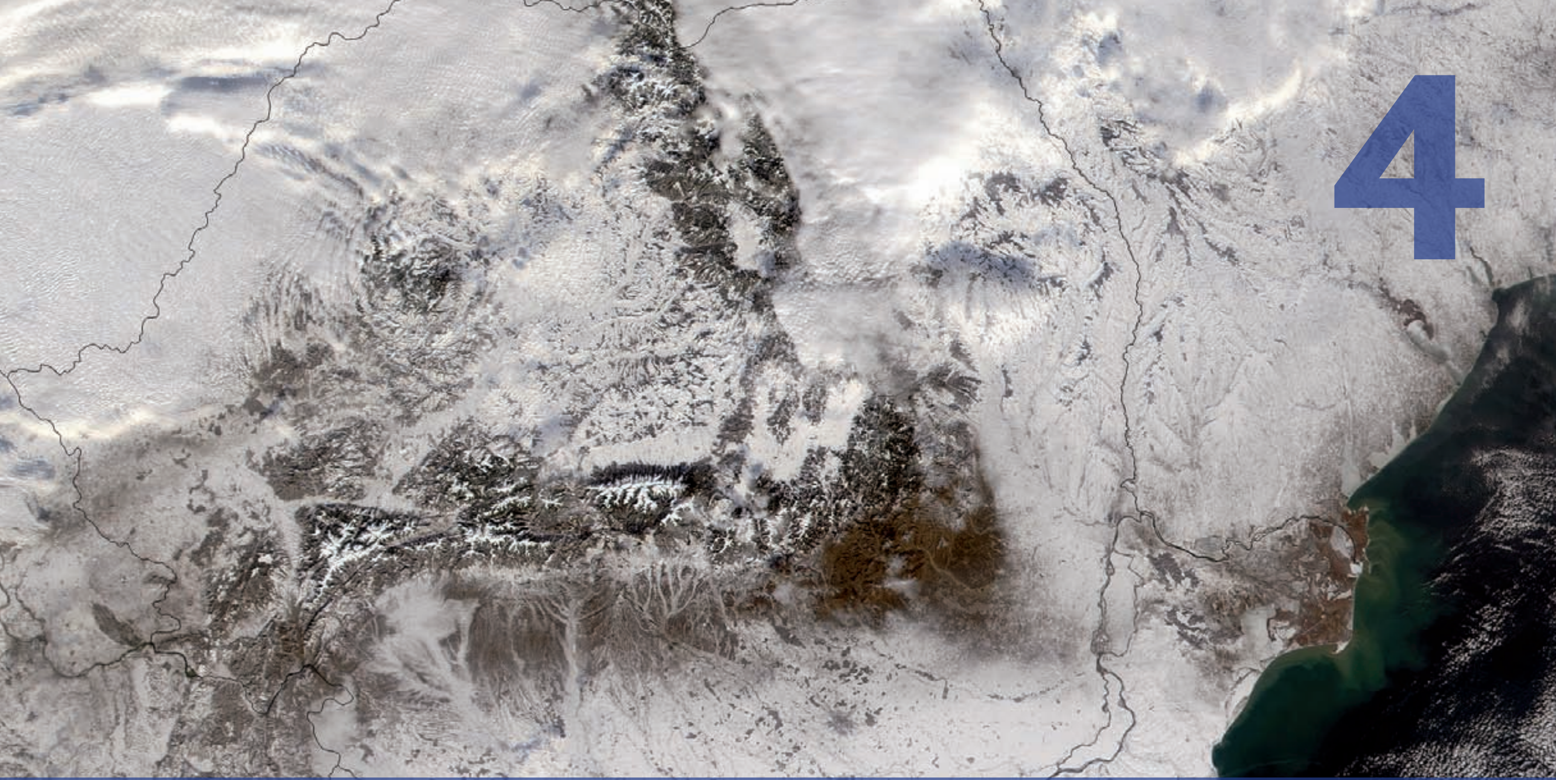

4

Snow

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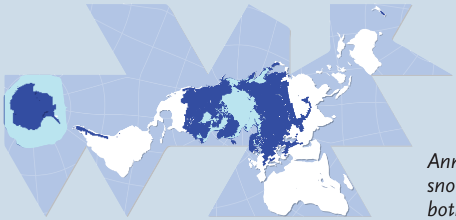
Snow

Summary

Snow exerts a huge influence on climate, through its high reflectivity, insulating properties, and cooling of the atmosphere, and on surface hydrology, through its effects on water resources in many parts of the world. Mean monthly snow-cover extent in the Northern Hemisphere has decreased at a rate of 1.3 per cent per decade during the last 40 years, with greatest losses in the spring and summer months. Climate models project significant decreases in snow cover by the end of this century, with reductions of 60 to 80 per cent in snow water equivalent (depth of water resulting from snow melt) in most mid-latitude regions. Increases are projected for the Canadian Arctic and Siberia. Higher temperatures and rises in snow line are projected for many mountain regions. Changes in snow cover, such as the formation of ice layers in snow due to increased frequency of snow thaw, have widespread impacts as snow is an important ecological factor. Snow-cover changes also have impacts on human well-being and economic activities, including water resources, agriculture, animal husbandry, transportation and winter recreation such as skiing.



Annual maximum snow-cover extent in both hemispheres

Snow: frozen precipitation in the form of ice crystals that fall in soft, white flakes.

Snow on land (Northern Hemisphere) (annual minimum ~ maximum):

Area Covered (million square km)	1.9 ~ 45.2
Potential Sea Level Rise (cm)	0.1 ~ 1

Source: IPCC 2007[1a]

Introduction to snow

Snow occurs predominantly on the northern continents, on the sea ice of the Arctic Ocean and on Antarctica. On the Northern Hemisphere continents, snow covers a maximum mean area of 45.2 million km^2, typically in January. The minimum snow-cover extent usually occurs in August and covers a mean area of 1.9 million km^2, most of which is snow on the Greenland ice sheet and on mountain glaciers. As a result, snow cover is the surface characteristic responsible for the largest annual and interannual differences in surface reflectivity (albedo) in the Northern Hemisphere (Figure 4.1). In the Southern Hemisphere, excluding the 14.5 million km^2 area of Antarctica, terrestrial snow covers a much smaller area, mostly in the Andes and Patagonia, and it plays a smaller role in global climate. Limited summer melt occurs in the Antarctic Peninsula and on the coasts of western Antarctica.

Snow is an important climate variable. Due to its high albedo, snow cover increases the amount of sunlight reflected from Earth's surface. The low thermal conductivity of snow insulates the ground, and its cold, moist surface affects the transfer of heat and moisture to and from the atmosphere. Thus, snow cover exerts a signifi-

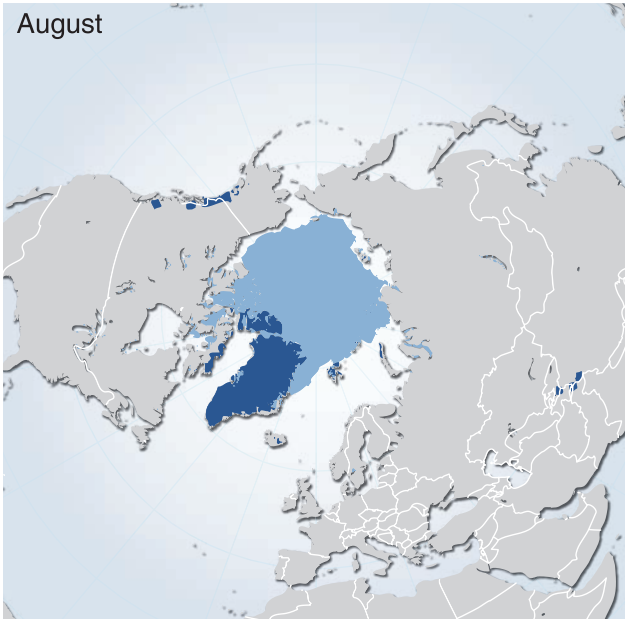


Figure 4.1: Mean snow-cover extent (dark blue) and sea-ice extent (light blue) in the Northern Hemisphere between 1966 and 2006, for February and August. The difference in snow cover between seasons causes significant differences in the surface reflectivity (albedo).

Source: Based on Armstrong and Brodzik 2005[1]

cant influence on climate and hydrology. Snow cover affects large-scale atmospheric circulation. Early season snow-cover anomalies in the Northern Hemisphere, for example, are known to lead to changes in atmospheric circulation. Autumn snow cover can also affect climate on a seasonal scale, with impacts extending into the subsequent winter. Snow cover is also a sensitive indicator of regional climate variability and change. Realistic simulation of snow cover in models and forecast schemes is essential for simulating surface energy balance and predicting winter water storage and year-round runoff.

Snow cover influences human activities directly and indirectly. Seasonal snow cover is the main source of runoff in many mountain regions, and over one billion people depend on it for their water supplies. Snow is a major factor in transportation, winter sports, agriculture and animal husbandry such as reindeer herding. It influences ecosystems and is important for conservation of biodiversity.

Trends and outlook for snow

Snow accumulation and melt are governed primarily by air and soil surface temperature, precipitation, wind and surface relief. Precipitation determines the overall amount of snow but air temperature determines whether the precipitation falls as rain or snow and governs the rate of snow melt. The recent rise in global temperatures, and the warming trends predicted for the future (see Chapter 3) thus affect global snow cover.

Data from satellite monitoring (see box on measuring snow cover extent) from 1966 to 2005 show that mean monthly snow-cover extent in the Northern Hemisphere is decreasing at a rate of 1.3 per cent per decade (Figure 4.2). For the calendar year of 2006 average snow-cover extent was 24.9 million km^2, which is 0.6 million km^2 less than the 37-year average[2]. In the Northern Hemisphere, spring and summer show the strongest decreases in snow-cover extent. Satellite observations of snow-cover extent show a decreasing trend in the Northern Hemisphere for every month except November and December, with the most significant decreasing trends during May to August[3]. The average Northern Hemisphere snow-cover extent for March and April decreased by 7.5 ± 3.5 per cent from 1922–2005[4] (Figure 4.3).

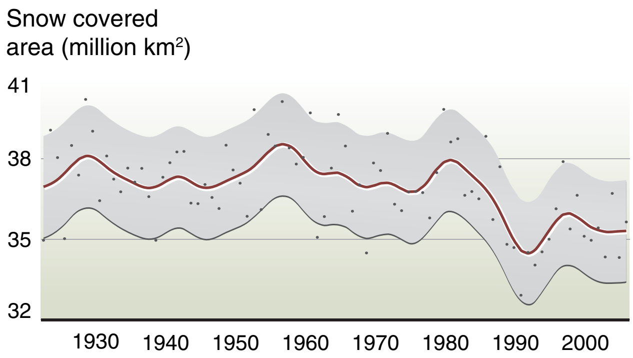


Figure 4.3: Northern Hemisphere snow-covered area (SCA) for the spring (March–April) from 1922–2005. The linear trend shows a decrease in SCA of 2.7 ± 1.5 × 106 km^2 or 7.5 ± 3.5 %. The shaded area represents the 5 to 95% range of the data.

Source: Based on IPCC 2007[4], updated from Brown 2000[5]

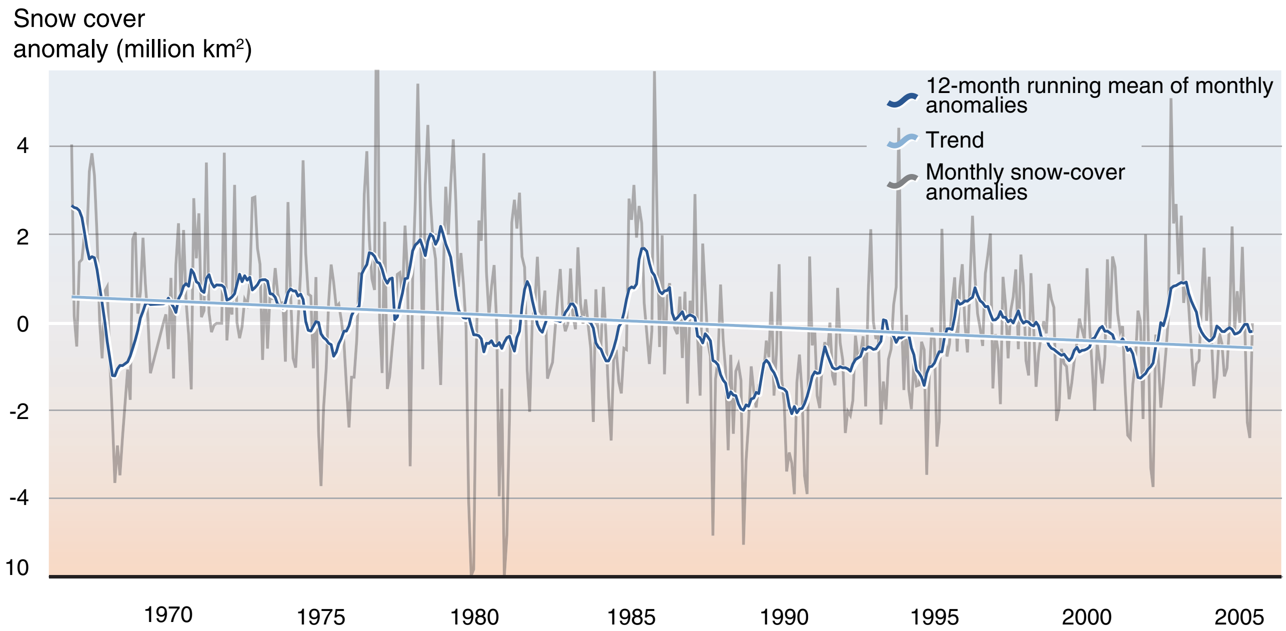


Figure 4.2: Northern Hemisphere snow-cover extent departures from monthly means from 1966 to 2005, with the 12-month running mean also shown. The decreasing trend of –1.3% per decade is significant at the 90% level.

Source: M.J. Brodzik; data from NOAA snow charts revised by D. Robinson, Rutgers University


Snow covered mountains in Alaska.
Photo: P. Slota/USGS National Wildlife Health Center (US)

Measuring snow-cover extent

Snow-cover fluctuations in the hemispheres are monitored by satellite. Since 1966 the National Oceanic and Atmospheric Administration (NOAA) has produced snow-extent charts on at least a weekly basis[6,7]. Until 1999 the charts were primarily derived from the manual interpretation of satellite images taken within the visible band of the electromagnetic spectrum. Passive microwave data, available since 1978, and other data are now included in the source data for the charts[8,9].

Satellite passive microwave sensors can detect the snow surface through clouds and in darkness but may not detect shallow snow that can be seen in visible band imagery. As a result, time series from microwave and visible data sources can differ. Data sets from both sources show a similar range for maximum Northern Hemisphere snow-cover extent that exceeds 40 million km^2 consistently[1,10,11]. NOAA data, derived primarily from visible band sensors, show a significant decreasing trend in mean monthly snow-cover extent (see text). Microwave data indicate a similar decreasing trend that is not significant at a 90% level. While NOAA data show decreasing trends in every month except for November and December (see text), data from passive microwave sensors is less clear. Both data sets indicate significant decreasing trends during May to August (see text).

Regional trends in snow cover

Examination of regional trends in spring snow-cover duration from 1969–2003 using NOAA snow-cover data shows the western United States to be among the regions with the strongest decreases (Figure 4.4). This supports results from studies based on measurements on the ground[12,13]. Springtime snow cover shows a decline particularly in the Pacific Northwest region of the western United States, where snow water equivalent, a common snow cover measurement equivalent to the depth of water which would result from snow melt, has decreased by as much as 50–75 per cent[13]. This decrease is attributed to an increase in temperature[14]; observations of temperatures in the western United States already show warmer winters[15]. There is abundant evidence of earlier spring warm spells in the western United States since 1950 at elevations below 2500 m, with impacts on snow-cover duration as well as amount. There are more frequent rain-on-snow events and snow melt begins earlier, with stream flows increasing in March and April and decreasing in May and June[16].

In contrast, for most of northern Eurasia there has been a long-term increase in snow depth and the duration of snow cover[17]. At Abisko in subarctic Sweden, increases in snow depth have been recorded since 1913[18]. During 1935–1995, snow-cover duration increased by about four days per decade in northern European Russia and small areas of west central Siberia and decreased by about two days per decade over southern and southeastern Siberia[19].

Outlook for snow cover

Decreases in snow-cover extent and duration will contribute to continued and accelerated temperature increases, due to changes in the albedo of the land surface (see Chapter 3). In Alaska, 95 per cent of recent summer warming trends have been attributed to the decrease in snow-cover duration[20].

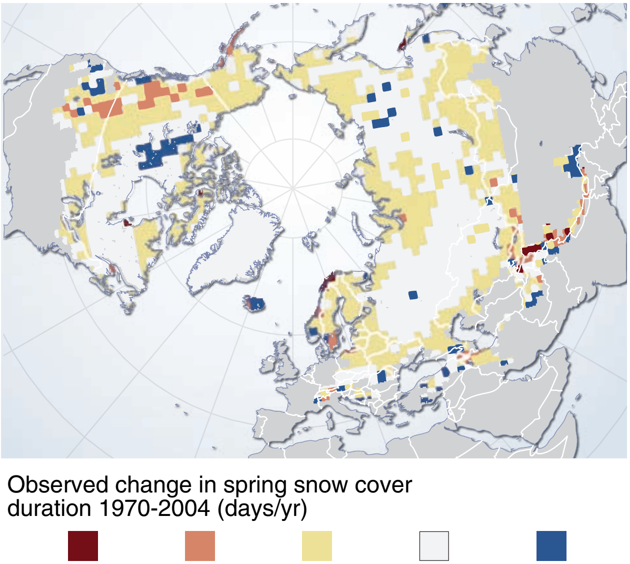


Figure 4.4: Trend (days/year) in spring (February–July) snow-cover duration from 1970–2004 from the NOAA weekly snow-cover dataset. Changes exceeding ~ ±1 represent significant local changes at the 95% level. Greenland was excluded from the analysis.

Source: R. Brown, Environment Canada; data from D. Robinson, Rutgers University

Shallow snow cover at low elevations in temperate regions is the most sensitive to temperature fluctuations and hence most likely to decline with increasing temperature[4]. In locations where snow accumulates at temperatures close to its melting point, small increases in temperature will have large effects on snow cover. For example, in the Pacific Northwest region of the United States, the temperate snow cover of the Cascade Range of mountains could be reduced by over 20 per cent with an increase in mid-winter temperatures of only 2° C[21].

Mountain regions are particularly sensitive to climate change[22], and increases in mean minimum temperatures are more pronounced at higher elevations than in valleys[23]. Temperatures are projected to continue rising in the mountains of the western United States, with accompanying reductions in snow cover[24]. Similar changes are expected in other mountainous regions of the world. In central Chile, air temperature data from 1975 to 2001 show an increase in elevation of the 0° C isotherm (the line on a map linking points at which the mean temperature is 0° C) by 122 m in winter and 200 m in summer[25]. It is estimated that the snow line of the European Alps will rise about 150 m for every 1.0° C increase in winter temperatures[26]. Climate model projections indicate that the Alps and Pyrenees will experience warmer winters with possible increases in precipitation[27], which, as in the western United States, will raise snow lines, reduce overall snow cover, and decrease summer runoff.

Snow water equivalent and snow-covered area are modelled in General Circulation Model experiments to predict global changes in snow cover. A comparison of results

Local observations of snow-cover changes

In many areas of snow cover, there are local people who rely on the snow for water, recreation, travel, and other activities. Through constant and close interaction with snow, these people develop a great body of knowledge about it. People who possess knowledge of snow include mountain villagers, ski patrollers, mountain climbers, and perhaps more than any other group, Arctic residents, especially Indigenous Peoples. These people have the most interaction with snow, as snow is present for most of the year and they depend on it for their livelihoods.

In the Canadian Arctic, Inuit and their ancestors have depended on snow, and held a keen understanding of it, for millennia. Traditionally, Inuit lived in snow houses called *igluit*. The ability to travel depended partly on the condition of snow cover, for example, hard, soft, deep, or drifted snow. Snow forms on the land or sea ice, running parallel with the dominant wind, helped hunters to navigate; this practice is still used by some today (Figure 4.5). Saami reindeer herders in Fennoscandia have also traditionally depended on snow for their activities and survival. Herders closely observe snow conditions and modify their herding strategies accordingly. For example, in hard snow conditions, herders may keep reindeer close together so that strong animals help to crush icy snow layers, allowing weaker animals to graze[30]. If the snow is relatively soft, animals may be allowed to graze a wider area. Today, Inuit no longer live in snow houses and some Saami employ modern technologies, such as helicopters or motorbikes, to herd reindeer. But elders, and many hunters and herders, still possess traditional knowledge about snow. They constantly gain new knowledge about snow and other aspects of the environment, and incorporate this knowledge into their everyday lives.

Many traditional knowledge holders have noticed changes in snow in recent years, along with other changes in the environment and climate. In projects such as the Arctic Climate Impact Assessment, scientists have begun working cooperatively with these people in order to understand environmental change in the Arctic. A number of other projects have documented indigenous knowledge of environmental change in the Arctic, primarily in Alaska and the Canadian Arctic[31–34]. Snow is a common theme in many of these studies. For example, in Nunavik (northern Quebec), residents observe less snow cover in spring time. This restricts travel into the bush by snowmobile to hunt and collect firewood[35]. Less snow in the hills also means fewer cold storage places for fish, which are kept cool in snow patches. This problem is shared by some communities in the Canadian territory of Nunavut[33]. At Clyde River, Nunavut, Inuit observe that permanent snow patches, *aniuvat*, are disappearing and at a quicker rate than in the past. In the community of Baker Lake, Nunavut, changes in snow have already had serious consequences. Changes in wind patterns are packing snow harder than normal, making it difficult or even impossible to build snow houses, which are still used for emergency shelters. Weather events seem to be less predictable to elders in the area, and hunters are being caught in unexpected storms unable to make shelter; several deaths in recent years have been blamed on this change in snow[33,36].

Communities all over the Arctic are living with environmental change and constantly responding to impacts of this change. Snow changes are only one part of this and local observers in the North will acknowledge that snow is bound in a web of environmental processes that are all connected. Knowledge of snow must be accompanied by knowledge of wind, weather, seasons, animals, ice, water, and ocean currents. With their long history in the Arctic and their continued use of the land, ocean, and ice, Arctic Indigenous Peoples play an important role in understanding the Arctic environment and its changes, including snow changes.

Figure 4.5: Arctic Indigenous Peoples have depended on snow for millennia, for example, using snow forms to navigate. This close interaction with snow makes them important observers of snow changes.
Photo: Shari Gearheard

from model simulations to a data set derived from NOAA visible band imagery found the model simulations of annual and interannual variability in snow-covered area to be reasonable at continental to hemispheric scales[28]. At regional scales, however, significant model biases were identified over Eurasia at the southern boundary of the seasonal snow cover. A simulation from one such model projects decreases of 60–80 per cent in monthly maximum snow water equivalent over most middle latitudes by the end of this century (Figure 4.6). The largest decreases are projected over Europe, while simulated increases are seen in the Canadian Arctic and Siberia.

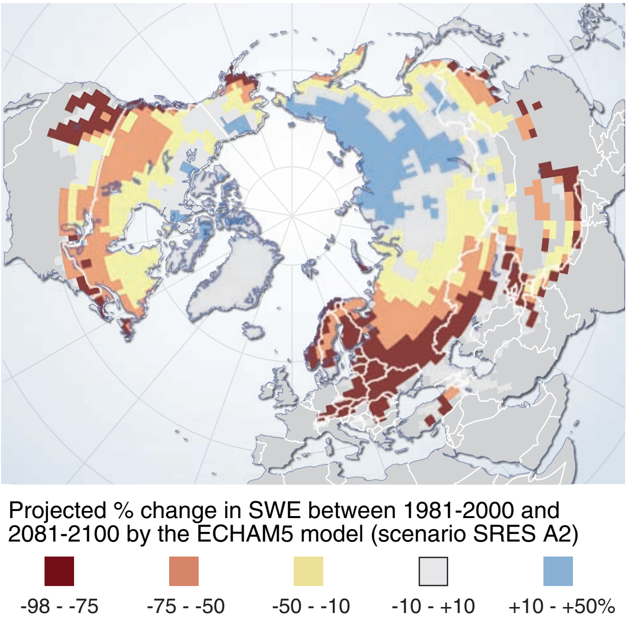


Figure 4.6: Percent change in monthly maximum snow water equivalent (SWE) between 1981–2000 and 2080–2100, simulated by the ECHAM5 climate model under conditions defined by the SRES A2 emission scenario (RUN 2). Results are plotted for grid points with a mean maximum SWE of 10 mm in 1981–2000.

Source: R. Brown, Environment Canada; data from ESG 2007[29]

Snow as an ecological factor

The importance of snow as an ecological factor has been recognized by science since at least the beginning of the 20th century[37,38]. However, even today many observations remain anecdotal. In the 1950s, Gjaerevoll[39] analysed the way in which the alpine plant community structure was shaped by snow. Within the past decade, snow manipulation experiments have explored the effects of snow depth and snow-cover duration on plant communities and ecosystem processes[40–42]. Recently, models of snow cover have been applied to ecological problems[43].

Snow cover plays a dual role in terms of temperature regulation. The high albedo of snow cover reduces net radiation, and snow also acts as a heat sink, removing energy from the atmosphere in the form of heat. This means that the presence of snow cover inhibits soil warming until the snow melts, preventing biological activity that requires temperatures above 0°C. However, snow is an efficient insulator, keeping soil temperatures near 0°C and reducing the extremes of temperature experienced by vegetation and soil in the zone under the snow (subnivean cavity). In autumn, the insulation effect of snow on unfrozen ground can even result in fungal decay of the vegetation, which can kill reindeer calves when they eat the vegetation[44]. The subnivean environment is also very humid. Under thin snow packs in spring, light levels permit limited photosynthesis for lichens and evergreen tundra shrubs[45]. This is an important adaptation given the short growing season. Plants in the “greenhouse of snow” created by the subnivean cavity can start to grow weeks before neighbouring plants covered by deep snow.

Snow exerts forces on the objects that it covers. For example, snow in southern Finland at the end of March, estimated to weigh 100–120 kg per m^2, compresses the

Figure 4.7: Snow has many effects on vegetation, including the ability to deform and break trees with its weight (see beech trees, left). Trees with a narrow canopy (see spruce trees, right) collect less snow and are less likely to suffer damage.
Photo: (left) Fillies Wo/UNEP/Still Pictures, (right) Terry Callaghan

shoots of bog moss[46]. The weight of snow can deform and break trees[38] (Figure 4.7), branches and the soft tissues of plants such as grasses and forbs. Snow can facilitate the spread of some woody plants by pressing branches to the ground surface – the branches then develop roots and form new individuals. Snow pressing directly onto vegetation protects it, to some extent, from grazing. Plants that are covered by the snow are also protected from drying out in the winter and from erosion of tissues by ice crystals. For this reason, the height of vegetation is often uniform and correlated with snow depth[47].

Snow also supports weight, including the various ground pressures that passing animals exert. While snow can support small animals such as birds, small mammals, hares and foxes with only minor deformation, larger mammals such as reindeer and moose experience a critical snow depth above which they cannot move. Snow can, therefore, enhance access across the landscape for animals by smoothing the terrain or forming bridges across gullies, or it can inhibit access by being too deep or too soft. The solid matrix of snow can be shaped and made into dens for polar bears. The consistency of snow also allows the formation of a subnivean cavity in which small mammals nest and feed, protected from predators such as foxes and snowy owls. Along streams in late winter, the subnivean cavity can be as wide as 2 m.

Snow provides a habitat for some "primitive" forms of life. A relatively abundant and diverse array of micro-organisms can be found on both seasonal snow cover[48] and persistent snow on glaciers[49]. These organisms include algae that can colour the snow red, blue or green, bacteria, fungi, diatoms, viruses, rotifers and tardigrades. On Signy Island, a small subantarctic island, cell numbers range from 5000 cells per cubic millimetre for coloured snow to 1 to 2 cells per cubic millimetre for clean snow[49]. The presence of organic matter in and on snow reduces albedo and results in local melt and accumulation of nutrients.

The fractional snow cover (snow in patches) in the spring months affects the breeding of certain ground nesting species, such as waders, ducks and geese (see box on migratory sandpipers and snow). Fractional snow cover, particularly associated with small-scale topographical differences within the landscape, also affects the distribution of plant communities and species. Plant communities that are characteristic of depressions where snow accumulates have short growing seasons and are waterlogged after thaw[39] whereas communities on wind-exposed ridges are more drought tolerant[50]. Traditional Saami knowledge has described the influence of snow cover on the vertical distributions of lichens that live on mountain birch stems in the subarctic; *Parmelia olivacea* grows above the winter snow line, whereas *Parmeliopsis ambigua* grows below the snow line and is covered by snow for six months per year[47].

Snow accumulates debris and chemicals including plant nutrients and pollutants from the atmosphere. Some of these, such as atmospheric nitrogen[54] and seeds, accumulate over the winter and are then released or re-

Animal tracks in the snow.
Photo: Artis Rams/iStockphoto.com

A knot in the snow.
Photo: Peter Prokosch

Migratory sandpipers and snow on the Arctic tundra

Snow very much determines the distribution of Arctic birds. In the spring, 24-hour daylight and vast food supplies attract billions of waterbirds to migrate from virtually all corners of the world to breed in the Arctic. These migratory waterbirds need snow-free patches to feed and nest in the tundra.

For sandpipers breeding in Greenland and Arctic Canada, such as the knot, dunlin and sanderling, both the density and timing of breeding have been shown to be strongly related to snow cover. Successful breeding for these birds depends on finding a nesting area with the right size of snow-free patches and timing breeding so that the chick-rearing period in July coincides with the emergence of insects. Breeding too early can mean losing the clutch due to adverse weather events or due to predation by Arctic foxes, which prey more easily on nests in small snow-free patches. In Siberia, researchers found that, while patch size does not matter for the well-camouflaged ptarmigan, breeding density of passerines and sandpipers increases strongly with the size of the snow-free patches.

The highest density of breeding sandpipers is found in central-eastern Greenland, where continental climate conditions provide an ideal balance between snow-free patches and suitable vegetation. In the northern-most part of Greenland, the vegetation is thinner and fewer sandpipers breed. Further south the conditions are different again. The Atlantic climate, with more snow, allows only late breeding. Large areas in the Arctic do not harbour any sandpipers at all, due to greater snow depth and later thawing. If the current observed trend of increased snow fall continues, the best breeding areas in Greenland will shift further north and push more and more birds to the edge, with a smaller window for breeding. The most affected species are those that breed in the high Arctic. In northern Europe, most of Siberia, and Alaska, earlier thawing will mean more snow-free patches and more favourable conditions for sandpiper breeding at lower latitudes.

Sources: Meltofte 1985[51], Rysgaard and others 2003[52], Summers and Underhill 1996[53] distributed over the landscape. Snow melt provides an important source of nitrogen for tundra ecosystems and can result in a flush of moss growth in spring. However, the accumulation of chemicals by snow can have negative effects on vegetation. Although accumulations of nitrate can be potentially assimilated by mosses and related plants under the snow pack, at high concentrations characteristic of areas south of the Arctic, both nitrate and sulphate can cause physiological damage to plants under the snow[54].

Just as snow has numerous effects on vegetation, vegetation in turn exerts major effects on snow-cover dynamics[20,55,56]. Wind can remove up to 70 per cent of the snow cover in alpine areas, as well as in polar regions and on the prairies[57]. Trees and tall shrubs reduce wind speeds and thereby affect the distribution of snow on the ground[58]. The forest canopy can trap snow, especially in mountain regions with coniferous vegetation, resulting in increased snow depth underneath the vegetation[59]. Depending on the canopy characteristics of the vegetation, the opposite scenario can also occur. In dense coniferous forests, up to 60 per cent of snow fall can be intercepted[60] by the canopy and stored on the branches of the trees. This results in a decrease in snow depth underneath the vegetation, as much of the snow changes to gas (sublimates) or blows away before it falls to the ground[61]. Snow that reaches the ground has been "filtered" by the canopy and is less dense than that in open areas.

Vegetation also affects the amount of snow precipitation and the rate of snow melt. Trees and shrubs affect surface albedo – for example, black spruce can intercept up to 95 per cent of incoming radiation. Trees and shrubs thus increase local temperatures that affect snow fall, thereby indirectly moderating the amount of snow precipitation. The presence of a forest canopy generally slows the rate of snow melt (up to three fold) because it reduces net radiation and wind speeds[62], while a shrub canopy slightly increases the rate of snow melt. Snow within shrub canopies is deeper and less dense, which reduces heat transfer through the snow pack and increases winter soil temperatures by 2 °C relative to adjacent shrub-free tundra[63]. In spring when the snow starts to melt, the contrasting albedos of the vegetation and the snow enable the vegetation to transfer heat to the ground, resulting in local melt which creates holes in the snow around vegetation.

Impacts of projected snow-cover changes on ecosystems

The effect of future snow regimes on vegetation will involve complex interactions between changes in the duration of snow cover and changes in snow depth. The timing of snow cover has effects on the productivity of ecosystems. For areas of seasonal snow cover, the snow-free period in summer determines the length of the potential growing season for plants and thus ecosystem and net primary productivity[64] (Figure 4.8). The timing of the spring melt has a great impact on productivity as, in the Arctic, leaf production occurs relatively late in the season following thaw when the amount of solar radiation received is already at its maximum or declining. At an alpine site, productivity was decreased by 3 per cent for each day that snow melt was delayed[65]. In contrast, the timing of onset of winter snow has less influence on productivity as it comes at a time when solar angles are low and potential plant production is also low.

The increased snow cover that is predicted in some northern areas as temperatures rise will affect both ecosystem structure and function. Long-term experimental increases in snow cover affected species abundance, height of the vegetation, and diversity of plant functional types in the Alaskan tundra[40]. The increase in snow cover had a greater impact on vegetation than experimental summer warming, partly because insulation by increased snow in winter caused higher soil warming than increased air temperatures. In the subarctic, an experimental doubling of winter snow cover on a peat moss bog increased air and soil temperatures and strongly increased moss growth[41]. This increase in moss growth could increase the carbon sink effectiveness of northern peat lands in areas where snow depth increases.

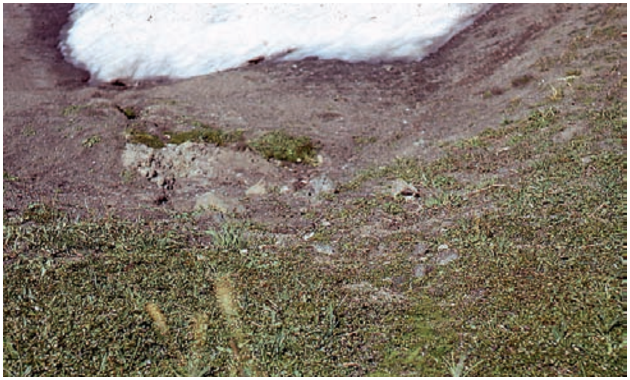


Figure 4.8: The duration of snow cover is a major determinant of the length of the growing season for plants. Shown here is a persistent snow patch in western Greenland. With increasing distance from the centre of the snow patch, the growing season becomes longer, and thus plant communities become more developed and productivity increases.
Photo: Terry Callaghan

More frequent winter thaws can also affect ecosystems. Thawing changes the mechanical properties of snow dramatically. This can reduce the insulating properties of the snow cover, with increased potential for frost penetration into the soil and root damage to certain plant species. During the brief thaw, soil microbial activity may also release greenhouse gases. This occurs at a time when plant uptake of carbon, which could offset the increase in atmospheric carbon, is not possible, and adds to atmospheric concentrations of greenhouse gases. In addition, re-freezing occurs after thawing, which forms ice layers that can be on the surface, throughout the snow cover or, if snow falls after a thawing event, under the snow in contact with the ground. Ice layers can act as a mechanical barrier, preventing herbivores such as musk oxen[66] and reindeer from digging through the snow to reach critical lichens and other forage (see box on the snow-loving deer of the Arctic). This greatly affects their health in winter and can determine their survival[67]. Ice layers may also inhibit the diffusion of organic compounds that reindeer possibly use to detect food[68]. Presence of ice layers affects the survival of other animals such as voles as well[69]. Ice layers can act as a barrier to small mammals accessing shelter, food, nests and protection from predators.

Snow cover in mountain regions is a critical source of freshwater; changes in snow cover could have indirect effects on ecosystems due to changes in availability of these water resources. One potential effect is increased intensity and size of wildfires because of moisture stress on mountain forests. There could also be impacts on anadramous fish, which require high stream flow for their migration to the ocean after hatching in fresh water.

Reindeer feeding after a heavy snowfall.
Photo: Inger Marie Gaup Eira/www.ealat.org

The snow-loving deer of the Arctic

Reindeer and caribou (*Rangifer tarandus*) have been called chionophiles, snow loving. In fact, Arctic island subspecies of *Rangifer* are associated with a snow environment for up to ten months out of the year. *Rangifer* are the most dominant large mammal species in Arctic environments. The species has specialized adaptations in order to thrive in a cold environment. Their diet is energy rich winter lichen, which they obtain mostly by digging (cratering) under the snow[70,71]. Large hooves aid in the cratering and allow *Rangifer* to better travel through snow[72–74]. *Rangifer* are the only member of the deer family in which both males and females grow antlers. Pregnant females retain their antlers until after spring-time calving, allowing them to dominate the social hierarchy in late winter. This dominance allows them to displace lower ranked animals from feeding craters, saving valuable energy[75]. The large migratory herds of *Rangifer* migrate north into regions of rapidly melting snow in spring during the calving period. The pregnant and birthing cows feed along the snow-melt line, and the newly emerged forage that they ingest is highly digestible, protein-rich and critical for milk production.

Although under normal conditions *Rangifer* are able to thrive in snow environments, snow can also severely limit the annual productivity of herds. During deep snow years, more energy is expended in digging to the lichens than is derived from eating them, so caribou limit cratering or move in search of more favourable snow conditions[75]. Under deep snow conditions, *Rangifer* severely deplete their fat and protein reserves to meet their daily energy needs. Late snow melt and deep snow stalls movement during spring migrations. Under severe conditions, calves are born before the herds arrive at the calving grounds. In such years, up to 40 per cent of calves can die before they are a month old[76]. In northwestern North America, recent warming has led to a dramatic increase in the number of days of above freezing temperatures during the *Rangifer* migration period. Thawing and subsequent re-freezing of snow results in ice layers in the snow pack which hinder travel of *Rangifer* and make it harder to crater for food[76]. There have been catastrophic declines in the Peary caribou on the Arctic islands of North America and they are now considered endangered (Figure 4.9). The formation of ice layers that prevent the caribou from accessing food has been identified as the chief cause of the declines[77,78].

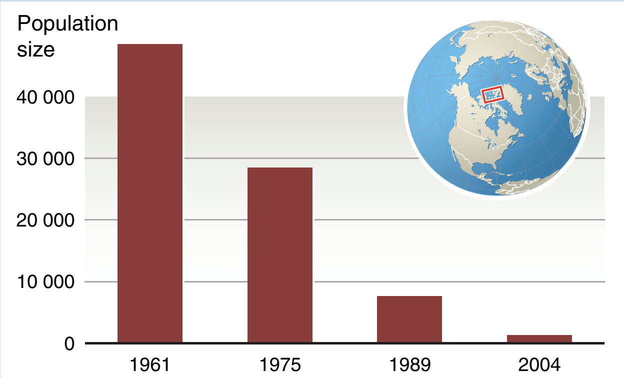


Figure 4.9: Population size of Peary caribou in the Canadian Arctic islands from 1961 to 2004, showing major declines.

Source: Based on data from D. Russell

Impacts of snow-cover changes on human economies and well-being

Impacts on water resources

One of the most dramatic impacts of changing snow cover is on water resources. Snow cover in mountain regions provides critical water supplies, serving nearly one-sixth of the global population with freshwater for domestic, agricultural and industrial uses[79]. Much of the arid American West[79] and Central Asia[80] (Figure 4.10) depends heavily (about 75–85 per cent) on snow melt to supply water for municipalities and agriculture. Snow melt driven water resources are crucial for generation of hydroelectric power, particularly in the American West, Canada, and Europe[81,82]. The declining springtime snow cover in the Pacific Northwest of the United States and rising snowlines projected for many mountain areas, noted in the 'Trends and outlook' section above, threaten these critical water supplies.

Mountain snow cover typically develops in the autumn and grows to a maximum depth in early spring (Figure 4.11). As day length and sun angles increase, so do air temperatures, causing snow cover to warm and begin to melt. Snow cover balances the availability of water in mountain environments. Where winter precipitation falls as rain, surface runoff occurs almost immediately. In contrast,

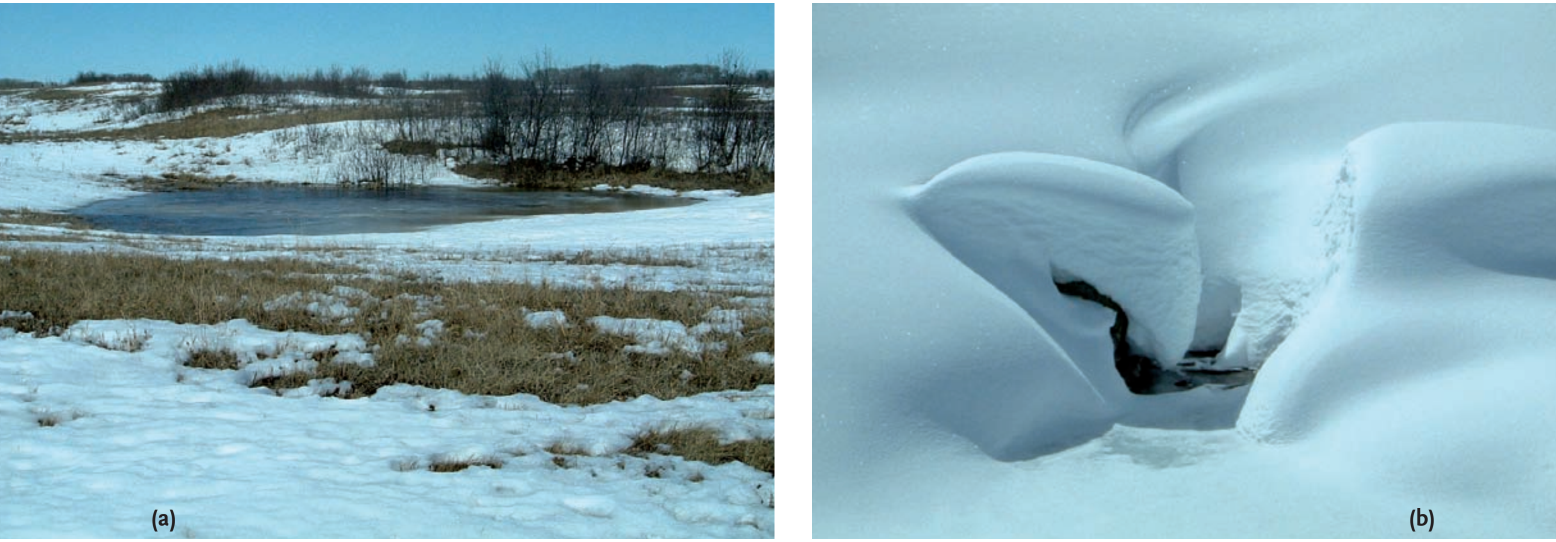


Figure 4.10: Snow cover provides critical water supplies used for many purposes.
(a) Melting of prairie snow cover, seen here in Saskatchewan, Canada, provides spring ponds that are essential for recharge of groundwater and soilwater, for farm water supplies and as spring wetlands for waterfowl migrations through what is otherwise a semi-arid environment.
(b) Melting of alpine snow cover forms a small stream in the Rocky Mountains in British Columbia, Canada. This segment of the Rocky Mountains contains the headwaters of the Columbia River, which supplies water to a large area of western Canada and north-western United States including many important irrigation and hydroelectric generation projects.
Photos: J. Pomeroy

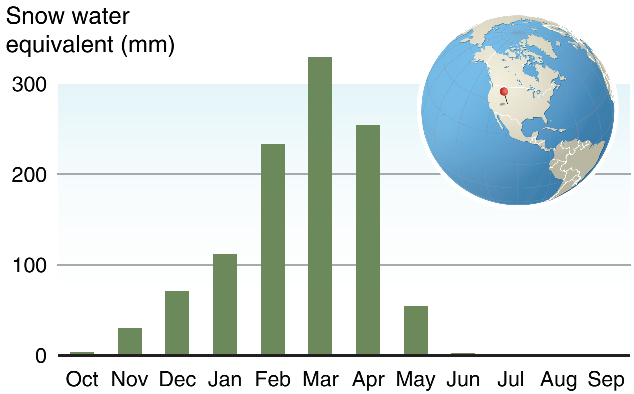


Figure 4.11: Mean monthly snow water equivalent, a common snow pack measurement, for Columbine Pass, Colorado from 1971 to 2000, showing a typical seasonal pattern in a mountain environment.

Source: Based on data from the U.S. National Resources Conservation Service

snow stores water during the winter and then melts in the spring and early summer, creating peak stream flows in the afternoon and an overall seasonal peak flow. In many semi-arid mountain environments, snow melt buffers the transition into the dry summer season. Mountain snow is also a key source of groundwater, since a significant portion of the snow melt enters the soil and drains downhill into valley sediments[83]. The timing, spatial distribution, and volume of snow melt are critical for determining how much water flows as surface runoff into rivers and lakes and how much becomes groundwater. Earlier snow melt across the western United States, for example, caused a one to four week earlier runoff for mountain rivers and longer periods of summertime low-flow[84].

Impacts on agriculture – crops and animal husbandry

The dramatic impacts of snow cover on vegetation also apply to agricultural crops. Gradual changes in snow cover, as well as incidences of extreme snow events, can have a strong impact on crops both at the start and end of the growing season. Snow typically disappears in the spring before the start of the growing season. If it occurs during the growing season, snow can insulate crops from cold air or cause damage by freezing crops or breaking off branches and stems. An early autumn snow may prevent a farmer from being able to harvest crops because snow can damage the plants, prevent

▲ Children playing in the snow.
Photo: Martha Main

◀ **Figure 4.12:** A herd of reindeer belonging to the Nenets, an indigenous people of the Russian Arctic, feed by digging under the snow in western Siberia. Reindeer herding, practiced for centuries by several Arctic peoples, is strongly impacted by snow cover.
Photo: Lars Miguel Utsi/www.ealat.org

them from ripening, or interfere with operation of machinery. In the long-term, changes in snow distributions and their impacts on the local water budget can contribute to changes in vegetation type[85,86] and change the economic cost-benefit of raising certain crops.

Changes in snow distribution can also influence animal husbandry. During extreme snow events, livestock can get lost, stressed, or fail to give birth successfully[87]. The melting of spring snow creates muddy ground conditions that, if prolonged, can lead to animal weight loss. In subsistence communities such as those across the Arctic, access to traditional hunting or herding of caribou and reindeer is strongly impacted by snow distribution[88] (Figure 4.12).

Impacts on recreational sector

Changes in snow distributions have had strong impacts on the recreational sector. Skiing is one example that is important to the economies of mountainous regions of North America, Europe, and Asia[89,90] (see text box on alpine ski resorts). Snowmobiling, used both recreationally and for transport in cold regions, is a growing pursuit and is, of course, dependent on a healthy base layer of snow. In 1985, snowmobiling contributed $300 million to the state economy of Minnesota alone[91]. Other less widespread winter sports such as dog mushing, sledding, and snowshoeing can be important to local economies, and are impacted when snow arrives anomalously late, too little, or not at all.

Making snow on the slopes of a ski resort.
Photo: UNEP/Still Pictures

Alpine ski resorts

Winter tourism is a significant part of the economy of Alpine countries and the most important source of income in many regions. In Austria, winter tourism revenue makes up 4.5 per cent of GNP and half of the total income from tourism. Much of winter tourism is based around the ski industry, which is dependent on reliable snow conditions. Although snow fall is expected to increase at high elevations, it is winter temperatures that largely determine the depth of snow that accumulates on the mountains. The Alps are currently warming at roughly three times the global average. Climate models project an increase in winter temperatures of about 1° to 3° C from 1990 conditions by 2050, with greater warming at higher elevations. An analysis of snow cover in the Alps concluded that each increase of 1° C corresponds to a 150 m move up the mountain of the line marking the lower limit of adequate snow for ski resorts. This means that each degree of warming will result in a further decline of snow conditions to the point that more and more current ski operations will not be viable (Figure 4.13).

Adaptation measures include more artificial snow making and expanding and building ski areas at higher elevations and on north-facing slopes. As the climate warms and the snow cover declines, many low-elevation ski resorts will not be able to adapt and will be forced to switch to other types of tourism or close.

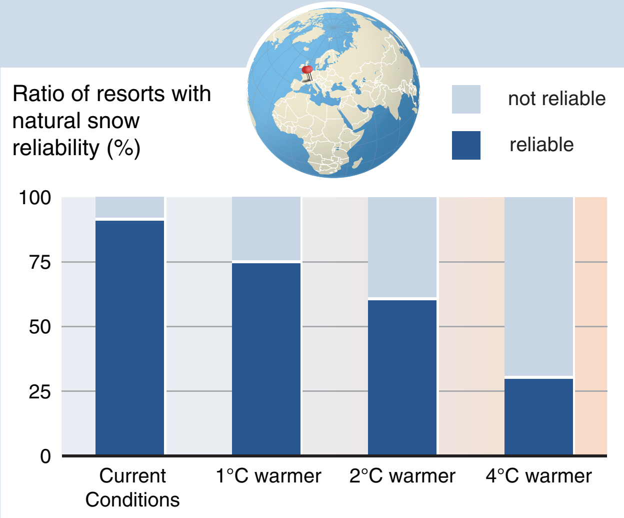


Figure 4.13: Per cent of existing ski areas in the Alps with natural snow-reliability under current conditions and warmer conditions, based on an analysis of 666 medium to large ski areas in France, Austria, Switzerland, Italy and Germany. Natural snow-reliability means on average a season of 100 days with at least 30 cm of snow on upper ski run.

Source: Based on Agrawala 2007[90]

Avalanche in the Swiss Alps.
Photo: Martin Wandel/iStock

Impacts on industry and infrastructure

Certain industries depend heavily on reliable snow cover. Oil and gas companies, for example, use ice roads in the Arctic to gain access to resource fields. In order to protect the tundra ecosystem, temperature and snow-depth criteria must be met before a company builds an ice road. Other industries benefit from less snow, as snow-removal costs can be significant for both small and large businesses. Events such as mid-winter melting or rain-on-snow can cause flooding and lead to damage of roads, bridges and homes[92].

The amount of snow per event, number of events per season, timing within the day and work week[93] all affect the economic impact of snow. The economic impact of a snow event on a region's infrastructure also depends on population density. For example, the Northeast Snow Impact Scale (referring to the northeast region of the United States) takes population density as well as snow-cover extent into account in assessing economic impacts of a snow event[94]. Expectations also play an important role in determining the economic impact of climate changes[95], including changes in snow cover. Weather model forecasts that depict weather conditions over a broad area have become important management tools for economic sectors impacted by snow. While they are not always accurate, they are the best available source of day-to-day information for most industries.

Impacts on environmental hazards

Snow avalanches, in which large quantities of snow slide down a mountainside, are major hazards in steep terrain, causing economic losses, injury and loss of life. Fatalities due to avalanches in the western United States increased to 25 per year in the 1990s[96]. In the European Alps, there was an average of 114 victims per year between 1975 and 1988, three quarters of them mountain and 'off track' skiers[97]. Factors that create high risk of avalanches are: slopes of 35–45°, new snow accumulations of 50–100 cm, and high wind speeds; the order and thickness of layers within the snow pack are also important[98]. Increasing events of rain-on-snow as in the western United States, noted in the "Trends and outlook" section above, may enhance the triggering of avalanche release. This is an increasing risk at lower elevations and in coastal mountains with rising winter temperatures.

References

[1a] IPCC (2007). *Climate Change 2007: The Physical Science Basis. Contribution of Working Group 1 to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* (eds. S. Solomon, D. Qin, M. Manning, Z. Chen, M.C. Marquis, K. Averyt, M. Tignor and H.L. Miller). Intergovernmental Panel on Climate Change, Cambridge and New York

[1] Armstrong, R.L. and Brodzik, M.J. (2005). *Northern Hemisphere EASE-Grid weekly snow cover and sea ice extent version 3*. National Snow and Ice Data Center, Boulder (Digital media)

[2] Robinson, D.A. (2007). Personal communications

[3] Brodzik, M.J., Armstrong, R.L., Weatherhead, E.C., Savoie, M.H., Knowles, K.W. and Robinson, D.A. (2006). Regional trend analysis of satellite-derived snow extent and global temperature anomalies. In: *American Geophysical Union Fall 2006, San Francisco, CA, USA*

[4] Lemke, P., Ren, J., Alley, R., Allison, I., Carrasco, J., Flato, G., Fujii, Y., Kaser, G., Mote, P., Thomas, R. and Zhang, T. (2007). Chapter 4: Observations: Changes in Snow, Ice and Frozen Ground. In *Climate Change 2007: The Physical Science Basis. Contribution of Working Group 1 to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* (eds. S. Solomon, D. Qin, M. Manning, Z. Chen, M.C. Marquis, K. Averyt, M. Tignor and H.L. Miller). Intergovernmental Panel on Climate Change, Cambridge and New York

[5] Brown, R.D. (2000). Northern hemisphere snow cover variability and change, 1915-97. *J. Climate,* 13, 2339-2355

[6] Robinson, D.A., Dewey, K.F. and Heim, R.R. (1993). Global snow cover monitoring: an update. *Bull. Am. Meteorol. Soc.*, 74, 1689-1696

[7] Frei, A. and Robinson, D.A. (1999). Northern Hemisphere snow extent: regional variability 1972-1994. *Int. J. Climatology*, 19, 1535-1560

[8] Ramsay, B.H. (1998). The interactive multisensor snow and ice mapping system. *Hydrol. Processes*, 12, 1537-1546

[9] NOAA/NESDIS/OSDPD/SSD (2004, update 2006). *IMS daily Northern Hemisphere snow and ice analysis at 4 km and 24 km resolution*. National Snow and Ice Data Center, Boulder (Digital media)

[10] Armstrong, R.L., Brodzik, M.J., Knowles, K. and Savoie, M. (2005). Global monthly EASE-Grid snow water equivalent climatology. National Snow and Ice Data Center, Boulder (Digital media)

[11] Armstrong, R.L. and Brodzik, M.J. (2001). Recent Northern Hemisphere snow extent: a comparison of data derived from visible and microwave sensors, *Geophys. Res. Lett.,* 28(19), 3673-3676

[12] Groisman, P.Ya., Karl, T.R., Easterling, D.R., Sun, B. and Lawrimore, J.H. (2004). Contemporary changes of the hydrological cycle over the contiguous United States: trends derived from in situ observations. *J. Hydrometeorol.,* 5, 64-85

[13] Mote, P.W., Hamlet, A.F., Clark, M.P. and Lettenmaier, D.P. (2005). Declining mountain snowpack in western North America, *Bull. of Amer. Meteorol. Soc.,* 86, 39-49

[14] Mote, P.W. (2003). Trends in snow water equivalent in the Pacific Northwest and their climatic causes. *Geophys. Res. Lett.,* 30 (12), 1601, doi:10.1029/2003GL017258

[15] Folland, C.K., Karl, T.R., Christy, J.R., Clarke, R.A., Gruza, G.V., Jouzel, J., Mann, M.E., Oerlemans, J., Salinger, M.J. and Wang S.-W. (2001). Chapter 2: Observed climate variability and change. In *Climate Change 2001: The Scientific Basis. Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change* (eds. J. T. Houghton, Y. Ding, D.J. Griggs, M. Noguer, P.J. van

der Linden, X. Dai, K. Maskell and C.A. Johnson). Intergovernmental Panel on Climate Change, Cambridge

[16] Regonda, S.K., Rajagopalan, B., Clark, M. and Pitlick, J. (2005). Seasonal cycle shifts in hydroclimatology over the western United States. *J. Climate,* 18, 372-384

[17] Kitaev, L., Førland, E., Razuvaev, V., Tveito, O.E. and Krueger, O. (2005). Distribution of snow cover over Northern Eurasia. *Nordic Hydrology*, 36, 311-319

[18] Kohler, J., Brandt, O., Johansson, M. and Callaghan, T.V. (2006). A long record of arctic snow-depth measurements from Abisko, northern Sweden, 1913-2002. *Polar Research,* 25, 91-113

[19] Ye, H.C. and Ellison, M. (2003). Changes in transitional snowfall season length in northern Eurasia. *Geophys. Res. Lett.*, 30(5), 1252, doi:10.1029/2003GL016873

[20] Chapin III, F.S., Sturm, M., Serreze, M.C., McFadden, J.P., Key, J.R., Lloyd, A.H., McGuire, A.D., Rupp, T.S., Lynch, A.H., Schimel, J.P., Beringer, J., Chapman, W.L. Epstein, H.E., Euskirchen, E.S., Hinzman, L.D., Jia, G., Ping, C.L., Tape, K.D., Thompson, C.D.C., Walker, D.A. and Welker, J.M. (2005). Role of land surface changes in Arctic summer warming. *Science*, 310, 657-660

[21] Nolin, A.W. and Daly, C. (2006). Mapping "at-risk" snow in the Pacific Northwest, U. S. A. *J. Hydrometeorol.,* 7, 1166-1173

[22] Beniston, M. (1994). *Mountain Environments in Changing Climates*. Routledge Publishing Co., London and New York

[23] Diaz, H. F. and Bradley, R.S. (1997). Temperature variations during the last century at high elevation sites. *Climatic Change*, 36(3-4), 253–279

[24] Service, R. (2004). As the West goes dry. *Science,* 303, 1124-1127

[25] Carrasco, J.F., Casassa, G. and Quimtana, J. (2005). Changes of the O C isotherm and the equilibrium line altitude in central Chile during the last quarter of the twentieth century. *Hydrol. Sci. J.*, 50, 933-48

[26] Beniston, M. (2003). Climatic change in mountain regions: a review of possible impacts. *Climatic Change*, 59, 5-31

[27] Marinucci, M.R., Giorgi, F., Beniston, M., Wild, M., Tschuck, P., Ohmura, A. and Bernasconi, A. (1995). High-resolution simulations of January and July climate over the western alpine region with a nested regional modeling system. *Theoretical and Applied Climatology*, 51, 119-138

[28] Frei, A., Miller, J.A. and Robinson, D.A. (2003). Improved simulations of snow extent in the second phase of the Atmospheric Model Intercomparison Project (AMIP-2). *J. Geophys. Res.*, 108(D12), 4369, doi:10.1029/2002JD003030

[29] ESG (2007). *WCRP CMIP3 Multi-Model Dataset*. Earth System Grid. https://esg.llnl.gov:8443/ [Accessed February 2007]

[30] Labba, N. (2006). *Project "Snow and Ice" Field Study Workshop in Abisko, Northern Sweden, April 2006.* Scannet Newsletter, 10, 11-12. http://www.scannet.nu/files/news/Newsletter10.pdf [Accessed 15 March 2007]

[31] McDonald, M., Arragutainaq, L. and Novalinga, Z. (1997). *Voices from the Bay: Traditional Ecological Knowledge of Inuit and Cree in the James Bay Bioregion*. Canadian Arctic Resources Committee, Ottawa and Environmental Committee, Municipality of Sanikiluaq

[32] IISD (2001). *Final Report: The Inuit Observations on Climate Change Project*. International Institute for Sustainable Development, Winnipeg

[33] Fox, S. (2003). *When the Weather is Uggianaqtuq: Inuit Observations of Environmental Change. A multi-media, interactive CD-ROM*. Produced at the Cartography Lab, Department of Geography, University of Colorado at Boulder. Distributed by the National Snow and Ice Data Center and Arctic System Sciences, National Science Foundation

[34] Krupnik, I., and Jolly, D. (2002). *The Earth is Faster Now: Indigenous Observations of Arctic Environmental Change*. Arctic Research Consortium of the United States, Fairbanks

[35] Furgal, C., Martin, D. and Gosselin, P. (2002). Climate Change and Health in Nunavik and Laborador: Lessons from Inuit Knowledge. In *The Earth is Faster Now: Indigenous Observations of Arctic Environmental Chang* (eds. I. Krupnik and D. Jolly). Arctic Research Consortium of the United States, Fairbanks

[36] Fox, S. (2002). These are Things that are Really Happening: Inuit Perspectives on the Evidence and Impacts of Climate Change in Nunavut. In *The Earth is Faster Now: Indigenous Observations of Arctic Environmental Change* (eds. I. Krupnik and I. D. Jolly). Arctic Research Consortium of the United States, Fairbanks

[37] Chernov, Yu. (1985). *The Living Tundra*. Cambridge University Press, Cambridge

[38] Fries, T. (1913). Botanische Untersuchungen im nördlichsten Schweden. Vetenskapliga och praktiske undersöckningar i Lappland. *Flora och Fauna*, 2

[39] Gjærevoll, O. (1956). The plant communities of the Scandinavian alpine snowbeds. *Det Kongelige Norske Videnskabernes Selskabs Skrifter*, 1956(1), 1-405

[40] Wahren, C.H.A., Walker, M.D. and Bret-Harte, M.S. (2005). Vegetation responses in Alaskan arctic tundra after 8 years of a summer warming and winter snow manipulation experiment. *Global Change Biology,* 11, 537-552

[41] Dorrepaal, E., Aerts, R., Cornelissen, J.H.C., Callaghan, T.V. and van Logtestijn, R.S.P. (2003). Summer warming and increased winter snow cover affect *Sphagnum fuscum* growth, structure and production in a sub-arctic bog. *Global Change Biology,* 10, 93-104

[42] Jones, M.H., Fahnestock, J.T., Walker, D.A., Walker, M.D. and Welker, J.M. (1998). Carbon dioxide fluxes in moist and dry arctic tundra during the snow-free season: responses to increases in summer temperature and winter snow accumulation. *Arctic and Alpine Research*, 30, 373-380

[43] Blyth, E., Clark, D., Finch, J., Dankers, R., Rees, G., Danks, F., Zöckler, C., Wolf, A., Jacob, D., Keup-Thiel, E., Göttel, H., Essery, R. and Callaghan, T. (2007). The representation of snow in models and its use for modelling of flora and fauna in northern Europe. In print

[44] Kumpula, J., Parikka, P. and Nieminen, M. (2000). Occurrence of certain microfungi on reindeer pastures in northern Finland during winter: 1996- 97. *Rangifer*, 20, 3-8

[45] Pomeroy, J. and Brun, E. (2001). Physical properties of snow. In *Snow ecology: an interdisciplinary examination of snow covered ecosystems* (eds. H.G. Jones, J. Pomeroy, D.A. Walker, and R. Hoham). Cambridge University Press, Cambridge

[46] Lindholm, T. and Vasander, H. (1990). Production of eight species of *Sphagnum* at Suurisuo mire, southern Finland. *Annales Botanici Fennici*, 27, 145-157

[47] Sonesson, M. and Callaghan, T.V. (1991). Plants of the Fennoscandian Tundra. *Arctic,* 44, 95-105

[48] Jones, H.G., Pomeroy, J.W., Walker, D.A. and Hoham, R.W. (2001). *Snow ecology: an interdisciplinary examination of snow-covered ecosystems*. Cambridge University Press, Cambridge

[49] Hodson, A.J., Anesio, A.M., Tranter, M., Fountain, A.G., Osborn, M., Priscu, J., Laybourn-Parry, J. and Sattler, B. (*2007*). Glacial ecosystems. In print

[50] Billings, W.D. and Bliss, L.C. (1959). An alpine snowbank environment and its effects on vegetation, plant development and productivity. *Ecology*, 40(3), 388-397

[51] Meltofte, H. (1985). Populations and breeding schedules of waders, *Charadrii*, in high Arctic Greenland. *Med. Grönl. Biosc*. 16, 1-43

[52] Rysgaard, S., Meltofte, H. and Pedersen, S.A. (2003). Climate change in Greenland. In *Denmark´s Third National Communication on Climate Change. Under the United Nations Framework Convection on climate change*. Danish Environmental Protection Agency, Danish Ministry of the Environment

[53] Summers, R.W. and Underhill, L.G. (1996). The dispersion of Arctic breeding birds according to snow free patch dimensions during the spring thaw in the north-eastern Taimyr Peninsula, Russia. *Polar Biol.,* 16, 331-333

[54] Woodin, S.J. (1997). Ecological effects of major pollutant sources in the Arctic. In *Ecology of Arctic Environments* (eds. S.J. Woodin. and M. Marquiss). Blackwell Science, Oxford

[55] Sturm, M., Douglas, T., Racine, C. and Liston, G.E. (2005). Changing snow and shrub conditions affect albedo with global implications. *Journal of Geophysical Research*, 110, G01004, doi:10.1029/2005JG000013

[56] Harding, R., Kuhry, P., Christensen, T.R., Sykes, M.T., Dankers, R. and van der Linden, S. (2001). Climate feedbacks at the tundra-taiga interface. *Ambio Special Report,* 12, 47-55

[57] Pomeroy, J., Marsh, P. and Gray, D.M. (1997). Application of a distributed blowing snow model to the Arctic. *Hydrol Pocesses*, 11(11), 1451-1464

[58] Pomeroy, J.W. and Li, L. (2000). Prairie and arctic areal snow cover mass balance using a blowing snow model. *J. Geophys. Res.*, 105(D21), 26619-26634

[59] Pomeroy, J.W., Gray, D.M., Hedstrom, N.R. and Janowicz, J.R. (2002). Prediction of seasonal snow accumulation in cold climate forests. *Hydrol. Proc.*, 16, 3543-3558

[60] Storck, P., Lettenmaier, D.P. and Bolton, S.M. (2002). Measurement of snow interception and canopy effects on snow accumulation and melt in a mountainous maritime climate, Oregon, United States. *Water Resour. Res.*, 38, 1-16

[61] Essery, R., Pomeroy, J., Parviainen, J. and Storck, P. (2003). Sublimation of snow from coniferous forests in a climate model. *Journal of Climate,* 16(11), 1855-1864

[62] Hardy, J.P., Davis, R:E., Jordan, R., Li, X., Woodcock, C., Ni, W. and McKenzie, J.C. (1997). Snow ablation modeling at the stand scale in a boreal jack pine forest. *J. Geophys. Res.*, 102, 29397-29405

[63] Sturm, M., McFadden, J.P., Liston, G.E., Chapin III, F.S., Racine, C.H. and Holmgren, J. (2001). Snow-shrub interactions in Arctic tundra. A hypothesis with climatic implications. *Journal of Climate,* 14, 336-344

[64] Callaghan, T.V., Björn, L.O., Chapin III, F.S., Chernov, Y., Christensen, T.R., Huntley, B., Ims, R., Johansson, M., Riedlinger, D.J., Jonasson, S., Matveyeva, N., Oechel, W., Panikov, N. and Shaver, G. (2005). Arctic Tundra and Polar Desert Ecosystems. In *Arctic Climate Impact Assessment*. Cambridge University Press, Cambridge

[65] Ostler, W.K., Harper, K.T., McKnight, K.B. and Anderson, D.C. (1982). The effects of increasing snowpack on a subalpine meadow in the Uinta Mountains, Utah, USA. *Arctic and Alpine Research*, 14, 203-214

[66] Forchhammer, M. and Boertmann, D. (1993). The muskoxen *Ovibos moschatus* in north and northeast Greenland: Population trends and the influence of abiotic parameters on population dynamics. *Ecography*, 16, 299-308

[67] Aanes, R., Saether, B.E. and Øritsland, N.A. (2000). Fluctuations of an introduced population of Svalbard reindeer: the effects of density dependence and climatic variation. *Ecography,* 23, 437-443

[68] Sommerfield, R.A., Mosier, A.R. and Musselman, R. (1993). CO_2, CH_4 and N_2O flux through a Wyoming snowpack and implications for global budgets. *Nature*, 361, 140-142

[69] Aars, J. and Ims, R.A. (2002). Intrinsic and climatic determinants of population demography: the winter dynamics of tundra voles. *Ecology*, 83, 3449-3456

[70] Pruitt, W.O., Jr. (1957). Observations on the bioclimate of some taiga mammals. *Arctic,* 10(3), 129-138

[71] Nasimovich, A.A. (1955). Role of the snowcover regime in the lives of ungulates on the territory of the USSR. Moscow

[72] Fancy, S.G. and White, R.G. (1985). Energy expenditures by caribou while cratering in snow. *J. Wildl. Manage.*, 49(4), 987-993

[73] Skogland, T. (1978). Characteristics of the snow cover and its relationship to wild mountain reindeer (*Rangifer tarandus tarandus L.*) feeding strategies. *Arctic and Alpine Research*, 10, 569–580

[74] Thing, H. (1977). Behaviour, mechanics and energetics associated with winter cratering by caribou in northwestern Alaska. *Univ. Alaska Biol. Paper,* 18

[75] Russell, D.E., Martell, A.M. and Nixon, W.A.C. (1993). The range ecology of the Porcupine Caribou Herd in Canada. *Rangifer Special Issue 8*

[76] Griffith, B., Douglas, D.C., Walsh, N.E., Young, D.D., McCabe, T.R., Russell, D.E., White, R.G., Cameron, R.D. and Whitten, K.R. (2002). The Porcupine caribou herd. In *Arctic Refuge Coastal Plain Terrestrial Wildlife Research Summaries. Biological Science Report USGS/BRD BSR-2002-0001* (eds. D.C. Douglas, P.E. Reynolds and E. B. Rhode). U. S. Geological Survey, Biological Resources Division

[77] Miller, F.L. and Gunn, A. (2003). Catastrophic die-off of Peary caribou on the western Queen Elizabeth Islands, Canadian High Arctic. *Arctic*, 56, 381–390

[78] Harding, L.E. (2003). *Peary caribou (Rangifer tarandus pearyi). Update status report: interim report*. Committee on the Status of Endangered Wildlife in Canada, Ottawa

[79] Barnett, T.P., Adam, J.C. and Lettenmaier, D.P. (2005). Potential impacts of a warming climate on water availability in snow-dominated regions. *Nature*, 438(23), 303-309

[80] Barlow, M., Salstein, D. and Cullen, H. (2005). Hydrologic extremes in Central-Southwest Asia, meeting report. *EOS Transactions AGU*, 218-221

[81] Cherry, J., Cullen, H., Visbeck, M., Small, A., and Uvo, C., (2005). Impacts of the North Atlantic Oscillation on Scandinavian hydropower production and energy markets. *Water Resource Management,* 19, 673-691

[82] Payne, J.T., Wood, A.W., Hamlet, A.F., Palmer, R.N. and Lettenmaier, D.P. (2004). Mitigating effects of climate change on the water resources of the Columbia River Basin. *Clim. Change,* 62, 233-256

[83] Earman, S., Campbell, A.R., Phillips, F.M. and Newman, B.D. (2006). Isotopic exchange between snow and atmospheric water vapor: Estimation of the snowmelt component of groundwater recharge in the southwestern United States. *J. Geophys. Res.*, 111, D09302, doi:10.1029/2005JD006470

[84] Stewart, I., Cayan, D.R. and Dettinger, M.D. (2005). Changes toward earlier streamflow timing across western North America. *J. Climate,* 18, 1136-1155

[85] Tape, K., Sturm, M. and Racine, C. (2006). The evidence for shrub expansion in Northern Alaska and the Pan-Arctic. *Global Change Biology,* 12(4), 686-702

[86] Myneni, R.B., Keeling, C.D, Tucker, C.J, Asrar, G. and Nemani, R.R. (1997). Increased plant growth in the northern high latitudes from 1981 to 1991. *Nature,* 386, 698

[87] Johnson, K. (2007). Colorado, still recovering from 2 storms, is hit with a 3rd. *New York Times*, 6 January

[88] Pruitt, W.O., (2005). Why and how to study a snowcover. *Canadian Field-Naturalist,* 119(1), 118-128

[89] Scott, D., McBoyle, G. and Mills, B. (2003). Climate change and the skiing industry in southern Ontario (Canada): exploring the importance of snowmaking as a technical adaptation. *Climate Research,* 23(2), 171-181

[90] Agrawala, S. (2007). *Climate Change in the European Alps: Adapting Winter Tourism and Natural Hazards Management*. Organisation for Economic Co-operation and Development, Paris

[91] Kreag, G. and Moe, J. (2007). *Minnesota's North Shore Snowmobile Trail: What is its value?* http://www.seagrant.umn.edu/tourism/snow.html [Accessed 6 February 2007]

[92] Middelkoop, H., Daamen, K., Gellens, D., Grabs, W., Kwadijk, J.C.J., Lang, H., Parmet, B.W.A.H, Schadler, B., Schulla, J. and Wilke, K. (2001). Impact of climate change on hydrological regimes and water resources management in the Rhine basin. *Clim. Change,* 49, 105-128

[93] Kristovich, D.A.R. and Spinar, M.L. (2005). Diurnal variations in lake-effect precipitation near the Western Great Lakes. *J. of Hydro.,* 6(2), 210-218

[94] Kocin, P.J. and Uccellini, L.W. (2004). A snowfall impact scale derived from northeast storm snowfall distributions. *Bull. Amer. Meteor. Soc.*, 85, 177-194

[95] Stewart, T.R., Pielke, R. and Nath, R. (2004). Understanding user decision making and the value of improved precipitation forecasts - Lessons from a case study. *Bulletin of the American Meteorological Society,* 85(2), 223

[96] Mock, C.J. and Birkeland, K.W. (2000). Snow avalanche climatology for the western United States mountain ranges. *Bull. Amer. Met. Sox.*, 81, 2367-92

[97] Vallo, F. (1990). Les accidents d'avalanches dans les Alpes (1975-1988). *Rev. Geogr. Alpine*, 78, 145-55

[98] Schweizer, J., Jamieson, J.B. and Schneebeli, M. (2003). Snow avalanche formation. *Rev. Geophys.*, 41(4), 1016, doi:10.1029/2002RG000123