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Sensitivity analysis of snow patterns in Swiss ski resorts to shifts in temperature, precipitation and humidity under conditions of climate change

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ABSTRACT: The value of snow as a resource has considerably increased in Swiss mountain regions, in particular in the context of winter tourism. In the perspective of a warming climate, it is thus important to quantify the potential changes in snow amount and duration that could have large repercussions on the economy of ski resorts. Because of the fine spatial variability of snow, the use of a Surface Energy Balance Model (SEBM) is adequate to simulate local snow cover evolution. A perturbation method has been developed to generate plausible future meteorological input data required for SEBM simulations in order to assess the changes in snow cover patterns. Current and future snow depths have also been simulated within the ski areas themselves. The results show a large decrease of the snow depths and duration, even at high elevation in a warmer climate and emphasize the sensitivity of snow to topographical characteristics of the resorts. The most vulnerable areas would be the Western regions of Switzerland or the Eastern Prealps whereas the Central Alps or Valais would be less affected. The study highlights the fact that not only the altitude of a domain but also its exposure, localization inland and slope gradients need to be taken into account when evaluating current and future snow depths. This method enables a precise assessment of the snow pattern over a small area. Copyright © 2008 Royal Meteorological Society

KEY WORDS snow depth; snow duration; climate change; ski resorts; numerical model; SEBM; Alps

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1. Introduction

For a few decades now, there have been substantial economic investments for tourism, winter sports in particular, in mountain regions. Snow in such areas plays a key role for ski resorts as a significant source of income (Beniston, 2000; Scherrer *et al.*, 2004). Therefore in the winter tourism sector, the presence or absence of snow, and its depth, are essential to the financial success of a region (Koenig and Abegg, 1997). In the context of climate change, it is thus necessary to evaluate the potential change of snow amount that may have significant repercussions on the economy. The current and future snow patterns in the Swiss mountains, and more particularly at selected ski resorts, are investigated with the help of a numerical energy balance model.

According to one climatic scenario, based on high levels of greenhouse-gas scenarios (the IPCC A2 scenario; Nakicenović *et al.*, 2000), winter temperatures would increase by 4 °C by the year 2100, generating a rise of 600 m in the line of natural snow-reliability for ski resorts in the Swiss Alps (OECD, 2006). However, the snow depths and duration are currently highly variable at

very fine scales and will increasingly be so in the future, depending in particular on the altitude, orientation, topography, slope, wind and solar exposure of an area (Barry, 1992). The use of a Regional Climate Model (RCM) with a relatively coarse grid mesh is therefore not adequate to analyse snow cover (Keller and Goyette, 2005; Scott *et al.*, 2006) for the purpose of this study. On the other hand, a Surface Energy Balance Model (SEBM) is able to depict, realistically enough, the complexity of snow depth and duration at a local level. It therefore enables a better and more complete understanding of the behaviour of snow in the Swiss mountains.

Simulating the potential future snow depth and duration in mountain areas has already been conducted in some countries, such as Canada (Scott *et al.*, 2006), Australia (Whetton *et al.*, 1996), France (Etchevers and Martin, 2002) and Austria (Breiling and Charamza, 1999) for instance. In Switzerland as well, future snow patterns have been analysed by Beniston *et al.* (2003b) Keller and Goyette (2005) or the OECD (2006) among others. As the characteristics of Swiss ski resorts are very diverse, the idea of the present study is not to give yet another general number for the rise in the level of snow-reliability in Switzerland but to compute a realistic value of the decrease in snow depth and duration for each mountainous region and selected ski area. In addition, low-lying ski stations that are the most vulnerable to climate change are

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also taken into account. Furthermore, a method of perturbation of the observed input data of the SEBM has been elaborated in order to reproduce local conditions' characteristics of a warmer climate for each of the selected ski resorts.

The projected increase in temperatures and decrease in atmospheric moisture are expected to lead to less snow, whereas the increase in precipitation in winter should be accompanied by more snow at high altitudes and more rain at low altitudes (Beniston *et al.*, 2003a). We shall see that every selected ski resort in Switzerland, despite their important climatic differences, will encounter a reduction, sometimes drastic, in snow amount and in terms of the duration of the winter season.

2. Experimental setup

The current and future potential spatiotemporal evolution of snow is hereafter computed with a SEBM. The procedure used to reproduce snow amount and duration over different winter seasons with atmospheric input data is detailed in the following sections.

2.1. Data

As the quantities of snow do vary widely from one year to another (Etchevers and Martin, 2002; Beniston *et al.*, 2003a) and to limit the amount of input data, four single-season sets have been chosen to represent four types of Swiss winter: cold (2005–2006), warm (1996–1997), humid (1999–2000) and dry (1995–1996). These typical seasons have been selected from the MeteoSwiss data archive (Bantle, 1989). Monthly mean temperatures and precipitation of 11 representative Swiss stations have been averaged over the longest period of available data (63 and 37 years respectively) from December to April. The mean deviation of every winter season has next been calculated. One season for each winter-type has been designated respectively under the 20% (cold, dry winters)

and over the 80% (warm, humid winters) quantile of the distribution of both datasets. The average results of these four winters give a presumably representative state of a Swiss average winter. Twenty meteorological stations are considered, distributed in different winter tourist regions of Switzerland that exhibit a range of altitudes, slopes and orientation (Figure 1). The availability of atmospheric data has guided the selection of the stations. The input data that drive the SEBM have been extracted from the MeteoSwiss ANETZ network (Bantle, 1989).

To assess the impacts of climate change on ski resorts, it is necessary to simulate values of snow depth within the ski areas themselves. However, the weather stations are usually not situated directly on ski slopes; consequently, the analysis of snow cover has been divided into two phases. Firstly, the 20 meteorological stations have been classified into 8 climatic regions where snow depths and duration have been investigated in order to have a general view of snow patterns. In a second step, a correction of altitude has been applied on input data in order to make them representative of the ski resorts. To that purpose, the highest point beyond which the snow is required for the ski lifts to run has been determined (Table I). This critical altitude has become the reference elevation for each ski area. The relative difference between the altitude of the weather station, z_w , and the critical altitude of the closest ski resort, z_{ski} , has next been calculated, such that $\Delta z = z_w - z_{ski}$.

A specific correction has been subsequently used on input air temperature, T_{in} , dew point temperature, $T_{d,in}$, and surface pressure, p_{in} , following Keller *et al.* (2005):

$$T_{corr} = T_{in} - \gamma \Delta z \quad (1)$$

$$T_{d,corr} = T_{d,in} - \left[\frac{1}{T_{corr}} - \frac{R_v}{L_v} \ln h \right]^{-1} \quad (2)$$

$$p_{corr} = p_{in} - p_{in} \left[\frac{T_{corr}}{T_{in}} \right]^{g/\gamma R} \quad (3)$$

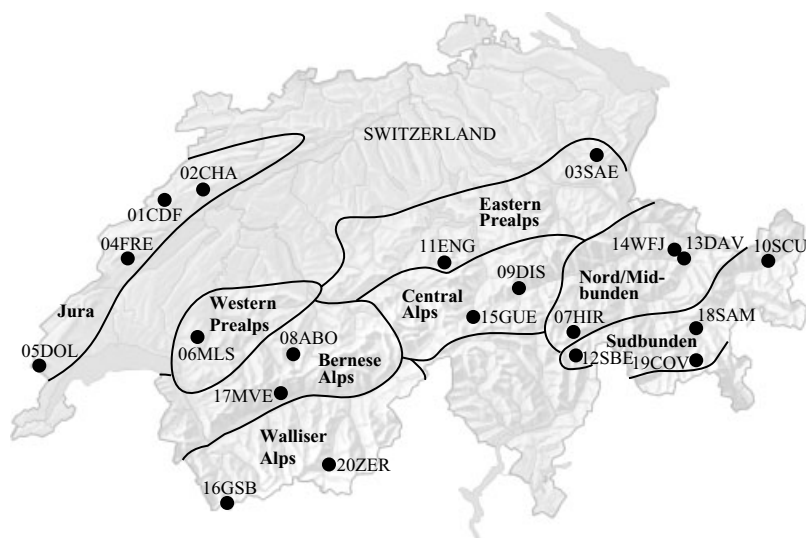


Figure 1. Regions and meteorological stations in Switzerland.

Table I. Critical altitude of ski resorts. It represents the highest point beyond which the snow is required for the ski lifts to run. The numbers and abbreviations refer to figure 1.

No.	Abbr.	Station	Critical altitude (m)
01	CDF	La chaux-de-Fonds	1 000
02	CHA	Chasseral	1 030
03	SAE	Saentis	1 352
04	FRE	La Frétaz	1 200
05	DOL	La Dôle	1 228
06	MLS	Molésón	1 268
07	HIR	Hinterrhein	2 140
08	ABO	Adelboden	1 491
09	DIS	Disentis	1 871
10	SCU	Scuol	2 146
11	ENG	Engelberg	1 800
12	SBE	San Bernardino	1 953
13	DAV	Davos	2 005
14	WFJ	Weissfluhjoch	2 662
15	GUE	Guetsch	2 212
16	GSB	Grand-St-Bernard	1 910
17	MVE	Montana	2 250
18	SAM	Samedan	1 720
19	COV	Corvatsch	2 702
20	ZER	Zermatt	2 939

where γ is the vertical lapse rate defined as 6.5 K/km, R_v is the water vapour constant ($461.5 \text{ J kg}^{-1} \text{ K}^{-1}$), L_v is the latent heat of vaporization ($2.5 \times 10^6 \text{ J kg}^{-1}$), h is the relative humidity measured, g is the constant of gravity (9.80616 m s^{-2}) and R is the gas constant for dry air ($287.04 \text{ J kg}^{-1} \text{ K}^{-1}$).

In this study, altitudinal corrections of the precipitation, wind speed and incoming solar radiation are neglected, as well as the horizontal correction between weather stations and ski resorts. According to the same method, input data for lower and upper runs of ski resorts have been corrected as well.

2.2. Model

The SEBM used in this investigation, named GRound ENergy Balance for natural Surfaces model (GRENBLS) is detailed in Keller and Goyette (2005). It is a one-dimensional physically based model that requires atmospheric input data in order to simulate snow cover. GRENBLS runs with hourly input variables of air temperature, dew point temperature, precipitation rate, surface pressure, wind velocity and incoming solar radiation. The simulated snow pack, resulting from the processes of land-atmosphere water and energy budgets, is computed as a single uniform layer of temperature and snow density. The parameterization scheme of the model enables the calibration of the impact of solar radiation on different slope angles and surface orientations.

Because of the unavailability of some observed snow depths data, GRENBLS has been calibrated at ten stations only. The observed snow depths of these stations have been compared to simulations of snow cover for the same stations (Figure 2). It is seen that not all the time variability is captured by the model. This is due to the rather simple approach of GRENBLS: single snow layer, lack of parameterizations for snow compaction and blowing snow for instance. Nevertheless, both series of data show generally a high correlation with each other, giving sufficient confidence in the model's capacity to reproduce the salient aspects of the snow pack.

2.3. Perturbation method to the 'observed' climate

To model climate change on the basis of key variables that determine snow simulations, including observed temperature, dew point temperatures and precipitation, perturbations according to the results of the HIRHAM Danish RCM have been used (PRUDENCE project, Christensen, 2005). The model's archive provides daily simulated values of minimum, maximum and mean air temperatures, as well as values of dew point temperatures and precipitation for the periods 1961–1990 and

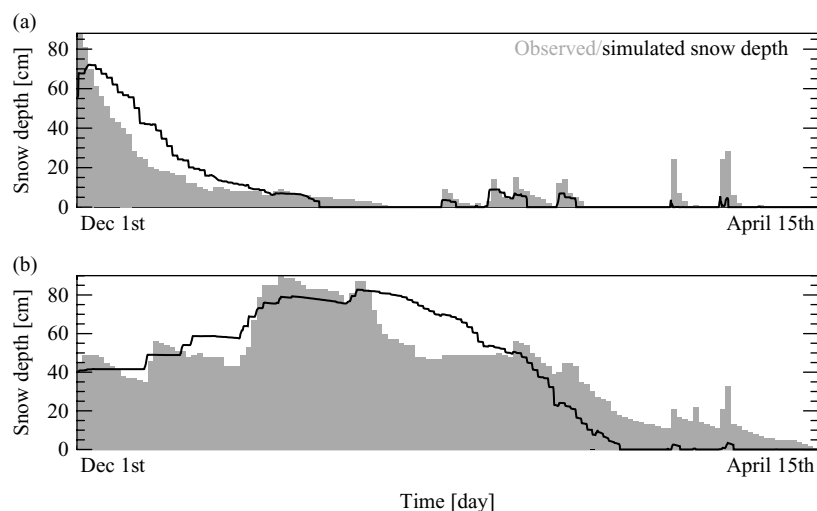


Figure 2. Comparison between observed and simulated snow depths for the station of DIS (a) and SAM (b) for a warm winter from December 1st to April 15th, where for (a), $r^2 = 0.822$ and for (b), $r^2 = 0.835$.

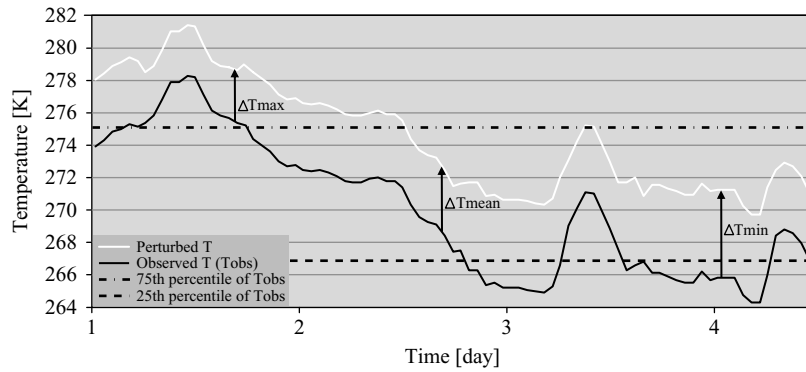


Figure 3. Sample of the construction of the perturbed air temperature scenario. In this example, $\Delta T_{\min} = 5.4^{\circ}\text{C}$, $T_{\text{mean}} = 4.1^{\circ}\text{C}$ and $T_{\text{max}} = 3.08^{\circ}\text{C}$.

2071–2100 for 21 grid points in Switzerland. Confidence has been placed in the HIRHAM for simulating future potential characteristics, as it has shown skill in reproducing contemporary climate (Christensen *et al.*, 1998; Beniston, 2005). The IPCC A2 scenario (IPCC, 2001) is the only projection used in this study, which assumes atmospheric CO_2 levels in excess of 850 ppmv by 2100, compared to 370 ppmv in 1990.

The input air temperature T_{in} , dew point temperature $T_{\text{d,in}}$ and precipitation P_{in} driving GRENBLS have been perturbed in order to emulate snow cover over Switzerland in response to a change in climate as follows:

$$\psi_{\text{in},i} = \psi_{\text{obs},i} + \gamma \Delta_i \quad (4)$$

$\psi_{\text{in},i}$ are the GRENBLS input parameters and $\psi_{\text{in}} \in [T_{\text{in}}, T_{\text{d,in}}, P_{\text{in}}]$, $\psi_{\text{obs},i}$ are the observed data, γ is an empirical parameter and $\gamma \in [0, 1]$, and Δ_i is the difference between the simulated future and current HIRHAM data. Therefore, γ is theoretically equal to 0 for the period 1961 and is equal to 1 for the period 2071. The other input parameters (wind speed, surface pressure and incoming solar radiation) have been left unchanged. For brevity, only the method of perturbation for T_{in} is detailed hereafter.

According to Jungo and Beniston (2001), minimum, maximum and mean temperatures will not evolve in the same manner and at the same rate. The trend during the last century shows that the warming in minimum temperatures is much greater than the maxima, especially in winter. Thus in the following method, a distinction has been made between extreme temperatures and those close to the median, the perturbation is different in each case. Moreover, the intensity of perturbation depends on the season of the year.

The first step involves determining the median of minimum, maximum and mean temperatures for the period 1961–1990 and for the period 2071–2100 given by the HIRHAM. The difference between each median of temperatures, adapted to each period and each season is then computed for the grid points closest to the ANETZ stations. The series of GRENBLS input temperatures are then perturbed for each season, according to the

computed differences (Figure 3). In fact, ΔT_{\min} perturbs every value under the 25% quantile, ΔT_{mean} every value between the 25% and the 75% quantile and ΔT_{max} every value above the 75% quantile.

The deltas show a larger increase in minimum temperatures, which corresponds to the results of Jungo and Beniston (2001). Moreover, increases in mean temperatures are situated within the limits of global annual average warming (1.9 – 5.1°C for the A2 scenario) published by the IPCC (2007). Therefore, it seems to give a realistic representation of future temperature patterns.

The cold, warm, humid and dry seasons have been perturbed in the same manner, that is without a particular delta specified for a given winter but, rather, a mean delta. Since extreme precipitation events may become more frequent in the 21st century (IPCC, 2007), this method with differentiated deltas has been implemented to perturb precipitation inputs as well. For P_{in} , null values have been left unchanged to prevent adding new events. These deltas have been confronted to the results of the averaged projected precipitation change of the PRUDENCE project (Christensen, 2005) and have shown good agreements. Dew point temperatures have been perturbed only according to the mean delta, due to the unavailability of $T_{\text{d,in min}}$ or $T_{\text{d,in max}}$.

3. Results and discussion

Simulations of the current and future potential snow depths and duration have been carried out over the four winter-types from December 1 to April 15. The first part of the analysis concerns the snow pattern on the whole in different tourist regions of Switzerland. The second part considers the current and projected situation of snow in selected ski resorts themselves. It is to be mentioned that the intra-annual variability of snow depth is greater than the influence of climate variability on snow depth (Hamilton *et al.*, 2007). However, the possible future shifts in the timing of both the beginning and end of the snow season, as well as potential changes in snow depth variations within the same season have not been investigated in the present paper; the principal reason is

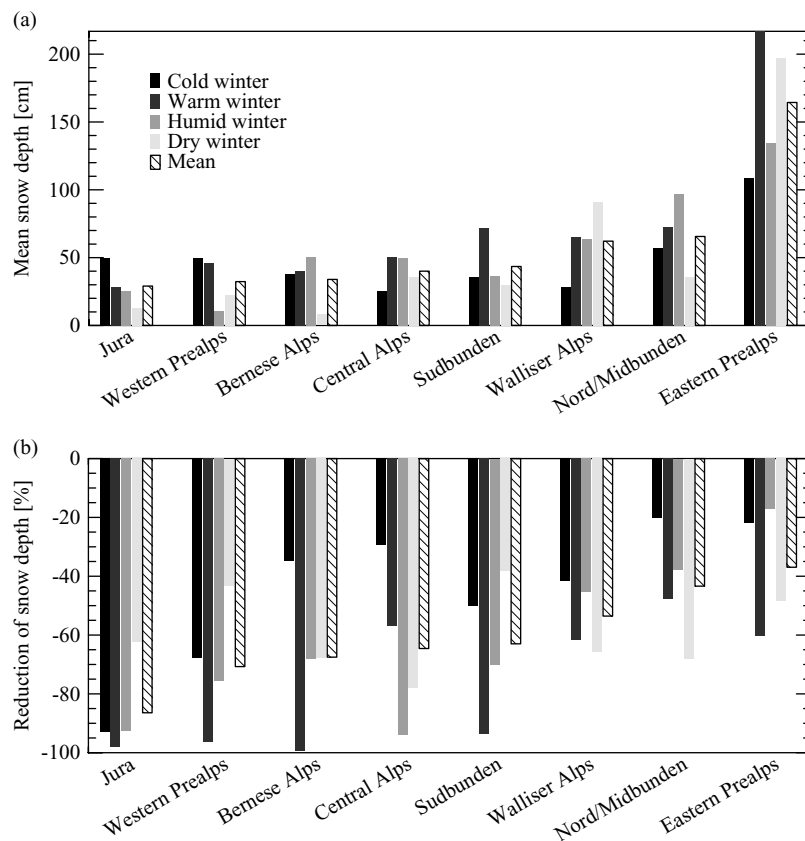


Figure 4. Simulation of current mean snow depths by winter-type (a) and simulated reduction of mean snow depths compared to current mean snow depths over an average winter, projections for the years 2071–2100 (b) by region from December 1st to April 15th.

that four years of analysis are insufficient to draw any meaningful conclusions on such fluctuations.

3.1. Snow patterns in Swiss regions

Figure 4(a) illustrates the current mean snow depth by region and winter-type. The graph shows a large spatiotemporal variability: it ranges from a value of 8-cm of snow depth in the Bernese Alps to almost 220-cm in the Eastern Prealps. It is not necessarily always the same type of winter that implies the greatest snow amount. But on an average, it is the cold winter that is the sparsest season in terms of snow since cold air is usually much drier, whereas the warm one is the snow-richest, owing to more moisture potentially leading to more abundant precipitation. Nevertheless, the Jura receives proportionally more snow during cold winters as snow cover at lower altitude is much more sensitive to even a small change in temperature (Beniston, 1997). Conversely, the snow depth is thicker for the Eastern Prealps during a warm winter because most of the precipitation falls as snow at these heights. However, a direct correlation between the quantities of snow and the mean elevation of an area (according to the height of the weather stations) is not systematic. It appears that the exposure, slope gradient and the localization inland of the station are also to be taken into consideration: a north-facing and steep slope, situated in an exposed region will normally benefit from a more abundant snow cover.

In a warmer climate, the situation would be much different. As seen in Figure 4(b), the simulated snow pack is reduced for every region. Moreover, some part of the country – especially the Jura, the Bernese Alps and the Western Prealps – could suffer from an almost total loss of their snow cover, particularly during a warm winter. These first three regions that already currently have little snow are the ones that are the most vulnerable in a warmer climate. No such trend can be inferred for the other areas. It is during a cold winter that the reduction of snow pack is the smallest, while the contrary applies to warm winters. In comparison, the difference in projected snow amount between humid and dry winters is much less pronounced. This suggests that air temperature is a more dominant factor than air moisture for the accumulation of snow.

The snow patterns simulated by GRENBLS generally match other studies (Beniston *et al.*, 2003a,b; Keller and Goyette, 2005; OECD, 2006). The few differences observed with respect to the results of previous investigations probably derive essentially from the small number of weather stations considered here, sometimes one single station represents an entire region. Nevertheless, this first general analysis enables a reproduction of the global pattern of snow depth and gives confidence in the model's ability in reproducing both current and potential future snow depths and duration at the local level of ski resorts.

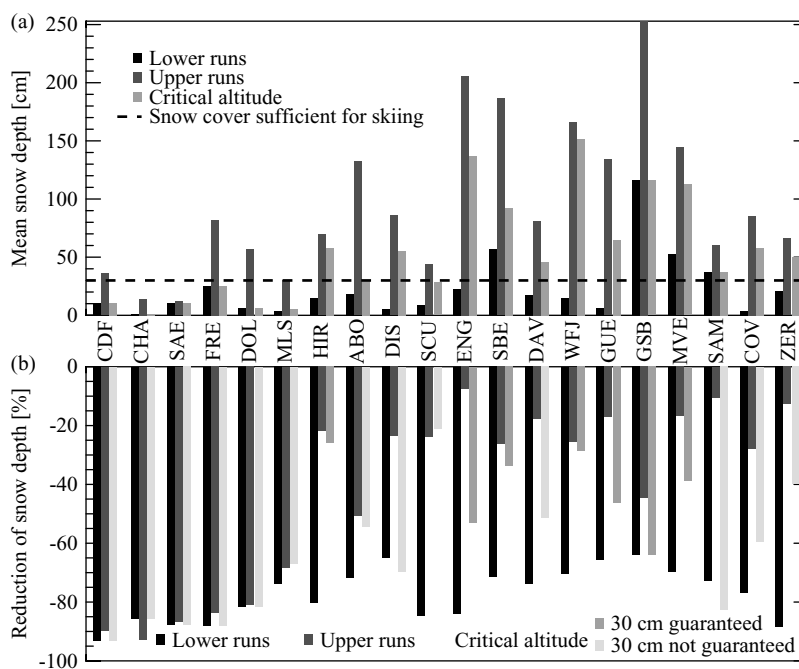


Figure 5. Simulation of current mean snow depths (a) and simulated reduction of mean snow depths compared to current mean snow depths over an average winter, projections for the years 2071–2100 (b) at lower runs, upper runs and critical altitude.

3.2. Snow patterns in Swiss ski resorts

To have a more precise picture of snow depth and duration in ski resorts, GRENBLS has been driven with the height-corrected input data (Section 2.1 for more details). Figure 5(a) shows the results obtained for the current mean snow depth at lower runs, upper runs and critical altitude. The dashed line indicates the 30-cm threshold of natural snow generally considered necessary for an economically viable skiing industry (Abegg and Froesch, 1994). The ski resorts are classified according to their mean altitude. Except for the stations of CHA and GSB, where snow depths seem a little under- and over-estimated respectively by the model, this figure gives a more accurate view of the current distribution of precipitation in Switzerland. Actually, the first ten stations, belonging to the western part of the country, the Sudbunden and the Eastern Prealps are rather dry and/or low-lying areas where the snow cover is fairly thin, whereas the reverse is true in the other ski regions. The fact that the amount of snow in a resort is, naturally, dependant not only on its altitude but also on its location in the country is highlighted on this figure. For instance, the slopes of ZER have the highest average altitude but are not the snow-richest runs. Topographical characteristics such as exposure or inclination of slopes may also have an influence. Currently, the snow layer is sufficient on average for skiing in almost every resort on upper runs and in 75% of the stations at the critical altitude. In contrast, it is notable that even at present, snow reaches the 30-cm limit on lower runs during a mean winter only in four resorts. However, the snow conditions for skiing seem reasonably good on average in Switzerland, a fact which has been

confirmed by other studies (OECD, 2006; Müller *et al.*, 2007).

In a simulated warmer climate, the projected mean snow depths compared to the current snow pattern show a decrease in every station and at every altitude (Figure 5(b)). We can also observe that the resorts with little snow at present are also the most affected in the future. This is, however, not true for snow at the lower runs where the reduction of snow cover is large everywhere. DAV and ZER are also exceptions: the snow fall at this location is normally low but thanks to the high elevation, the generally steep gradient and north-oriented ski runs, the simulated reduction of snow depths is also attenuated. For the opposite reasons, but despite their high altitude, SAM and COV suffer from a larger decrease in snow pack than DAV. In addition, at the critical altitude for 13 of the selected stations, the 30-cm limit is no longer guaranteed during an average winter.

If we consider the current and projected percentage of days with more than 30-cm of snow during a mean winter season at the critical altitude (Figure 6), a clear threshold can be observed between MLS and HIR. Indeed, the first six resorts are at the moment those that exhibit the least snow and, at the same time, are the ones most threatened by a warmer climate. Some of them do not encounter a single day with 30-cm of snow, and duration of the snow season is reduced in every resort. The situation also becomes difficult for some resorts in the Bernese Alps and in the Sudbunden, as the percentage of days where skiing is possible is reduced to a great extent. In contrast, the conditions of snow cover are not much affected in HIR, ENG, WFI or MVE.

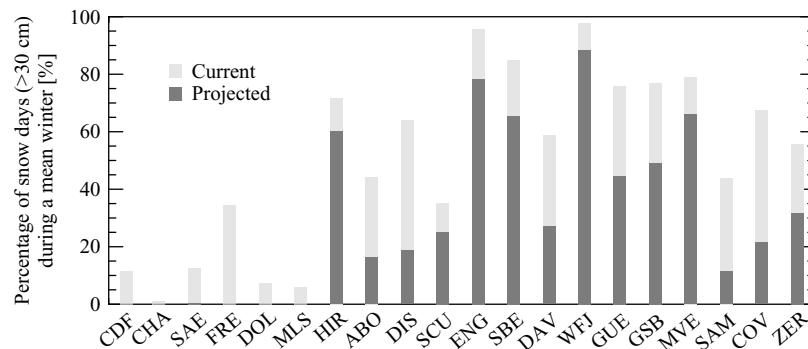


Figure 6. Simulated current and projected percentage of days with more than 30 cm of snow on the ground at the critical altitude for each ski resort during a mean winter season.

4. Conclusions

The SEBM used in this study shows skill in representing the current snow amounts in different parts of Switzerland for different winter-types. Due to the small number of stations investigated per climatic region, the results of the model are more significant when simulating the snow cover in the ski resorts themselves.

By using a perturbation method based upon a climate change scenario of the HIRHAM RCM, GRENBL5 is used to make projections of potential snow amount in a warmer climate. This method of perturbation has the advantage of being relatively simple. It can be rapidly implemented, especially when the amount of input data is large. One limitation of the method though is that it suffers from a lack of precision, since there are only three different deltas of temperatures per season and that these deltas are computed from 30-year average temperatures. Nevertheless, each ski resort analysed in this paper encounters a reduction of the snow pack, as well as a radical decrease in the number of skiable days following climate warming, which confirms other studies (Koenig and Abegg, 1997; OECD, 2006). This suggests that the projected increase in precipitation in winter over the Alps shown by the majority of RCMs (Christensen, 2007) will not compensate for the projected increase in temperature, even in higher resorts (Beniston, 2006).

The most threatened resorts are those situated in the western part of the country and in the Eastern Prealps, where snow depth is already at present generally thinner. In these regions, days with more than the 30-cm depths necessary to operate ski lifts decrease drastically and even disappear in some places. Furthermore, snow becomes scarce on the lower runs of all 20 resorts. In addition, at the critical altitude, more than half of stations will experience snow amounts below the critical 30-cm, on average. A small number of ski resorts however, such as WFJ or MVE, are much less affected by climate change because of particular site characteristics.

The GRENBL5 model emphasizes the variable character of snow depth, depending on several geographical factors, including not only the altitude but also the localization in the country and the exposure or the inclination

of slopes of a particular area. From this analysis, we cannot provide a single number for the rise of the line of natural snow-reliability in the Swiss mountains; rather, the SEBM enables to go beyond the simple relation between altitude and amount of snow and reveals the regional contrasts of such a parameter. The possible use of such results would be to better quantify the economic, social, hydrological or biological impacts that a projected reduction of snow cover could have in a particular resort.

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