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Integration of snow management processes into a detailed snowpack model

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ABSTRACT

The understanding and implementation of snow management in detailed snowpack models is a major step towards a more realistic assessment of the evolution of snow conditions in ski resorts concerning past, present and future climate conditions. Here we describe in a detailed manner the integration of snow management processes (grooming, snowmaking) into the snowpack model Crocus. The effect of the tiller is explicitly taken into account and its effects on snow properties (density, snow microstructure) are simulated in addition to the compaction induced by the weight of the grooming machine. The production of snow in Crocus is carried out with respect to specific rules and current meteorological conditions. Model configurations and results are described in detail through sensitivity tests of the model of all parameters related to snow management processes. In-situ observations were carried out in four resorts in the French Alps during the 2014–2015 winter season considering for each resort natural, groomed only and groomed plus snowmaking conditions. The model provides realistic simulations of the snowpack properties with respect to these observations. The main uncertainty pertains to the efficiency of the snowmaking process. The observed ratio between the mass of machine-made snow on ski slopes and the water mass used for production was found to be lower than was expected from the literature, in every resort.
Nevertheless, the model now referred to as "Crocus-Resort" has been proven to provide realistic simulations of snow conditions on ski slopes and may be used for further investigations.

1. Introduction

The management of snow on ski slopes is a key socio-economic and environmental issue in mountain regions. Indeed, the winter sports industry has become a very competitive global market (Agrawala et al., 2007). Ski lift operators face multiple expectations from both consumers and investors (Fauve et al., 2002; DSF, 2014) such as ensuring opening/closing dates and maintaining safe and homogeneous conditions, etc. Further to operating costs (Damm et al., 2014), the increasing attention paid to environmental issues (Steiger, 2010; Magnier, 2013) arouses the interest of both policy makers and ski lift operators concerning optimization levers of energy and water consumption and for reliable data concerning the ability of the snow industry to face climate challenges (Scott and McBoyle, 2007).

Several methods such as snow grooming are employed by ski resort operators to provide comfortable skiing conditions, to protect snow from natural and human-induced ablation processes, or to compensate for snow deficits by means of snowmaking (Guily, 1991; Fauve et al., 2002). Snow management processes (grooming and snowmaking in particular) induce significant changes in the physical state and behaviour of the snowpack so that snow on ski slopes is markedly different from natural snow conditions in their surroundings (Fahey et al., 1999; Rixen et al., 2001). Indeed, be it fully natural or under the influence of human interference, snow cover constantly undergoes physical transformations which occur under the influence of atmospheric conditions (Armstrong and Brun, 2008) and due to the intrinsic physical properties of snow layers. These in turn influence the surface energy budget and the evolution of internal properties (Brun et al., 1992; Vionnet et al., 2012). An assessment of the snow conditions in ski resorts therefore requires a method which handles simultaneously physical processes occurring in snow and the impact of snow management practices. This is because the reaction of the snowpack to all of its drivers is strongly non-linear and is affected by several thresholds.

However, investigations of the vulnerability of the ski industry have often been based on natural snow conditions and employed empirical rules (Crowe et al., 1973; Durand et al., 2009). Since the early 2000s, several studies have initiated accounting for snow management practices in assessments of snow conditions in ski resorts. Rixen et al. (2011) for example, computed potential snowmaking days based on climate projections of air temperature and humidity. These computations took place on several study sites in Switzerland without further analysis

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of snow conditions. This was due to the lack of a snowpack model able to process the information in question. Scott et al. (2003) implemented snowmaking operational rules in a simple snowpack model (degree-day approach). This was in order to assess the impact of climate change on ski season duration using various snowmaking technologies represented by different model configurations. However, this study does not account for the fact that the physical properties of machine-made snow (MM snow; Fierz et al., 2009) differ from natural snow, and it would not be possible with the model to handle this information. Explicitly accounting for snow management techniques in snowpack models is something that has already been developed in a few cases. For example, Keller et al. (2004) used field observations of snow depth on groomed slopes to determine the compaction rate on a groomed ski slope. While this method may be informative in terms of processes occurring during the course of a simulated snow season, it depends on the weather conditions during this specific season and on local measurements. This hampers utilization on a large scale. Climate projection or the testing of various snow management policies is even more affected. Interdisciplinary programs recently combined physical snowpack models with detailed human approaches of snow management (Howard and Stull, 2014; Hanzer et al., 2014).

Nevertheless, the effects of snow management on snowpack properties are still rarely described in literature and only a few studies have reported detailed field observations (Keddy et al., 1979; Guily, 1991; Keller et al., 2004; Howard and Stull, 2014). In order to build a tool capable of addressing snow conditions on ski slopes for a wide range of resorts we have explicitly integrated comprehensive grooming and snowmaking approaches into the detailed multi-layer snowpack model Crocus (Vionnet et al., 2012). Grooming and snowmaking were implemented in Crocus based on our physical comprehension of processes, literature and interviews with professionals. The latter were involved in our development strategy to represent their management practices in the most consistent way, which is critical for any further use of such a model. The model was evaluated with field measurements (depth, snow water equivalent and vertical profiles) carried out in four resorts in the French Alps during the 2014–2015 winter season. These measurements and the model implementation are described in an extensive manner including decision schemes and model parameterization. Instead of integrating in detail the specific snow management practices of one particular ski resort (Hanzer et al., 2014), this development aims to build a tool able to simulate the snow conditions for a wide range of resorts and geographical areas (François et al., 2014), and thus requires a rather generic formulation if possible. We tested the sensitivity of the model to the values of parameters and evaluated the results of simulations with respect to in-situ observations.

2. Material and methods

2.1. In-situ observations

Ski patrols from four specific resorts located in the Northern French Alps (Tignes, Chamrousse, Autrans and Les 2 Alpes) helped us to perform measurements during the 2014–2015 winter season (Table 1, Fig. 1), covering a large range of meteorological conditions and operators' habits and means.

2.1.1. Observations sites

Three observation sites with natural snow conditions (Reference site), grooming and packed and skied snow conditions (Site G) and grooming plus snowmaking and skiing (Site SM) were chosen in each resort with the aid of ski patrollers. All three sites within a given ski resort are located as closely as possible to each other and are easy to access. In every case local topography consists of flat or almost flat areas with as little wind disturbance as possible. None of the sites are in erosion or accumulation areas. However all sites are located in mountain areas where the wind may always play a significant role and be a factor of uncertainty.

2.1.2. Snowmaking data on SM sites

The most likely surface on which MM snow was spread (S_{mid}) was calculated from ski slope edges, snow gun distribution on the ski slope, in-situ observations and interviews with professionals. For example in Tignes, snow guns are equally distributed on “Double M” ski slopes and the distance between them is 67 m. The width of the site SM is 36 m, resulting in a 2400 m^2 surface. Assuming an uncertainty of ± 400 m^2 i.e. $\pm 17\%$ on the surface (an uncertainty of about 8% concerning length and width), the resulting range on the surface is $S_{min} = 2000$ to $S_{max} = 2800$ m^2 (the minimum and maximum surfaces on which MM snow could have been spread respectively). Similar treatments were applied in other resorts (Table 2).

The uncertainty on spreading surfaces is shown in figures (Section 5) as an envelope (corresponding to simulations using S_{min} and S_{max}) around the standard simulation (which uses S_{mid}).

2.1.3. Measurements

A measurement protocol was instigated in order to deliver a maximum amount of information within the available time and means.

- Snow depth (SD) was measured once a week by ski patrollers, on each site. Depending on local topography several measurements were made for each site so as to provide reliable integrated results as well as an indication of the deviation of measurements.
- The average density of the snowpack was measured once a month on each site. We used a Polar Ice Coring Office (PICO) lightweight coring auger (Koci and Kuivinen, 1984).
- The snow water equivalent of the snowpack was deduced from these observations, as the product of SD and average density.
- A complete stratigraphy of the main site SM with grooming and snowmaking was carried out every month. It included the measurement of snow layers specific surface areas (SSA), using the DUFISSS instrument (Gallet et al., 2009; Morin et al., 2013) and snow layers density (Fierz et al., 2009).

Average observations are displayed as dots on results figures (Sections 3, 4 and 5) with a surrounding envelope corresponding to $\pm$ the standard deviation of the observations.

2.2. SAFRAN–Crocus model chain

2.2.1. Snowpack model

The multilayer snowpack model SURFEX/ISBA-Crocus (hereafter, Crocus; (Vionnet et al., 2012)) explicitly solves the equations governing

Table 1
Main features of the four ski resorts where we carried out our 2014–2015 winter season field campaign. Resort categories from (François et al., 2014).

Resort	Lat.	Lon.	SAFRAN massif	Elevation range (m.a.s.l)	Resort category
Tignes	4526°N	6°53 E	Haute-Tarentaise	1550–3456	Very large
Chamrousse	456°N	5°53 E	Belledonne	1400–2253	Large
Autrans	45°12 N	5°33 E	Vercors	1000–1630	Nordic ski
Les 2 Alpes	45°0N	6°7 E	Oisans	1300–3568	Very large