HOW THE ALPINE TOPOGRAPHY INDUCES A CLIMATOLOGICAL PRECIPITATION MAXIMUM IN AUTUMN OVER THE LAGO MAGGIORE AREA

François Gheusi* and Huw C. Davies (ETH Zürich, Switzerland), and Joël Stein (Météo-France).

1. INTRODUCTION AND MODEL

A precipitation climatology of the Alpine region given by Frei and Schär (1998) (figure 1a) clearly shows that the slopes facing the Mediterranean are at most affected by heavy rainfalls in autumn. Local occurence maxima are found in relation with some particular features of the topography. This is the case for the Lago Maggiore (hereafter LM) area, which forms a low region with a diameter of a hundred km surrounded by high massives and embedded within the concavity of the Alpine arc.

Previous idealized numerical studies using a simplified topography (Schneidereit and Schär 2000, Rotunno and Ferretti 2001) stressed the role of the concave shape of the Alpine chain to force the convergence of the low-level flow. Small-scale topographic features such as the LM area were however ignored and the precipitation enhancement associated to the low-level convergence was found to be less spatially concentrated than in the climatology.

It is intended here to study quasi-stationary rain producing flows over the Alps with more attention to smaller-scale orographic effects. The real topography is thus kept but an idealized configuration is adopted for the inflow upstream from the Alps, which can thus be controlled with only few parameters. Only the main two ingredients of a typical heavy rainfall episode to the south of the Alps are retained:

1. a stationary uniform upstream flow with a dominant southerly component, driving:

2. conditionnally convectively unstable humid air towards the Alps.

The inflow is geostrophically balanced. The vertical profiles of temperature and humidity are prescribed at the inflow boundary with the sounding of Cagliari (south tip of Sardinia) on 19 September 1999 2246 UTC (MAP IOP2B). This sounding reveals a conditionnaly unstable maritime boundary layer (CAPE $\approx$ 2000 J/kg) strongly inhibited (CIN$\approx$200 J/kg) by a capping deep stable layer of warm and dry air ($N \approx 0.0075\text{s}^{-1}$). This vertical structure is quite typical of pre-frontal air masses over the Mediterranean during south-alpine heavy-rain episodes.

The numerical simulations are performed with the Europa Modell (EM) of the German and Swiss weather services. The dynamical core is based on hydrostatic equations. The cloud microphysics and the convection are parametrized with Kessler's and Tiedtke's schemes, respectively. The $(1400\,\text{km})^2$ model domain is a f-plane centered over the Alps (45°N). The horizontal resolution is 11 km (*i.e.,* 0.1° on the sphere). The model has 37 vertical pressure levels with a maximum resolution of 10 hPa near the ground.

The results are presented as soon as a stationary regime for the flow and precipitation is reached on the upstream side of the Alps (at least).

A comparison has been made between some of the present EM simulations and more sophisticated MesoNH simulations (non-hydrostatic dynamics, microphysics including several species of iced hydrometeors, Kain-Fritsch convection scheme, model nested in a largest model covering western Europe - see Gheusi 2001). The two models appeared to be in excellent agreement. This gives robustness to the results and allows a larger variety of simulations thanks to smaller numerical costs with EM.

2. SENSITIVITY TO THE FLOW DIRECTION

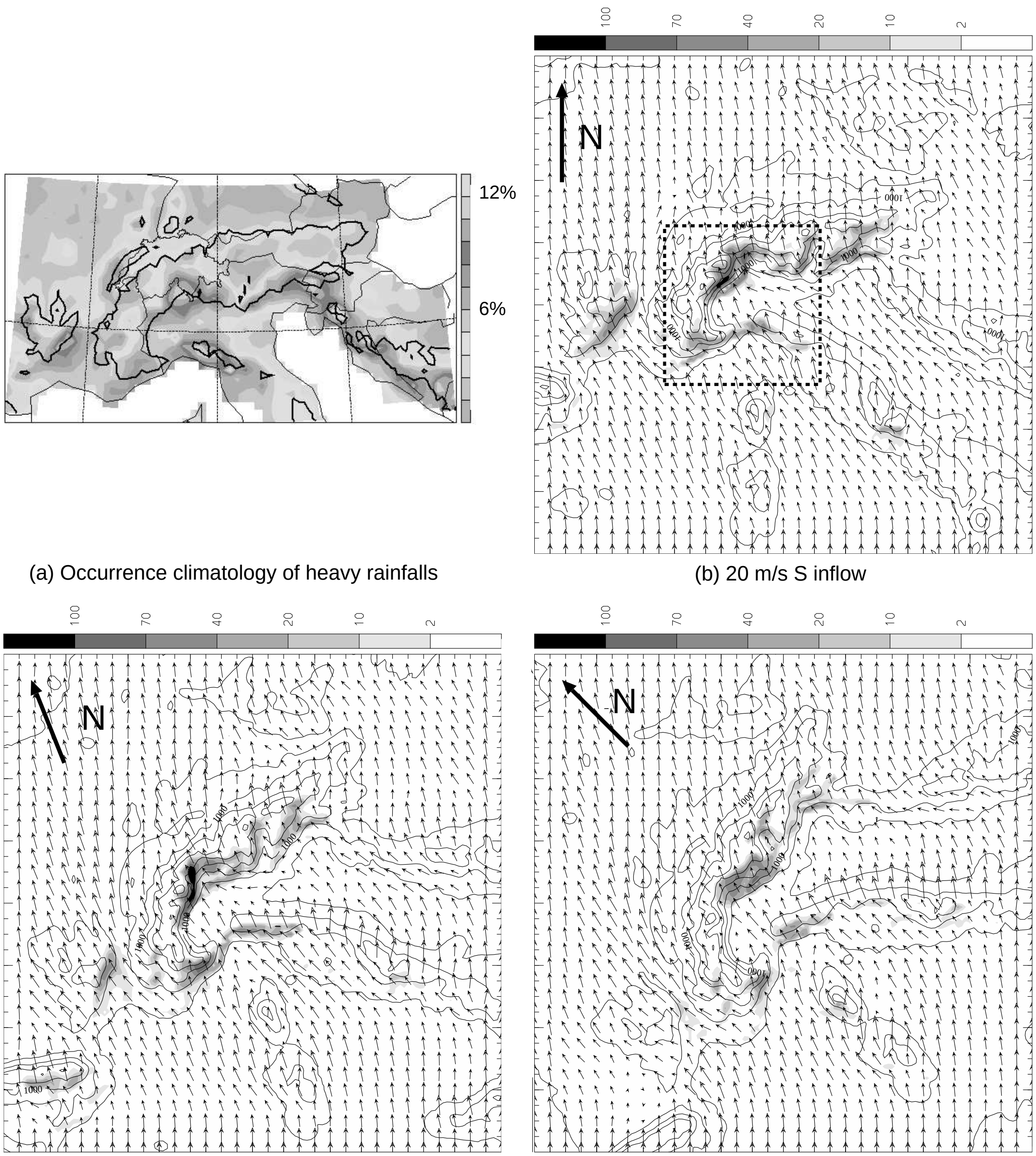
In this section, the inflow direction is varied from S to SW, the wind speed being kept constant at 20 m/s (this value corresponds to observations in the free low troposphere collected during MAP IOP2B).

The 6h-accumulated rain distributions in stationary regime are shown in Fig.1(b-d) for S-, SSW- and SW- inflows. The striking agreement between the spatial distributions of the heavy precipitation cores in the climatology (Fig.1a) and in the simulations, in particular the S and SSW cases, confirms the relevance of the chosen basic ingredients. More complex elements in the inflow, such as synoptic or frontal uplifts, or zonal gradients in the humidity field (as suggested by Rotunno and Ferretti 2001), do not appear to be necessary to produce heavy rainfalls at the location of the climatological maxima (although these elements remain likely to further enhance precipitation). This indicates that the major acting mechanisms of local precipitation enhancement are orographically induced convergences and uplift forcings at the small scale. This statement is confirmed by the corresponding adiabatic simulations[1] (not shown) which evidence horizontal convergence cores below the Alps crest co-located with the climatological rain maxima, over the LM area in particular.

Focusing the attention onto the precipitation core within the Alpine concavity, figures 1(b-d) show a eastwards shift of the core as the inflow turns to the west. Despite this, the LM region corresponds to the commonly

**Corresponding author address*: Institute for Atmospheric and Climate Science, Swiss Federal Institute of Technology (ETH), Hönggerberg HPP, 8093 Zürich, Switzerland, e-mail: schwierz@atmos.umnw.ethz.ch

[1] The flows over the Alps in the adiabatic experiments differ from the full physics flows since the release of latent heat favours a *flow-over* behaviour of the low layers. The flow regime however does not change dramatically and the overall characteristics of the adiabatic flows remain valid for the diabatic cases.



(a) Occurrence climatology of heavy rainfalls

(b) 20 m/s S inflow

(c) 20 m/s SSW inflow

(d) 20 m/s SW inflow

Figure 1: (a) Occurrence climatology (in percent of days) of daily rainfalls $>$20mm for the October month (from Frei and Schär 1998). (b-d) EM simulations in stationary regime for uniform 20 m/s inflows with various directions: 6h-accumulated precipitation (greyscale in mm); wind field 5hPa above the ground level (vectors every 4 grid points). The dashed box in (b) marks the domain of Fig.2.

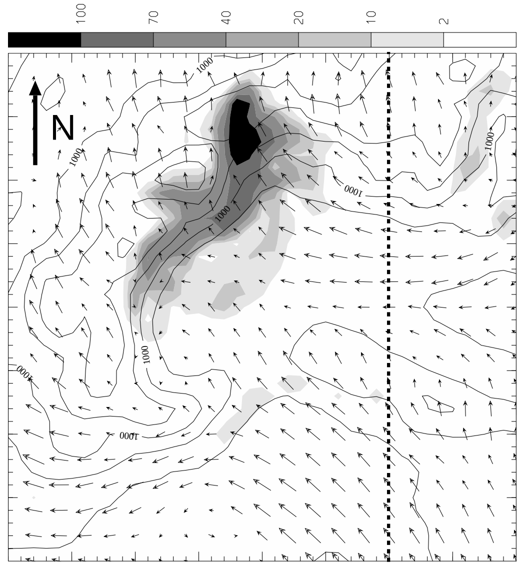


Figure 2: EM simulation in stationary regime for a uniform 10 m/s S inflow: 6h-accumulated precipitation (greyscale in mm); wind field 50m above the ground level (vectors every 2 grid points, same length scale as in Fig.1). The dashed line indicates the vertical cross section of Fig.3.

shared area throughout the cases. The LM area is thus affected by high rain amounts quite independently on the upstream flow direction - at least in the considered range S to SW.

The local flow and precipitation patterns do not however appear to linearly depend on the upstream flow direction. The S and SSW cases strongly resemble to one another in terms of rain distribution as well as low-level wind regime, with in particular: the presence of easterly wind flowing along southern flank of the Alps (known as the *barrier wind*) which supplies the precipitation over the LM; the guidance of a south-easterly wind jet by the Apennines along their maritime flank, which is then channelled in the gap between the Apennines and the Maritime Alps, continues over the plain and eventually impinges upon the slopes of the Piemontese Alps, producing there precipitation. In the SW case in constrast, there is no barrier wind and the channelled jet is now directly oriented towards the LM area.

Whatever the origin of the low-level humid air supply (barrier-wind or channelled jet), the flow within the LM "cul-de-sac" appears in all cases to be forced by the topography to converge towards the Gotthard pass. Such a convergence has been observed by means of multiple Doppler-radar synthesis during MAP IOP5 (see Bougeault *et al.* 2001).

3. SENSITIVITY TO THE FLOW VELOCITY

A simulation is now considered where the S-inflow velocity is reduced down to 10 m/s (hereafter S10). The ability of the low-level air to flow over the obstacles is thus reduced with respect to the previous 20 m/s S-inflow simulation (hereafter S20).

The precipitation distribution for simulation S10 is shown in figure 2 and can be compared to S20 (Fig.1b). The findings are as follows. As expected, the precipitation is reduced over the slopes directly exposed to maritime air. This is however not the case over the LM area where (i) the rainfall remains almost as intense as in simulation S20, in particular in the bottom of the LM cul-de-sac. (ii) The very intense precipitation (greater than 100mm in 6h) present over the Piemontese slopes in S20 is reduced in S10 (to less than 70mm), while (iii) the region of weak precipitation ($>$2mm) extends further to the south over the plain.

Point (iii) is in agreement with the finding of Houze *et al.* (2001) that moderate precipitation is favoured in cases of blocked low-level air over the plain due to upstream uplift.

Point (ii) is due to a less intense channelling of the wind impinging upon the Piemontese slopes.

An explanation for point (i) can be found upon examination of the lateral (easterly) advection of humidity by the barrier-wind, shown in figure 3 for both S10 and S20. The respective intensities differ much less than the expected factor 2. Pierrehumbert and Wyman (1985) indeed give an order of magnitude for the westwards component of the barrier-wind, namely $fL \approx 10$ m/s (where $f = 10^{-4}\,\mathrm{s}^{-1}$ is the Coriolis parameter and $L = 100$ km is approximately the half-width of the Alps), which does not depend on the flow speed far upstream[2].

This is a strong indication that the barrier wind has the major role in supplying in humidity the convection over the LM in the case of a large scale southerly upstream flow.

4. CASE OF A MERIDIONAL LOW-LEVEL JET

The configuration of an incident southerly wind-jet impinging on the Alps is investigated in the spirit of Schneidereit and Schär (2000). The non-uniform wind field is obtained by quasi-geostrophic inversion of an idealized potential vorticity distribution and is used as stationary forcing at the inflow model boundary. The jet has a zonal width of 300km and mimics a low-level jet ahead of a cold front. The flow regime over or around the Alps thus varies locally with longitude, due to the varying wind-speed approximately between 10 and 20 m/s. Characteristics of both S10 and S20 flows are thus obtained according to the location.

The precipitation over the LM area is found to remain intense quite independently of the meridian position of the jet, while it is much more variable for other Alpine areas.

For the case where the jet is centered just at the longitude of the LM area, the precipitation is found heavy over the Maritime Alps as well as over the Piemonte and LM areas but much weaker over the eastern Alps (this is in better agreement with reality since heavy rainfalls are rarely observed simultaneously over the whole chain but more often move from west to east in few ten hours). The precipitation over the Maritime Alps has a distribution close to simulation S20, and is due to the direct impinging of the jet, which is slightly deviated westwards in the low levels by the Coriolis force when approaching the Alps and decelerating. More to the east, the barrier wind remains as efficient as in simulation S10 to sustain intense precipitation over the LM area.

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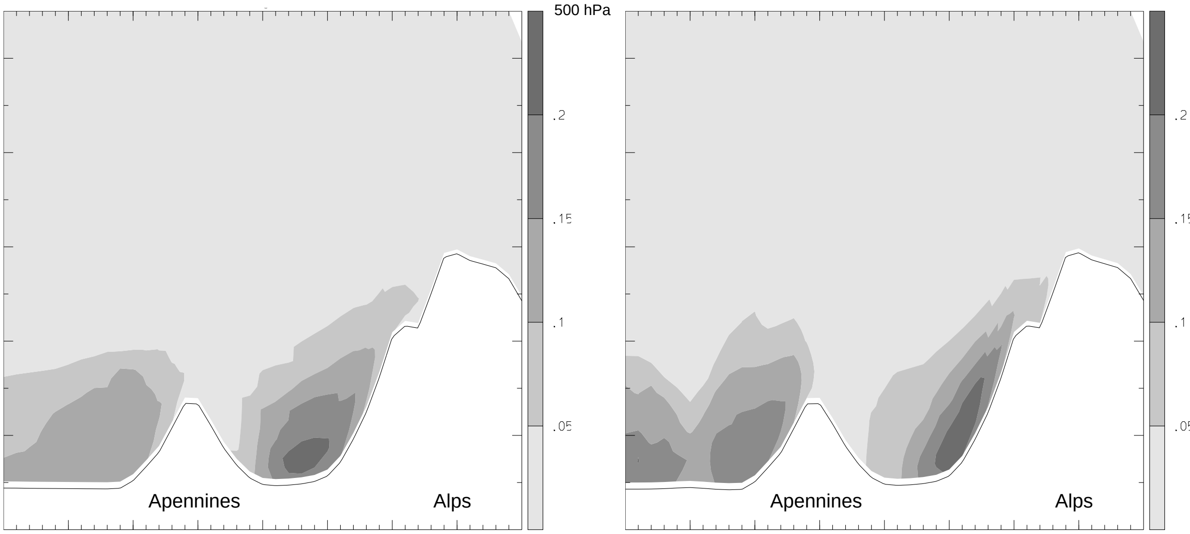
[2]Providing both Froude and Rossby numbers remain in an appropriate domain of the parameter space. This condition is fulfilled in the considered cases.



(a) S inflow 10 m/s

(b) S inflow 20 m/s

Figure 3: EM simulations in stationary regime: westwards advection of water vapour ($-\rho q_v v$, in kg.m^{-2}.s^{-1}, where ρ is the air density, q_v the specifi c content in water vapour and v the eastwards velocity component). The location of the vertical cross section is indicated in Fig.2.

5. CONCLUSION

A mesoscale idealized numerical model has been carried out to investigate how systematically some features of the Alps topography enhance locally the precipitation in the case of upstream humid flows with a dominant southerly component. The focus has been made on the Lago Maggiore area which forms a small-scale cul-de-sac embedded within the main concavity of the Alps.

At the local scale, such a topography appears to make the low-level humid flow to converge and to release intense precipitation. At a larger scale, the rest of the Alpine chain and the Apennines contribute to drive low-level moisture-laden wind jets towards the LM area with weak sensitivity on the upstream flow in term of direction, intensity or distribution. For S to SSW upstream flows at least, the precipitation over the LM is found to be mainly supplied by the barrier wind.

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