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Source: Arctic, Antarctic, and Alpine Research, 41(3) : 323-329

Published By: Institute of Arctic and Alpine Research (INSTAAR), University of Colorado

URL: https://doi.org/10.1657/1938-4246-41.3.323

Arctic, Antarctic, and Alpine Research, Vol. 41, No. 3, 2009, pp. 323–329

Snow Cover Effects on Glacier Ice Surface Temperature

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Abstract

Snowpack evolution and glacier ice surface temperatures were studied on the Indren glacier (Northwestern Alps, Italy) under different meteorological conditions: in winter 2002–2003, rich in snow from the beginning of the season, and in winter 2005–2006, poor in snow until February. Periodical snow profiles were made to measure the physical properties of snow, while data loggers measured the snow/ice interface temperature. Furthermore, in winter 2002–2003, the influence on the snowpack evolution of an artificial increase in the snow density was evaluated.

During the season rich in snow there was a prevalence of rounded crystals originated by melt-freeze metamorphism, while in the season poor in snow depth hoar and faceted crystals prevailed, due to the higher temperature gradient.

From these two winter seasons, it appeared that a deep snow cover of at least 100 cm was able to maintain the snow/ice temperature at around −5°C until the snow cover reached isothermal conditions, whereas, during the winter of 2005–2006, the shallow depth of snow did not allow basal temperature to reach an equilibrium value and the snow/ice interface temperature oscillated between −2 and −8°C. The altered snow density had no effect on the snow/ice interface temperature, whereas it caused a delay in the time of reaching isothermal conditions, thus allowing snow cover on the glacier to persist longer.

DOI: 10.1657/1938-4246-41.3.323

Introduction

When snow crystals are deposited in a seasonal snowpack on the ground or on glacier ice or firn, the crystals start to evolve in specific ways under different environmental conditions, such as differences in temperature and humidity. A fundamental variable in the evolution of the snow cover is the temperature gradient, which is in turn related to basal temperature. The temperature at the basal snow/substratum interface is determined by different nivo-meteorological variables, such as snow depth, snow density, and air temperature, but also by the type of substratum (Freppaz et al., 2008). In the Alps, the substratum can be unfrozen soil, permafrost, or ice (Phillips and Schweizer, 2007). Generally, unfrozen soil has a temperature at the snow/soil interface of around 0°C, even in cold winter seasons, if the amount of snow is enough to insulate the soil from the air temperature (Edwards et al., 2007). Permafrost-affected soils under a consistent snow cover are generally characterized by lower temperatures, ranging between −3 and −5°C. The bottom temperature of the snow cover (BTS) is a diagnostic feature for the presence of permafrost (Haeberli, 1973). The temperature at the snow/soil interface, both in unfrozen and frozen conditions (permafrost), has been measured in several studies (Brooks et al., 1996; Stadler et al., 1996; Brooks and Williams, 1999; Shanley and Chalmers, 1999) while less literature exists reporting on temperatures at the interface between snow and ice. Kuhn et al. (1998), in their research about the seasonal development of the chemistry of the snowpack on a Tyrolean glacier, found that consistent early snowfalls (November) were sufficient to keep the lower layers between freezing and −5°C throughout the winter season. Kojima et al. (2004), in their preliminary study of snow-covered sea ice in Barrow, Alaska, calculated the relation between snow/ice interface temperature and snow depth as a function of air temperature.

In addition to the type of substratum, the temperature at the snow/substrata interface is also related to snowpack properties such as snow density and depth (Rixen et al., 2008). Climate change in the Alps over the last couple of decades shows increasing air temperature (IPCC, 2007), warmer and wetter snowfalls, and more rain-on-snow events, resulting in a snow cover with higher densities (Beniston et al, 2003). The grooming of snow in ski areas changes not only its density, but also particle sizes, wetness, and temperature (IASA, 2005), and accelerates sintering (Fauve et al., 2002). The reduced snow particle size and the increased number of bonds influence both the thermal conductivity of the snowpack and liquid water transport during snowmelt, since effective permeability depends on average grain diameter and water saturation (Sellers, 2000). The snowpack characteristics, for example the types and size of snow grains along with density, influence the transport of heat energy to the base of the snowpack along with resistance of the snow to the melting process, both of which affect the basal temperature of the snowpack.

At present there have been few studies that have evaluated how snow cover may influence the temperature of glacier ice at the snow/ice interface and if the characteristics of snow cover during the accumulation season have an effect on the glacier mass balance at the end of the ablation season. It appears that a compaction of the snow cover and injection of water inside the winter snow, inducing a densification of the snow cover, have no significant impact on total ice ablation (Olefs and Obleitner, 2007; Olefs and Fischer, 2008). Even the cumulative snowfall during the accumulation season appears to have less influence on the glacier mass balance than air temperature during the ablation season, as found by IAHS(ICSI)/UNEP/UNESCO (1996). Zemp et al. (2007) also found that the steady-state equilibrium line altitude is more sensitive to a change in air temperature than to a precipitation

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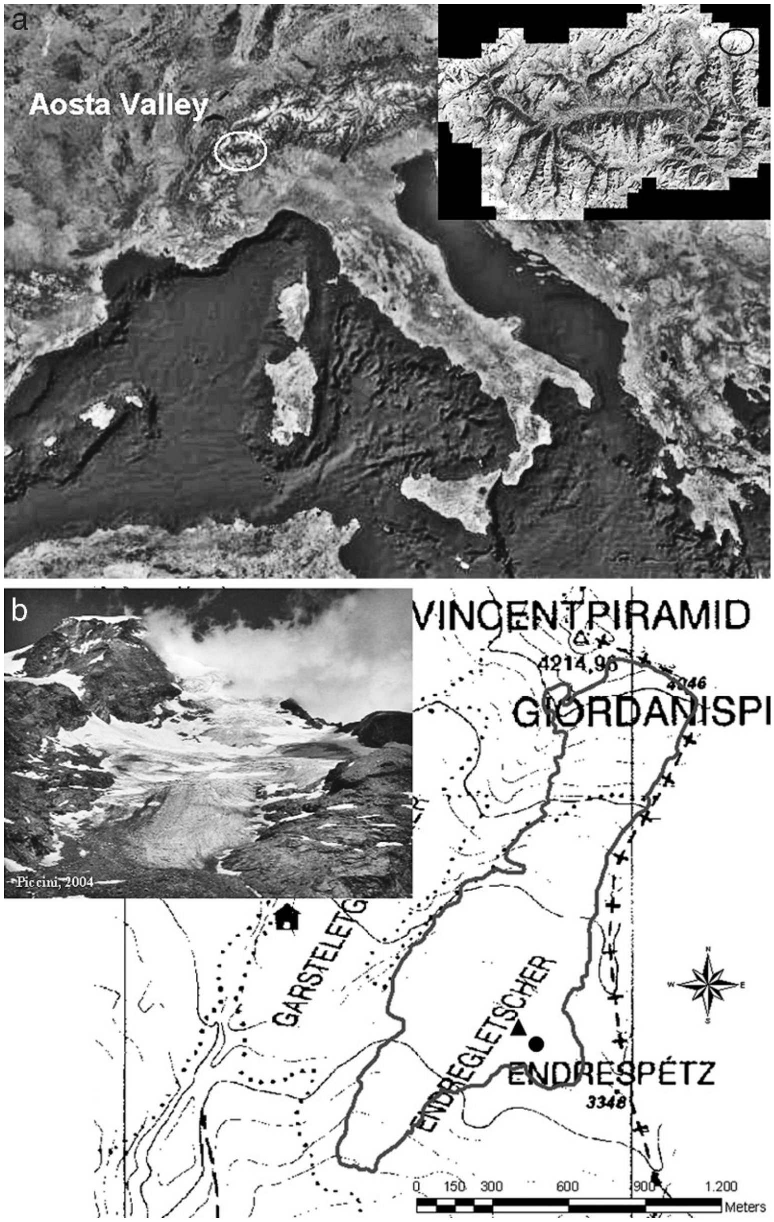

FIGURE 1. (a) Location of the Indren glacier in the Northwestern Alps. (b) Location of the study site. The triangle shows the position of the study plots of winter 2002–2003, the circle the position of that of winter 2005–2006. Aut. n. 1072.

change. Previous studies showed that it is very hard to find a direct link between the characteristics of winter snow accumulation and glacier evolution.

In this study, we analyzed the snowpack characteristics on an Italian glacier, with particular attention to the evolution of temperatures at the snow/ice interface in relation to different meteorological conditions. Winter 2002–2003 was characterized by heavy snowfalls at the beginning of the season. In contrast, winter 2005–2006 had relatively little snowfall until the end of January. The main goal of this research is to explore the influence of different snow properties on the thermal regime of the ice at the snow/glacier interface.

Materials and Methods

STUDY SITE

The study site is located on the Indren glacier, which is a temperate glacier of about 100 ha in size, located in the Northwestern Alps in the Aosta Valley, Italy (Figs. 1a and 1b). Elevation ranges between 3000 and 4100 m a.s.l., with a predominantly southwest aspect (45°55′29″N; 7°51′09″E). Most seasonal snow accumulation results from snowfall, but drifting snow and avalanches also contribute to the seasonal snowpack on the glacier. In 1965 a cable car was built from Alagna to Punta Indren (3260 m a.s.l.) and in 1966 the first ski lift was built on the glacier. In the early 1970s the glacier started to be used for skiing and mountaineering in both summer and winter. A second cable car was constructed in 1982. Due to a great reduction in the glacier surface, summer ski activity stopped in 1997 and cable car access to the glacier was discontinued in the winter of 2006–2007.

SNOW AND METEOROLOGICAL DATA

The evolution of the seasonal snowpack was monitored by continuous automatic measurements and periodical manual surveys (dates in Table 1), in order to determine the physical properties of the snow cover.

TABLE 1

Dates of periodical snow profiles in seasons 2002–2003 and 2005–2006.

Winter 2002–2003	Winter 2005–2006	
17 January	18 November	24 April
15 February	10 January	12 May
24 March	25 January	17 May
25 April	3 April	26 May
12 July	14 April	20 June
	18 April	23 June
		9 July

During the winter season 2002–2003 the experiment consisted of paired treatments to evaluate current and potentially future snowpack regimes. Each plot was 15 m × 15 m in area. In the natural density plot (NDP), the snowpack was allowed to accumulate with no artificial manipulations. In the increased density plot (IDP), after every snowfall a snow-grooming machine compressed the snowpack in order to generate a denser snow cover that climate change might produce with warmer temperatures and wetter snowfalls. During the winter season of 2005–2006 only the natural density plot was maintained, at the same location as the NDP in 2002–2003 (Fig. 1b).

For both winter seasons, UTL-1 data loggers were placed in the late summer at the snow/ice interface to continuously measure the temperature at the bottom of the snowpack: the loggers were programmed to record temperature on an hourly basis. The recording period was 175 days (from 17 January to 12 July 2003) for winter 2002–2003, and 264 days (from 18 November 2005 to 8 July 2006) for winter 2005–2006. Air temperature, snow depth, and other meteorological parameters were measured in both seasons every 30 minutes by the automatic station of the Regione Autonoma Valle d'Aosta placed near the dam of Gabiet (2379 m a.s.l.), about 1 km south of the Indren glacier. Snow depth and air temperature were also measured every 30 minutes by an automatic station of the Italian Army, located at the Col d'Olen (2901 m a.s.l.).

Periodical snow profiles were recorded to determine the structure of the snowpack and the temperature gradient within it according to the standard procedures recommended by the AINEVA (Interregional Association of Snow and Avalanche) (Cagnati, 2003). Physical properties such as snow depth, snow density, snow hardness, and snow crystal type and size were measured during the surveys. From November to July, during the winter season 2002–2003, 5 snow profiles were dug, while during winter 2005–2006 13 were dug.

The effective thermal conductivity k of the snow cover is described in this study by $k\,[W\,m^{-1}\,K^{-1}] = 0.138 - 1.01\,\rho + 3.233\,\rho^2$, where ρ is density (Sturm et al., 1997). The heat flux through the snowpack was calculated as $q = k{\cdot}\Delta T/\Delta Z$, where $\Delta T/\Delta Z$ is the temperature gradient (Rixen et al., 2004). In the season of 2002–2003, during spring, to evaluate the influence of snow density on the time taken from the snowpack to become isothermal, we calculated the time interval from the initial rise of the temperature at the snow/ice interface to a condition of isothermia in the snow.

Statistical analyses were performed by the software SPSS 13 (SPSS, 2003). We searched for a possible correlation between the snow depth and the absolute value of the difference between air and snow/ice interface temperatures ($|T_a - T_i|$). Correlation analyses were carried out also between daily air temperature variation (ΔT_a) and snow/ice interface temperature variation (ΔT_i), which was calculated as the difference between the mean values at two subsequent days (i and i + 1).

Results

Winter 2002–2003 was characterized by heavy snowfalls at the beginning of the season, while winter 2005–2006 was snow-poor until the end of January (Fig. 2). The mean air temperature from November 2002 to June 2003 was −2.4°C, 1 degree warmer than in the winter of 2005–2006. During the winter season of 2002–2003, December and March were warmer than during winter 2005–2006 by +3°C. During January the mean air temperature was similar in both seasons (−8.2°C), while February 2003 was 3°C colder than February 2006. In January, as during April and May, when the snow cover reached isothermal conditions, the air temperature was not different in the two winter seasons.

The physical properties of the snow cover in the two seasons are compared in Table 2 and described in sections (A) and (B).

(A) SNOW COVER EVOLUTION IN THE EARLY HEAVY SNOWFALL SEASON (WINTER 2002–2003)

In the winter season 2002–2003 there was 77 cm of firn at the start of the snow accumulation season. The accumulation of snow was above average that year, in particular during the early winter; the biggest snowfall event was in the month of November 2002, bringing 90 cm of new snow in 2 days. On 17 January, the snow depth was 324 cm at 3350 m: 77 cm of firn from the previous season and 247 cm from seasonal snowfall.

The snow depth decreased from January through the ablation period on the Indren glacier for both the natural density plot (NDP) and the increased density plot (IDP), due to the limited precipitation events that characterized the winter season after December 2002 (Fig. 3a). Between 25 April and 12 July, snow depth decreased by about 205–250 cm, or 2.6–3.1 cm per day, including the addition of modest amounts of new snow.

The graph in Figure 3a shows how the temperature at the snow/ice interface varied during the season, while Figure 3b focuses on the period April/May to highlight the difference between the natural and the increased density plots. Four different periods are identifiable from when the snow/ice interface temperature (T_i) presents different patterns:

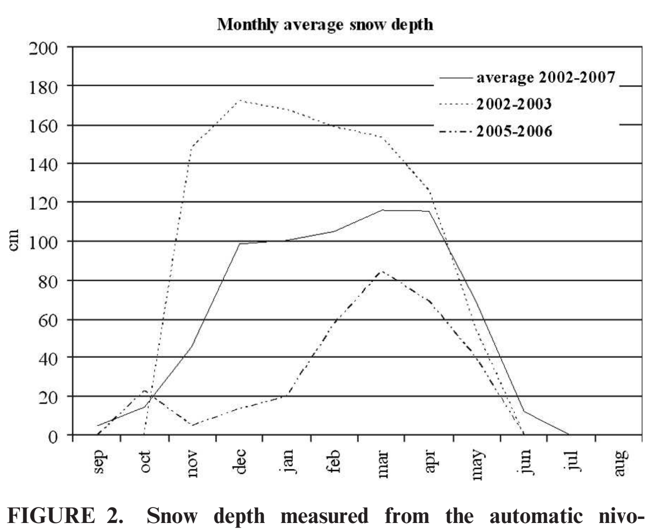

FIGURE 2. Snow depth measured from the automatic nivo-meteorological station of Gabiet (2379 m a.s.l.).

TABLE 2

Snow cover characteristics for seasons 2002–2003 and 2005–2006. Except for the max snow depth, the values are mean values. (*) measurements from data loggers from 18 January to isothermal conditions.

Parameter	2002–2003 NDP	2002–2003 IDP	2005–2006
Max snow depth (cm)	324	315	200
Grain type in bottom layer of snowpack	6b	6b	4a, 5a
Maximum grain size in bottom layer (mm)	—	—	3
Hand hardness index in bottom layer	6	6	4
Snow/ice interface temperature (°C)*	−4.9	−4.7	−5.6
Temperature gradient within the snowpack (°C m^{-1})	−0.8	−0.8	−2.8
Snow temperature at 50 cm above ice (°C)	−3.7	−3.8	−5.2
Temperature gradient in lowest 50 cm (°C m^{-1})	−0.04	−0.6	−2.29
Density (Kg m^{-3})	531	563	341
Effective thermal conductivity (W m^{-1} K^{-1})	0.525	0.598	0.186

(a) 18 January–14 March: T_i cooling at a rate of -0.03°C d^{-1}.
(b) 15 March–18 April: T_i warming at a rate of 0.04°C d^{-1}.
(c) 19 April–29 April: T_i rapid increase of 2°C in one day then remaining constant for 10 days.
(d) 30 April–5 May: for the NDP T_i made a second rapid step of 2°C in one day with the snowpack becoming isothermal, while for the IDP the snowpack became isothermal with a warming rate of 0.51°C d^{-1}.

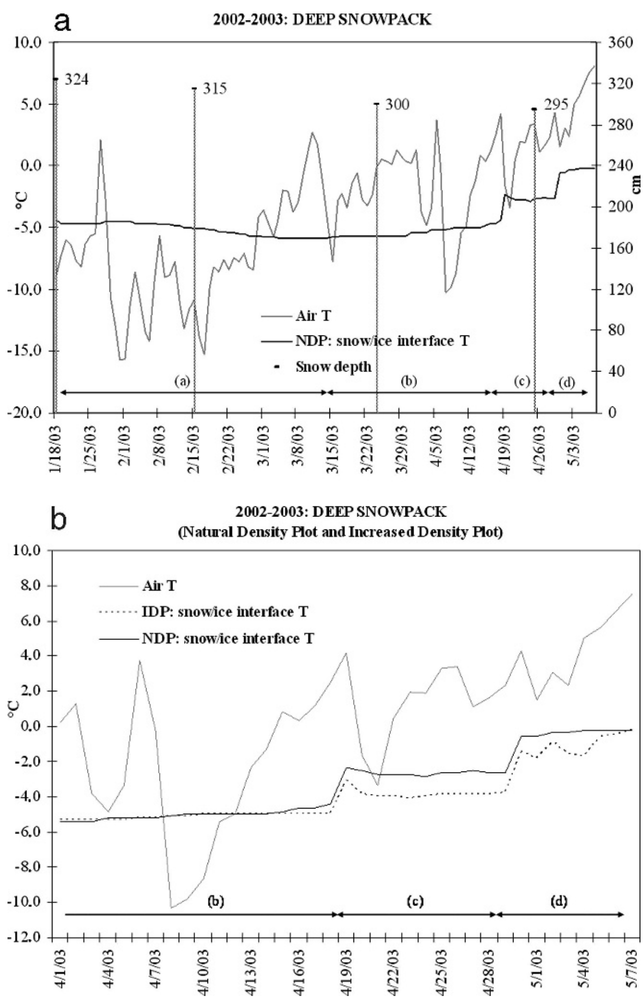

FIGURE 3. (a) Evolution of the temperature at the snow/ice interface in 2002–2003 for the natural density plot, NDP (black line). The gray line shows the air temperature registered at the automatic station of Gabiet (2379 m a.s.l.) in the same period and the black dots the snow depth measured during the field surveys. The pattern of the interface temperature for the IDP was similar except for the last month before isothermal condition. (b) Zoom on the period 1 April–7 May 2003. The black line refers to the NDP and the dashed black one to the IDP.

In periods (a) and (b) we can consider T_i as almost constant around a value of -5°C with a snow depth of more than 3 m. From 7 to 17 April the air temperature increased rapidly from -10 to 4°C as a result of a warm air mass reaching the Alps from the southwest. The reaction of the temperature at the snow/ice interface to this air temperature rise started only at the end of the episode, on 18 April, when the temperature reached -3°C for the NDP and -4°C for the IDP and remained constant until 29 April (period (c)). Between 28 and 30 April a rapid air temperature rise of almost 2°C brought the NDP to an isothermal condition, while the IDP needed 7 more days to reach 0°C (period (d)). On the IDP the snow cover remained on the glacier longer, and the previous year's ice appeared 9 days later on the surface.

The snow depth and the absolute value of the difference between air and snow/ice interface temperatures ($|T_a - T_i|$) were not correlated for both the natural and the increased density plots.

The daily air temperature variations (ΔT_a) and snow/ice interface temperature variations (ΔT_i) were significantly correlated in period (b) ($r = 0.409$, $p < 0.01$) for the NDP and in periods (b) ($r = 0.386$, $p < 0.05$) and (d) ($r = 0.951$, $p < 0.05$) for the IDP.

Natural Density Plot (NDP)

For the natural density plot, during the months of January and February only equi-temperature metamorphism was found in the snowpack. In all the snow profiles, rounded snow crystals were the prevalent type. In February a wind crust was found on the surface of the snowpack above a layer of 80 cm with a density of 280 kg m^{-3}. At the end of March, melt-freeze metamorphism set in, generating a superficial crust of corn snow. Uniquely in this snow profile we found a thin layer of faceted crystals just below the surface crust. During the survey of 25 April, the snowpack was almost in isothermal condition and composed mainly by wet grains of 3 mm and some ice layers.

On 12 July, 10 cm of superimposed ice was found at the bottom of the snowpack. The mean effective thermal conductivity of snow (k), calculated by the equation of Sturm et al. (1997) with a mean density of 531 kg m^{-3}, was 0.525 W m^{-1} K^{-1}. The time needed from the snowpack to become isothermal in periods (c) and (d) was equal to 12 days.

Increased Density Plot (IDP)

For the increased density plot, the greater density influenced snow temperatures within the snowpack. In the month of

February, the surface layer (50 cm thick) of this plot was very hard with a density of 470 kg m^{-3}, higher than that of the NDP. At greater depths, the layers in the two plots had similar densities, while snow temperatures showed significant difference: −7.7°C for the NDP and −12.5°C for the IDP. During March, snow densities were similar to those of the previous month. Air temperature was in the positive range (+4 to +5°C) and had an influence on the superficial layers, where the grains were already rounded forms. Still, at a depth of 1 m below the snow surface, a thermal difference was present: −5.5°C for the NDP and −8.3°C for the IDP.

In April, while the NDP was already experiencing melt-freeze metamorphism (0°C), the snow temperature of the IDP, with the exception of the first 10 cm, varied between −1 and −2°C. On 12 July, 20 cm of superimposed ice was found at the bottom of the snowpack.

The mean effective thermal conductivity k for the IDP, calculated by the equation of Sturm et al. (1997) with a mean density of 563 kg m^{-3}, was 0.598 W m^{-1} K^{-1}, slightly greater than that of the NDP. The time needed from the snowpack to become isothermal in periods (c) and (d) was equal to 19 days, one week longer than that of the NDP.

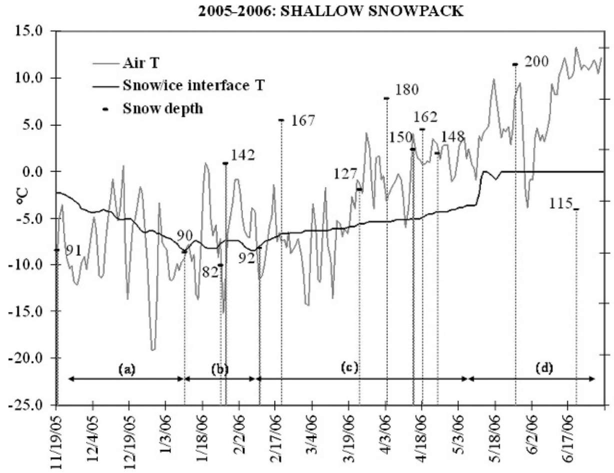

FIGURE 4. Evolution of the temperature at the snow/ice interface in 2005–2006 (black line). The gray line shows the air temperature registered at the automatic station of Gabiet (2379 m a.s.l.) in the same period and the black dots the snow depth measured during the field surveys.

(B) SNOW COVER EVOLUTION IN THE LOW SNOWFALL SEASON (WINTER 2005–2006)

The winter season 2005–2006 differed greatly from that of 2002–2003. There was no firn at the start of the snow accumulation season, and the year was very poor in snowfall in the area of the Monte Rosa Massif. The snow depth on 18 November 2005 was only 90 cm at 3400 m a.s.l. and it remained so until the end of January. At the beginning of April the snow depth was 180 cm, still unusually shallow for the altitude.

The automatic station placed at Col d'Olen (2901 m a.s.l.) recorded for this winter two snowfall events: on 27 January 70 cm of new snow fell, with an air temperature of −23°C at night and around −15°C during day and on 16, 17, and 18 February, when the weather was unstable with irregular snowfalls which brought about 80 cm of new snow, resulting in a total snow depth of 170 cm.

During the months of January and February kinetic metamorphism set in and created conditions for the formation of faceted crystals that we found in the periodical snow profiles until the month of May. Though already in February the snow depth and the thermal condition led to predominantly equi-temperature metamorphism, the faceted crystals remained in the snowpack until the snow cover reached isothermal condition and the facets started to undergo melt-freeze.

We can recognize four different periods (Fig. 4), when the snow/ice interface temperature (T_i) presents different patterns:

(a) 19 November–10 January: T_i cooling with a rate of −0.12°C d^{-1}.
(b) 11 January–8 February: T_i oscillating around a mean value of −7.9°C.
(c) 9 February–10 May: T_i warming with a rate of 0.07°C d^{-1}.
(d) 11 May–20 May: T_i rapid increase to 0°C with a warming rate of 0.34°C d^{-1}.

In period (a) the temperature decreased almost linearly to a value of −8°C in the middle of January; it was not stable around a constant value as in winter 2002–2003, but fluctuated by some degrees until the end of February (period (b)), when the snow cover was sufficient to insulate the glacier surface. In fact, only from 17 February was the snow depth greater than 100 cm and the interface temperature started to raise steadily (period (c)), even if during the beginning of the period (March) the air temperature was comparable or even lower than the values recorded during the early winter (respectively −8.1°C and −7.6°C). The snowfall at the end of January increased the snow depth from 82 cm to 142 cm, which however decreased to 92 cm in 13 days, most probably because of wind erosion. Therefore, in this period, the snow cover was not sufficient to insulate the ice surface from air temperature. Isothermal conditions were reached by 20 May.

The mean effective thermal conductivity k, calculated by the equation of Sturm et al. (1997) with a mean density of 341 kg m^{-3}, was 0.186 W m^{-1} K^{-1}.

As in season 2002–2003, the snow depth and the absolute value of the difference between air and snow/ice interface temperatures ($|T_a - T_i|$) were not correlated. In this season, the correlation between the daily air temperature variation (ΔT_a) and the daily snow/ice interface temperature variation (ΔT_i), was significant in periods (b) ($r = 0.459$, $p < 0.05$) and (c) ($r = 0.409$, $p < 0.01$).

Discussion

The monitoring of the snowpack evolution on the Indren glacier under different meteorological conditions allowed the understanding of the interrelation between some snow parameters. In particular, the temperature at the snow/ice interface was shown to be sensitive to the fluctuations of air temperature when the snow cover was insufficient to insulate the glacier surface. A snow depth of at least 100 cm was necessary to keep the basal temperature around values between −5 and −6.5°C in both monitored seasons. The value of −5°C was also found by Kuhn et al. (1998) on an alpine glacier in Austria. The lower rates of cooling and of warming calculated in season 2002–2003 might be attributed to the greater insulating effect of the consistent snow cover. However, it seems that a variation of the air temperature reflects in a variation of the snow/ice interface temperature even with a deep snow cover (period (b) in season 2002–2003 and period (c) in season 2005–2006, when ΔT_i is correlated with ΔT_a).

In period (d) of both seasons isothermal conditions were reached in a very short period (1 day) as a result of the influence of meltwater on the glacier surface. Meltwater is generated at the snow surface by a positive energy balance and percolates downward when its content exceeds the irreducible water content, which is that held within a snow layer by capillary forces (Colbeck, 1976). During spring, net radiation along with sensible and latent heat fluxes are positive in sign and responsible for melting the surface of the snowpack. Here, we consider only sensible heat flux, which is related to air temperature. As the snowpack has temperatures below 0°C, when liquid water infiltrates, that liquid water will freeze, warming up the snow towards 0°C and filling the cold content of the snowpack. The cold content of a snowpack is defined as the amount of energy needed to raise the temperature to 0°C throughout the snowpack, and it is directly proportional to the mass of snow m (U.S. Army Corps of Engineers, 1956). For some unit area, $m = H_{snow} \cdot \rho$, where H_{snow} is the snow depth and ρ the snow density. As the IDP has a higher density than the NDP, considering similar depths, then the mass of the IDP is greater than that of the NDP. Consequently, it will take more meltwater to fill the cold content of that snowpack so that liquid water can reach the base of the snowpack. Therefore, the snow/ice interface temperature raised at a slower rate at the IDP compared to the NDP, assuming the same amount of melt at the surface of each plot.

The very fast reaching of the isothermia in the NDP (which happened in one day) is also the possible reason why for this plot we found no correlation between ΔT_a and ΔT_i in period (d), while the correlation was found in the IDP during the same period.

In both seasons, after a sharp increase of the air temperature, there was again a cooling period (18–20 April in 2002–2003 and 28–31 May in 2005–2006), which, however, had no effect on the snow/ice interface temperature, as the snowpack was already very wet and the predominant factor governing the temperature pattern was the heat driven by meltwater.

The warming rates of the interface temperature in the last period of the seasons (period (d)) were comparable with that recorded also during winter 2006–2007 (+0.22°C d^{-1}), characterized by 125 cm of snow (data not shown).

For both seasons, the heat flux through the snow cover was positive until the end of April, when it changed sign; thus heat flowed from the bottom to the surface of the snow cover during winter, cooling the glacier surface, while it flowed from the surface to the bottom in spring, when the surface layer is heated by the warmer atmosphere and the bottom layer remains colder than the surface.

Snow density is likely to increase in a warmer climate, as higher temperatures may cause wetter snow and increase the frequency of rain-on-snow events (e.g. Rasmus et al., 2004). Rain-on-snow events play a major role in wetting the snow surface and in forming ice crusts, especially during midwinter, when the energy balance is generally unable to generate sufficient snow melt to wet deep snow layers. In regions where such events are very rare under present climate, climate change could increase their frequency and consequently change drastically the structure of the snow cover (Pomeroy and Brun, 2001).

In this study, the increased density in the IDP during winter 2002–2003 might simulate denser snow cover deriving from wetter snowfalls. Here, the IDP, generated by machine grooming, was not able to simulate all the characteristics of a natural snowpack deriving from wetter snowfalls, as the mechanical action limited the natural layering (e.g. formation of ice lenses) and influenced also the natural meltwater flow within the snow cover. However, we could give simple information about how higher density influenced the snow/ice temperature interface.

Because of global warming, there is much interest in studying how the climate change might influence different natural systems. In fact, glaciers are very sensitive to climate change, loosing a considerable amount of their mass every year because of the rising temperatures and reduced snow accumulation. Olefs and Fischer (2008), in a field experiment, found that the snow compaction induced a delay of 4 days in the bare ice exposure in comparison with an undisturbed site. In our study the delay was slightly greater, revealing a modest but significant effect of the increased snow density on ice ablation.

In the future, we plan to measure the heat flux from the glacier to the snow cover to quantify the energy that flows from the glacier into the snow cover. Measurements of air temperature, glacier surface temperature, and glacier temperature at 10 cm depth, already before the first winter snowfalls, might clarify the thermal condition of the glacier. When the air temperature is lower than that of the surface ice, heat may be lost to the atmosphere, thus cooling the ice. Therefore, in areas where there is pronounced seasonal air temperature variation (as in our case), the surface firn of a glacier experiences marked annual changes in temperature, with the firn becoming colder in winter as a *cold wave* penetrates down from the surface (Sverdrup, 1935; Paterson, 1994).

The importance of studying the interaction between glacier and snow cover is also clear when reading the following sentence: "The temperature of the snow that falls on a glacier surface provides a convenient starting point for considering ice temperatures." (Benn and Evans, 1998). This is an ongoing project, which we hope to enrich in the future with the analysis of data from seasons with further meteorological conditions.

Conclusions

The present study aimed to analyze snowpack characteristics on an alpine glacier, with particular interest to the influence of snow depth and snow density on temperature evolution at the snow/ice interface.

The snowpack was characterized by a prevalence of round crystals originated by equi-temperature and melt-freeze metamorphisms in the season rich in snow, while in the season poor in snow depth hoar and faceted crystals prevailed, due to the higher temperature gradient.

From the two considered winter seasons, it appears that a deep snow cover is able to maintain the snow/ice temperature around −5°C until the snow cover reaches isothermal conditions, whereas a shallower snowpack did not allow basal temperature to reach equilibrium values and the temperature oscillated between −2 and −8°C. The increased density caused a greater temperature gradient in the lowest 50 cm but had no effect on the snow/ice interface temperature, whereas it caused a delay in the time of reaching isothermal conditions, thus allowing snow cover on the glacier to persist longer.

Acknowledgments

This study was possible also thanks to the collaboration with Comando Truppe Alpine–Servizio Meteomont, MonterosaSki, Comune di Gressoney-La-Trinité, Alpine Guides of Alagna Valsesia, Ufficio Neve e Valanghe and Centro Funzionale of Regione Autonoma Valle d'Aosta, Emil Squinobal and Hervé Jaccond, to whom we are grateful. Thanks to two anonymous reviewers who gave precious suggestions to improve the manuscript. Manuscript writing was supported in part by the Niwot Ridge Long-Term Ecological Research program, with funding from the National Science Foundation of the U.S.A. (award DEB-0423662).

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MS accepted March 2009