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Ensemble forecasting of snowpack conditions and avalanche hazard

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ABSTRACT

The prediction of avalanche hazard involves an analysis of current snow conditions, the upcoming meteorological conditions and their combined impact on the future state of the snowpack. The SAFRAN–SURFEX/ISBA-Crocus–MEPRA (S2M) chain of numerical models is used by avalanche forecasters in France to estimate present and future avalanche hazard over areas assumed to be meteorologically homogeneous (massifs), primarily as a function of altitude. Until now, the meteorological forecast data provided to S2M comes from the deterministic numerical weather prediction model ARPEGE with a lead-time of 2 days. In this study, we introduce the application of ensemble meteorological forecasting to avalanche hazard forecasting by using the output of an ensemble of 35 ARPEGE predictions to feed S2M and thus provide an ensemble of 35 different predicted snowpack conditions. A posteriori ensemble forecasts were generated and evaluated in the French Alps for the winter 2013–2014 with 4 days lead time, initialized each day at 6 UTC. Forecasts over the Pyrenees during the exceptional winter and spring 2012–2013 were also carried out. Results indicate that accounting for the uncertainty in meteorological forecast significantly improves the skill and the usefulness of the model chain, regardless of the prediction lead time. The predictability of snowpack conditions using the ensemble forecast technique remains good at a 4 day lead time. These results provide the foundation for the development of probabilistic estimates of simulated avalanche hazard levels for operational avalanche hazard forecasting.

1. Introduction

The prediction of regional-scale avalanche hazard for the production of avalanche bulletins, for example, involves an analysis of current snow conditions, the upcoming meteorological conditions and their combined impact on the future state of the snowpack. In France, the SAFRAN–SURFEX/ISBA-Crocus–MEPRA (S2M) chain of numerical models (Durand et al., 1999; Lafaysse et al., 2013) is used to provide an objective assessment of the past and future snow conditions including mechanical stability. It explicitly accounts for altitude, slope and aspect within geographical areas assumed to be meteorologically homogeneous (so-called massifs). Météo-France avalanche forecasters use S2M outputs for current and predicted snow conditions in combination with weather forecasts and field information from a dedicated ground observation network. Until now, the meteorological inputs to S2M used for operational forecasting have primarily been based on the output of the deterministic numerical weather prediction (NWP) model ARPEGE operated by Météo-France with a lead-time of 2 days. This setup only provides relevant information for the day after the bulletin has been issued and does not take into account errors originating from the meteorological forecast itself or intra-massif variability of snowpack properties within a given elevation band, incline category and aspect sector.

Ensemble forecasting is increasingly used for meteorology and hydrology applications. Several major meteorological centers such as the European Center for Medium-Range Weather Forecasts (ECMWF, Molteni et al., 1996), the National Centers for Environmental Prediction (NCEP, Toth and Kalnay, 1997) and the Canadian Meteorological Centre (CMC, Pellerin et al., 2003) have developed operational ensemble forecasting systems with global NWP models for medium-range prediction accounting for uncertainties related to synoptic and large scales. These ensemble meteorological forecasts are sometimes used as input of hydrological models for medium-term forecast of river discharges (e.g. Thirel et al., 2008, 2010; Voisin et al., 2011). For several years, ensemble forecasting has also become an essential tool for forecasting high-impact weather events two or three days in advance. Reliable information about uncertainties in the localization and the intensity of these events is crucial for issuing meaningful warnings. This requires to keep increasing the horizontal and vertical resolutions of ensemble global systems and to keep improving their perturbation methods. Ensemble systems based on limited-area NWP models are also increasingly used for that purpose (e.g. Bowler et al., 2008; Frogner et al., 2006; Marsigli et al., 2008). The benefits of multimodel weather forecasts are also currently explored through projets such as the THORPEX Interactive Grand Global Ensemble (TIGGE, Bougeault et al., 2010).

To the best of our knowledge, ensemble forecasting has so far not been applied to avalanche hazard forecasting, despite the fact that the

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large sensitivity of the snowpack to meteorological conditions and the numerous threshold effects make its prediction challenging, especially in mountain regions. Snowpack modeling and avalanche hazard warning therefore provide an excellent opportunity for the application of ensemble-based prediction techniques. In this study, we introduce an ensemble forecasting system bringing together tools and data operated by Météo-France. The performance of the system is comprehensively assessed by comparing its output with the current deterministic prediction system and the analysis of snow conditions using height of 24-hour new snow (HN24) and a dedicated regional scale natural avalanche hazard index (NHI) as target variables.

2. Models

2.1. SAFRAN SURFEX/ISBA-Crocus MEPRA model chain

The generation of consistent meteorological input data for the numerical snowpack simulation is carried out by the meteorological downscaling and surface analysis tool SAFRAN (French acronym for Système d'Analyse Fournissant des Renseignements Adaptés à la Neige, Durand et al., 1993, 1999). SAFRAN operates at the geographical scale of meteorologically homogeneous mountain ranges (so-called "massifs", Fig. 1) within which meteorological conditions are assumed to depend only on altitude and aspect. For the analysis of meteorological surface fields, the guess used by SAFRAN consists of vertical atmospheric profiles from NWP models. A robust assimilation scheme corrects the initial guess based on ground-based and radiosonde observations as well as remotely-sensed cloudiness. Thus, SAFRAN provides hourly meteorological conditions for each massif for 300 m-spaced elevation bands. Variables covered by SAFRAN do not only include precipitation (rainfall and snowfall rate) and air temperature, but also relative humidity, wind speed, incoming longwave and shortwave radiation. SAFRAN also has a forecast mode, in which it solely uses NWP output (vertical atmospheric profiles and precipitation fields). In this mode, SAFRAN is simply a downscaling tool that converts the NWP model grid to the massifs/altitude bands geometry. SAFRAN outputs feed the detailed snowpack model SURFEX (Surface Externalisée)/ISBA (Interactions between Soil Biosphere and Atmosphere)-Crocus (Vionnet et al., 2012), which computes the energy and mass balance to simulate the evolutions of the physical properties of a multi-layer snowpack and the underlying ground as a function of altitude, slope and aspect within each massif (slopes of 0, 20 and 40° for 8 aspects: North, North-East, East, South-East, South, South-West, West and North-West). The mechanical stability of the snowpack simulated by Crocus is subsequently estimated by the model MEPRA (Modèle Expert d'aide à la Prévision du Risque d'Avalanche, Giraud, 1992). First, the shear resistance/shear stress ratio (Föhn, 1987) is computed for each layer of each simulated snowpack. An expert approach then associates natural and accidental avalanche

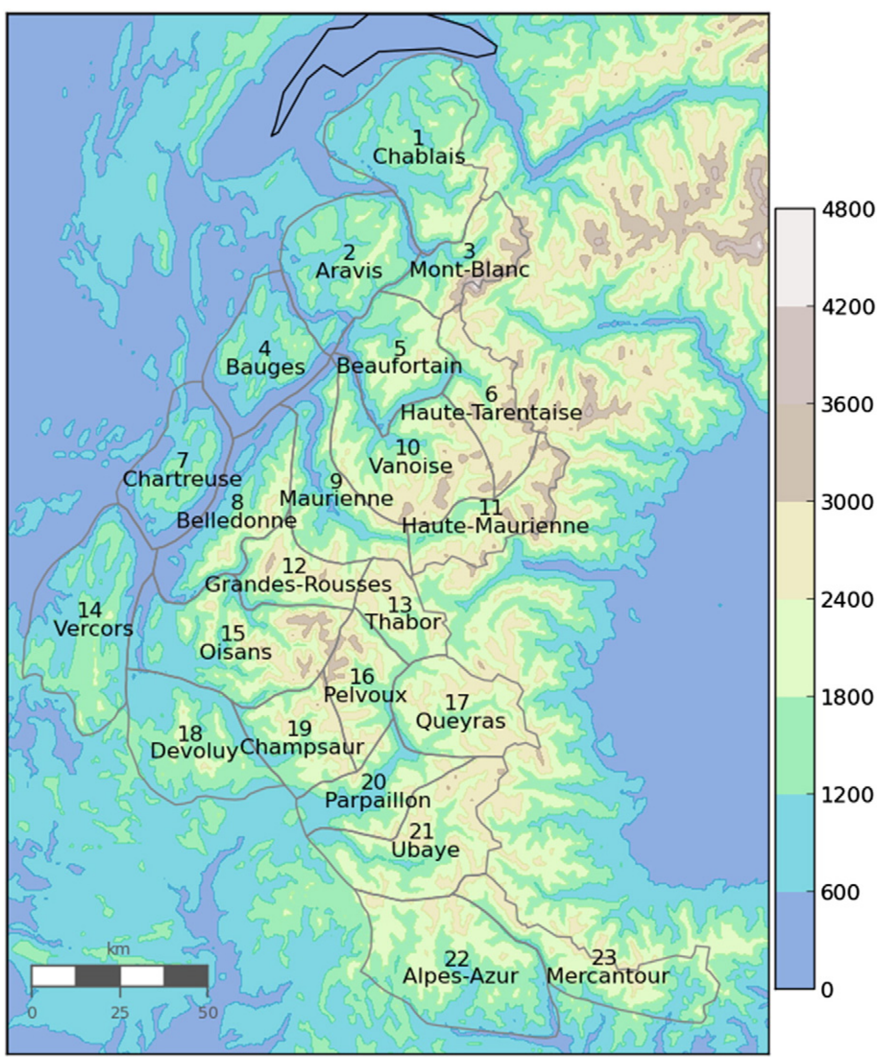

Fig. 1. Map of the 23 French alpine massifs, with altitude in meters.