about 500 km and takes the typical feature of a cut-off cyclone of mid-latitudes.

2. Experimental layout similarity criteria

The need to describe in detail different scales characterizing the orographic cyclogenesis makes it indispensable to use large platforms. In fact, even if the large-scale features of synoptic baroclinic circulations do not strictly depend on the precise geometrical details of the topography, nevertheless the interaction of these circulations with a mountain, and the trigger of baroclinic instability by the latter, are strongly related to the variations of many different parameters, like shape, orientation, vertical and horizontal extent, whose simulation cannot be easily accomplished in small rotating tanks.

For this reason, our experiments were carried out on the turntable of the Institute of Mechanics, Grenoble University. This platform (Chabert d'Hieres *et al.*, 1991) (fig. 1) consists of a 14 m diameter, flat reinforced concrete table, bearing a coaxial, 13 m diameter, cylindrical tank which can be loaded with fresh and salted water up to about 150 tons. In these conditions, the total weight of the facility is in the order of 300 tons. The turntable, supported centrally by a spherical thrust bearing and peripherically by 23 rollers, equally spaced around the circumference of the table, is constant to within 0.03 mm across its radius (corresponding to an error of only $5 \cdot 10^{-6}$ rad from the vertical); its rotational speed (Ω) can be adjusted berween 0.4 and 0.006 rad s^{-1}, and kept constant within 0.01%.

Two large storage tanks, placed 2 m underground, can supply fresh and salt water whose temperature and salinity are adjusted to the desired value through heaters and facilities for mixing solutions of water with different salt concentrations. The thermal inertia of such a large water mass used for the experimental runs allows both temperature and density to be

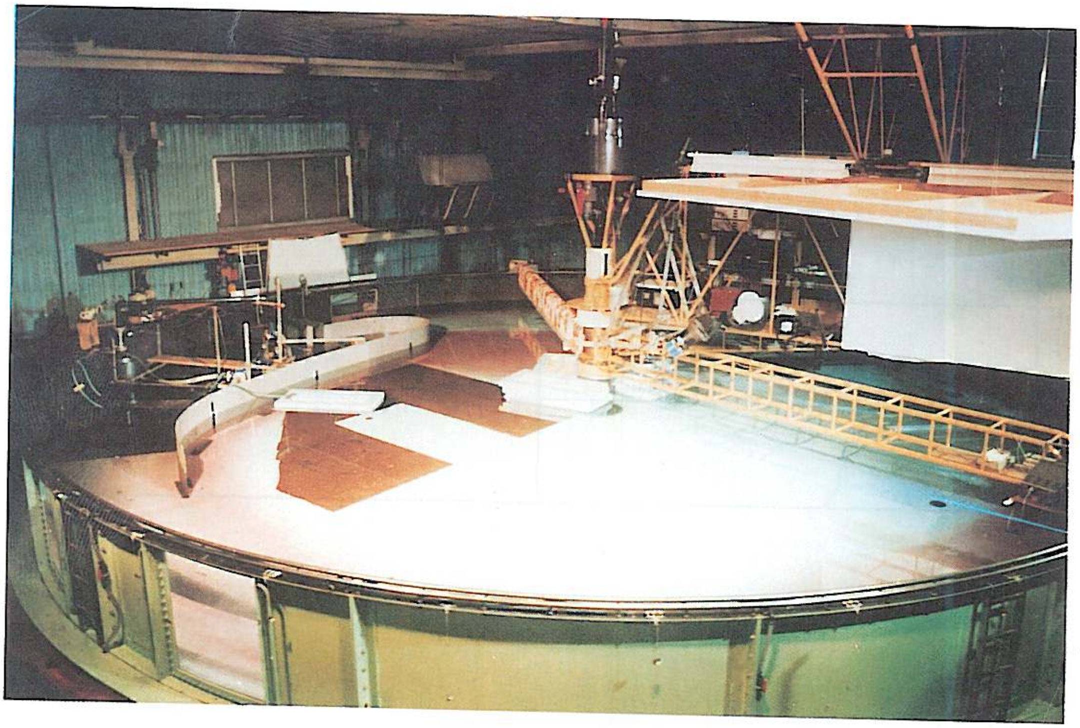

Fig. 1. The hydraulic turntable of the «Coriolis Laboratory», Grenoble.

held constant for the whole duration of each experiment (6-8 h).

In the present simulation of lee cyclogenesis we aimed at simulating a typical baroclinic flow (which is considered a forerunner of secondary, Alpine cyclogenesis), represented by a cold northwesterly airstream, associated with a strong, primary cyclone located north of the Alps, coupled with an anticyclone north-west of the Alps (see fig. 2, taken from Buzzi and Tibaldi, 1978). In other words, we were interested in studying the behaviour of a baroclinic zonal flow which, in the absence of the mountain, could not have necessarily given rise to a secondary baroclinic development, so as to ascertain in a manifest way the effective role played by the latter in the cyclogenetic process.

The baroclinic frontal flow, simulating the flow described above, was created in the laboratory experiments using a modified version of

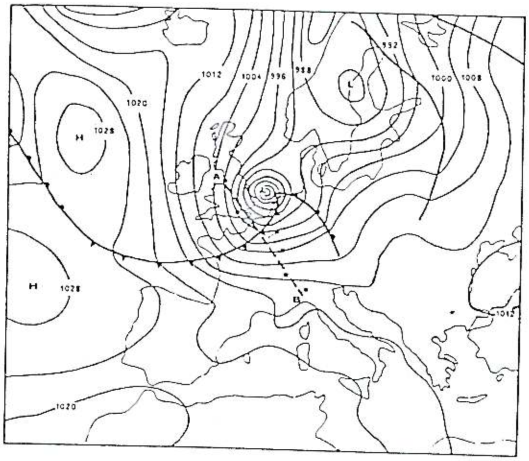

Fig. 2. Surface analysis of the initial pressure distribution (on April 2, 1973, 12 GMT), showing the most favourable situation to lee cyclogenesis development (taken from Buzzi and Tibaldi, 1978).

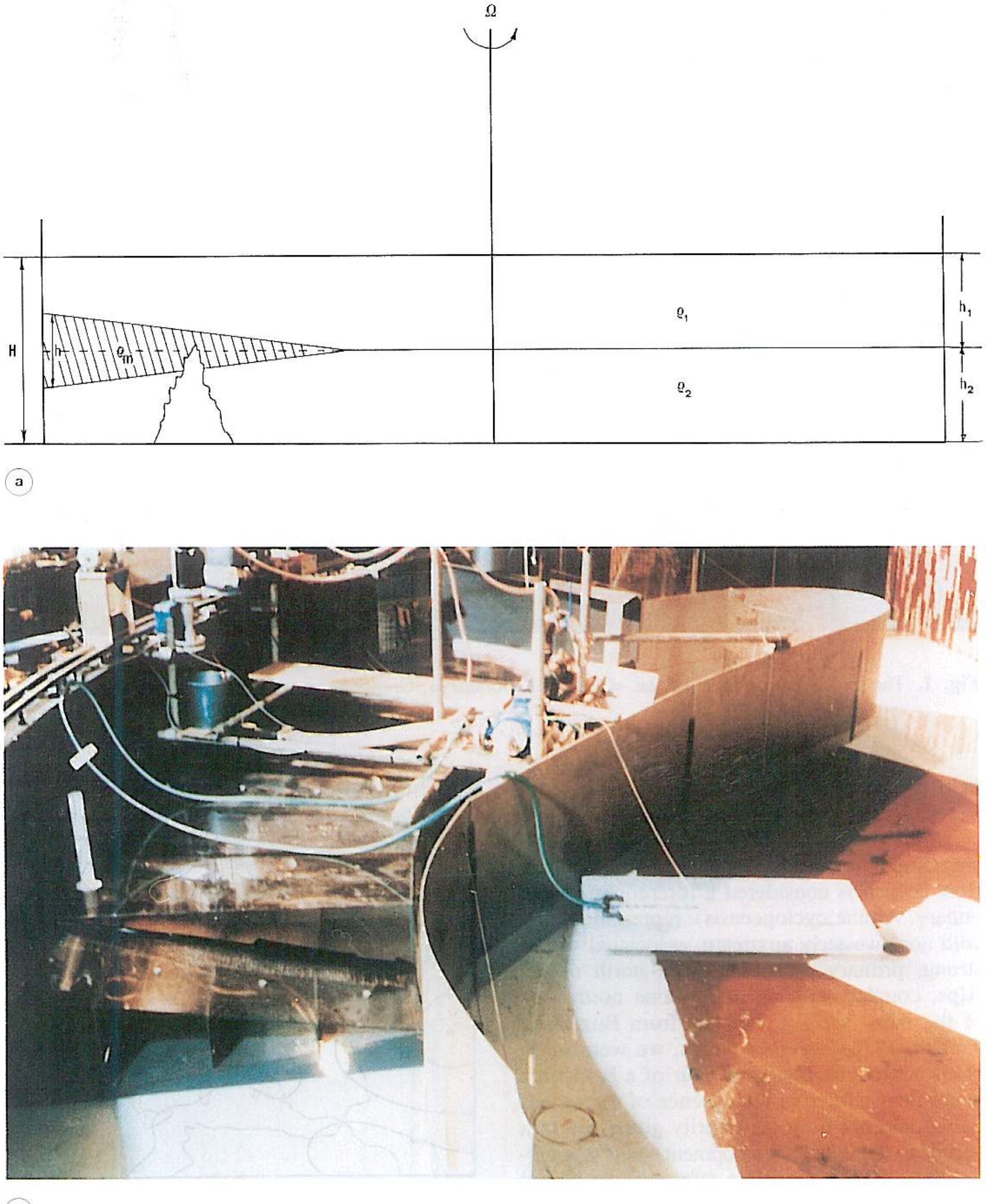

Fig. 3a,b. a) Cross-section of the intermediate current downstream from the outlet end of the generator (indicated by the dashed triangle). b) The intermediate density current generator.

the generation technique of surface density currents (Chabert d'Hieres *et al.*, 1991).

The background atmosphere was initially represented by a two-layer fluid, whose densities were ρ_1 and ρ_2, respectively, with a separating interface layer in equilibrium with the rotating frame of the cylindrical tank. This stratification was obtained by introducing into the tank, from its bottom, at first fresh water of density ρ_1 and, afterwards, salted water of density ρ_2, in a volume ratio of 1 to 1.6, so as to produce layer depths h_1 and h_2 of 25 and 40 cm, respectively, to a total depth H of 65 cm (fig. 3a).

A fluid of density ρ_m (intermediate between ρ_1 and ρ_2) was then generated by a system which mixed waters from the two above-mentioned layers.

This system, placed along the peripheral wall of the tank (see fig. 3b) was made up of a rectangular channel 0.6 m high, 1.5 m wide and 5 m long, with a triangular outlet end whose function was to facilitate the geostrophic equilibrium configuration of the intermediate current, shown in fig. 3a (vertical section).

When the intermediate density stream leaves the outlet mouth of the front generator and penetrates between the two fluid layers, a typical meandering due to adjustment processes (bringing about compression and stirring of vortex tubes) occurs, which simulates the relevant features of a cyclone-anticyclone dipole structure (see fig. 4), closely corresponding to the above-mentioned synoptic natural situation which is most favourable to lee cyclogenesis development south of the Alps (Buzzi and Tibaldi, 1978) (fig. 2).

This peculiar dipole structure originates irrespectively of the presence or absence of the obstacle, and only depends on the Burger number Bu of the current:

$$Bu \equiv \frac{g}{f^2}\frac{\Delta\rho}{\rho}\frac{h}{L_{h/2}^2} = \frac{g'}{f^2}\frac{h}{L_{h/2}^2}.$$

In the above definition of Bu, f is the Coriolis parameter, $\Delta\rho = \rho_2 - \rho_1$, $g' = g\frac{\Delta\rho}{\rho}$ is the reduced gravity, h is the maximum vertical depth of the intermediate current downstream from

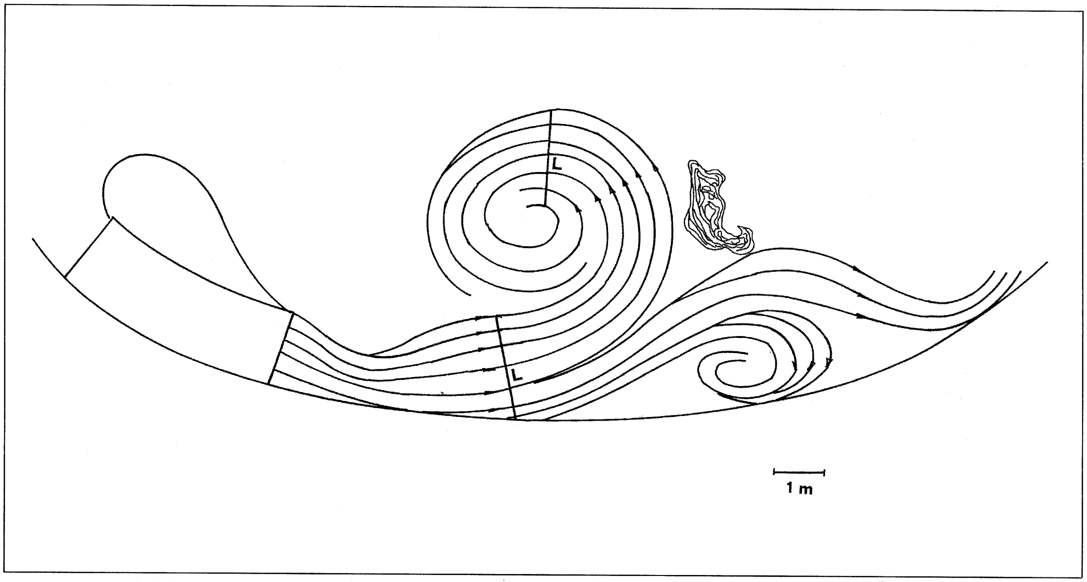

Fig. 4. Schematic view of the simulated cyclone-anticyclone dipole structure.

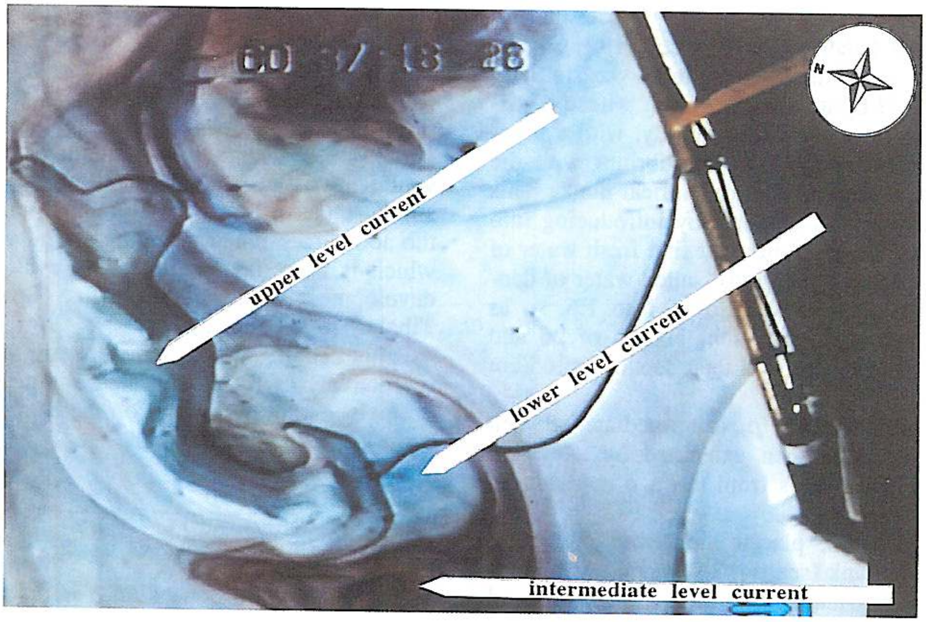

Fig. 5. Circulation pattern over and around the model of the Alps at lower, intermediate and upper levels of the simulated front, respectively marked by blue, red and green dye tracers, at the beginning of the secondary cyclogenetic development (37′18″ from the start of the experiment).

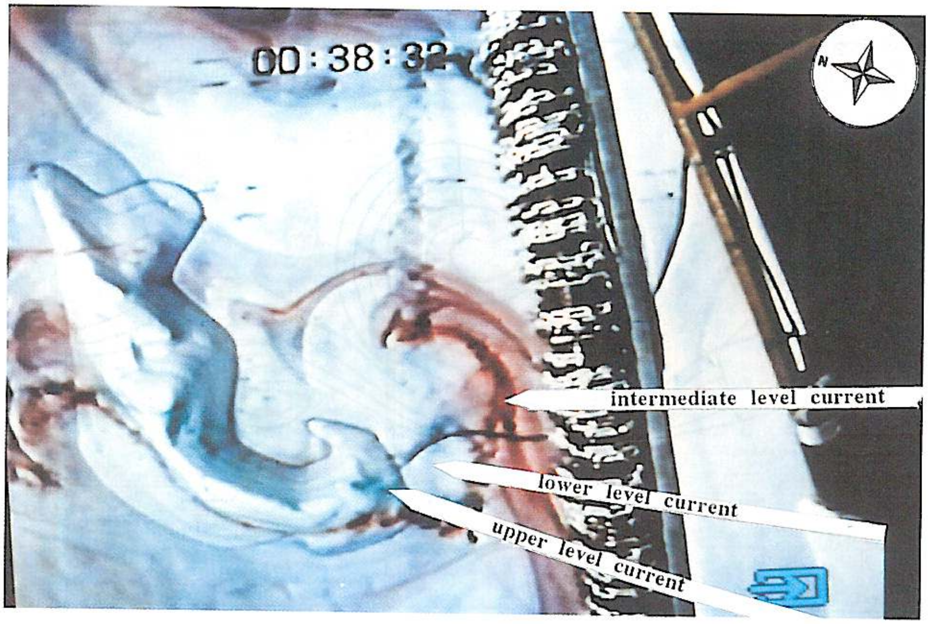

Fig. 6. Same as fig. 5, but 1′14″ later.

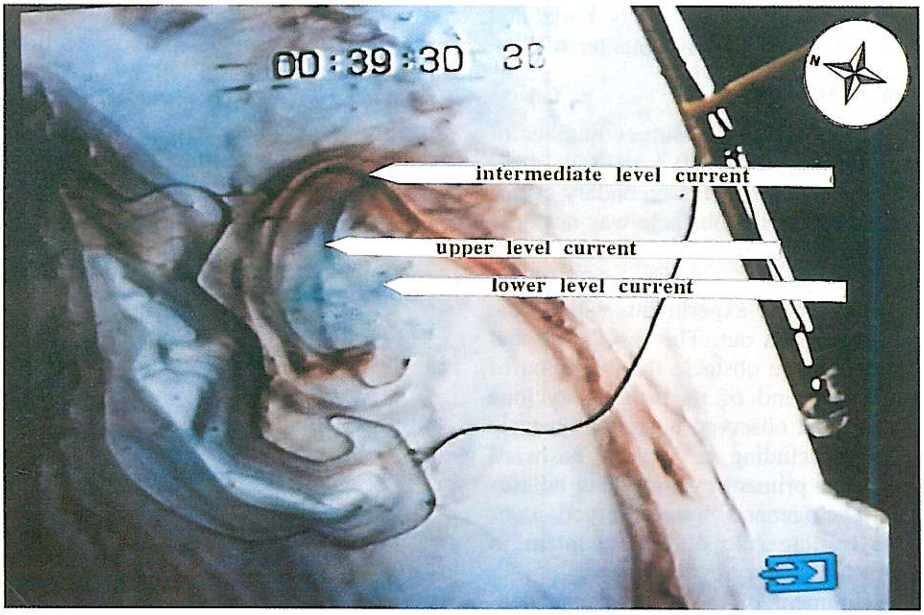

Fig. 7. Same as fig. 5, but 2′12″ later.

Fig. 8. Same as fig. 5, but 3′8″ later.

its source (fig. 3a) and $L_{h/2}$ is its horizontal width at half depth ($h/2$). As a matter of fact, $L_{h/2}$ was approximated by $\frac{L}{2}$.

In our experiments, the Burger number of the current was in between 0.3 and 0.4.

In order to be sure that the secondary cyclogenesis in the lee of the obstacle was not only a consequence of the instability of our boundary flow, which gave rise to the initial dipole pressure pattern, many experiments without the obstacle were carried out. The result was that in the absence of the obstacle the evolution of the initial dipole and of its primary cyclone was similar to that observed when the obstacle was present (including a typical eastward movement of the primary cyclone), but no secondary lee cyclogenesis was observed, confirming the leading role of the mountain in triggering the secondary cyclogenesis.

The development of the intermediate density current, simulating our synoptic front, and its interaction with the obstacle simulating the Alps, were observed both by three TV cameras and by a rectangular mesh of 15 ultrasonic density samplers. Each TV camera recorded, in its own field of view, the tracks of dye tracers emitted at three different levels in the layer simulating the front, thus giving a synoptic representation of the baroclinic development occurring near and downstream from the obstacle (figs. 5 to 8).

At each time it was operated, the density sampler network provided continuous vertical density profiles, simultaneously recorded at 15 points upstream and downstream from the obstacle. These allowed us to reconstruct the density field at many levels in the region of the synoptic cyclone-anticyclone dipole and around and downwind of the obstacle, where the baroclinic interaction and the lee cyclogenesis occurred.

In order to test the occurrence of the physical conditions characterising the natural phenomenon we wanted to simulate, these density patterns were then transformed into the corresponding schematic atmospheric fields of pressure and potential temperature.

The obstacle used to simulate the Alps was overall given the shape of the actual mountain range, with a smoothed cross-section profile reaching a maximum height of 30 cm and a horizontal extent of 2 m. This means a geometrical distorsion between vertical and horizontal dimension of the mountain in the model of the order of 10, which can be allowed by the Burger similarity (Boyer and Chen, 1987).

In fact, in the prototype $\left(\frac{h_m}{L_m}\right)_p$ (where suffix p stands for «prototype» and suffix m stands for «mountain») is in the order of 10^{-2}, while $\frac{1}{f}\left(\frac{g'}{h_m}\right)_p^{1/2}$ is in the order of 10^{+2} at mid-latitudes: this means that the Burger number is $O(1)$ in the atmosphere.

Then, if in the laboratory the aspect ratio of the mountain is $O(10^{-1})$, it is sufficient that $\frac{1}{f}\left(\frac{g'}{h_m}\right)_l^{1/2}$ (where suffix l stands for «laboratory»), be made $O(10)$ for the Burger similitude to be obtained, even if the geometrical ratio is distorted. Actually, $\frac{1}{f}\left(\frac{g'}{h_m}\right)^{1/2}$ ranged from 5 to 8 in our experiments.

3. Analysis and discussion of the results

We discuss here the results of a particular experiment that, according to our TV camera records (figs. 5 to 8), turned out to be characterized by a very clear-cut development of cyclogenesis in the lee of the obstacle. The experimental conditions of this simulation were:

$T = 100$ s $\quad h_1 = 25$ cm $\quad U = 5$ cm$\cdot$s^{-1}

$f = 0.126$ s^{-1} $\quad h_2 = 40$ cm $\quad \rho_2 = 1.011$ g$\cdot$cm^{-3}

$h = 30$ cm $\quad L = 2$ m $\quad \rho_1 = 0.999$ g$\cdot$cm^{-3}

Figure 5 shows the circulation pattern over and around the model of the Alps at the lower, intermediate, and upper levels of the simulated front, at the time the primary cyclone attained its mature stage, shown by the green dye (upper level) over the obstacle which heralds the arrival of the mid-tropospheric front above the mountain and the lee region.

The blue and red dyes, marking the lower and intermediate levels of the front, respectively, herald the onset of the cold outbreak of the north-westerly surface and low-tropospheric front in the lee region and its initial eastward bending.

This situation is documented, in the natural prototype, by the 500-hPa geopotential pattern at the beginning of the lee cyclogenesis (fig. 9a taken from Buzzi and Tibaldi, 1978), which shows that the airstream exhibits, at that altitude, a deflection above the Alps, crossing them south-eastward and penetrating the Mediterranean area.

The subsequent pictures (figs. 6, 7 and 8), taken about 1 min apart, show the development of the secondary cut-off cyclone in the lee area. The three level currents, marked by three dye tracers, converge on a vertically coherent cyclonic circulation, which conforms to the situation depicted by figs. 9b,c, taken from Buzzi and Tibaldi (1978), showing that the centres of the low level and mid-tropospheric cut-off cyclones are approximately located along a vertical line.

Taking account of the space and time scales of this experiment, each minute in the model corresponds to about 15 h in the prototype, which means that the three minutes taken by the cyclogenesis to develop in the laboratory corresponds to about 2 days, the lifetime of the natural episode.

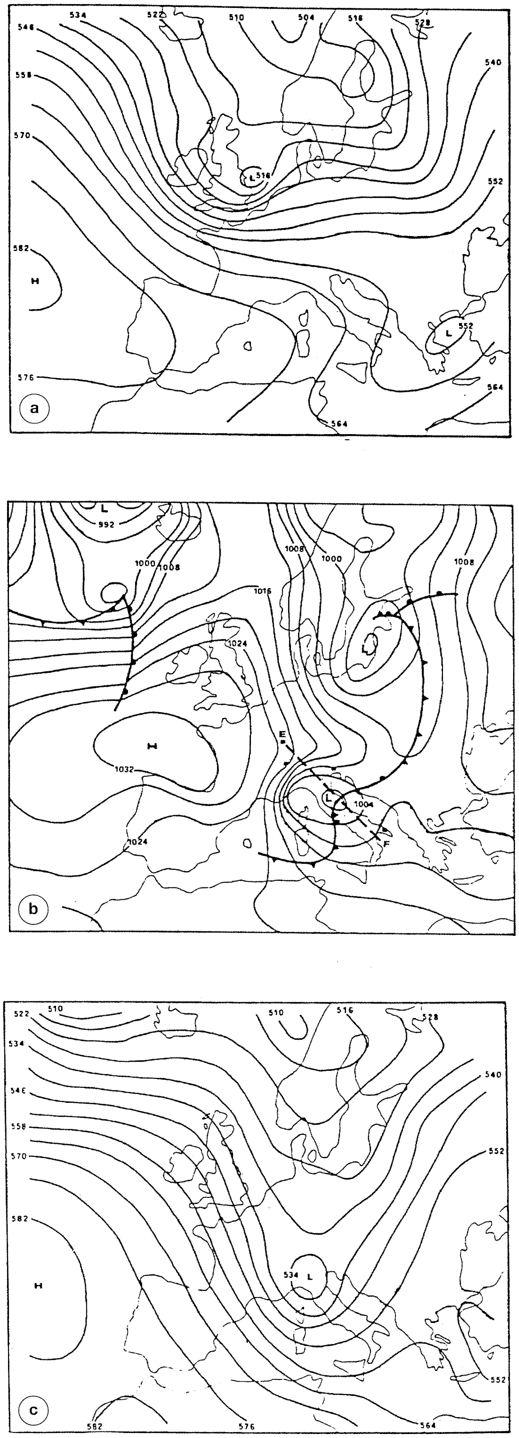

Fig. 9a-c. a) The 500-hPA geopotential pattern on April 2, 1973, 12 GMT. b) Surface analysis of the pressure distribution on April 3, 1973, 12 GTM. c) The 500-hPa geopotential pattern on April 3, 1973, 12 GTM (taken from Buzzi and Tibaldi, 1978).

4. Conclusions

The analysis of a laboratory experiment in a hydraulic turntable of a lee cyclone development produced some interesting results, which have shown that this modelling technique is able to simulate, at reduced scale, some relevant patterns of complex subsynoptic atmospheric processes of interaction between airflows and mountains, whose prediction is still not fully resolved.

In the laboratory experiment described in this paper, the time and space evolution of the vertical isentropic field and some circulation patterns observed upwind and downwind from the obstacle, showed a satisfactory qualitative agreement with the corresponding structures appearing in a cyclogenetic episode which actually occurred in the lee of the Alps.

The interest in experiments like the one here discussed is the possibility they offer to inspect, under controlled conditions, some schematic examples of physical processes occurring in the interactions of atmospheric circulations with large mountains, taking advantage of their capability to represent the continuity of the fluid

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