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Forecasting and modelling ice layer formation on the snowpack due to freezing precipitation in the Pyrenees

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ABSTRACT

In the Pyrenees, freezing precipitation at high elevations is quite frequent in winter, leading to the formation of an ice layer on the surface of the snowpack. It may cause many accidents amongst mountaineers and skiers, with sometimes more fatalities per winter than avalanches. Such events are not predicted by current operational systems for snow and avalanche hazard forecasting. A crowd-sourced database of surface ice layer occurrences was first built up, using reports from Internet mountaineering and ski-touring communities, to mitigate the lack of observations from conventional observation networks. Simple diagnostics of freezing precipitation were then developed, based on the cloud water content and 2-m temperature forecast by the Numerical Weather Prediction model AROME, operating at 2.5-km resolution. An evaluation over five winters gave a probability of detection reaching 81% and a false alarm ratio of 23% compared to occurrences reported in the observation database. A new modelling of ice formation on the surface of the snowpack due to impinging supercooled water was added to the detailed snowpack model Crocus. It was combined with the atmospheric diagnostic of freezing precipitation. Resulting snowpack simulations over five winters captured the formation of the main observed ice layers. The performance of the diagnostic associated with the ice formation modelling was assessed for the event of 5–6 January 2012, with altitudinal and spatial distributions of the ice layer matching the observations. These simple methods enable to forecast the occurrence of surface ice layer formations and to simulate their evolution within the snowpack, even if an accurate estimation of the amount of freezing precipitation remains the main challenge.

1. Introduction

The most common risks encountered by mountaineers and skiers in mountains during the winter season are snow avalanches (Schweizer et al., 2003). Over the period 1980–2014 in France, ANENA (French National Association for Snow and Avalanche Studies) reported an average of 31 fatalities every winter due to avalanches (Jarry, 2015). Avalanche hazard forecasts are issued daily during the winter season in the Alps, Corsica and the Pyrenees by Météo-France forecasters. They recently reported another source of numerous accidents in the Pyrenees. Freezing precipitation, leading to the formation of a pure ice layer at the surface of the snowpack, is a quite frequent phenomenon in the Pyrenees.

An intense event of ice formation on the snowpack highlighted the necessity to better understand and predict such a phenomenon. During the night of the 5–6 January 2012, a thick ice layer formed due to freezing precipitation at high elevations, in a synoptic context of warm front in a North-West flow with strong winds and orographic blocking on the French side of the Pyrenees. The ice layer thickness often reaching 5 cm or more was prevalent over the Pyrenean massif. Because of subsequent clear sky conditions, this ice layer remained two weeks or more on the surface of the snowpack. During this period, mountain rescue services reported an exceptionally high number of accidents by sliding of back-country skiers and mountaineers caused by this glassy and very hard surface, which made the progression in mountainous terrain hazardous (Fig. 1). 9 fatalities occurred during the two following weeks. This human toll was greater than the average number of two fatalities due to avalanches in the Pyrenees per winter over the last five years (source: ANENA). The consequences of this event were particularly marked due to the persistence of ice on the surface. However, according to avalanche forecasters such events are rather frequent in the Pyrenees. New methods to predict and model the phenomenon are sorely needed to warn mountaineers and skiers in advance.

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Fig. 1. Mountaineer using crampons on the ice layer after the event of 5–6 January 2012. Credits: Club Alpin Français des Montagnards Ariégeois.

Currently, operational snowpack simulations for avalanche hazard forecasting run with the detailed snowpack model SURFEX/ISBA/Crocus (Vionnet et al., 2012), mentioned as Crocus hereafter. It is used within the SAFRAN–Crocus–MEPRA model chain applied over the main French mountainous areas (Durand et al., 1999; Lafaysse et al., 2013). The meteorological analysis and forecasting system SAFRAN (Système d'Analyse Fournissant des Renseignements Atmosphériques à la Neige; Analysis System Providing Atmospheric Information to Snow; Durand et al., 1993) provides the meteorological forcing for Crocus. In particular, the precipitation phase is derived from a simple threshold of 1 °C for air temperature at 2 m above the ground. It only enables the representation of snowfall and rain but not of freezing precipitation. An inaccurate estimation of the precipitation phase may change the stratigraphy simulated by Crocus and consequently the stability and avalanche hazard predicted by the expert system MEPRA (Giraud, 1992). Since no snowpack observations are assimilated in operational models, the snowpack stratigraphy may remain skewed during the whole winter season. Thus, freezing precipitation events are considered as a source of errors in numerical snowpack forecasting by French operational services in the Pyrenees.

The latest developments in mesoscale Numerical Weather Prediction (NWP) systems offer new opportunities to forecast atmospheric icing and freezing precipitation, since they include advanced cloud micro-physics schemes with a representation of mixed-phase cloud processes and a higher diversity of water species. For instance, Thompson et al. (2009) used the Weather Research and Forecasting (WRF) model at kilometric resolution with an improved microphysics scheme for winter precipitation (Thompson et al., 2004) to predict icing due to freezing rain, freezing drizzle or freezing fog. Forecasting freezing precipitation is still a challenge: in the Integrated Forecasting System of ECMWF (European Centre for Medium-Range Weather Forecasts), cloud and precipitation physics were recently modified to improve freezing rain predictions (Forbes et al., 2014). Additionally, the high horizontal resolution of mesoscale NWP systems gives a better representation of the topography, which allows to study these events in complex terrain. Drage and Hauge (2008) used MM5 to simulate atmospheric icing in a Norwegian coastal mountainous terrain, in-cloud icing was also simulated by Yang et al. (2012) on Mount Washington (U.S.A.) with the regional mesoscale model GEM-LAM at 1-km grid spacing, and WRF was used by Podolskiy et al. (2012) to simulate rime formation on Mount Zao (Japan) and by Fernández-González et al. (2015) to simulate a freezing drizzle event in the Guadarrama Mountains (Spain), both at 1-km resolution.

AROME (Application of Research to Operations at MEsoscale; Seity et al., 2011; Brousseau et al., 2016) is the mesoscale NWP system of Météo-France, operating at kilometric grid spacing over France (2.5 km from 2008 to 2015, 1.3 km since then). It was recently used to drive snowpack simulations with Crocus at kilometric resolution over the French Alps (Vionnet et al., 2016) and the Pyrenees (Quéno et al., 2016). Vionnet et al. (2016) highlighted AROME potential for mountain meteorology and Quéno et al. (2016) showed a good representation of the snow cover spatial distribution and benefits in terms of daily snow depth variations, despite strong positive biases in terms of snow depth. More specially, AROME includes a comprehensive cloud micro-physics scheme, and thus, simulates supercooled cloud water, which is of particular interest in regard to the issue of freezing precipitation. The aim of the present study is to assess the potential of AROME associated with Crocus for the detection of freezing precipitation events and the modelling of the formation of an ice layer on the snowpack in the Pyrenees. The original character of the study derives from the use of cloud microphysical informations from a mesoscale NWP system in mountainous terrain combined to a snowpack model for ground icing.

The paper is organized as follows. In Section 2, we briefly present the observed phenomenon and its meteorological context, as well as available observations for identified events. We introduce an observation database built up using information posted on Internet by the ski-touring community. Section 3 describes the NWP model AROME and the detailed snowpack model Crocus. Section 4 presents the development of a simple method to detect freezing precipitation in the Pyrenees using AROME, and the implementation of a module to simulate the ice layer formation due to freezing precipitation in Crocus. These new methods are assessed in Section 5 following two axes: (i) sensitivity study and temporal occurrence of the detections over five winters, (ii) spatial and altitudinal distribution of the simulated freezing precipitation and ice formation for the 5–6 January icing event. Results are discussed in Section 6 with a particular emphasis on the limitations of the methods and the observation database.

2. Description of the observed phenomenon

2.1. Meteorological context in the Pyrenees

This study focuses on the Pyrenees (Fig. 2), the natural border separating France from Spain, stretching from the Atlantic Ocean to the Mediterranean Sea, a mountain range with many summits exceeding 3000 m a.s.l. The domain of study covers France, Andorra and Spain, from 41.6°N to 43.6°N and from −2.5 °E to 3.5°E.

In the Pyrenees, freezing precipitation on the snowpack occurs in very specific meteorological conditions. During common freezing rain situations in plains, snow flakes melt in an intermediate warm layer to form water drops and these drops become supercooled in a layer close to the ground below freezing point. In the situations studied here, freezing precipitation is associated with an entirely negative temperature sounding, which implies that water drops stay supercooled all along the vertical profile.

It is almost always associated with a warm front and N/NW flow with orographic blocking in the French Pyrenees. The cloud top temperature is between −5 °C and −10 °C, so that cloud droplets stay supercooled and do not turn into ice crystals and snow flakes (Rauber et al., 2000). The temperature vertical profile remains below freezing point down to the ground. Cloud droplets undergo a collision-coalescence process (Cober et al., 1996) which contributes to the formation of drops up to the size of drizzle (100 μm–500 μm) falling on the ground (the so-called "warm rain process"). The process of coalescence is favoured by strong winds and vertical updraft giving significant precipitation (Rasmussen et al., 1995; Fernández-González et al., 2015).

To avoid the formation of ice or snow, the ice nuclei must have a low number concentration. Furthermore, at temperatures warmer than −10 °C, only few ice nuclei are active (Rauber et al., 2000). The Pyrenees are mostly exposed to oceanic westerly winds, which very likely favour the formation of freezing drizzle due to the low amount of ice

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