Is snow in the Alps receding or disappearing?

BENISTON, Martin

Abstract

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BENISTON, Martin. Is snow in the Alps receding or disappearing? *Wiley interdisciplinary reviews. Climate change*, 2012, vol. 3, no. 4, p. 349–358

DOI : 10.1002/wcc.179

Focus Article

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How to cite this article:
WIREs Clim Change 2012. doi: 10.1002/wcc.179

INTRODUCTION

Snow is an important element of the natural environment in many mid- to high-latitude mountain regions around the globe, such as the European Alps, and its presence or absence can have a range of consequences for many socio-economic sectors.[1] Snow is probably the biggest single contributor to seasonal runoff[2] in hydrological basins like the Rhine or the Rhone rivers when the snow-pack releases water during the spring and summer melt. Its presence at high elevations up to the middle or the end of the summer ensures, along with seasonal glacier melt, a sustained discharge in most mountain rivers even during prolonged dry spells.[3] As a result, the Alps have often been referred to as 'the water tower of Europe'[4] because of the key contribution of alpine rivers to populated lowland water resources in France, Germany, northern Italy, and Central and Eastern Europe. In terms of ecosystem functioning, snow is a major determinant for many alpine plant species since the timing of snow-melt often signals to dormant plants the beginning of the annual vegetation cycle.[5] Plant survival largely depends on the duration of the snow season, because the protective cover of snow that insulates plants from extreme mid-winter cold conditions.[6] In economic terms, snow is an important resource for winter tourism, and in many mountain resorts income from the ski sector far outweighs other tourist activities.[7] Through its major role in the hydrological cycle, the presence of snow and ice in high mountains has a direct bearing on the energy sector, since hydropower infrastructure is ultimately dependent on the timing and amount of runoff during the period of snow-melt. This is important in countries like Austria or Switzerland that depend for more than 60% on hydropower for electricity generation.[8]

Because snow is central to so many different environmental and economic sectors, an assessment of past and future snow patterns can help assess how these sectors are capable of adapting to shifts in the quantity and seasonality of the mountain snow-pack. This article will begin by a short inventory of the changes in the determining factors for snow, namely temperature and precipitation, and how the evolution of these factors has influenced alpine snow cover. Following this first appraisal, more subtle mechanisms

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than just warming temperatures or changes in winter precipitation will be explored, such as the impact of changing weather types and modes of decadal-scale variability, in particular the North Atlantic Oscillation. Finally, this article will address issues related to the future behavior of snow in a warming climate, to assess whether recent changes in alpine snow may be a forerunner of future winters in the course of the 21st century.

CHANGES IN THE ALPINE SNOW-PACK IN THE COURSE OF THE 20TH CENTURY

Available Data

Most of the national weather services within the European Alps have archives of basic meteorological data that include snow parameters. For example, MeteoSwiss (the Swiss weather service) climate archive contains daily data in digital form spanning most of the 20th century for over 100 locations.[9] Snow data is archived in the form of depth and new accumulation over a 24-h period; hence seasonal statistics of snow accumulation in relation to other parameters such as temperature, precipitation, or pressure can be compiled with relative ease. Unfortunately, the coverage of regular recording stations becomes sparse as one enters regions of complex topography, so that the number of high-elevation stations or those in remote parts of the Alps is low compared to lowland regions, for reasons of access, maintenance, and cost. For the climate observing network of MeteoSwiss (the National Basic Climate Network—NBCN), 40% of the recording stations are located below 1000 m above sea-level, 45% between 1000 and 2000 m, 10% between 2000 and 3000 m (i.e., three stations), and just one station is found above 3000 m. The representativeness of stations is nevertheless reasonably well respected in terms of station coverage as a function of surface area for each altitude class. The quality of snow data, compared to more standard variables such as temperature and pressure may, however, be open to question, since the depth of the snow cover depends upon many complex factors, such as wind, radiation, infiltration of melt-water, or the difficulty of verifying the quality of an automatic measurement at a remote location on a regular basis. Despite these drawbacks, the available snow data is generally of sufficient quality to be of use to assess some broad, long-term trends and the manner in which these are influenced by weather and climate.

While much of the information used in the sections to follow is based on Swiss climate data, because of its high spatial and temporal density and its recognized quality, the conclusions reached here are in general valid for many other parts of the Alps, from the Savoie region in the northern French Alps, across the northern Italian Alps, into southern Germany and Austria.

In terms of regional climate model (RCM) simulations, use will be made in this paper of model results compiled in the context of two major European projects, 'PRUDENCE'[10] and 'ENSEMBLES'.[11] In these projects, a suite of state-of-the-art climate models were used to simulate 'current' climate (i.e., for the reference 1961–1990 period) and scenario climates over Europe based on a limited number of carbon emission pathways. The procedures to generate model-simulated data involves using global climate model (GCM) to provide the initial and boundary conditions for the RCMs, that operate at a much finer time and space resolution, but restricted to the European scale.[12] According to the regional climate model, snow characteristics are either directly simulated and available as gridded output data, or can be inferred from temperature, radiation and precipitation data using dedicated models that simulate the fine-scale behavior of snow accumulation or snow melt (as, e.g., the French SAFRAN/CROCUS model,[13] now used operationally for forecasting).

Observed Changes in Winter Temperature and Precipitation, and Consequences for Snow

Because temperature and precipitation are the principal weather determinants for snow, a brief overview is given here of the behavior of these key parameters in the Swiss Alps in the time-frame ranging from 1931 to 2010. The map in Figure 1 shows the location and altitude of the climatological stations used in the analyses conducted in the framework of this article. The locations for which temperature and temperature data is discussed in this article have not undergone any significant changes capable of biasing the results and trend estimates.[9]

Figure 2(a) shows the winter-time mean temperature anomalies for seven selected sites, computed by taking the average of daily data over the months of December, January, and February (DJF), and subtracting the 30-year mean value of the 1961–1990 reference period. These include here the north-eastern Swiss Plateau (Zurich, 556 m above sea level), the western Prealpine region (Château d'Oex, 985 m), the central Alpine Forelands (Engelberg, 1035 m), the eastern Swiss Alps (Davos, 1590 m), and high elevation mountain sites (Saentis, 2505 m, and Jungfraujoch,

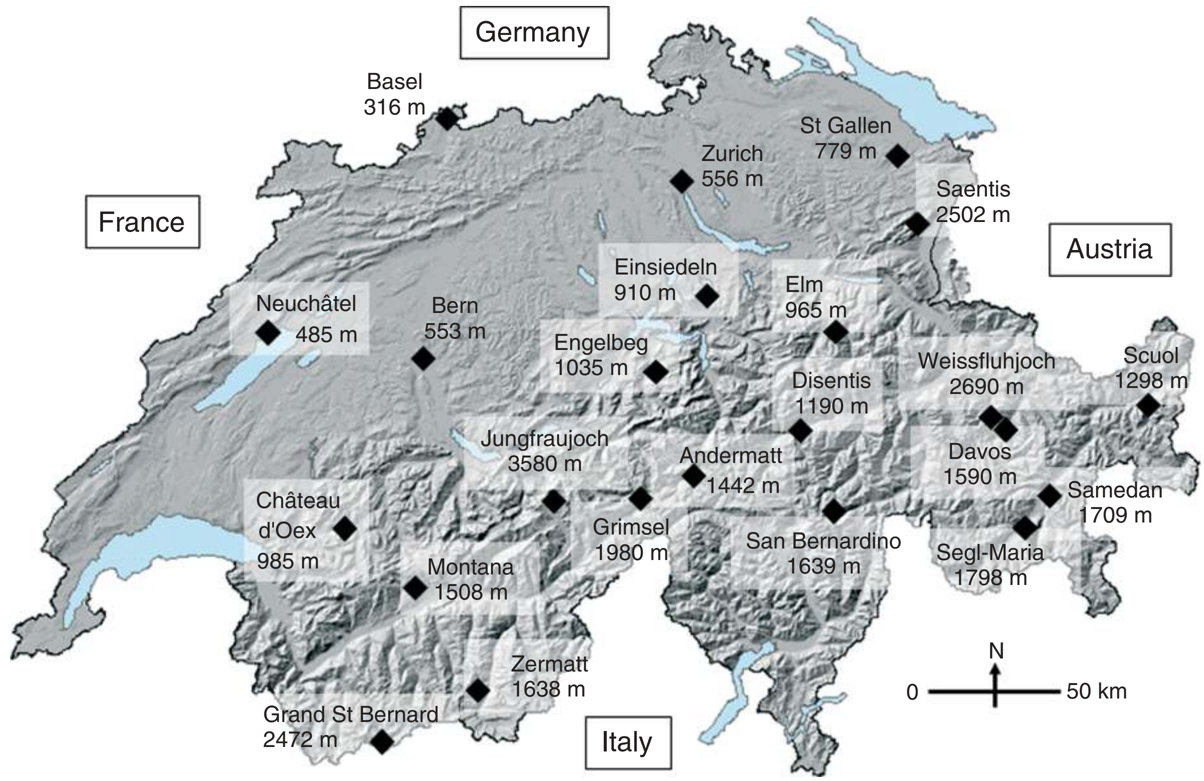

FIGURE 1 | Map of Switzerland showing the climate observation sites used in this article.

3580 m). Whatever their location, the temperature trends are remarkably in phase despite differences in altitude and geographic location (i.e., between the drier or wetter regions of the Swiss Alps), a feature observed for an additional 12 NBCN sites not shown here. Particularly conspicuous are the cold winter of 1962/1963 and the warm winters in 1989/1990 and 2006/2007. Decadal scale wintertime mean temperature trends for the 1931–2010 period range from 0.14 °C per decade in Zurich to 0.40 °C per decade at the Jungfraujoch, with no clear difference between trends at low/medium and those at high elevations. For example, trends at Château d'Oex are almost as large as at Säntis and larger than at Davos. Overall, temperatures in the Alpine region exhibit are far greater rates of change than the global average temperature increase,[14] a feature that has been observed in other mid-latitude mountain regions.[1] Reductions in snow cover and duration, that contribute to positive feedback effects between the surface and the atmosphere, may partly explain these observations. Use of the nonparametric Mann–Kendall statistical test to assess whether trends in time series are statistically significant shows that all temperature trends illustrated here are highly significant beyond the 99.9% confidence level. Figure 2(b) illustrates the changes in winter precipitation anomalies for the same locations as above (except for the Jungfraujoch, where precipitation measurements are absent in view of its extreme location). As for temperature, the precipitation records are well in-phase with each other, despite widely varying differences in site characteristics between stations. In general, precipitation increases with height, but there is also a decreasing precipitation gradient from north–south and west–east. Despite the large variability in the precipitation records, there is an overall decline over the 1931–2010 period of 15–25% in winter-time precipitation amount according to location except for the high-elevation Saentis site which exhibits an increasing trend of the 80-year record, although the last decade has seen a decline as for the other sites. At Engelberg, for example, precipitation has ranged from 234 mm/season (the decade beginning in the winter 2000/2001) to 320 mm/season (decade of the 1960s), a difference of almost 30%). Precipitation in the latter part of the record is comparable to that experienced in the 1970s, where a succession of drier-than-average winters was observed. These decadal-scale fluctuations are likely linked to long-term shifts in synoptic weather patterns between the North Atlantic, the Mediterranean, and continental

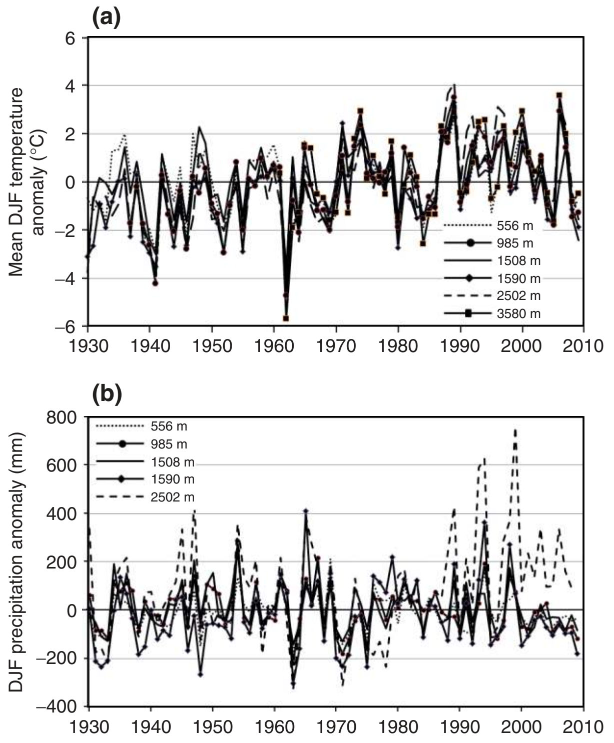

FIGURE 2 | (a) Evolution of mean winter (December–January–February, or DJF) temperature anomalies (based on the baseline period 1961–1990) from the winter 1930/1931 to the winter 2009/2010 (80-years) for six representative sites ranging from 550 to 3580 m above sea level (Zurich, 556 m; Château d'Oex, 985 m; Montana, 1505 m; Davos, 1590 m; Saentis, 2502 m; Junfraujoch, 3580 m). (b) As for (a), except for total winter precipitation (without the Jungraujoch site).

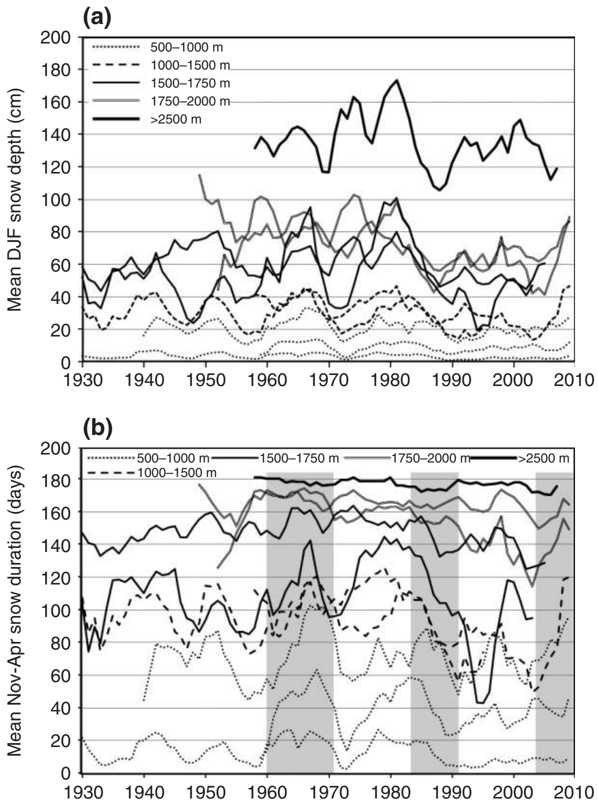

FIGURE 3 | (a) Mean winter snow thickness for the winter months December. January–February–April for 10 representative stations ranging from 500 to 2700 m above sea-level (Zurich, 556 m; St Gallen, 779 m; Château d'Oex, 985 m; Engelberg, 1035 m; Scuol, 1298 m; Montana, 1508 m; Davos, 1590 m; Segl-Maria, 1798 m; Arosa, 1840 m; Weissfluhjoch, 2690 m). Values have been smoothed with a 5-year running mean to remove the high noisiness of interannual snow variability. (b) As for (a), except for mean snow duration beyond a 10-cm depth threshold for the 6-month period November–April.

Europe. Unlike temperature, there are no significant precipitation trends, whatever the altitude considered.

The change in the behavior of the alpine snow-pack is provided in Figure 3(a) and (b) (changes in mean snow depth and duration of continuous snow cover), for 10 sites located at different altitudes ranging from 556 m in Zurich to 2690 m at Weissflujoch. For the purposes of clarity, a 5-year filter has been applied to the data to remove the high interannual variability of alpine snow cover and highlight possible long-term trends. There is an obvious altitudinal dependency of snow depth on altitude, but regional characteristics also modulate the snow-pack, such as the south-facing station of Montana in Valais or Segl-Maria in the Engadine (not shown in this graph), both located in a conspicuously dry part of the country. The figure shows that there are decadal-scale fluctuations in snow depth, with varying amplitude according to location. These fluctuations are reasonably in phase, whatever the location, such as the relative peaks in the mid-1960s and late 1970s and the trough in the early 1970s. All sites exhibit a decline in the average winter snow-depth that range from about 10% in Château d'Oex to over 50% in Zurich. The moister northern part of the Alps has experienced a lower decline (10–25%) than the drier parts of the country, such as the Engadine in south-eastern Switzerland, with reductions in snow depth of about 35% despite the higher elevation.

In Figure 3(b), the duration of the snow season (defined here as the number of days where snow exceeds a 10-cm thickness threshold) shows that there is a general shortening of the season at all levels, with declines stronger in the drier parts of the country (e.g., in the Engadine, not shown in this graph with about 15% less days over the period of record) and at low elevations (e.g., in Zurich where the average duration has been reduced by 50%). In most other locations, the general decline is between 5 and 15%, although there are marked decadal-scale changes, such as the increases in the 1960s (shaded column to the left), or the recent increases in snowy winters toward the end of the record (shaded column to the right). For example, in the south-facing station of Montana, the average decadal snow duration ranges from 79 in the 1990s to 126 in the 1980s, and snow amounts since 2000 are roughly the same as in the 1930s. In the more precipitation-prone location of Engelberg, the 1990s saw on average 65 days of snow per winter compared to 105 in the 1960s, a figure that is close to observed in the latest decade.

A decline is visible in the late 1980s (shaded column at the center of the figure), a feature that has been referred to as a regime shift by Marty,[15] who suggests that for many locations in Switzerland, there is a clear step-like decrease in the number of days with snow on the ground and unclear trends thereafter. In the last years of the record, an increase is observed as a result of the snow-abundant winter of 2008–2009 and the snowier-than-average winter that followed.

The noisiness of the snow record on annual-to-decadal time scales makes it difficult to assess visually whether an underlying trend exists. Applying the Mann–Kendall test to the trends over the period of observation shows that snow-depth and duration trends are not significant beyond the 95% confidence level at low to intermediate levels, and exhibit no significance at elevations beyond 2,000 m where atmospheric warming has not yet begun to disrupt the behavior of the mountain snow-pack.

Causes of Observed Change in the Behavior of the Alpine Snow-Pack

Temperature and Precipitation Trends

The most obvious explanation for the observed changes is to be found in the strong rise in mean, minimum and maximum temperatures recorded over the past century at all elevations. Temperature has a more important impact on snow below altitudes around 1500–2000 m than above, since even with the higher temperatures observed in recent years at high elevations, they nevertheless remain below the freezing point for much of the season and thus snow can accumulate and remain on the ground for extended periods of time. Any changes in snow behavior at high altitudes are thus for the moment a function of changes in precipitation. As seen in Figure 2(b), there have been varying amounts of precipitation over the 80-year period under consideration, with obvious impacts on total seasonal accumulation illustrated in Figure 3(a). At lower elevations, however, increases in precipitation have not always managed to compensate for increases in temperature, because in many instances precipitation falls in the form of rain and thus tends to undermine a pre-existing snow-pack, as seen for Château d'Oex in Figure 3. Although precipitation remains roughly the same for the 1940-1970 and the 1980–2010 periods, snow abundance is seen to decrease by 35% as a result of temperatures that are on average 1.8 °C higher for minimum temperatures and 1.2 °C higher for maximum temperatures. Table 1 summarizes the climatic influence on snow duration for three alpine sites, in the form of the change in the average number of days as a function of 1 °C shifts in minimum and maximum temperatures, 100 mm changes in precipitation, and 10 Pa changes in pressure. Each additional degree rise in temperature reduces the duration of snow on the ground by up to 12 days according to altitude and local site characteristics of the weather station (slope, exposure, etc.), whereas increases in precipitation by 100-mm increments contribute to increases in snow duration that is clearly altitude-dependent, with higher altitudes extending their snow season when precipitation is greater. High pressure periods, on the contrary, have a bearing on snow duration, through the associated reduction in precipitation that they imply. Lower elevations are much more sensitive to high pressure than higher altitudes, since the presence of high pressure can prevent the snow season from beginning or contribute to the melting of a thin layer of snow, whereas at higher levels, a period of persistent high pressure that intervenes once snow is already on the ground will not significantly change the duration of the snow season.

TABLE 1 | Average Changes in Snow Duration at Various Altitudes When using Winter Minimum or Maximum Temperatures, Precipitation or Pressure as Predictors for Snow Duration

	$T_{\min}$ Days/°C	$T_{\max}$ Days/°C	Precip Days/ 100 mm	Pressure Days/10 Pa
Davos (1590 m)	−9	−12	8	−8
Ch. d'Oex (980 m)	−6	−8	4	−16
Zurich (567 m)	−8	−7	2.5	−22

In Figure 3(b), the stations located below the 1500–2000 m level (i.e., all but the four uppermost curves) reflect the dominant control of temperature over precipitation in determining the amount of snow that ultimately accumulates on the ground, particularly in the 20-year period between the early 1980s and late 1990s. The temperature influence is greatest at the lower elevations where the number of freezing days is the lowest. Transitions from snow to liquid precipitation at increasingly higher elevations, under increased winter temperatures, may be one explanatory factor for these trends.

Influence of Weather Types

It is possible to quantify the characteristics of winters not just in terms of the changes in temperature or precipitation taken separately, but in terms of the behavior of joint quantile distributions, as shown in earlier studies.[16] Particular combinations of temperature and precipitation have been shown to be closely related to the underlying atmospheric circulation patterns that are responsible for either snow-abundant or snow-sparse winters in the Alps.[17] This is because cold winters are not always associated with abundant snow, and dry winters can still have snow if prior to a dry spell snow has accumulated in sufficient quantities.

In order to define joint temperature/precipitation quantiles, use is made of the quantile thresholds defined in 2009 by Beniston,[18] where the frequency of days when temperature and precipitation are simultaneously above or below the 25% and 75% quantiles have been counted. Hence Cold/Dry conditions prevail when the joint quantiles are equal to or below $T_{25}p_{25}$, (the subscript refers to the threshold for each variable), Cold/Wet ($T_{25}p_{75}$), Warm/Dry ($T_{75}p_{25}$), and Warm/Wet ($T_{75}p_{75}$). Daily mean temperature and precipitation statistics for the winter half year, that is, from early October to end April, for the reference period 1961–1990 have been used to define the reference quantile thresholds.

Figure 4 illustrates the rather significant mode changes that have been observed at the Zurich site, by comparing the average number of days per winter for each decade since the 1930s. The most conspicuous change is that of the Warm/Dry mode that doubled in persistence between the 1960s and the 1990s and still remains a dominant mode even if it has declined since 2000. Less marked but just as important in its relative change is the Warm/Wet mode that has also doubled between the early and most recent parts of the record. The Cold/Dry and Cold/Wet modes have declined by roughly 50%. In other words, the dominance of warm modes is clear today, in sharp contrast to the period prior to the 1970s when the frequencies of cold and warm modes, whether dry or moist, were roughly equivalent.

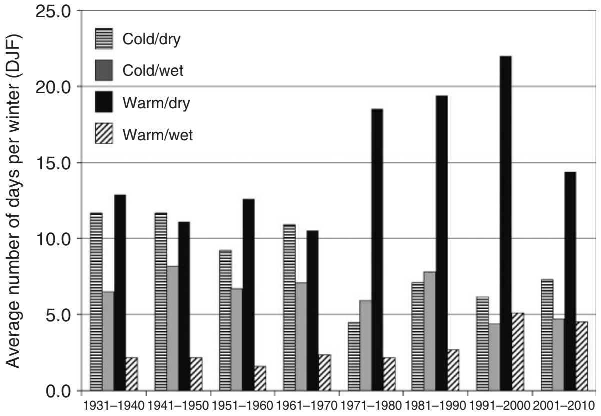

FIGURE 4 | Decadal changes in the four winter modes Cold/Dry, Cold/Wet, Warm/Dry, Warm/Wet for the Zurich measurement site.

Snow behavior is sensitive to these four modes. Clearly the transition toward a majority of warm modes implies that it is difficult for sustained snow cover to persist at low to medium elevations. At higher altitudes, the amount and duration of snow will be controlled by precipitation amounts, since whatever the mode, temperatures at height still remain below the freezing point for much of the season. In a recent study, Beniston and co-workers[17] showed that snow-abundant winters at most altitudes are not so much governed by, for example, the Cold/Wet mode, but by a reduced frequency of the Warm/Dry mode. If the number of winter days within this mode is 1 standard deviation or more below its average value for the 1961–1990 baseline, then the likelihood of having a snow-abundant winter is high; conversely, if the number of days is 1 standard deviation or more above the mean frequency, then the winter will be generally snow-sparse. Since the tendency for this weather type has increased substantially over the past 40 years, the number of snow-sparse winters has increased while snow-abundant winters have declined. Nevertheless, several winters since the 1990s have been endowed with much snow in the Alps, such as the 1998–1999 winter or the 2008–2009 season that were in some parts of the mountains record-breaking winters in terms of snow amount and duration, despite the overall context of a dominance of the Warm/Dry mode.

Influence of the North Atlantic Oscillation

The North Atlantic Oscillation (NAO) is widely recognized as one of the major decadal-scale modes of climate variability that influences features of winter weather from the eastern seaboard of North America to large portions of western and northern Europe.[19] The NAO is related to the relative intensities of two major centers of activity that influence the mid-latitude Atlantic, namely the Azores high pressure anticyclone and the Iceland low pressure zone. This pressure dipole determines the intensities and trajectories of storm tracks across the North Atlantic. The positive (or warm) mode of the NAO, is associated in general with drier and warmer than average conditions over southern Europe and the Mediterranean, and mild but wetter conditions in northern Europe,[20] whereas during the negative (or cold) phase of the NAO, the situation is reversed (hence the term 'oscillation'). The Alps are located in a pivotal region and often exhibit Mediterranean characteristics during positive NAO events and northern/continental European weather patterns during the negative phase. The behavior of the mountain snow-pack can thus be expected to be fairly sensitive to that of the NAO, in particular the wintertime (DJF) value of the index that will be used hereafter.

Numerous studies have investigated the links between the NAO and alpine climate characteristics.[20–22] One of the most significant findings is that a strongly-positive phase of the NAO is related to a strong persistence of high pressure fields over the Alps,[20] that in turn negatively affect precipitation since atmospheric perturbations are routed either far to the north of the Alps or well south in the Mediterranean region. In addition, strong correlations have been established between anomalously warm winter temperatures at most elevations during periods with a strongly positive NAO index. Other synoptic patterns have also been explored[21]; this particular study suggests that 50% of the variability of snow-pack behavior is related to the establishment of blocking patterns over Europe, and that the direct influence of the NAO on snow pattern is less obvious. It is indeed through a 'cascade' of consequences (NAO mode on pressure fields; pressure fields on precipitation; and precipitation/temperature thresholds on snow) that the NAO influence can be detected. For a study undertaken for the entire French alpine chain, Durand et al.[22] have not been able to detect a significant influence of the NAO on snow-pack behavior. It is worth noting, however, that the left-hand and right-hand shaded areas in Figure 3(b) correspond to periods of lower-than-average NAO index values, and more extended snow duration, while the central shaded area with the declines in snow duration correspond to some of the strongest positive modes of the NAO in the second half of the 20th century.

ALPINE SNOW COVER IN A 'GREENHOUSE CLIMATE': POSSIBLE TRENDS UP TILL 2100

Many studies have focused on possible trends of mountain snow-packs[23–26] because there is an interest by various sectors (e.g., ski operators or the hydropower companies) to know how this economically-important resource may change in the future. The Intergovernmental Panel on Climate Change (IPCC) has also explored these issues from both the physical perspective and that of the environmental and socioeconomic impacts of changing snow cover.[27]

Most studies have focused on the end of the 21st century, as this is the period that has received most attention in the climate-modeling community, because by 2100 the anthropogenic climate signal is likely to be stronger than at any other time during the 21st century. This may not necessarily be the most useful time horizon for policy making and for formulating adaptation strategies, however, and an increasing number of studies and research projects are considering projections of change within the first half of the 21st century (e.g., the EU 'ACQWA' project[28] and its policy implications[29]).

Climate model projections *per se* are generally not sufficient to assess the future behavior of snow in complex topography. It is thus necessary to interface some form of downscaling technique that enables to 'translate' the grid-point values of climate parameters into an estimate of snow depth and duration at a very local scale. Statistical downscaling techniques[30] can be applied, but also physically based snow models[13,31] that use RCM-generated outputs as initial and boundary conditions for a snow and surface energy-balance model.

Whatever the technique used to generate estimates of snow depth/duration, all studies reach the same conclusion, namely that in a warming climate, snow will become increasingly rare below about 1500–2000 m altitude in the Alps (although this figure can vary according to the orientation and the location within the alpine domain, that experiences both north–south and east–west precipitation gradients). RCM projections for the alpine region[32] suggest a range of 3–5 °C increase in mean temperatures and an increase in seasonal precipitation by 5–20%. Using this information, Beniston et al.[33] focused upon the temperature-precipitation-snow depth relations and the changes in snow volume that these levels of climatic change would imply. Table 2 shows the

TABLE 2 | Estimates of Changes in Snow Volume in the Alps between the Baseline 1961–1990 Climate and a Scenario Climate Based on the IPCC 'A2' Greenhouse Emissions Pathways by 2100

Elevation m	Current Snow Volume 10^9 m^3	Future Snow Volume 10^9 m^3	Change in Volume Future-Current
500	6–8	0–0.5	98–100% loss
1000	15–20	0.2–1	95–98% loss
1500	28–35	8–12	65–70% loss
2000	40–50	20–28	50–60% loss
2500	30–38	18–22	40–45% loss
3000	8–10	8–10	<5% change
3500	2–3	2.5–3.5	15–20% gain
4000	0.8–1.2	1.0–1.4	15–20% gain

range of snow volume for the baseline 1961–1990 climate, which reflects both geographical site characteristics and the variability of winter temperature and precipitation. On the basis of the plausible range of temperature and precipitation using the IPCC high emissions 'A2' scenario,[34] it is seen that by the end of the 21st century, low to medium elevations (below 1500 m above sea-level) will experience between 70 and 100% loss of snow volume, while with increasing height the loss diminishes and even increases above 3000 m. The conclusions reached here require caution in their interpretation, because RCM-simulated snow cover does not always correspond to reality. Indeed, simulated snow cover is seen to be highly sensitive to physical parameterization schemes, model grid resolution, and the type of atmospheric forcing that is considered.[35] The results discussed here simply attempt to show the type of changes that could intervene by 2100, but should in no way be considered to be predictions of future snow behavior.

A recent study by Uhlmann et al.[26] has shown that for many ski domains in Switzerland, the conditions for economically-viable skiing (i.e., at least 80–100 days with snow exceeding the 30-cm threshold[7]) will no longer hold for numerous resorts. Table 3 highlights the changes in the number of days that exceed the 30-cm threshold for a number of representative sites in the Jura Mountains, and the western, central, and eastern Swiss Alps. Reductions in snow duration from 30 to 100% are projected, and are dependent on altitude and geographic location. The numbers provided in Table 3 suggest that many resorts will need to diversify rapidly their tourism offer in order to be less dependent on the ski industry for the essential part of their financial revenues. Although many communities have installed snow-making equipment in order to buffer the effects of certain adverse snow seasons, this will become increasingly obsolete as winter temperatures exceed the critical thresholds above which snow-making equipment cannot be used for snow-making.

TABLE 3 | Changes in Snow Duration for Various Swiss ski Resorts between the Baseline 1961–1990 Climate and a Scenario Climate Based on the IPCC 'A2' Greenhouse Emissions Pathways by 2100

Resort, Altitude and Region	Current Duration	Future Duration
Chaux-de-Fonds, 1000 m, Jura Mountains	30	0
Adelboden, 1350 m, west-central Alps	60	20
Engelberg, 1100 m, central Alps	120	30
Disentis, 1100 m, eastern Alps	90	30
Davos, 1600 m, eastern Alps	100	70
Zermatt, 1600 m, south-central Alps	75	40

CONCLUSION

This overview of the behavior of snow has focused essentially on the case of the European Alps and more particularly on Switzerland, as there is a wealth of relevant data and long records that enables detailed studies to be undertaken.

It has been shown that, over the past 80 years, snow has exhibited considerable interannual and interdecadal variability. As a general rule, the fact that winter temperatures have risen over the intervening period by 2 °C or more according to location implies that, particularly at elevations below 1000–1500 m, the long term trends in snow point to a general decline in both duration and total accumulation. This linear trend since the early part of the 20th century is to some extent masked by decadal-scale fluctuations where snow thickness and duration does actually increase for a number of years, as seen in the most recent part of the record.

The conclusions reached in this article confirm other recent findings undertaken in Switzerland and in neighboring alpine countries.[36–38] For example, Schöner et al.[40] have shown for one of the longest climate records in Austria that '*both maximum snow-depth and winter season precipitation show a clear decreasing trend for interannual variability,*' a conclusion also reached by Hantel et al.[41] for an extensive study of the European Alps in which winter temperature can be considered to be a close proxy for snow duration. Changes in the alpine freeze–thaw mechanisms during winter in particular in the Italian Alps have been studied[41] to assess how the impacts on snow affect soil leaching processes and their influence on living organisms. An extensive study in the French Alps[22] shows that for a half-century period, '*Snow patterns in the French Alps are characterized by a marked declining gradient from the northwestern foothills to the southeastern interior regions. This applies mainly to both depths and durations, which exhibit a maximal latitudinal variation at 1500 m of about 60 days, decreasing strongly with the altitude.*'

Under current climatic conditions, snow cannot be considered to be 'disappearing' but, certainly, it is beginning to recede at low elevations. According to climate model projections, however, it is likely that at elevations below perhaps 3000 m, snow will recede increasingly quickly. This is because the higher levels of precipitation projected by many RCMs for the Alps will not compensate for the strong rise in winter temperatures. As a consequence, snow may well have disappeared in the lowland and foothill regions around the alpine chains by the end of the 21st century, and will have significantly declined at medium levels. The possible increases in snow amount above 3000 m represent only a fraction of the total surface area and snow volume that the Alps have experienced up till now.

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