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THE GAP AND KATABATIC CONTRIBUTIONS FOR THE MAP IOP 15 MISTRAL WINDSTORM

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1. INTRODUCTION

A severe mistral event has been documented by two UHF wind profilers during the MAP IOP 15 from the 6 to the 8 November 1999. The wind profilers monitored the time evolution of wind profiles up to 3000 m height at the Rhône valley exit, near Marseille, and downstream the Alps, at Toulon (denoted by STC and TLN respectively on Fig. 1).

The paper proposes to analyze the gap and downslope contributions for this mistral event by using the hydraulic theory (Arakawa, 1968).The paper focuses on the mistral observed from 07 to 08 November 00 UTC since the vertical structure of the wind dramatically changed as observed by the wind profilers. Note that this period has escaped from aircraft measurement contrary to the 06 November (Jiang et al., 2003). Non-hydrostatic simulations performed by RAMS (Pielke et al., 1992) complete the discussion on the processes involved in mistral situations. The motivations of this work consist in (i) interpreting the vertical profiles of the mistral measured by the two wind profilers and also (ii) extending the work of Pettré (1982) who used the hydraulic theory in a conservative form to describe the mistral within the Rhône valley.

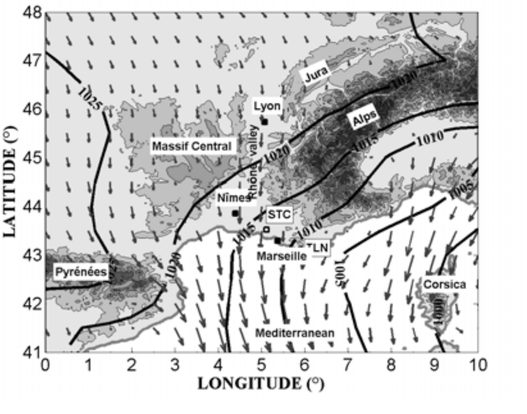

Fig. 1. Target area in southeastern France. STC and TLN are the locations of the UHF wind profilers. Lyon and Nîmes are the locations of routine radio soundings. Solid lines sketch surface pressure (hPa) and vectors display the horizontal wind at 950 hPa from the ECMWF analysis chart on the 07 November 1999 00 UTC.

2. SYNOPTIC ENVIRONMENT OF THE MAP IOP 15

The mistral is a northerly to northwesterly, cold and dry wind that blows in southeastern France from the Rhône valley to the northwestern Mediterranean (Fig. 1). The Rhône valley separates the Alps from the Massif Central. The mistral blows at any season but is more frequent in spring when it can persist during one week long.

During the MAP event, a severe mistral event had been documented from the 06 to the 08 November 1999. The synoptic environment of this mistral event is classic.

The Genoa cyclogenesis (1004 hPa) is initiated after the passage of a cold front from the Atlantic toward the Alps on the 06 November 12 UTC. The Azores ridge (1028 hPa) over Spain strengthens the surface pressure gradient resulting in a strong northerly flow (Fig. 1). The cyclone (1003 hPa) rapidly moves southeastward and is located over the southern Italy on the 08 November 12 UTC. At the end of the mistral event, high-pressure conditions prevail (1034 hPa).

3. THE HYDRAULIC THEORY AND THE RAMS SIMULATIONS

3.1 The hydraulic theory

The hydraulic theory describes the response of a two-layered perfect flow to a mountain and/or a valley (Arakawa, 1968). The flow is assumed steady, non-rotating and the turbulence is neglected.

Under these strong hypotheses, the flow past obstacles can be predicted by upstream conditions defined by the thermal inversion height and its associated mean wind speed.

The formulation is based on the conservation laws of mass and momentum that lead to a single equation

$$\left(F^2-1\right)\frac{1}{v}\frac{dv}{dx}=\frac{1}{b}\frac{db}{dx}-\frac{1}{h}\frac{dm}{dx} \qquad (1)$$

F is the Froude number. h is the well-mixed layer topped by a thermal inversion. v is the mean wind speed in that layer. m is the

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mountain height, b is the valley width and x the valley axis.

As hydraulic jumps appear at singular points in equation (1) when F equal unity, a basic parameterization on the jump discontinuity based on Euler's equation is used (Ball, 1956; Pettré, 1982).

The main advantage of the hydraulic theory is its simple formulation where unique solutions can be easily computed with a basic finite differencing explicit scheme. Pettré (1982) applies the equations of the hydraulic theory written in conservative form to describe the mistral within the Rhône valley and finds non unique solutions. With that approach, Pettré gives a phenomenological description of the mistral for incident Froude number greater than 0.28. The local formulation works with any kind of flows even incident supercritical flows. Moreover, in the hydraulic theory, the gap and downslope forces are decoupled so that their effects can be easily analyzed. Two transects of the thermal inversion height taken North of STC and TLN are given from the hydraulic theory to interpret the wind profiler data. Thus, the theory needs the mountain heights m and the valley width b to compute these transects. Along the Rhône valley, the maximum height is 400 m while the transect crossing the Alps is featured by a 2300 m mountain height. The valley ranges from 90 km near the latitude 45N to 230 km near the latitudes 46N and 43.5N.

3.2 The RAMS simulation

Non-hydrostatic simulations are performed with the RAMS model (Pielke et al., 1992) to make comparisons with the 2D predictions of the hydraulic theory and also to illustrate the 3D processes involved in mistral situations. In the simulations, a 9 km horizontal spacing mesh is selected. The simulation is initialized the 06 November 12 UTC and integrated over 48 hours.

The prognostic fields of the simulations are validated through some comparisons of the vertical profiles of the wind and potential temperature measured by the radio soundings at Lyon and Nîmes. The simulations (not shown) are also validated by the time evolution of the wind profiles observed by the STC and TLN wind profilers.

4. THE MISTRAL OBSERVATIONS

4.1 Upstream conditions

The hydraulic theory needs the thermal inversion height and the component of the component of the wind normal to the obstacles. The incident conditions are given by the radio soundings launched each 6 hours at Lyon (Fig. 1). Fig. 2 gives the vertical profiles of the potential temperature and the v-component of the wind from 07 to 08 November 00 UTC.

The potential temperature profiles point out the well-mixed layer that gets progressively thinner with time from 3100 to 1350 m above ground level (AGL). The strong thermal inversions that range from 10 to 20 K.km^{-1} fulfil the conditions of two-layered fluid system needed by the hydraulic theory. The incident wind speed ranges from 10 to 20 ms^{-1}.

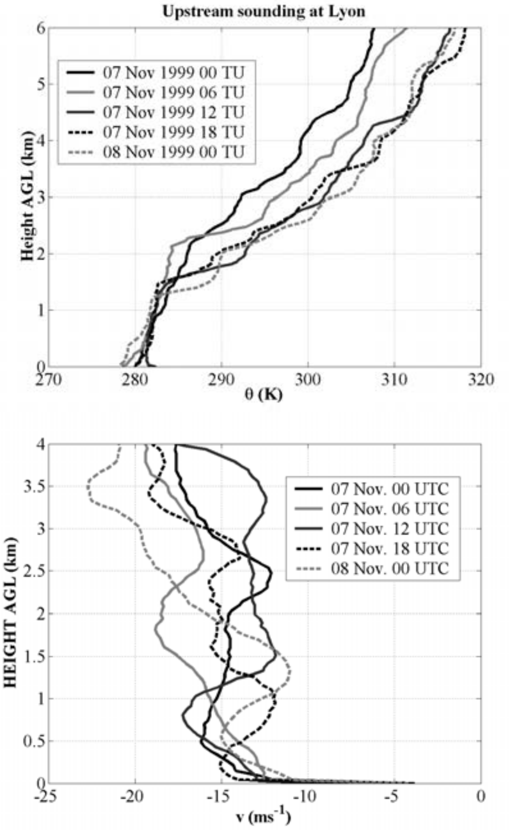

Fig. 2. Upstream radio sounding data at Lyon from 07 to 08 November 00 UTC. The top panel displays the vertical profile of the potential temperature (K). The bottom panel sketches the v-component of the wind (ms^{-1}).

4.2 Downstream conditions

The downstream conditions are obtained thanks to the radio soundings launched every 6 hours at Nîmes and to the wind profilers STC at the Rhône valley exit and TLN downstream the Alps (see Fig.1 for their locations).

The wind profilers show that the mistral onset occurs at the same time above the two sites at 06 November 12 UTC with a deep mistral structure. The radio soundings of Nîmes, that is located further west STC, indicate that the mistral has a 6 km depth. The deep mistral evolves in a low-level jet the 06 November 21 UTC downstream the Alps and the 07 November 06 UTC at the Rhône valley exit.

While the mistral stops the 07 November 12 UTC downstream the Alps, the shallow mistral persists at the Rhône valley exit until the 08 November 12 UTC. The wind speed maxima reach 40 ms^{-1} at the Rhône valley exit and 30 ms^{-1} downstream the Alps.

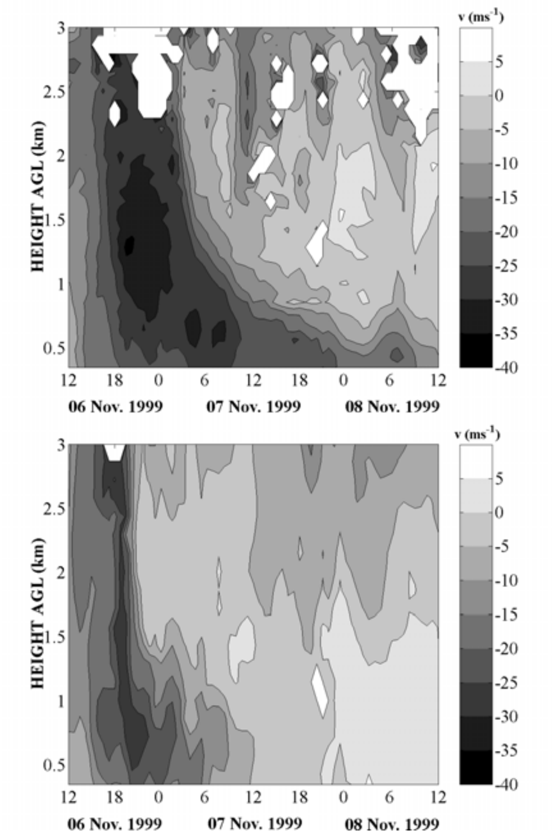

Fig.3. Time evolution of the v-component profiles (ms^{-1}) at the Rhône valley exit (top panel) and downstream the Alps (bottom panel) from 06 to 08 November 12 UTC.

5. THE RESULTS

The results of the hydraulic theory consist of two transects along the Rhône valley and across the Alps of the well-mixed depth from 07 to 08 November 00 UTC.

5.1 Downslope effects

If only downslope effects are considered, the well-mixed depth follows the terrain of the Rhône valley (Fig. 4a) suggesting that they are weak. From 07 November 12 UTC, small amplitude hydraulic jumps are noticeable near the latitude 44N and farther downstream.

Downstream the Alps (Fig. 4b), only the downslope effects are possible since too far from the Rhône valley. The height of the thermal inversion is 2 km downstream the Alps on the 07 November 00 UTC that suggests the occurrence of the low-level jet since the upstream conditions are featured by a 3 km

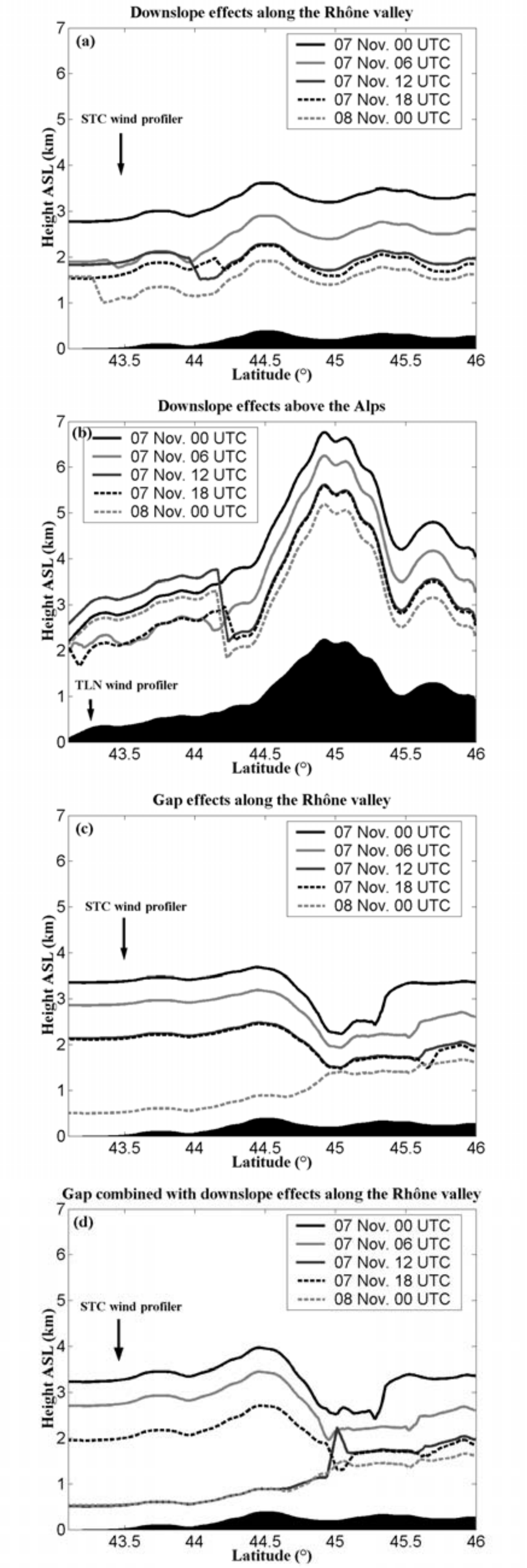

Fig. 4. Thermal inversion height predicted with the hydraulic theory from 07 to 08 November 00 UTC (a) along the Rhône valley with downslope effects only, (b) across the Alps with downslope effects only, along the Rhône valley with (c) gap effects only and with (d) the combination of gap and downslope effects.

well-mixed layer. From 07 November 12 UTC, large amplitude hydraulic jump occurs near the latitude 44.25N and is presumably responsible for the mistral cessation observed by the TLN wind profiler (Fig. 3).

5.2 Gap effects along the Rhône valley

If only the gap effects are considered (Fig. 4c); a low-level jet occurs along the Rhône valley on the 08 November 00 UTC while the observations show that it is triggered earlier on the 07 November 06 UTC (Fig. 3).

The superposition of the gap and downslope effects also leads to a shallow mistral but triggered earlier on the 07 November 12 UTC that better fits with the observations. Thus, downslope effects are not negligible along the Rhône valley. The study shows that the non-linear synergetic combination of the two effects determines the flow structure along the Rhône valley. Note that the acceleration of the mistral along the Rhône valley (Fig. 4d) linked with a decreasing well-mixed layer looks similar with the oblique shocks found in transient flows past obstacles (Schär and Smith, 1993; Drobinski et al., 2004). The mistral accelerates despite the broadening of the valley without considering the diminishing surface roughness towards the Sea.

5.3 Non-hydrostatic simulations with RAMS

A non-hydrostatic simulation with a 9 km horizontal mesh spacing is performed to analyze the validity of the hydraulic theory and to highlight that 3D processes also play a major role in the mistral spatial distribution.

The analysis of the horizontal wind field at 1000 m AGL (Fig. 5) highlights that the mistral blows along the Rhône valley and downstream the Alps on the 07 November 00 UTC. The hydraulic theory confirms that feature since at this time, no hydraulic jump is predicted.

12 hours later, the non-hydrostatic simulation exhibits the Alps lee wake that marks the breakdown of the mistral downstream the Alps. That feature is confirmed by the wind profiler observations and at this time, the hydraulic theory predicts a large amplitude hydraulic jump located over the descending slopes. Its position is marked by a white star on Fig. 5. Along the Rhône valley, the simulation confirms the persistence of the mistral indicating that gap effects prevail. The hydraulic theory predicts the presence of small-amplitude hydraulic jumps resulting from the downslope effects (Fig. 4a).

Figure 6 displays the South North transects of the wind speed and isentropes along the Rhône valley (top panel) and across the Alps (bottom panel) given by the RAMS simulation on the 07 November 12 UTC. Isentropes along the Rhône valley point out small hydraulic jumps above the low-level jet.

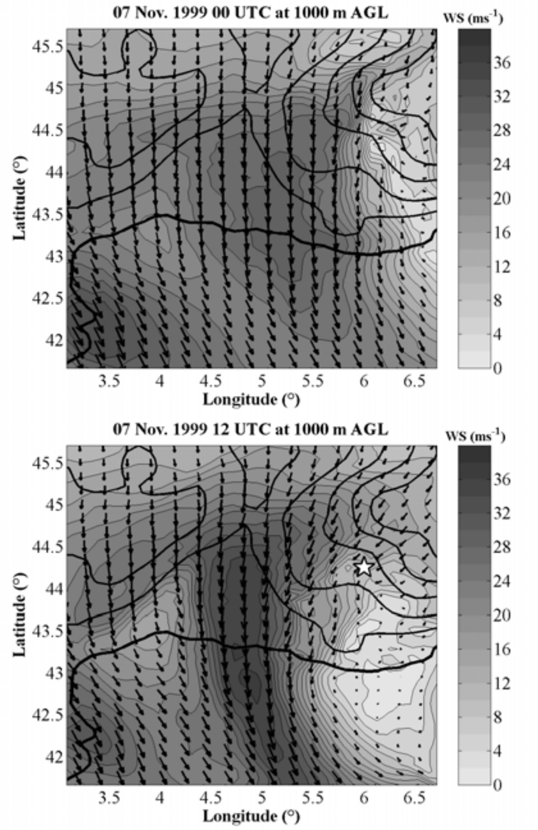

Fig. 5. Horizontal wind field at 1000 m AGL simulated by RAMS the 07 November 00 UTC (top panel) and 12 UTC (bottom panel). The white star locates the position of the hydraulic jumps predicted by the hydraulic theory.

Isentropes across the Alps exhibit a large amplitude hydraulic jump as predicted by the theory.

Thus, the two-dimensional analysis of the hydraulic theory is compatible with three-dimensional effects. The large amplitude hydraulic jump found downstream the Alps is associated with the mistral breakdown and can be related to wave breakings over the mountain (Jiang et al., 2003). Non-hydrostatic simulations confirm that the classic hydraulic jump found downstream the Alps is involved in the baroclinically generation of the potential vorticity (Smolarkievicz and Rotunno, 1989).

However, some care must be taken in interpreting the hydraulic results. The strength of the assumptions, especially the absence of turbulence, surface roughness and the basic parameterization of jump discontinuity, prohibits an accurate and quantitative description of the well-mixed layer and wind speeds. Moreover, thermal effects, as heating by föhn effects, that are not considered in the theory play also a crucial role in the southern part of the Rhône valley (Drobinski et al., 2004).

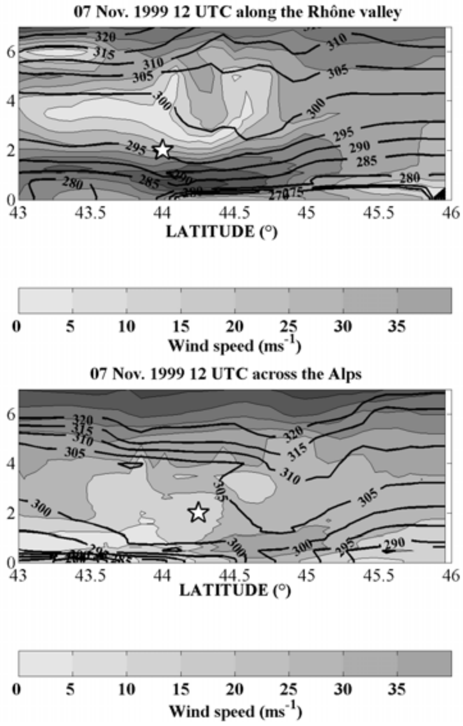

Fig. 6. South North transects of the wind speed in ms^{-1} (grey scale) and the isentropes (solid lines) along the Rhône valley (top panel) and across the Alps (bottom panel) from the RAMS simulation on the 07 November 12 UTC. The white stars locate the positions of hydraulic jumps predicted by the hydraulic theory.

6. CONCLUSIONS

The hydraulic theory is successfully applied to interpret the wind profiles observations of the mistral at the Rhône valley exit and downstream the Alps. Despite the simplicity of its formulation, the theory gives interesting results on the nature of the MAP IOP 15 mistral event especially on the 07 November when the flow has two distinct layers.

The theory predicts small amplitude hydraulic jumps that are not associated with the mistral cessation along the Rhône valley when downslope are considered. The gap effects maintain the flow within the valley. Thus, at the Rhône valley exit, the mistral is a mixture of gap and downslope winds.

Downstream the Alps, the flow is governed by downslope effects that provoke large amplitude hydraulic jump responsible for the early cessation of the mistral as revealed by the wind profilers.

The western boundary of the mistral is thus mainly affected by gap effects while its eastern boundary is under influence of downslope effects. This explains its strong spatial and time variability.

Comparing with non-hydrostatic simulation, the hydraulic results are found compatible with three-dimensional processes as flow splitting and mountain wakes. Moreover, despite that the wind speed and well-mixed depth are not realistic, the locations of hydraulic jumps fit well with the RAMS solutions.

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