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Fine-scale numerical study of northerly snow episodes over Andorra

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ABSTRACT

The forecasting of the effects of the northerly weather episodes that affect Andorra (Pyrenees) is a challenge, especially during the winter. These episodes usually generate heavy snowfalls and intense windstorms and can greatly increase the hazards and the probability that accidents will occur in this small mountainous region (468 km^2). Due to orographic blocking, when moist northerly flows impinge on the Pyrenees, the resulting precipitation mainly affects the northern slopes of these mountains and nearby areas. However, under particular atmospheric conditions, moist flows cross the mountain range and heavy precipitation falls over a much wider area. These events are also associated with lower-than-average temperatures, which in the cold season favour heavy snowfalls in the populated valley of Andorra that seriously affect road conditions. Given the difficulty in forecasting the regional effects of these events over a small mountainous area, the challenge is to use the atmospheric models and to predict how far they will spread on the southern side of the Pyrenees (extent and altitude). Four different episodes were selected to assess the performance of the high-resolution mesoscale WRF model (Weather Research and Forecast model), with particular emphasis on precipitation. The main goals were to analyse the interaction of northerly flows with this mountain range, the effects of this interaction and to detect the features that could be important for operational forecasting.

Keywords: orographic precipitation, upslope snow, WRF, Andorra.

1 INTRODUCTION

The Principality of Andorra is a tiny country located in the eastern half of the Pyrenees. It covers 468 km^2 and has the highest average elevation (2044 m) of any country in Europe (highest peak: Comapedrosa, 2942 m). Consequently, steep mountain slopes are ubiquitous in this country and represent a key factor in the potential occurrence of natural hazards such as avalanches, flash floods, landslides and rock falls [2]. For geographical and historical reasons, Andorra was an unknown and isolated country up to the second half of the 20th century. Nevertheless, from this moment on, the country's economic growth based on commercial and winter tourism began, which has made Andorra the most exposed region to natural hazards in the Pyrenees – more so than either Spain or France – due to the high density of infrastructure and population (>140 pp km^2).

The climate of Andorra can be defined as subcontinental with Mediterranean tendencies; the exception, however, is the northernmost part of the country, which is very exposed to northerly flows and has a suboceanic cold climate. Particular synoptic circulation types combined with local orography make this northerly area ideal for heavy snowfalls. In [1], seven circulation types related to heavy snow events in Andorra (≥30 cm in 24h) were identified. These results confirm that, despite its south-facing location within the Pyrenees, in Andorra northerly advections are the main types of circulation that cause snow episodes.

The prediction of northerly upslope snow events is one of the greatest challenges in weather forecasting in Andorra. Upslope precipitation in general is produced when cool moist air is forced up mountain slopes, in our case, the Pyrenees. During these events strong winds and important accumulations of fresh snow affect the region and entail severe risks to the population and infrastructures (roads). Although the exact details of each event vary, their impact can range from just a few centimeters of snow on the northern slopes of the Pyrenees to a 1-m snowfall on the ridge/peaks and even into the valley of Andorra itself (southern slopes). Yet, the question remains – what turns one event into a high-impact event while others are only registered at altitude in ski resorts?

2 METHODOLOGY

2.1 Selected snow episodes

The selection of the events was based on the following two criteria: presence of northerly winds over the Pyrenees (low and mid-levels) and the amount of precipitation registered at the CENMA (Snow and Mountain Research Center of Andorra) weather stations (Fig.1b). The four selected episodes vary in terms of the intensity and spatial distribution of the precipitation on a north-south axis across Andorra. Table 1 shows the amounts of precipitation reported from three different meteorological stations during these events. The geographical distribution of these stations on a north-south axis allows us to detect differences in the precipitation field on both slopes of the Pyrenees. Despite having in common a northerly flow at synoptic scale affecting the Pyrenees, the main goal of this article is to highlight the main differences observed between each of the four events.

Event	*Start*	*Sorteny (2294 m)*	*Bony Neres (2098 m)*	*Perafita (2415 m)*
E1	00 UTC 15 Dec 2008	11,7 mm	5,1 mm	5,4 mm
E2	00 UTC 18 Dec 2008	4,4 mm	0,1 mm	1,5 mm
E3	00 UTC 7 Feb 2009	23,5 mm	12,8 mm	4,9 mm
E4	00 UTC 10 Feb 2009	56,5 mm	52,2 mm	33,8 mm

Table 1. Simulation dates and times (48-h periods) and precipitation registered at the three weather stations in the CENMA network for each event. The weather stations are ordered from left to right on a north-south axis.

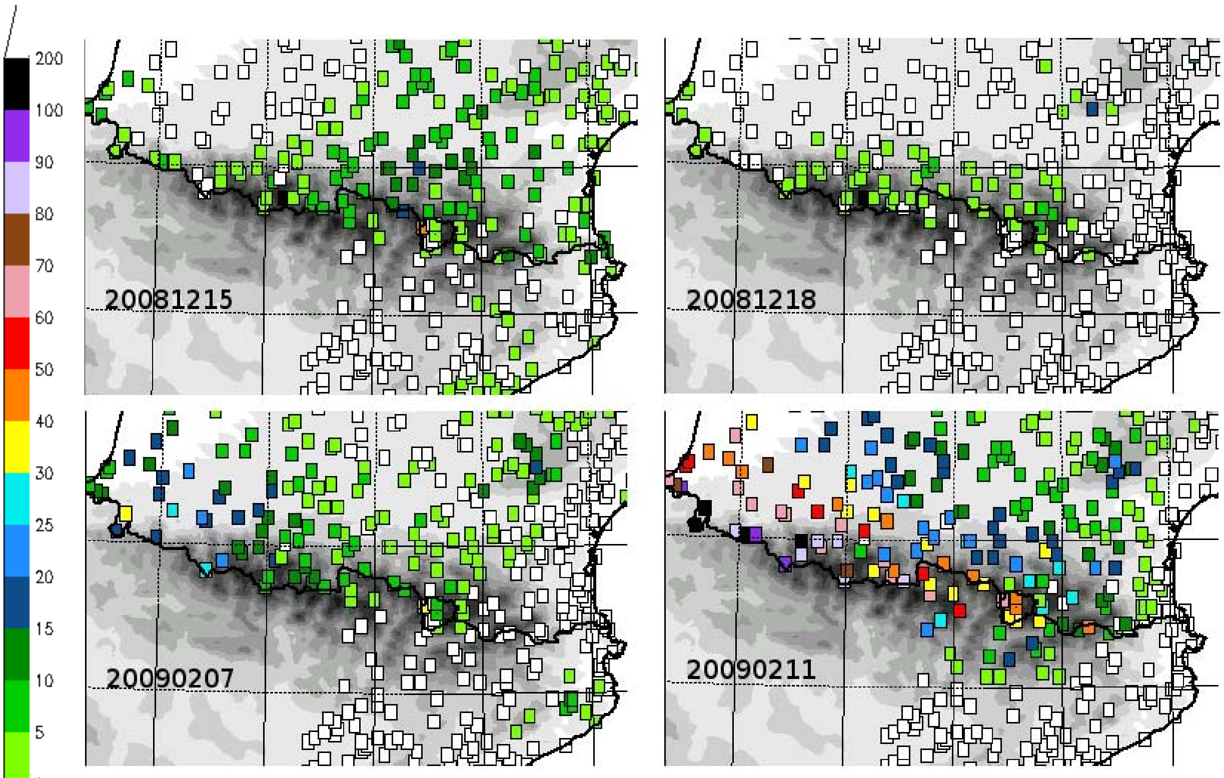

Figure 1. 24 h accumulated precipitation (mm) from CENMA, Météo-France and SMC raingauge network.

2.2 Model description and numerical set-up

The numerical simulations were conducted with the Weather Research and Forecasting (WRF) model [6]. Version 3.0 of the Advanced Research WRF (ARW) dynamic solver, developed primarily at NCAR, was used. The ARW combines compressible, non-hydrostatic Euler equations. The equations are formulated using a terrain-following mass-based vertical coordinate [1], [4]. The ARW solver uses a time-split integration scheme (slow or low-frequency modes are integrated using a third-order Runge-Kutta time integration scheme, while the high-frequency acoustic modes are integrated over smaller time steps to maintain numerical stability. The spatial discretization in the ARW solver uses a C-grid staggering for the variables.

For this study, three one-way nested domains were used with horizontal resolutions of 32, 8 and 2 km. In all, 30 vertical levels were defined to ensure the best vertical resolution for analysing the interaction between the orography and the atmospheric flow. The area corresponding to the coarsest domain covers the synoptic environment over the North Atlantic and Western Europe, with an inner domain centred on Andorra covering the entire Pyrenees massif with a 2-km horizontal resolution. The NCEP Climate Forecast System Reanalysis (CFSR) with a horizontal resolution of 0.5° latitude × 0.5° longitude [5] was used as initial and boundary conditions for the simulations.

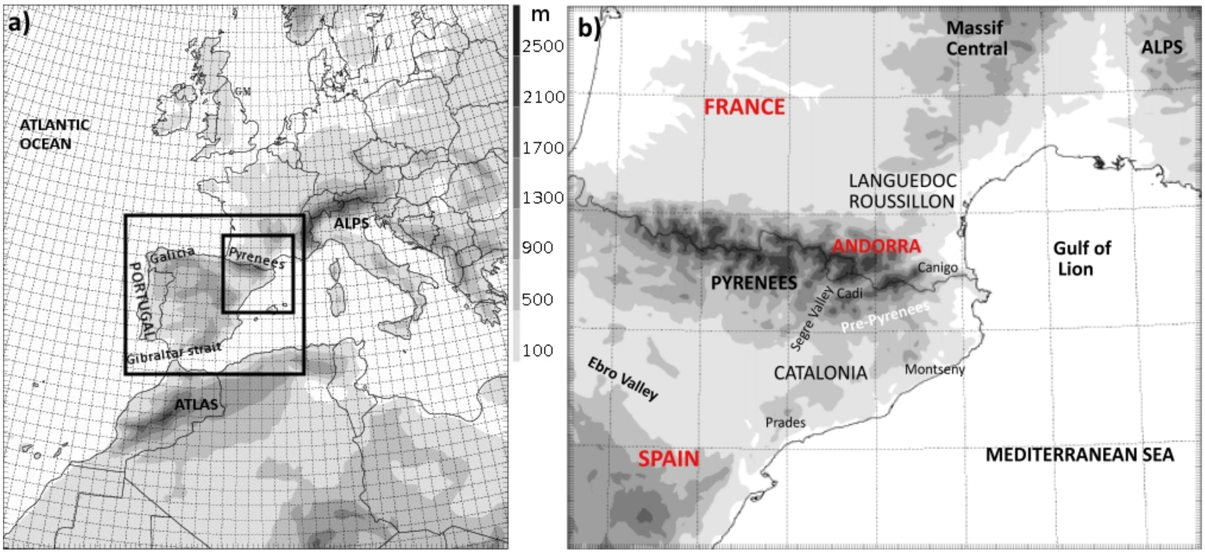

Figure 2. a) Area covered and topography of the coarser domain (horizontal resolution: 32 km). The two other nested domains (8 and 2 km) used in this study are shown by black boxes. b) Area and topography defined for the inner domain (2 km) centred on Andorra. Orography is shown in shades of grey (m).

The model configuration and the physical parameterizations used in the model simulations are described below. The sub-grid-scale effect of convection is parameterized for horizontal resolutions of 32 and 8 km by the Kain-Fritsch scheme, while for the inner grid (2 km) convection is explicitly resolved. Due to the winter nature of the studied events, the microphysical scheme was chosen by taking into account both ice and mixed-phase processes. A preliminary evaluation for a specific event (E4) was performed, six different microphysical schemes were tested and the associated precipitation fields evaluated. The Thompson scheme, referred as [7], was used as the selected microphysical parameterization scheme. This is a relatively sophisticated scheme that includes six classes of hydrometeors: water vapour, cloud water, rain, cloud ice, snow and graupel.

3 MESOSCALE ANALYSIS

This section focuses on the analysis of the mesoscale factors that trigger and maintain northerly upslope snowfall, the model's ability to forecast precipitation over Andorra and how far the snowfall will extend on the southern side of the Pyrenees. The intrinsic low predictability of the spatial precipitation distribution is due to the variety of responses that a flow (front, cyclone, etc.) can produce as it approaches a mountain chain. These responses depend on several factors, including wind speed and wind direction, the height and orientation of the mountains, and the stability of the lower atmosphere. The ratio defined in Eq. (1) is a non-dimensional parameter (Froude number) that takes into accounts several of these factors and represents the reaction of a flow that reaches a mountain range.

$$F_r = \frac{U}{N \cdot h} \tag{1}$$

$$N = \left(\frac{g}{\theta} \frac{\partial \theta}{\partial z} \right)^{\frac{1}{2}} \tag{2}$$

where U is the cross-mountain component of the wind, which is divided by the stability (N = Brunt-Vaisala Frequency Eq. (2)) and the characteristic mountain height (h= 2000 m). If the Froude Number is low (< 1) due to high atmospheric stability or low wind speeds, the flow is called subcritical and will be blocked by the mountain barrier. In this case, the air will not cross the mountain and the precipitation will back up behind the barrier. On the other hand, if the Froude Number is high (>1), it is referred to as supercritical and will not be blocked by the barrier. The air will flow freely over the mountains and deposit the heaviest precipitations on the southern side. A Froude Number near 1 is considered to be critical and in this case the heaviest precipitation will probably fall along the barrier.

Backward trajectories initialized at the time of maximum precipitation have been computed in order to identify for each selected event an optimal upstream source area representing the inflow flux that affected Andorra and to calculate the respective Froude Number (Table 2).

Event	*U (m/s)*	*N* (s^{-1})	F_r
E1	6	0.01	0.3
E2	8	0.01	0.4
E3a	11	0.0065	0.8
E3b	10	0.005	1.1
E4	11	0.006	0.9

Table 2. Forecasted Froude numbers of the representative inflow flux identified for each northerly event.

Besides the Froude Number, the synoptic situation at upper and lower levels were described in terms of (i) surface pressure, (ii) 850 hPa equivalent potential temperature, (iii) 500 hPa geopotential height, and (iv) winds at upper and lower levels. Some specific parameters such as the water vapour flux from the surface to 3 km were also calculated to improve the characterization of the moisture supply over the northern slope of the Pyrenees. The objective was to detect the main ingredients (lift and moisture) required for generating precipitation.

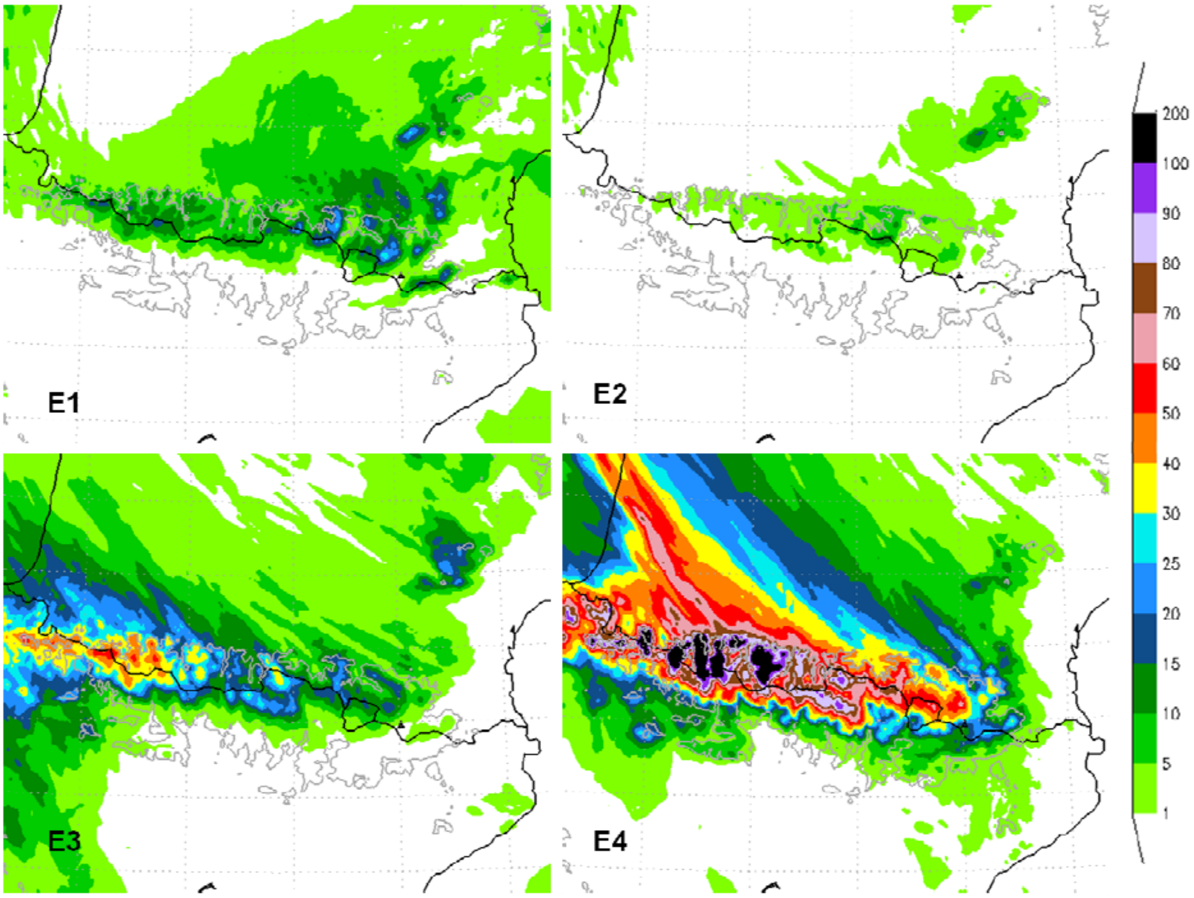

Figure 3. 24 h quantitative precipitation forecast (mm) for each event.

3.1 Event 1: 15 Dec 2008

The surface synoptic situation was characterized by a deep Mediterranean low centred over the Golf of Lyon and a weak Azores high, which progressively extended northwards. At 500hPa the presence of a cold cut-off low (-35ºC) favoured unstable conditions at mid-levels. Consequently, the Pyrenees were affected by a humid NE flow, above all over its easternmost extreme. However, at low levels – despite the dominant cyclonic conditions – the flow showed a distinct westerly component, clear proof of the blocked upslope flow (F_r=0.3, see Table 2), associated with low wind speeds and high stability at low levels. The intensity and spatial distribution of the precipitation is fairly well reproduced by the model (Fig. 3), which reveals light precipitation over Languedoc-Roussillon on the windward slope of the Pyrenees, as well as over the slopes in the Canigó and Cadi ranges exposed to the NE flow. Windward local maxima above 15 mm were forecast despite the blocking and stable nature of the flow. The uncoupled flow between low and mid-levels suggests the formation of a shear layer. As Houze and Medina (2005) have pointed out, the presence of a shear layer favours turbulent overturning within the airstream passing over the mountain range, and this turbulence in turn promotes the growth of precipitation-sized particles and hence precipitation over windward slopes.

3.2 Event 2: 18 Dec 2008

This event was the natural sequence leading on from event 1 after the Azores high had deepened and clearly extended to the Iberian Peninsula and the Tyrrhenian Sea, thereby displacing the low over the Adriatic Sea. At 500 hPa the cold cut-off also moved eastwards and a ridge entered from the western Pyrenees. This low-pressure gradient configuration generated a weak anticyclonic northerly flow at all levels over the Pyrenees that favoured highly static stability at synoptic scale and blocking (F_r=0.4). Precipitations, less intense than in event 1 due to the limited amount of moisture available, were restricted to the northern slope (Fig. 3). This event is very representative of the frequent weak upslope snow events occurring during the stable anticyclonic conditions that settle over Andorra.

3.3 Event 3: 7 Feb 2009

On the morning of 7 February 2009, an elongated north-south low pressure centre moved eastward towards Germany and generated a N-NW flow that pumped cold air in from polar latitudes over the Pyrenees. Simultaneously, at higher levels the axis of the upper-air trough was located over the Pyrenees. Thus, the jet stream came to be situated over the northwest of the Iberian Peninsula. During this event, the flow was characterized by a Froude Number in the range 0.8–1.1 by the end of the episode. These values are close to the critical value and originated due to the less stable nature of the flow (~0.006 s^{-1}) and higher winds speeds (10 m/s) compared to event 1. The forecasted precipitation field was successful in predicting the heaviest precipitation values over the main mountain ridges, as well as the west-east intensity gradient with weakest values over the eastern Pyrenees. This spatial pattern slightly overestimates the maxima but is consistent with the moisture distribution. Thus, it follows that, given a similar upslope flow, the greatest precipitation will occur where the flow is moister. During the unblocked upslope event, the precipitation in Andorra reached the country’s southern border and also affected the lee south-facing slope.

3.4 Event 4: 11 Feb 2009

This episode started on 10 February 2009 at midnight when the Azores High and a low over southern England moved northeastwards, thereby generating a NW flow over the Pyrenees behind a cold front. This NW flow was present at all levels as a narrow band of moist air, which advected an anomalous flux of water vapour exceeding 300 kg m^{-1} s^{-1} that directly affected the mountain range. This narrow band of moisture transport ensured the resupplying of humidity, thereby favouring the occurrence of a major precipitation event. Besides this key ingredient, the lower atmosphere was characterized by a Froude number of 0.91 (critical flow), a consequence of a mean wind speed of 11 m/s, and a Brunt-Vaisala frequency of 0.006 s^{-1} (low stability). During this event, the Froude parameter only contributed partially to explaining the recorded precipitation and, in particular, the heavy snowfall along the mountain ridge that began on the afternoon of 10 February. On the morning of 11 February, snow crossed the Pyrenees and began to affect a large area of the southern slope. Fresh snow ranged in depth from 30 cm in the valleys to 100 cm at highest altitudes. Due to the avalanche risk, one building was evacuated, ski resorts were closed and transport systems were disrupted. In addition to the orographic forcing, there was another major source of atmospheric lift: the sheared vertical wind profile had its maximum wind speed at high levels due to the fact that the axis of a jet-stream was located over the western end of the Pyrenees. Thus, the left exit of the jet stream generated the upper level divergence and so ensured the ascent of the moist air along a NW-SE axis and crossed over the mountain range.

4 CONCLUSIONS

Based on numerical simulations using the Weather and Research Forecast (WRF) model, four northerly flow regimes were analysed.

The role of atmospheric stability at low levels and the intensity of the cross-mountain flow in precipitation enhancement were investigated using the Froude parameter. Under stable conditions, as is the case of the four selected events, this parameter can help identify the most likely nature of the upslope flow (blocked or unblocked). The distribution of the snowfall and the location of the greatest amounts were correctly forecast for each event and revealed a pattern that was dependent on the identified upslope flow regime, as occurs in other mountainous regions worldwide (Alps and North America). Several other important facts were also identified. As the analysis of E1 demonstrates, the presence of a shear layer separating low-level blocked flow from upper-level unblocked flow played a crucial role in the precipitation enhancement process over the windward slopes [3]. Moreover in E4, the presence of an anomalous narrow moist band, not detected by the operational weather models, combined with the left exit of the jet stream, turns out to be a key factor in the generation of a high-impact snowfall event.

This study also highlights the importance of working with high resolution mesoscale models over mountainous areas. At a horizontal resolution of 2 km, the model is able to capture realistic topographic effects and accurately depicts low-level atmosphere stratification. Thus, low-level stability is also one of the major contributing factors, as it will determine whether the flow is blocked or not, which significantly affects the mesoscale winds and the precipitation field.

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