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Crossing numerical simulations of snow conditions with a spatially-resolved socio-economic database of ski resorts: A proof of concept in the French Alps

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ABSTRACT

Snow on the ground is a critical resource for winter tourism in mountain regions and in particular ski tourism. Ski resorts are significantly vulnerable to the variability of meteorological conditions already at present and threatened by climate change in the longer term. Here we introduce an approach where detailed snowpack simulation results were crossed with a resort-level geographical and socio-economic database containing information from about 142 ski resorts spanning the entire French Alps domain. This allows us to take into account explicitly the geographical, topographical (altitude, slope and aspect) and spatial organization (distribution of ski-lifts and slopes) features of the ski resorts considered. A natural snow resort viability index was built using all the above information and simulated natural snow conditions from 2000 to 2012. Results were compared to economically relevant information (skier day values) highlighting a complex relationship between ski resort operation and natural snow conditions. The method introduced in this study holds great potential for physically-based and socio-economically-relevant analyses of the functioning of winter tourism economy and projections into the future under climate change conditions. This requires, however, that further improvements are carried out, in particular the explicit integration of snow management practices (e.g. snowmaking and grooming) into the modeling suite.

1. Introduction

Snow on the ground is a critical resource for winter tourism in mountain regions and in particular ski tourism. The ski tourism industry has continuously carried out heavy investments to maintain or improve its competitiveness (Abegg, 1996; Abegg et al., 2007; Elsasser and Bürki, 2002; Koenig and Abegg, 1997) and counteract the impact of the interannual variability of meteorological conditions (Beniston, 1997; Durand et al., 2009a). This concerns in particular snowmaking facilities, enhanced slope design and grooming practices (e.g. Fauve et al., 2008; Guily, 1991; Steiger and Mayer, 2008). Climate projections of significant temperature increase and reduction of natural snowfall amounts in the European Alps (e.g. Gobiet et al., 2014; Steger et al., 2013) and in particular in the French Alps (Lafaysse et al., 2014; Martin et al., 1994; Rousselot et al., 2012) may provide challenging environmental conditions for this economic sector. This requires us to pay close attention to the links between meteorological conditions, snow conditions and socio-economical functioning of the ski tourism industry.

In France, the building of ski resorts was closely linked to spatial planning and local development under direct governmental influence (George-Marcelpoil and François, 2012). Nowadays, the future of ski resorts is closely linked with the economy of an entire geographical area. This context has led policymakers to adopt a contractual framework to help resorts meet the challenges of the economic risks induced by meteorological variability. In contrast to North America where tourism offer is generally provided by a single enterprise in a given ski resort, ski tourism industry in French ski resorts involves a diversity of stakeholders (ski-lift companies, ski area managers, hotels, restaurants etc.) (Flagestad and Hope, 2001; Gerbaux and Marcelpoil, 2006). Public support of French ski resorts has been carried out under the assumption that the resilience of ski resorts can be improved through better organization of the tourism offer and its governance at the community level (Gerbaux, 2004; Gerbaux and Marcelpoil, 2006; Svensson et al., 2005). Due to the complexity and diversity of both mountain societies and tourism production, diversification has been funded preferentially because its enhancement reduces the dependence on snow-based business, in contrast to snowmaking facilities which have thus not been favored by public funding (Achin and George-Marcelpoil, 2013; François, 2007). From a social point of view, this approach contributes directly to the local ski system flexibility, improves its resilience (Luthe et al., 2008, 2012) and increases its capacity to overtake

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meteorologically-induced difficulties. These public policies were particularly designed for mid-altitude resorts (i.e. altitude of critical ski area lower than approximately 1500 m altitude). Facing numerous disadvantages such as their small size and the lower snow reliability than high-altitude resorts (i.e., bottom of ski resort higher than approximately 1500 m altitude), the diversification approach aims to bypass the impact of climate change. However, snow-based activities in such resorts still play a crucial role for local economy. In addition, the gap is growing between high-altitude resorts and mid-altitude resorts: on the one hand, snow remains the main resource and justifies investments in snow production equipments, while on the other hand, mid-altitude resorts currently have to deal with chronic lack of snow (Lorit, 1991; Pascal, 1993) without the help of public policies to overcome it using technical means such as snowmaking. Addressing the socio-economic component of the winter tourism economy thus requires accounting explicitly for altitude range, size, management and organizational characteristics of ski resorts, and has been attempted so far only for a limited number of case studies (see e.g. Damm et al., 2014, and references therein).

The viability of ski resorts is most often summarized by the so-called "100 day rule", which postulates that a ski resort is economically viable if snow depth above 30 cm is encountered for more than 100 days (Abegg et al., 2007). It was suggested to refine this crude rule by taking into account some structural characteristics for operating resort facilities, especially ski area organization (accounting for low and high altitude sectors) and holiday periods but also adding complexity to the 100 day rule in a multiannual perspective (Abegg, 1996; Steiger, 2010). In the latter case, a resort is considered viable if it meets at least the 100 day rule requirement 7 seasons out of 10.

While the 100 day rule has been established using natural snow depth records and may be used as such, characterizing snow conditions in ski resorts should explicitly account for the amount of snow on ski slopes. Indeed, snow management practices including grooming and snowmaking, and skier-induced erosion, exert a strong influence on snowpack properties on ski slopes with respect to surrounding natural snow areas (Fauve et al., 2008; Guily, 1991). However, many studies apply the 100 day rule using natural snow conditions, in which case the 100 day rule can be viewed as a convenient common metric to assess ski resort reliability despite its shortcomings. Numerical simulations of snow conditions can be used instead of snow depth observations allowing us to cover larger spatial extent, and open the way to long-term reanalysis of snow conditions in ski resorts and projections into the future under various climate scenarios. Several studies have attempted to address the potential viability of ski resorts on the basis of simulated natural snow depth records. For example, in the French Alps, Durand et al. (2009b) have carried out a long-term reanalysis of simulated meteorological and natural snow conditions from 1958 to 2006, and computed the average minimum snow depth which is encountered during 100 days in the same snow season, allowing us to characterize, as a function of altitude, which areas meet the 100 day rule.

Alternative modeling approaches attempt to account for technical answers to the lack of snow, more generally referred to as snow management practices. Scott et al. (2003) developed a snowmaking model they used to assess snow reliability accounting for snow production constraints. The physical part of this model is a simplified snowpack model, estimating snow cover from regional meteorological data and computing the balance between snowfall and snow melt processes. The latter was estimated using a degree-day approach. This model has progressively been refined accounting for snowmaking in an increasingly elaborated manner, while the simulation of intrinsic snowpack processes has remained relatively simple. A combination of the 100 day rule with modeling results has been used by Steiger and Mayer (2008) and Steiger (2010) to assess the future of ski resorts under different conditions of operations of a ski resort using projected climate change scenarios. These studies are partly based on previous studies by Scott et al. (2003) and Scott and McBoyle (2007). Because the snow conditions strongly depend on the regional (large scale meteorological conditions) and local (altitude range, aspect, slope) geographical characteristics of ski resorts and ski slopes, explicitly accounting for such factors is a worthwhile refinement to snow modeling studies applied to the viability of ski resorts.

Here we introduce an approach where the SAFRAN–Crocus model chain for snow on the ground numerical simulations (Durand et al., 1999; Vionnet et al., 2012) was used in combination with the "BD Stations" database, which provides resort-level geographical and socio-economic information about a total of 142 French ski resorts in the Alps (François et al., 2012; see http://www.observatoire-stations.fr). Numerical simulations carried out under a wide range of altitude, range and aspect conditions, were associated to the geographic characteristics of ski slopes within 130 French alpine ski resorts based on spatial information crossing. The method was tested for the period from 2000 to 2012. It shows the high potential of crossing meteorological and snowpack modeling with socio-economic information to produce synthetic assessments of the relationships between snow conditions and economic results of mountain ski resorts, although only natural snow conditions are considered so far in our analysis. Our work follows the logics of deeper integration of physical science and socio-economic science results allowing for transdisciplinary assessments of the relationships between these two interlinked drivers of human activities (Strasser et al., 2014). In addition, this work introduces a framework which will be expanded in the future to account explicitly for snow management techniques (including snowmaking and grooming) and allow a diversity of applications including climate projections of snow conditions in ski resorts.

2. Material and methods: integration of BD Stations and Crocus

2.1. Numerical simulation of natural snow conditions

This study uses the combination of the meteorological downscaling system SAFRAN (Durand et al., 1993, 1999, 2009a, 2009b) and the detailed snowpack model Crocus (Brun et al., 1992; Vionnet et al., 2012). In analysis mode, i.e. when surface and atmospheric observations are available for a given date, SAFRAN carries out an optimal merge of numerical weather prediction model output (large scale atmospheric fields including vertical profile of atmospheric variables), surface observations (including precipitation in mountain regions), radiosonde observations and remotely sensed cloud cover information. Surface observations consist of various sources of information. A few automated meteorological monitoring stations are located in high altitude mountain regions and measure temperature, relative humidity, wind speed and snow depth. In addition, manual meteorological observations including daily precipitation amounts, daily minimum/maximum temperature and snow board fresh snow measurements are carried out in ski resorts during their period of operation. SAFRAN is able to combine these various sources of information to provide hourly records of meteorological data needed to run the detailed snowpack model Crocus. These records depend on altitude (by steps of 300 m) within geographical zones, referred to as massifs, which have been selected because of their climatological homogeneity and are thus assumed to be meteorologically homogeneous. This means in practice that two locations at the same altitude within the same massif are assumed to encounter the same meteorological conditions. Fig. 1 shows a map of the 23 SAFRAN massifs defined for the French Alps, whose mean size is about 800 km^2. This map shows that some resorts fall outside the regions covered by the SAFRAN massifs, so that only 130 out of 142 resorts are concerned by the information crossing developed below. However, our sampling includes the most significant ski resorts in the French Alps.

The detailed snowpack model Crocus solves the surface energy and mass balance of the snowpack and features an explicit representation of snow metamorphism, snow compaction, thermal diffusion and