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Will snow-abundant winters still exist in the Swiss Alps in an enhanced greenhouse climate?

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ABSTRACT: Snow cover and duration are very variable components of the alpine environment and are often poorly reproduced in climate models. Using joint probability temperature/precipitation distributions to categorize cold/dry, cold/moist, warm/dry (WD) and warm/moist situations in winter, this study demonstrates that one particular mode (WD) exerts the strongest influence on snow. When the number of WD days is low, snow in the Swiss Alps is abundant, and vice versa. Since the 1950s, there has been an increase in the WD events and a subsequent reduction in snow cover. Snow-abundant winters have nevertheless occurred in recent years, when WD days are low, despite winter temperatures that are more than 1 °C higher than those in the mid-1900s. The WD mode thus represents a form of proxy to snow amount and duration; its evolution in an enhanced greenhouse climate can help identify whether snow-abundant winters may still occur in a much warmer world. Copyright © 2010 Royal Meteorological Society

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1. Introduction

A warmer climate will undoubtedly reduce the general abundance of snow, because the zero-degree isotherm will be displaced on average towards higher latitudes and altitudes. A number of studies have shown how the average conditions of mountain snow packs may change in a 'greenhouse climate' by the end of the 21st century in the Alps (Beniston *et al.*, 2003; Uhlmann *et al.*, 2009), but little attention has been paid to the variability of winter snow conditions (Lopez-Moreno et al., 2009). It is interesting to note that today in the Alps, periods of snow abundance still occur despite the fact that winter temperatures in many parts of the alpine domain are 1–2 °C warmer than they were a century ago (Beniston, 2004). Over the past decade, sharply contrasting winters have been observed (Scherrer *et al.*, 2004), from the exceptionally mild snow-sparse conditions experienced in 2006–2007 (up to 4 standard deviations above the mean in terms of winter temperature anomalies) or 2001–2002, to the snow abundance of 1998–1999 and 2008–2009 (up to 3 standard deviations below the long-term temperature average). It is thus of interest to investigate whether snow-abundant winters could still occur in a greenhouse climate, because abundant snow has many environmental (e.g. hydrology, vegetation and natural hazards) and socio-economic (e.g. hydropower, agriculture and tourism) implications in the Alps. It is a key element for the timing and amount of runoff for rivers flowing off the alpine domain, and any long-term reductions in snow amount would significantly impact water use in major rivers such as the Rhone and the Rhine, not only within the mountains themselves but also far downstream in the populated lowlands (Beniston *et al.*, 2003). The presence or absence of snow is an important determinant of the vegetation cycle of many plant species, some of which commence their vegetation cycle as soon as the snow cover has been removed; some species can cope with an earlier start to the season, whereas others cannot. There will thus be competition leading to shifts in species distribution (Keller *et al.*, 2005). In economic terms, snow is a major source of income for ski resorts (Koenig and Abegg, 1997), with obvious benefits for tourism when the snow season is long; many alpine resorts need at least 100 days of snow per year above a threshold depth of 30 cm to break even in financial terms (Abegg *et al.*, 2006).

Joint distributions of two weather variables, such as temperature and precipitation, have been shown *inter alia* by Beniston and Goyette (2007) and Beniston (2009) to be reasonable proxies for weather patterns and their persistence. This is because particular combinations of temperature and precipitation are closely related to the underlying synoptic circulations that may or may not bring snowy winters to the Alps. Joint distributions will be shown in this study to better reflect the weather conditions that lead to snow-abundant or snow-sparse winters than temperature or precipitation statistics taken separately. This is because cold winters are not necessarily snow-abundant winters, and vice versa. In addition, because snow is a variable that is difficult to reproduce in global

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and even regional climate models (Räisanen, 2008), use of joint distributions can help estimate the duration and amount of snow at a particular location without necessarily applying detailed energy-balance models, snow models or other downscaling techniques to infer snow characteristics.

This study will firstly provide an insight into the behaviour of snow in relation to specific modes of temperature and precipitation since the middle of the last century, to establish the relationships between the snowpack thickness and its duration for the observed climate. In a second step, an assessment will be made of the ability of regional climate models (RCMs) to reproduce the observed temperature–precipitation relationships for the reference climate (or 'control climate') of the period 1961–1990. Finally, the changes in the frequency of occurrence of particular combinations of temperature and precipitation for the period 2071–2100 will be analysed to determine whether, despite the much warmer Alpine climate projected for the end of the century, snow-abundant winters may still occur.

2. Data and methods

The observed climate data have been provided by the Swiss weather service, MeteoSwiss, that manages a digital database containing numerous variables at a daily time scale; the data are for the most part homogenous and have proven to be of high quality for climate-related investigations (Begert *et al*., 2005). For this study, and to highlight the methodology applied in this study, daily mean temperature, precipitation and snow-depth statistics have been compiled for four weather stations that span an altitudinal range of 1000–2500 m above sea level, and cover the period from 1 January 1951 through 30 April 2009. Stretching from west to northeast Switzerland, the stations include, respectively, Château d'Oex (980 m), Andermatt (1440 m), Arosa (1850 m) and Saentis (2500m). Although obviously not fully representative of all the complexity of Alpine climates, the four selected sites do provide an insight into the spatial variability that can be expected on the northern side of the Alps (south Alpine climates, as for example in northern Italy or the Swiss Canton of Tessin that are strongly influenced by Mediterranean regimes, exhibit different winter characteristics and will not be discussed in this study). Additional stations could have been added to the study, as for example in Beniston *et al*. (2003), where up to 20 Swiss locations were investigated, but the purpose of this study was to illustrate the feasibility and merits of the methodology to be discussed and not to provide an exhaustive analysis of snow conditions over the entire Alpine chain.

Winter statistics have been derived, which include mean winter snow-pack depth, continuous snow duration (using a 10-cm snow-depth threshold to avoid counting dispersed intermittent snow fall recorded at the beginning or end of the winter season) and joint temperature/precipitation quantiles. For this study, the 25 and 75% joint quantiles were used to define winter situations that are cold/dry (CD; when the joint quantiles are equal to or below $T_{25}p_{25}$, where the subscript refers to the quantile threshold), cold/wet (CW; $T_{25}p_{75}$), warm/dry (WD; $T_{75}p_{25}$) and warm/wet (WW; $T_{75}p_{75}$). The threshold values are computed on the basis of daily mean temperature and precipitation statistics for the 'winter half-year' (i.e. beginning of November through the end of April) for the reference period 1961–1990. A 6-month period, rather than the more usual definition of the 3 winter months December–January–February, is used in this study because at many Alpine sites, snow is likely to appear and remain on the ground for more than 3 months. In this study, snow-sparse or snow-abundant winters are defined as those where mean snow depth is below or beyond 1 standard deviation around the mean. Because snow depth and snow duration are generally well correlated (Beniston *et al*., 2003), a snow-sparse winter is also likely to be one with a fairly short period of snow cover and vice versa.

The regional scenario climate data were obtained from regional climate model (RCM) simulations undertaken in the context of the EU 'PRUDENCE' project (http://prudence.dmi.dk), and in particular the HIRHAM model of the Danish Meteorological Institute (Christensen *et al*., 1998). Simulations of the reference climatic period 1961–1990 have shown that the HIRHAM model exhibits genuine skill in reproducing contemporary climate, including mean and extreme climate in the Alps, thereby providing some confidence as to its capability for simulating the characteristics of temperatures and precipitation in the future (Beniston, 2006; Beniston *et al*., 2007). The model operates at a 50-km resolution and has completed two 30-year simulations, i.e. 'current climate' or the 'control simulation' for the period 1961–1990, and the future 'greenhouse-gas climate' for the period 2071–2100. Of the range of possible emission scenarios, only results based on the IPCC SRES A2 scenario (Nakicenovic *et al*., 2000) are discussed in this study; A2 assumes a high level of emissions in the course of the 21st century, resulting from low priorities on greenhouse-gas abatement strategies and high population growth in the developing world. The A2 scenario leads to atmospheric CO_2 levels of about 800 ppmv by 2100 (three times their pre-industrial values) and provides an estimate of the upper bound of climate futures discussed by the IPCC (2007). The fully coupled ocean–atmosphere general circulation model (GCM) of the UK Hadley Centre, HADCM3 (Johns *et al*., 2003), has been used to drive the higher-resolution atmospheric HadAM3H model (Pope *et al*., 2000), which in turn provides the initial and boundary conditions for the RCMs used in the PRUDENCE project, including HIRHAM4.

Although it could be argued that more recent ensemble simulations would be more appropriate for investigating the intricacies of future climate and enabling an assessment of the inter-model variability, it should be emphasized here that this study does not aim to provide a precise forecast of future snow behaviour, but rather to demonstrate broadly how snow events may change in an enhanced 'greenhouse climate', according to one of the stronger emission scenarios. As a consequence, the use of one rather than an ensemble of RCM results should not be seen as a limiting factor. Indeed, the statistical noisiness of ensemble simulations is probably more of a hindrance for this type of study than using the data from a single model that has in the past proven to be reasonably accurate in mountain regions.

3. Results and discussion

3.1. Observed climate

In terms of snow sparseness or snow abundance, the present analysis shows that the determining factor is the frequency of occurrence of the WD mode. If the frequency of this mode is low, the chances of seeing a snow-abundant winter are high, because of the absence of extended warm conditions with little precipitation that are detrimental to snow. In parallel, snow abundance will also be reflected in the CW mode, i.e. when sufficiently cold conditions with precipitation in the form of snow occur. Table I provides the correlation between each of the four modes and snow duration and average snow thickness. In almost all cases, the strongest correlation was observed between snow duration, snow depth and the WD mode. Although the correlation coefficients are highly significant at the 95% and (for values beyond $r = 0.5$) the 99% levels, and the signs of the correlations are consistent across stations, there are differences in the strength of the correlation from one station to another. These differences are probably related to both individual site characteristics (e.g. valley floor in the case of Château d'Oex and mountain top in the case of Saentis) and the differentiated climate characteristics of the chosen locations (generally drier in the east than in the west, more open to contrasting northerly or southerly flows in Andermatt). These local and regional influences serve to modulate the strength of the correlations between a given mode and a particular snow-pack characteristic.

Table I. Correlations between the four joint temperature–precipitation modes and snow duration and average snow thickness.

	Ch. d' Oex (980 m)	Andermatt (1440 m)	Arosa (1850 m)	Saentis (2500 m)
CD/duration	0.58	0.57	0.67	0.54
CD/thickness	0.68	0.78	0.66	0.33
CW/duration	0.74	0.43	0.87	0.60
CW/thickness	0.68	0.50	0.83	0.69
WD/duration	−0.84	−0.78	−0.90	−0.77
WD/thickness	−0.92	−0.81	−0.84	−0.92
WW/duration	−0.48	−0.45	−0.51	−0.24
WW/thickness	−0.47	−0.32	−0.64	−0.25

All absolute values beyond 0.4 are significant at the 95% level and beyond 0.5 are significant at the 99% level.

Synoptic situations characteristic of a snow-sparse winter, reflected in the frequency of occurrence of the WD mode, are generally related to the establishment of a persistent high-pressure ridge extending to the Alps that deflects storm systems well to the north. Snow-abundant winters, on the contrary, are associated with southerly incursions of moist and cold air. The North Atlantic Oscillation seems to have at least a partial bearing on sharply contrasting winters, as experienced in the Alps in the past two to three decades (Beniston, 2005).

It is thus of interest to assess the manner in which the four modes have evolved since the middle of the last century, especially the WD mode, as it is very closely linked to snow-sparse or snow-abundant winters. Figure 1 shows that since 1951, there have been changes in the behaviour of the four joint quantile modes at the four selected stations. Although there is some variability in the curves that reflect regional climatic differences and local site characteristics, the curves exhibit very similar, in-phase behaviour. This same figure also shows that there are decreases within the CD mode from approximately 30 days per winter in the 1950s to less than 15 days currently, and increases in the WD mode from an average of around 30 days per winter in the 1960s to 50 days currently. The CW and WW modes are less frequent than the dry ones, but exhibit a decrease and an increase since the 1950s, respectively. Thus there is clearly a long-term change in the frequency of occurrence of each of these four modes, as already discussed by Beniston (2009), partly associated with the rise in mean winter temperatures that the Alpine region has experienced over many decades.

The controls exerted by the WD mode on snow amount and duration help to explain much of the change towards reduced snow amount and duration today than was the case 40 or 50 years ago. The average of the number of WD days in the 1961–1990 baseline period for the four sites considered is 40, with a standard deviation of 8 days. The five most snow-sparse winters are associated with the WD modes that exceed 55 days per winter (i.e. 2 standard deviations above the mean), whereas the five most snow-abundant winters occur when the number of WD days is below 30 (i.e. 1–2 standard deviations below the mean). Snow duration in Andermatt, e.g. ranges from 99 days for the 2006–2007 winter (November–April) with 81 WD days, to 180 days for the same 6 months during the 1974–1975 winter, which experienced only 25 WD days. Average snow depth between these two extremes ranges from 28 to 150 cm. The situation is even more extreme in Château d'Oex, at an elevation of less than 1000 m above sea level: there were only 14 days of snow on the ground during the 2006–2007 winter, averaging 3 cm for the season, but 121 days and 36 cm average snow depth for the snowiest winter in 1969–1970. It is thus interesting to note that even under today's warmer climate, snowy winters can still make a remarkable return when the number of WD days is low, as exemplified by the winters of 1998–1999, with 29 WD days (one of the record-breaking winters in terms of snow amount in the

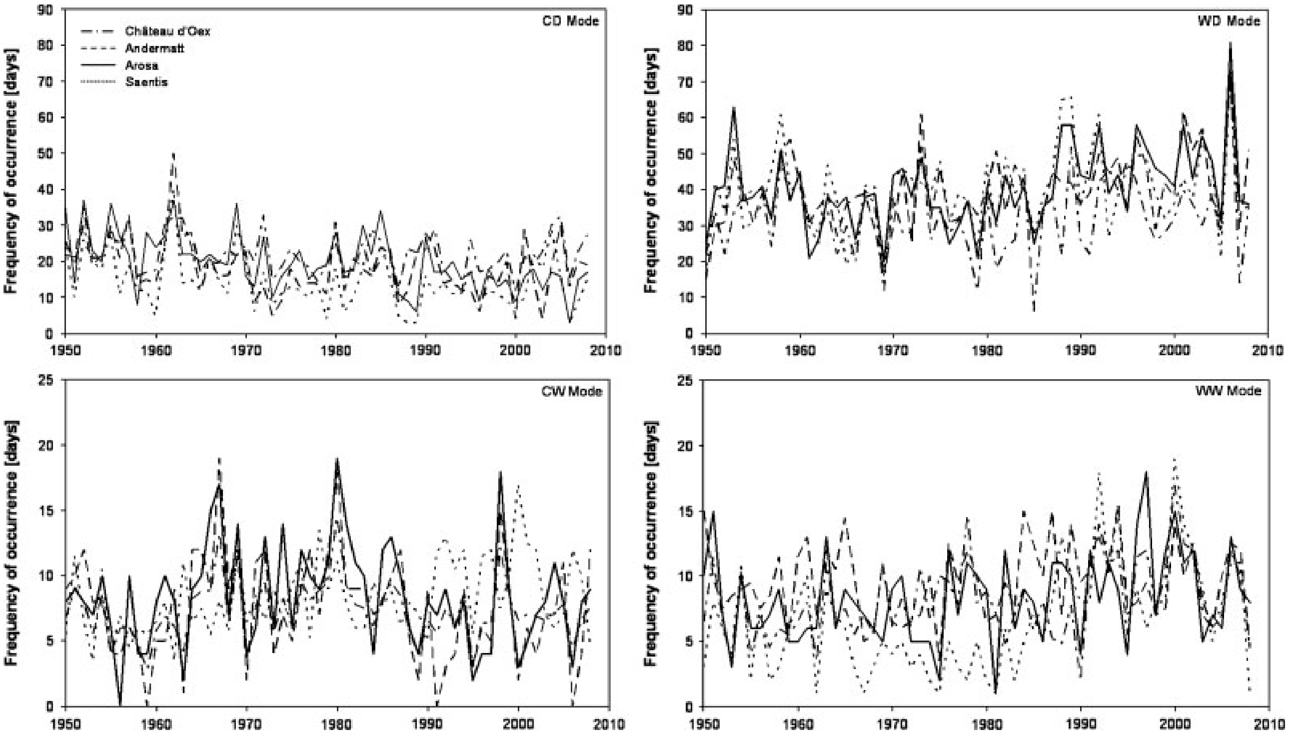

Figure 1. Changes the CD (upper left), WD (upper right), CW (lower left) and WW (lower right) temperature-precipitation modes at the four sites studied in this paper.

Swiss Alps, with numerous adverse side-effects ranging from high costs for road maintenance to devastating avalanches in some valleys), or 2008–2009 with 31 WD days, although winter temperatures are 1–1.5 °C higher today than they were in the 1950s (Beniston, 2004).

Closer scrutiny of the data suggests that temperature exerts a strong influence on the frequency of occurrence of the 'dry' modes (roughly 40% for the CD mode and 60% for the WD mode, based on the ratio of cold/warm days with respect to cold/dry and warm/dry days, respectively), whereas for the 'wet' modes, the temperature influence is much smaller (about 15–20%).

Table II. Comparisons between the four CD, CW, WD and WW modes observed for the 30-year control period 1961–1990 and simulated by the HIRHAM RCM.

	CD	CW	WD	WW
Observed mean	20.9	9.1	36.3	7.6
Simulated mean	22.4	9.8	34.2	12.8
Observed SD	7.6	4.1	9.7	2.5
Simulated SD	7.4	6.2	9.4	3.0

Values are given as 30-year mean values, averaged for the four locations used in the study.

3.2. RCM ability to reproduce the four temperature–precipitation modes

Prior to investigating whether, on the basis of the temperature–precipitation modes as a proxy for snow duration and snow amount, snowy winters may occur in a much warmer climate in the future, it is necessary to see whether the HIRHAM RCM is capable of adequately reproducing the four modes in the 1961–1990 baseline climate. Table II provides an overview of the four modes, averaged over all sites and for the reference 30 years from 1961 to 1990, and computed using the HIRHAM RCM for the model grid-points closest to the observation sites. The results are comparable, even if the RCM tends to overestimate the WW days; the number of CW days simulated by the model is in close agreement with observed number of CW days. This is certainly linked to the difficulties inherent in RCMs in simulating particularly precipitation over complex terrain, partly because topography is rather poorly resolved. The table also provides the observed and modelled standard deviations of the four modes; the observed and simulated data are fairly consistent on dry days, but the simulated values are too high on wet days. On the whole, therefore, the model results are reasonably good for dry days, but the number of WW is overestimated and the variability of CW days is too high. However, despite these discrepancies, the model can be applied with a reasonable degree of confidence to investigations of changes in these four modes in a scenario climate.

3.3. Snowy winters in a scenario climate

Table III illustrates the average shifts in the four temperature–precipitation modes (percentages with respect to the total frequency of occurrence), averaged as previously for the four sites considered in the study, between the control and the future greenhouse climates.

Table III. Comparisons between the four temperature–precipitation modes simulated by the RCM for the control (1961–1990) and the scenario (2071–2100) climates.

	CD	CW	WD	WW
1961–1990	26 (28.9%)	11 (12.2%)	38 (42.5%)	15 (16.7%)
2071–2100	6 (6.7%)	6 (6.7%)	55 (61.1%)	24 (26.7%)

Values are given both in total number of days and, in parentheses, as percentages of the overall occurrences, averaged for the four locations used in the study.

As could be intuitively expected, the frequency of the cold modes is substantially reduced for the future climate in 2071–2100; CD days diminish from about 26 days per winter in the control climate to 6 days in the scenario climate, whereas CW days are reduced by almost half, from 11 to 6 days. In sharp contrast, the warm modes increase significantly, by 50% in the case of the WD and WW modes, from about 38 to 55 days and 15 to 24 days per winter, respectively. The change in WD mode and the quasi-disappearance of the cold modes in the scenario climate will certainly weigh heavily on Alpine snow amount and duration in the last 30 years of this century, but will there still be room for an occasional snow-abundant winter?

It was discussed above that snow-abundant winters are today associated with a low number of WD days, less than about 30–35 days per winter (or at least 1 standard deviation below the mean number of WD days). Exploration of individual winters in the 30-year set simulated by the RCM shows only one winter exhibiting less than 30 WD days and two winters with less than 40 days; in comparison, the control climate shows 8 winters with less than 30 WD days and 21 winters with less than 40 WD days. These statistics incorporate the model-simulated seasonal shifts in precipitation regimes that are likely to increase quite substantially in winter in the Swiss Alps, as reported in a number of studies including those of the EU PRUDENCE project. It is assumed in this study that the statistical relationships between the four modes and the characteristics of the snow pack will not change in the future. This assumption is justified by the fact that in the baseline climate, certain winters have already exhibited conditions similar to those that are expected to occur more frequently in the future. These situations that are characteristic of warm winters have been well described by the correlations between a particular mode and the duration and thickness of the snow pack, and there is thus no reason to believe that this will change substantially in the future.

Figure 2 illustrates the change in the range of snow duration and mean snow depth that can be expected for 2071–2100 for the four Alpine stations, using the information inferred from current climate where similar numbers of WD days occur. The grey-shaded zone delimited by thin lines represents the ranges observed for the control climate, whereas the area within the dotted lines represents the range simulated for the end of the 21st century. In both cases, maximum snow duration is equal to the 180 days of the November–April winter half-year, but obviously at high elevations, snow can last on the ground for much longer than 6 months. The changes between control and enhanced greenhouse climates are quite marked, particularly below 2000 m altitude, where winters without snow are projected to occur (e.g. 9 winters out of 30 at Château d'Oex and 2 winters at Arosa). The dashed curves in both graphs show the threshold beyond which a winter in the control climate can be considered as snow abundant, as defined earlier in the text. Similar snow abundance for the scenario climate is seen to occur whenever the dashed line enters the area within the dotted lines, with snow abundance occurring to the right of the dashed curve. Such winters can thus still occur at medium to high elevations in the future,

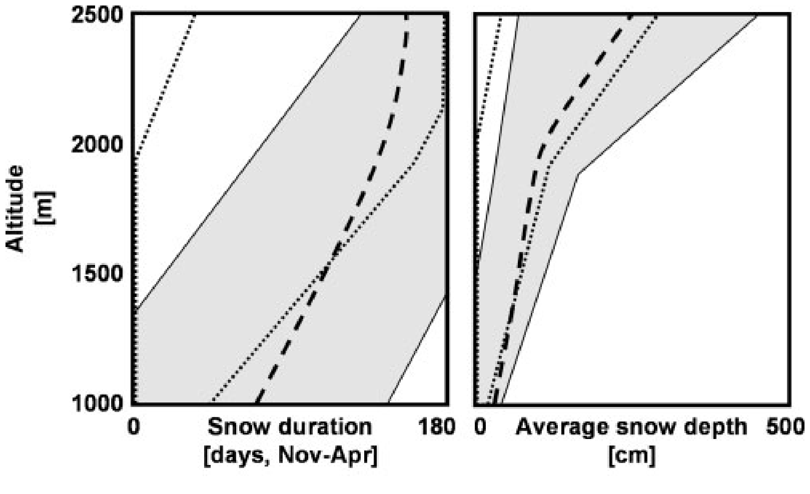

Figure 2. Range of snow duration (left) and mean snow thickness (right) in the control climate (shaded zone within thin lines) and scenario climate (zone within dotted lines), inferred from the behaviour of the WD mode. The dashed curve gives the threshold for snow-abundant winters in the control climate as a function of 1 standard deviation above the mean snow duration and mean snow depth.

and even at low elevations under specific conditions of topography. The results discussed in this study are reasonably consistent with other studies using more detailed approaches to estimate future snow conditions in the Alps (Abegg and Froesch, 1994; Uhlmann *et al.*, 2009).

The conditions for snow-abundant winters thus almost disappear in the future, but 1–2 of the 30 winters may still see significant amounts of snow, mainly at elevations above 1500 m where precipitation will continue to fall in the solid phase, as opposed to predominantly in the liquid phase beneath this level. By 2100, many winters will probably be at least as mild and snow sparse as the record 2006–2007 winter, but the occasional snow-abundant winter may be somewhat similar to the 2008–2009 winter. The response of environmental systems to rare snow-abundant events may, however, be different in the future compared with that of today, because many systems may have adapted at least partially to a warmer climate and may thus be less well geared to coping with a long and snowy winter season and the high runoff conditions that could occur in the spring.

4. Conclusions

This study has shown that the behaviour of snow in the Alps is very sensitive to one of four temperature–precipitation modes, computed on the basis of joint exceedances of the lower and upper quartiles of these two variables. These four modes are closely related to synoptic weather patterns that can be either favourable or detrimental to snow in the mountains; as a result, the mode most closely correlated to snow amount and duration (WD) can be used as a proxy for these parameters in climate models that do not adequately simulate snow.

The study has shown that since the 1950s, there have been significant changes in the four modes, reflecting shifts in the frequency of occurrence of the underlying weather patterns. Although the WD episodes have almost doubled during winters over the past half-century, some exceptions where the WD mode is low and snow-abundant winters have occurred in recent years still remain, despite the overall warmer climate that the Alps currently experiences compared with that several decades ago.

A comparison of the four modes observed for the control period 1961–1990 and modelled by the HIRHAM RCM in the context of the EU PRUDENCE project has shown that the results compare sufficiently favourably for the RCM simulations to be applied to an enhanced greenhouse climate. The model shows that snow-abundant winters as experienced even in recent years of this century may occur less than 5% of the time in the latter 30 years of this century, but they will not totally disappear even in a much warmer climate. Although they will be rare events, it may be necessary to consider appropriate measures to adapt to the consequences of such winters, whose impacts on hydrology or vegetation may be different to today because the environment itself may have changed to the extent that it would no longer be geared towards unusual abundant snow events.

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