ABSTRACT: Snow temperatures are strictly related to the heat balance of the snowpack and are commonly used to calculate the temperature gradient, which is one of the driving factors for snow metamorphisms. In this work we analyze the snow temperature profiles generated from the continuously recorded data from five automatic weather stations located at an elevation ranging between 2000 and 2800 m asl in Aosta Valley (Northwest Italy) in the period 1998-2009. The aims of this work are: a) to evaluate the influence of solar radiation on snow temperature profiles and on the calculation of thermal gradients; b) to compare the temperature profiles from the automatic weather stations with manually recorded data; c) to define an objective method to define the onset of an isothermal snowpack. We present some scientific findings but also some practical outputs, useful e.g. for the Avalanche Warning Services: a) 60 cm is the surface layer thickness where relevant daily temperature changes occur; b) 8.00 am is the best time to calculate the thermal gradient; c) there is good agreement between the automatic and manual temperature profiles; d) contour plots may be an easy method to assess when the snowpack reaches isothermal conditions.

1. INTRODUCTION

Snow temperatures are strictly related to the heat balance of the snowpack and are commonly used to calculate temperature gradients. Temperature gradients are responsible for the snow metamorphisms which can lead the snowpack towards stability or instability conditions. Therefore, it is common among the Avalanche Warning Services to periodically measure, beside other physical properties, the snow temperature profile in specific locations, in order to know the snowpack structure and its possible evolution.

In some cases, the snow temperatures are continuously registered from automatic weather stations or are calculated by models, which are able to describe the snowpack structure only on the basis of few snow and meteorological data, such as for example air temperature, solar radiation, surface snow temperature (e.g. Brun et al., 1989; Morland et al., 1990; Jordan, 1991; Lehning et al., 1999). It is this last variable that is commonly used by models to determine the thermal gradient within the snowpack. Also when using data from manual snow profiles, the temperature gradient is calculated considering the snow surface temperature, the snow/soil interface temperature and the snow depth.

But the snow surface temperature greatly varies during day and night time. Diurnal temperature fluctuation within the top portion of the snowpack is the result of the net energy balance at the snow surface, which includes different contributions. Among them the most relevant are the radiation fluxes: short wave radiation flux and net long wave radiation flux (Gray and Male, 1981).

McClung and Sharer (1993) suggested that short wave radiations can penetrate within the snowpack to a depth of 10-20 cm. In other works (for ex. Fierz et al., 2008) the same threshold of 20 cm is reported.

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However, the depth of short wave penetration is strictly related to the properties of the surface snowpack layers (Bakermans and Jamieson, 2006). Therefore we think it is not possible to find a general rule to determine the thickness of
the “active layer” anywhere and at any time in the world. Another important question is the time when the snowpack becomes isothermal and then starts to melt producing a water input into the soil and then to water reservoirs. In this work we contribute to these topics presenting our findings based on data recorded in Aosta Valley, in the North-western Italian Alps.

The aims of this work are: a) to evaluate the influence of solar radiation on snow temperature profiles and on the calculation of thermal gradients; b) to compare the temperature profiles from the automatic weather stations with manually recorded data; c) to define an objective method to define the onset of an isothermal snowpack.

2. STUDY AREA

Aosta Valley is a region of about 3000 km² located in NW Italy (Fig. 1). It is a mountainous region with more than 80% of its territory above 1500 m of elevation. The region is characterized by an inner part with low precipitation amount (500 mm/year), while on the border with Switzerland and France are the maximum values recorded (1200 mm/year).

![Aosta Valley map](image)

Figure 1. Study area: Aosta Valley. The dots indicate the location of the automatic snow and weather stations used in this work.

3. DATA COLLECTION

3.1 Automatic weather stations

In Aosta Valley there are 91 automatic weather stations. Beside measuring the classical meteorological parameters (such as precipitation, air temperature, wind speed and direction), 40 of them also measure snow parameters, such as snow depth and in five cases also snow temperatures. In this work we analyzed the data recorded by the following automatic stations (Fig. 1):

1. Courmayeur - Ferrache (2290 m asl), 2001-2009;
2. Courmayeur - Mont de la Saxe (2076 m asl), 1992-2009;
3. La Thuile - La Grande Tête (2430 m asl), 1998-2009;
4. Pré-St-Didier - Plan Praz (2044 m asl), 1992-2009;

Snow temperatures were recorded at 20 cm increments between 0 and 400 cm from the ground with a sampling frequency of 4 hours. Each temperature sensor is rotated 120° compared to the next one, resulting in three different orientations. As a result, the sensor at 400 cm has the same orientation as the one at 340 cm, and at 280 cm, and so on. For the analysis, the 4-hour raw data were used as well as the daily aggregated data.

3.2 Manual snow profiles

Throughout the whole region, snow profiles are periodically made by the Avalanche Warning Service for avalanche danger evaluation. In winter 2008-2009 they were made also close to the automatic weather station of Plan Praz. Therefore, we had the possibility to compare the manual snow temperature profiles with the values registered by the automatic snow temperature sensors. Moreover, we compared these data also with the temperature profiles calculated by the SNOWPACK model (Bartelt and Lehning, 2002; Lehning et al., 2002a and 2002b)

4. DATA ANALYSIS

All data have been analyzed using R software for statistical computing (R development core team, 2010). Before any further analysis, temperature data in the snowpack were checked for drifts/wrong
acquisition by means of a comparison with air temperature data. We first calculated the difference between air $T$ and snow $T$ at each level. We then applied a threshold on the difference of -20 and +30 °C respectively and removed all data falling outside that interval.

### 4.1 Influence of solar radiation on snowpack thermal conditions

The five weather stations used in this study were also equipped with radiometers. To assess the influence of solar radiation on the snowpack temperature, we used either a visual representation based on contour plots or correlation analysis between solar radiation and temperature records. The daily variation of the snow temperature profile, which is primarily driven by the effect of solar radiation, was also visually shown by means of an animated gif image that collates hourly temperature profiles of a given time frame and allows to see the changes in a motion sequence.

### 4.2 Thermal gradient

The snow thermal gradients were calculated in different ways: (1) as a surface gradient according to the following formula:

\[
SG = \frac{(T_0 - T_S)}{H_s}
\]

where $SG$ is the surface gradient (°C/cm), $T_0$ is the temperature at 0 cm depth (snow/soil interface) and $T_S$ is the temperature at the surface; and (2) as a reduced gradient, within 60 cm from the snow surface, according to the formula:

\[
RG = \frac{(T_0 - T_{S-60})}{H_{S-60}}
\]

This so called reduced gradient was meant to represent the internal snow gradient unaffected by the solar radiation.

### 4.3 Isothermal conditions

One main objective of this work was to establish the onset of the isothermal conditions for a given station and year. We used two different approaches: (1) a visual representation of the isothermal conditions by means of contour plots; (2) by finding the time when the thermal gradient equals 0, in its seasonal course.

### 5. RESULTS and DISCUSSION

#### 5.1 Influence of solar radiation on snowpack thermal conditions

Figure 2 illustrates, by means of simple scatter plot, an example of how the radiation influences the temperatures measured by the sensors. When the sensor is in the snow, but within 60 cm from the snow surface, the relationship between solar radiation and snow temperature is still relatively strong, indicating that the radiation penetrates into the snowpack by as much as 60 cm.

![Figure 2](image)

The same finding can be seen in figure 3, where we show a contour plot of the seasonal course of the daily standard deviation (sd) of the snow temperature. The daily sd was used here as an indicator of the effect of solar radiation that influences the daily fluctuation in snow temperature and, hence, impacts on the sd.
Figure 3. Contour plot showing the seasonal course of hydrological year 2002/2003 in Lavancher. The black line denotes the snow depth, while the red dashed lines depicts the 60 cm threshold from the snow surface. The color gradient represents the daily standard deviation of snow temperatures at different heights. Colors between measured points are linearly interpolated.

The blue area in the contour plot represents the portion of the snowpack where the daily sd is approximately lower than 1 °C, and it clearly follow the 60 cm threshold from the snow surface, indicating that only below such level, snow temperature is not affected by the strong daily fluctuations due to solar radiation.

5.2 Thermal gradient

A typical example of the seasonal course of the thermal gradients is shown in figure 4. There is a fairly good agreement between surface (SG) and reduced (RG) gradients. The seasonal pattern indicates slightly negative gradients in Fall, when air temperatures are still positive, maximum gradients between December and March, when air temperatures are well below 0 °C, isothermal conditions in early Spring and again negative gradient later, due to the rising air temperatures and lowering snow depths.

Figure 4: Seasonal course of median daily thermal gradients in Lavancher, year 2008/2009.

Note that figure 4 shows the daily median values, indicating a strong day-by-day variability also using daily aggregation. Diurnal variability of thermal gradients will not be presented visually, but daily CVs may exceed 200%.

By means of simple scatter plots we compared the gradients measured at each of the 4 hour intervals of measurements (12 am, 4 am, 8 am, 12 pm, 4 pm, 8 pm) with the daily median gradients and found that the best estimate of the daily median gradient is the gradient measured at 8 am (Fig. 5).

Figure 5. Relation between median daily surface gradients and gradients measured at 8 am.

The comparison between the snow temperature profiles registered from the automatic weather station of Plan Praz, the data collected with periodically snow pits in 2009 (16th February, 13th and 27th March, 14th April, 5th, 21st and 25th May) and the outputs of the SNOWPACK model is shown in figure 6 (the snowpack in May was isothermal therefore we do not included the last three profiles).

Figure 6. Plan Praz, year 2009: comparison between the snow temperature profiles from the automatic station, snow pits and SNOWPACK.
The shape of the profiles are similar, but the automatic profiles systematically show slightly higher values than the manual snow pits (the difference is however less than 0.5 °C) (Fig. 7).

Figure 7. Scatter plots for the automatic and manually measured snow temperatures.

5.3 Isothermal conditions

The two different approaches we used for establishing the onset of isothermal conditions are illustrated in figure 8. Because of the high variability of thermal gradients we computed a smoothed spline for reducing noise of the measured gradients and then we computed the x coordinate (doy) of the intersection between spline and x axis (0 °C/cm thermal gradient).

Figure 8. Station Mont de la Saxe, year 2002/2003. Contour plot of daily snow temperatures where the dashed blue line is the onset of isothermal conditions set manually looking at the plot itself, while the dashed black line is the onset of isothermal conditions as computed by the thermal gradient (see text for details).

The analysis shown in figure 9 represents the variability of the difference between manually set and computed onset of the isothermal conditions, separated by sites. This analysis shows that the difference may be as high as 60 days (2 months). It furthermore shows that the onset computed from the thermal gradients is systematically lower than the manually placed onset. In three out of five sites this difference is statistically different from 0.

Figure 9. Boxplots showing the difference between manually set and computed onset of isothermal conditions, aggregated by sites. The asterisks denote differences significantly different from 0.

5. DISCUSSION AND CONCLUSIONS

The analysis of this dataset (about 3 millions temperature records, from 5 stations, and on average 10 years time span) is to date the most extensive analysis conducted on this topic and has lead to:

1) Identify a 60 cm threshold where snow temperature is consistently influenced by solar radiation; this threshold must be taken into account while modeling the snow metamorphisms and while measuring snow temperature profiles in the field. The diurnal variability within the snowpack, as determined by the effect of solar radiation may be as much as 10 °C.

2) Temperature profiles measured at 8 am, as already used worldwide as a standard procedure, represent the best estimate of the daily average temperature profile.

3) Thermal gradients within the snowpack vary widely, also when aggregated on a daily basis, due to a combination of solar radiation, temperature fluctuations and changes in snow depth.
4) Snow temperature profiles registered from the automatic weather stations, collected with periodically snow pits and calculated by SNOWPACK have a similar shape (though little shifted) in winter time, while in Spring can present some discrepancies.

5) Contour plots provide an immediate picture of the seasonal pattern of snow temperatures and are a valuable tool to show the onset of the isothermal conditions. In turn, this piece of information may be very important for water management at the regional level, because it indicates that the snow melting front has reached the soil/substrate.

6) The setting of the isothermal conditions based on the thermal gradient looks promising and will be a more objective calculation compared to manual setting, however so far the difference between manually set and computed isothermal conditions is still too high for effectively using it.

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7. REFERENCES


