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Using daily air temperature thresholds to evaluate snow melting occurrence and amount on Alpine glaciers by T-index models: the case study of the Forni Glacier (Italy)

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Abstract. Glacier melt conditions (i.e., null surface temperature and positive energy budget) can be assessed by analyzing data acquired by a supraglacial automatic weather station (AWS), such as the station installed on the surface of Forni Glacier (Italian Alps). When an AWS is not present, the assessment of actual melt conditions and the evaluation of the melt amount is more difficult and simple methods based on T-index (or degree days) models are generally applied. These models require the choice of a correct temperature threshold. In fact, melt does not necessarily occur at daily air temperatures higher than 0 °C. In this paper, we applied both energy budget and T-index approaches with the aim of solving this issue.

We start by distinguishing between the occurrence of snowmelt and the reduction in snow depth due to actual ablation (from snow depth data recorded by a sonic ranger). Then we find the daily average temperature thresholds (by analyzing temperature data acquired by an AWS on Forni Glacier) which, on the one hand, best capture the occurrence of significant snowmelt conditions and, on the other, make it possible, using the T-index, to quantify the actual snow ablation amount. Finally we investigated the applicability of the mean tropospheric lapse rate to reproduce air temperature conditions at the glacier surface starting from data acquired by weather stations located outside the glacier area.

We found that the mean tropospheric lapse rate allows for a good and reliable reconstruction of glacier air temperatures and that the choice of an appropriate temperature threshold in T-index models is a very important issue. From our study, the application of the +0.5 °C temperature threshold allows for a consistent quantification of snow ablation while, instead, for detecting the beginning of the snow melting processes a suitable threshold has proven to be at least −4.6 °C.

1 Introduction

Melting processes at glaciers occur when the surface temperature is equal to 0 °C and the surface energy budget is positive (see, among others, Hock, 2005; Senese et al., 2012a). It is, however, very difficult to assess these conditions, especially if no supraglacial automatic weather station (AWS) is installed and in operation at the glacier surface; thus, simple models are generally adopted which assume empirical relationships between air temperature and snow or ice melting rates (i.e., T-index or degree-day models; see Braithwaite, 1985; Cazorzi and Dalla Fontana, 1996; Hock, 1999; Pellicciotti et al., 2005). Observations based on remote sensing are particularly useful in remote areas with limited in situ observations. Components of mass balance (accumulation and ablation) cannot be measured directly from space (Bamber and Kwok, 2004), but parameters extracted from airborne and spaceborne scanning can be used to estimate glacier-wide mass balances. On the one hand, the remote sensing data provide useful information for glaciological applications such as glacier area, length, surface elevation, surface flow fields, accumulation/ablation rates, albedo, equilibrium line altitude (ELA), accumulation area ratio (AAR) and

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the mass balance gradient $\delta b/\delta z$. On the other hand, ground truth data are generally still crucial for a precise interpretation of remotely sensed data (Koenig et al., 2001). In addition, some limitations in applying these methods are posed by Racoviteanu et al. (2008): (i) lack of standardized image analysis methods for debris-covered ice, (ii) lack of accurate algorithms for automatically distinguishing debris-covered ice from non-ice areas with debris, (iii) limited field validation data (mainly GPS measurements and specific mass balance measurements), (iv) lack of accurate elevation data for remote glacierized areas, and (v) difficulty of acquiring cloud-free satellite scenes at the end of the ablation season. Moreover, these approaches are temporally limited so that a daily resolution cannot be achieved.

Consequently, T-index models provide an easier and more suitable approach for quantifying daily glacier melt whenever a supraglacial AWS is not present. In particular, the degree-day amount during the ablation period should be calculated for any point of the glacier surface. The estimation of the distribution of degree-day amount based on air temperature data acquired by meteorological stations located outside a glacier is not always simple, and the use of an appropriate lapse rate is very important, especially if the meteorological station features a marked difference in elevation with respect to the glacier of interest. Unfortunately, this condition often occurs, as meteorological stations are mainly located close to urbanized areas which are at the foot of the mountain valleys, and only very few glaciers are equipped with AWSs. The availability of a supraglacial AWS is also very important for assessing the presence and persistence of snow cover. This information is particularly valuable during the spring/early summer period (February–June) at the glacier ablation zone, in order to establish in detail if the snow is at the melting point and for how long this phenomenon occurs.

Another very important issue in the application of T-index models is the choice of daily air temperature threshold, for which the most common choice is 0 °C (Braithwaite, 1985; Hock, 2003; Bocchiola et al., 2010). Nevertheless, the melting can occur with daily average temperature not exceeding 0 °C. In fact, there can be days featuring a negative daily air temperature but for a fraction of the time (from a few to several hours) the air temperature being positive (thus giving rise to melt). Moreover, the surface energy balance can be positive even with negative air temperatures (Kuhn, 1987). Then the choice of an appropriate daily air temperature threshold is fundamental for detecting the actual melting days and for evaluating the melt amount. In addition, distinguishing the occurrence of snow melting from the beginning of the actual diminishment of the snowpack is crucial. Despite the fact that snowmelt starts at some point, the melt period is dominated by percolation and refreezing of meltwater, delaying the actual snow loss. Later, the melt process along the snow layer becomes an actual snow ablation and a mass loss. Detecting the occurrence of snowmelt is important, for instance, in studying snow avalanches (e.g., Luckman, 1977) or permafrost phenomena (e.g., Ling and Zhang, 2003). However, in studies aimed at computing the hydrological budget or the glacier mass balance the correct assessment of snow ablation is fundamental (e.g., Hock, 2005). The availability of high-resolution data acquired by the AWS at the Forni Glacier surface made it possible to distinguish these phenomena and the different times of their occurrence, thus also enabling us to look for the specific air temperature thresholds associated with such conditions.

Within this context, here we analyze air temperature conditions and snow depth and SWE (snow water equivalent) data acquired in the period 2006–2012 at the surface of Forni Glacier (Fig. 1) by an automatic weather station. The analysis is aimed at (i) distinguishing between the beginning of snowmelt and the beginning of the actual snow ablation; (ii) finding the best and most suitable daily air temperature thresholds to be applied for estimating the occurrence of snow melting process and for modeling the amounts of snow ablation, and (iii) evaluating the reliability of reconstructions of air temperature conditions at the glacier surface starting from data acquired down valley and shifted to the glacier elevation by applying the mean atmospheric lapse rate.

2 Study area

The Forni Glacier is the largest Italian valley glacier (ca. 11.36 km^2 of surface area; D'Agata et al., 2014) in the Ortles–Cevedale group, Stelvio National Park, central Italian Alps. This glacier is widely debris-free, with only few occurrences of sparse, fine debris and dust at the ice melting surface (Diolaiuti and Smiraglia, 2010; Diolaiuti et al., 2012; Azzoni et al., 2014). It presents a north aspect and an elevation range between 2600 and 3670 m a.s.l. (Fig. 1).

The Forni Glacier is included in the official "Geosites Inventory" of the Sondrio Province, Lombardy Region (Italy) and is located in areas identified as SICs (Sites of Community Importance) according to directive 92/43/CEE. Moreover it is inserted in the list of the glaciers monitored by the Italian Glaciological Committee (CGI) to evaluate its recent volume, area and length changes. The results of this monitoring indicate that the glacier has experienced a strong decrease in area and length: it shrank from 17.80 km^2 at the end of the Little Ice Age (LIA; ∼1860) to 11.36 km^2 in 2007 (−36.2 %), and at the same time its tongue has retreated about 2 km (Diolaiuti and Smiraglia, 2010; D'Agata et al., 2014). At the Forni ablation tongue an AWS has been running (Citterio et al., 2007; Senese et al., 2012a, b) thus providing meteorological and energy data and snow depth information with a hourly resolution. The AWS here located (named AWS1 Forni) is already included in the international meteorological network SHARE (Stations at High Altitude for Research on the Environment; SHARE, 2014) managed by the Ev-K2-CNR and in the former CEOP network (Coordinated Energy and Water Cycle Observation

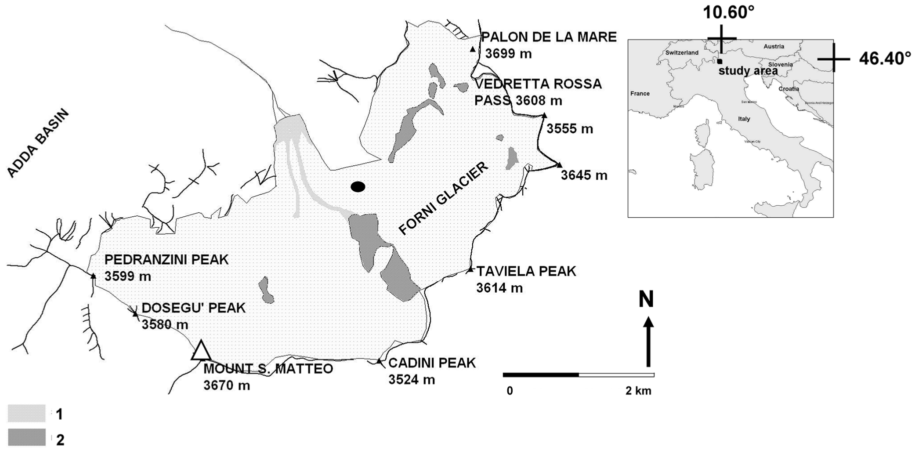

Figure 1. The location of the Forni Glacier and the AWS1 Forni (black dot, WGS84 coordinates: 46°23′56.0′′ N, 10°35′25.2′′ E, geodetic elevation: 2631 m a.s.l.). The light-grey areas (1) are used to mark supraglacial debris coverage and the dark-grey areas (2) indicate rock exposures and nunataks.

Project), promoted by the WCRP (World Climate Research Programme) within the framework of the online GEWEX project (Global Energy and Water Cycle Experiment). The long sequence of snow data also permitted the insertion of the AWS1 Forni into the SPICE (Solid Precipitation Intercomparison Experiment) project managed and promoted by the WMO (World Meteorological Organization). For this experiment another station (named AWS Forni SPICE) was installed on 6 May 2014.

3 Data and methods

The analyses presented in this paper are based on data collected in the period 2006–2012:

1. Data input to the energy balance model (available from 2006 to 2012): hourly air temperature, relative humidity, wind speed, air pressure, solar and infrared radiation (both incoming and outgoing) collected by the supraglacial AWS1 Forni (see Citterio et al., 2007; Senese et al., 2012a, b).

2. Data input to T-index model (available from 2006 to 2012): daily average air temperature records from the supraglacial AWS1 Forni (at 2631 m a.s.l., T_{AWS}), and from a meteorological station located at Bormio, a town at 1225 m a.s.l. and about 20 km from the glacier terminus (Fig. 1); the air temperature data acquired by this second weather station were shifted to the AWS1 Forni elevation by applying the mean tropospheric lapse rate ($-6.5\,^{\circ}\mathrm{C\,km^{-1}}$; the resulting temperature values from here are indicated as T_{B}).

3. Data input to SWE estimation: snow depth from the sonic ranger installed at the AWS1 Forni (available from 2006 to 2010; Fig. 2).

The AWS1 Forni (Fig. 1) was set up at the glacier melting surface on 26 September 2005. It was developed in the framework of the SHARE (Stations at High Altitude for Research on the Environment; SHARE, 2014) program and data are quality checked and validated according to the SHARE (2014) protocol and available to all the scientific community upon request. This data set is practically uninterrupted (since 26 September 2005) with very few gaps (3.05 % of the total period). The Bormio meteorological station is managed by the Lombardy Regional Agency for Environmental Protection (ARPA Lombardia, 2014), which provides data validation and dissemination through a dedicated website.

In this study, we evaluated the length of the melting season and we also distinguished between the occurrence of the snow melting process and the beginning of the actual diminishment of the snow cover. The first one occurs when three conditions are found: positive energy budget, surface temperature at the melting point and surface albedo of snow (this latter was considered higher than 0.4 according to our previous analyses at the Forni Glacier; see further explanations below). Nevertheless, in this period meltwater is affected by surface refreezing or by percolation into the snowpack and then refreezing. This is highlighted by the snow depth data set acquired by the sonic ranger. The actual snow ablation begins when the snow cover curve starts to diminish and from this time, meltwater runoff prevails and the refreezing processes can be considered negligible. Then the snowmelt occurrence with an actual mass loss that is negligible due to the refreezing of the meltwater is inferred only by a positive energy balance and null surface temperature. The period featuring an actual snow ablation is deducted from snow depth trend and by positive energy balance and null surface temperature. The end of these two periods corresponds to the date

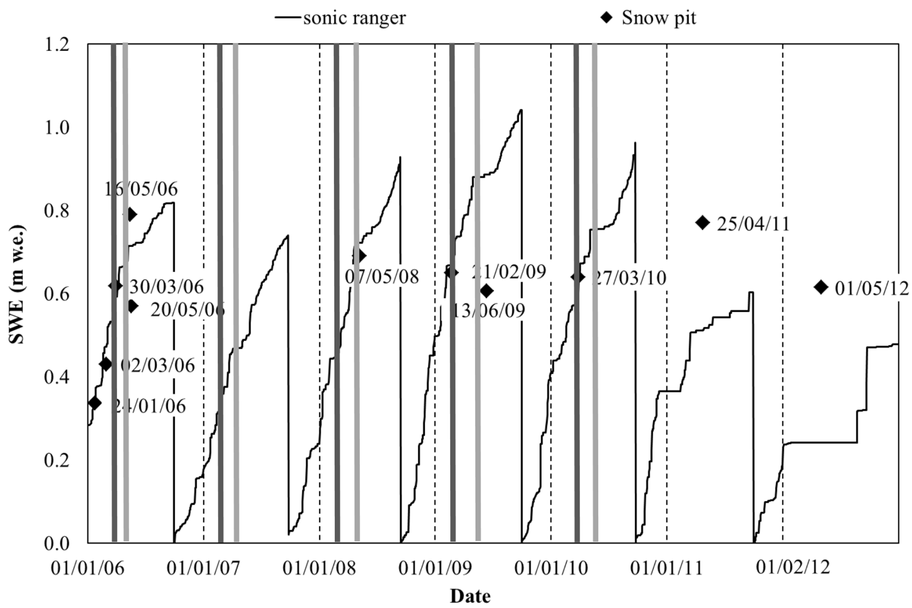

Figure 2. Comparison between SWE measured by sonic ranger and by snow pit from 2006 to 2012. The beginning of the snow melting and the actual snow ablation is shown by light-grey and dark-grey lines, respectively.

with surface albedo value lower than 0.4, thus marking the beginning of the ice melting time.

The albedo values are quantified from the solar radiation measured by the AWS1 Forni (CNR1 net radiometer, Kipp & Zonen):

$$\alpha = \frac{\mathrm{SW_{out}}}{\mathrm{SW_{in}}}, \tag{1}$$

where $\mathrm{SW_{out}}$ corresponds to the reflected shortwave radiation and $\mathrm{SW_{in}}$ to the incoming one (both measured in $\mathrm{W\,m^{-2}}$). The chosen threshold of 0.4 is driven by the reflectivity values generally featured by the ice and the snow. Indeed, in a previous study (see Tables 1 and 3 in Senese et al., 2012a) analyzing data from 2006 to 2009 at the Forni Glacier the mean ice albedo was found to be consistently lower than 0.4.

The snow and ice melting is assessed from the surface energy budget. The net energy (R_S) available for heating the surface and melting snow and/or ice is calculated following Senese et al. (2012a):

$$R_\mathrm{S} = \mathrm{SW_{net}} + \mathrm{LW_{net}} + \mathrm{SH} + \mathrm{LE}, \tag{2}$$

where $\mathrm{SW_{net}}$ and $\mathrm{LW_{net}}$ correspond to the net radiation (shortwave and longwave, respectively), and SH and LE to the sensible and latent heat fluxes. All the fluxes ($\mathrm{W\,m^{-2}}$) were defined positive when directed towards the surface. The conductive heat flux at the surface was not considered since no temperature sensors were located in the snowpack and in the ice surface layer.

Table 1. For each year the following data are shown during snow melting period: cumulative energy budget M_3C value, cumulative energy budget neglecting albedo values (M_EB until 30 June), cumulative energy budget M_PEB, and percentages with respect to the M_3C values. All energy amounts are in megajoule.

Year	Energy budget M_3C	Energy budget M_EB	M_EB percentage with respect to the M_3C	Energy budget M_PEB	M_PEB percentage with respect to the M_3C
2006	384	647	68.3 %	473	23.0 %
2007	340	698	105.3 %	383	12.6 %
2008	282	519	84.1 %	395	40.0 %
2009	538	566	5.2 %	595	10.6 %
2010	516	550	6.7 %	595	15.5 %
2011	457	771	68.9 %	513	12.4 %
2012	322	575	79.0 %	386	20.2 %
TOT	2838	4328	52.5 %	3341	17.7 %
MEAN	405	618	59.6 %	477	17.7 %

The energy is available for melting snow and ice (M_EB) whenever the following two conditions are present:

$$M_\mathrm{EB} = \begin{cases} R_\mathrm{S}, & \text{if } T_\mathrm{S} = 0\,^\circ\mathrm{C} \text{ and } R_\mathrm{S} > 0\,\mathrm{W\,m^{-2}} \\ 0, & \text{if } T_\mathrm{S} < 0\,^\circ\mathrm{C} \text{ or } R_\mathrm{S} \leq 0\,\mathrm{W\,m^{-2}} \end{cases}. \tag{3}$$

Whenever the surface temperature (T_S, derived from outgoing LW data acquired by the AWS1 Forni) is at 0 °C and R_S is positive, the energy is used to melt snow and/or ice. Then the melt amount ($\mathrm{kg\,m^{-2}}$ or mm w.e., water equivalent) can be computed as

$$\mathrm{Melt} = \frac{R_\mathrm{S}}{L_\mathrm{m} \cdot \rho}, \tag{4}$$

where L_m is the latent heat of melting ($3.34 \times 10^5\,\mathrm{J\,kg^{-1}}$) and ρ is the density of water.

The results obtained are considered reliable and indicative of the glacier's actual melt since in a previous paper (Senese et al., 2012a) the melt amount derived from energy budget computations was compared to field measurements of the melt amount at a selection of ablation stakes located near the AWS1 Forni. These two data sets appeared to be strongly correlated (a difference of less than 3 % between the modeled cumulative melt and the measured cumulative one), thus supporting the usefulness of energy budget computation in assessing the actual melt amount.

In addition to M_{EB}, we also calculated two other energy amounts in order to compare them to M_{EB} for assessing the most suitable one in evaluating snowmelt occurrence and amount:

i. The energy available to melt snow whenever three driving conditions are present ($M_{3\mathrm{C}}$): positive energy balance, a surface temperature of 0 °C, and presence of snow found by albedo $(\alpha) > 0.4$:

$$M_{3\mathrm{C}} = \begin{cases} R_\mathrm{S}, & \text{if } T_\mathrm{S} = 0\,^\circ\mathrm{C} \text{ and } R_\mathrm{S} > 0\,\mathrm{W\,m^{-2}} \text{ and } \alpha > 0.4 \\ 0, & \text{if } T_\mathrm{S} < 0\,^\circ\mathrm{C} \text{ or } R_\mathrm{S} \le 0\,\mathrm{W\,m^{-2}} \text{ or } \alpha \le 0.4. \end{cases} \quad (5)$$

ii. The energy available for melt only considering the positive energy budget (M_{PEB}), which is estimated neglecting glacier surface temperature and conditions:

$$M_{\mathrm{PEB}} = \begin{cases} R_\mathrm{S}, & \text{if } R_\mathrm{S} > 0\,\mathrm{W\,m^{-2}} \\ 0, & \text{if } R_\mathrm{S} \le 0\,\mathrm{W\,m^{-2}} \end{cases}. \quad (6)$$

Then we compare the three energy amounts (M_{EB}, $M_{3\mathrm{C}}$ and M_{PEB}) to analyze differences and to find the most suitable for describing snowmelt occurrence and amount.

This computation also represents a verification of the importance of considering the surface temperature in estimating melt from the energy budget. In fact, whenever a supraglacial automatic weather station is not present, almost all the energy fluxes occurring at the glacier surface can be modeled but the surface temperature cannot be quantified. Then, in order to evaluate the reliability of the melt amount computed without considering surface temperature, we calculated the melt amount neglecting the null surface temperature conditions (M_{PEB}).

Finally, the snowmelt is assessed by a T-index model ($M_{T\text{-INDEX}}$) following Braithwaite (1985):

$$M_{T\text{-IDEX}} = \begin{cases} \sum\left[(T_\mathrm{B} - T_\mathrm{t}) \cdot \mathrm{sDDF}\right], & \text{if } T_\mathrm{B} > T_\mathrm{t} \\ 0, & \text{if } T_\mathrm{B} \le T_\mathrm{t} \end{cases}, \quad (7)$$

where T_t corresponds to the daily air temperature threshold (°C) and sDDF to the snow degree-day factor ($\mathrm{mm\,^\circ C^{-1}\,d^{-1}}$). This latter was found considering the degree-day amount (depending on the chosen T_t) and the SWE values estimated from the snow depth data acquired by the sonic ranger considering a fresh snow density of $140\,\mathrm{kg\,m^{-3}}$ (Senese et al., 2012a):

$$\mathrm{sDDF} = \frac{\mathrm{SWE}}{\sum_{1}^{N}(T_\mathrm{B} - T_\mathrm{t})}, \quad (8)$$

where N corresponds to the number of days necessary for melting the whole snow cover (i.e., up to the occurrence of ice albedo).

Both Eqs. (7) and (8) depend on the daily air temperature threshold, thus they give many solutions. In order to detect the most suitable T_t, from 2006 to 2012 we considered hourly $M_{3\mathrm{C}}$ values (obtained from AWS1 Forni data) and studied how long melting occurred in each day (number of hours per day featuring positive energy budget and surface temperature at the melting point). We referred this part of our analysis to the $M_{3\mathrm{C}}$ energy amount and not to the other ones since this is the unique energy computation which assures that snow is present at the glacier surface ($\alpha > 0.4$) thus supporting the reliability of the following results.

Then we evaluated how many days featured null melt ($0\,M_{3\mathrm{C}}\,\mathrm{h\,d^{-1}}$) and how many days featured 4, 6, 12, 18 and 24 melting hours (4, 6, 12, 18 and $24\,M_{3\mathrm{C}}\,\mathrm{h\,d^{-1}}$, respectively). In this way we sorted the days according to the length of the melt process (which can occur during a part of the day or all the time). Then we analyzed the air temperature conditions (mean, maximum and minimum of average daily values) of the different classes (i.e., days without melting, days with at least 4 h of melting, days with at least 6 h of melting, days featuring melting at least half of the time, days with at least 18 h of melting, days with continuous melt) and we also calculated the energy amount occurring in each class to evaluate its role with respect to the total energy available for melting. The minimum temperatures in average daily data found analyzing the different classes represent possible thresholds to be applied to calculate degree days driving snowmelt. This analysis was performed during the snow melting season (detected by $M_{3\mathrm{C}}$ conditions; see Table 2) and during the actual snow ablation period (detected analyzing the sonic ranger data, in particular the snow depletion curve; Table 3). We made several attempts at running the T-index model applying the different temperature threshold values, and the obtained melt amounts ($M_{T\text{-INDEX}}$) were compared with the measured snow ablation (i.e., sonic ranger depletion curve) thus making it possible for us to select the most suitable and useful threshold values.

To validate the SWE estimation, the values calculated from the sonic ranger data set (available from 2006 to 2010) were compared with those observed from snow pit observations performed annually near the AWS1 Forni (Fig. 2). The snow pit data have been provided by personnel from the Centro Nivometeorologico di Bormio of ARPA Lombardia (2014) according to the AINEVA (2014) protocol. The pits were dug annually at the end of the accumulation period (April–May), only in 2007 were no surveys performed.

It is clear that the date when the snow pit is dug is very important for not underestimating the actual accumulation. Whenever the observation is performed before the beginning of the snow ablation (Fig. 2, light-grey lines), there is a very good agreement between the two series of data (i.e., measured and calculated SWE). This confirms the fact that if percolation and refreezing affect the meltwater, the occurrence of the melting processes does not entail an actual mass loss. Otherwise, the SWE values observed after the beginning of the snow ablation appeared to be lower than the modeled ones. During the last 2 years (2011–2012) there were some problems with sonic ranger data acquisition thus making it impossible to elaborate these data. Due to the differences between the measured and the modeled totally cumulative SWE, we preferred to exclude these last 2 years from the analysis, then the T-index computation was performed from 2006 to 2010.

4 Results

4.1 Snow melting process and actual snow ablation at the Forni Glacier

In this study, we distinguished between the beginning of the snowmelt and the beginning of the actual snow ablation. This issue was achieved evaluating the length of the melting season (from AWS energy and meteorological data; see further details in Sect. 4.2) and also distinguishing between the occurrence of the snow melting process (null surface temperature and positive energy budget) and the beginning of the actual diminishment of the snow cover (from snow depletion curve by sonic ranger). The results are reported in Fig. 3. The snow melting proved to start generally earlier, in March (Fig. 3, dark-grey lines), and the meltwater was affected by surface refreezing or by percolation into the snowpack and then refreezing. This is highlighted by the snow depth data set acquired by the sonic ranger: the snow depth tends to increase or to remain almost stable until April/May (even if snowmelt occurs), thereafter it shows a pronounced decrease. Consequently, the actual snow ablation begins later (Fig. 3, light-grey lines), when the snow cover curve starts to diminish (April/May): from this time, meltwater runoff prevails and the refreezing processes can be considered negligible.

4.2 Snow melting occurrence from energy balance

To detect the period featuring the snowmelt we analyzed the energy balance (M_{3C}) estimated at the AWS1 Forni site from hourly meteorological and energy data (Table 1).

The snowmelt period observed (M_{3C}) ranged from 69 to 108 d per year (the beginning of this period is shown with dark-grey lines in Fig. 3) and it was in general shorter than the ice melt period (with an average value of 89 d per year versus 100 d per hydrological year of bare ice melt) with the sole exception of the hydrological year 2009/2010 (101 and 88 d for snow and ice, respectively). Moreover, we found that at the latitude and altitude of the Forni Glacier the snowmelt season generally starts in February/March and finishes in June (Fig. 3).

In order to assess the importance of the conditions concerning the glacier surface temperature, we also performed a test calculating the energy available for ablation whenever the energy balance is positive (M_{PEB}) during the snowmelt period (starting from 1 February and including snow albedo data as well) and not considering the glacier surface temperature. The results were compared with M_{3C} values (Table 1). A total M_{3C} value of 2838 MJ is calculated. This value differs from the M_{PEB}, which is equal to 3341 MJ. This energy difference is equal to an overestimation of snow ablation of up to about 18 %. This is due to the fact that whenever the energy budget is positive but the surface temperature is below 0 °C, the energy input is used to heat up the surface and the melt processes do not occur until the melting point is reached. Without considering surface conditions, all the positive energy budget is used to compute melt thus driving a slight overestimation.

4.3 Daily air temperature thresholds associated with snowmelt conditions

To choose the most suitable daily air temperature threshold (T_t) for detecting the beginning of snowmelt processes, we analyzed T_{AWS} data from 1 February to the end of the snowmelt season (see Table 2).

Days without melting ($0\,M_{3C}\,\mathrm{h\,d^{-1}}$; third column in Table 2) occurred over 37.5 % of the total time frame (February–June over a 7 year period). However, days featuring melting (at least $1\,M_{3C}\,\mathrm{h\,d^{-1}}$, fourth column in Table 2) cover 62.1 % of the total time. These days are characterized by a daily mean value of +0.8 °C, the maximum daily average is +8.9 °C and the minimum daily average −7.4 °C.

Days with continuous and interrupted melting ($24\,M_{3C}\,\mathrm{h\,d^{-1}}$; tenth column in Table 2) occurred 2.0 % of the time and they represent 3.9 % of the whole energy (cumulative M_{3C}: 112 MJ). Days with at least $18\,M_{3C}\,\mathrm{h}$ (ninth column in Table 2) occurred during 15.8 % of the melt period and they represent 24.1 % of the whole energy (cumulative M_{3C}: 684 MJ). Days with at least $12\,M_{3C}\,\mathrm{h}$ (eighth column in Table 2) occurred 36.5 % of the time and represent 56.9 % of the whole energy (cumulative M_{3C}: 1616 MJ). Days with at least $6\,M_{3C}\,\mathrm{h}$ (seventh column in Table 2) occurred 77.9 % of the time and represent 94.8 % of the whole energy (cumulative M_{3C}: 2690 MJ). Days with at least $4\,M_{3C}\,\mathrm{h}$ (sixth column in Table 2) occurred 87.9 % of the time and represent 98.5 % of the whole energy (cumulative M_{3C}: 2796 MJ).

Therefore the largest part of the energy for melt occurred on days with at least 4–6 $M_{3C}\,\mathrm{h}$, thus suggesting that we

Table 2. Number of days, cumulative energy budget (M_{3C}) and daily temperature values (mean, maximum and minimum of the average data) during the snow melting season from 2006 to 2012 considering different temporal length classes of M_{3C} hours per day. The percentage values with an asterisk refer to a period featuring melting (i.e., at least 1 M_{3C} h d^{-1}). The air temperature data are recorded by AWS1 Forni (T_{AWS}).

Snow melting	M_{3C} hours								
Hours per day	All	0	≥ 1	< 4	≥ 4	≥ 6	≥ 12	≥ 18	24
Number of days	970	364	602	73	529	469	220	95	12
Percentage with respect to the total studied period	100.0 %	37.5 %	62.1 %	12.1 %*	87.9 %*	77.9 %*	36.5 %*	15.8 %*	2.0 %*
Cumulative M_{3C} (MJ)	2838	0	2838	42	2796	2690	1616	684	112
Percentage with respect to the total cumulative M_{3C}	100.0 %	0.0 %	100.0 %	1.5 %	98.5 %	94.8 %	56.9 %	24.1 %	3.9 %
Mean average daily T_{AWS} (°C)	−2.8	−8.8	+0.8	−3.8	+1.4	+1.9	+3.7	+3.9	+5.1
Max. of average daily T_{AWS} (°C)	+8.9	+0.9	+8.9	+1.9	+8.9	+8.9	+8.9	+8.9	+8.9
Min. of average daily T_{AWS} (°C)	−21.6	−21.6	−7.4	−7.4	−7.2	−4.6	−1.2	−0.2	+2.3

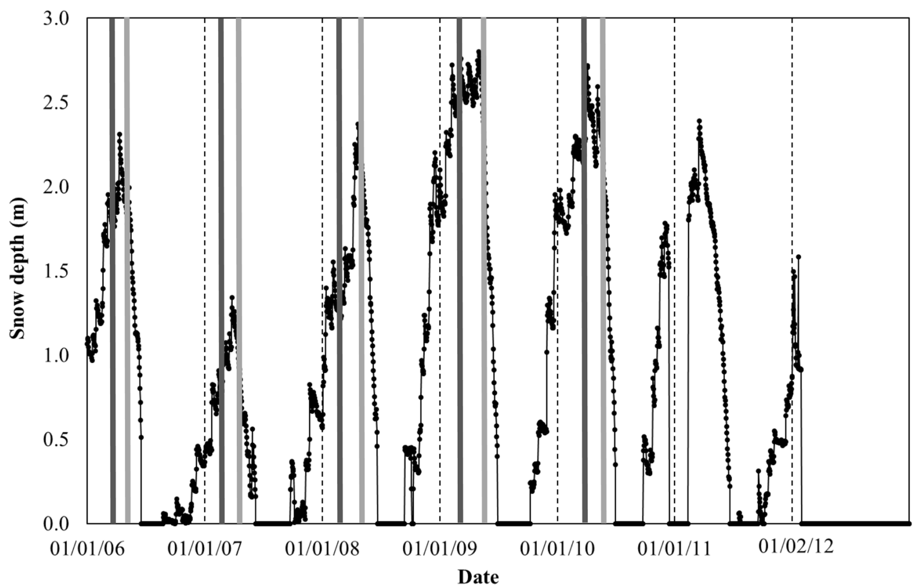

Figure 3. Snow depth data measured by the sonic ranger (Campbell SR50) installed on the mast of the AWS1 Forni. The beginning of the snow melting process is shown with a dark-grey line and the beginning of the actual snow ablation with a light-grey line.

consider daily air temperature data (minimum values) of these classes as suitable T_t (−7.2 and −4.6 °C, respectively).

Then we performed further tests: we applied these T_t values to T_{AWS} air temperature data for detecting the actual melting days and computing their total number (Table 3). The threshold of −7.2 °C (i.e., the minimum daily average temperature calculated for days featuring at least 4 M_{3C} h) allowed us to select 598 melting days (99.2 % with respect to the 602 total melting days). As regards the temperature threshold largely reported in the literature dealing with the T-index model (0 °C; e.g., Braithwaite, 1985; Hock, 2003), our tests indicate that it drives an underestimation of snow melting days. In fact, this value applied to the AWS1 Forni temperature data suggests 347 melting days (57.5 % with respect to the total melting days). Then, in order to detect the beginning of melt processes affecting the snowpack, the most

Table 3. Number of days featuring melting (i.e., at least 1 M_{3C} h d^{-1}) and the percentage with respect to the 602 total melting days.

	Number of melting days	Percentage with respect to the total studied period
$T_t = 0\,°C$	347	57.5 %
$T_t = -7.2\,°C$	598	99.2 %
$T_t = -4.6\,°C$	569	94.4 %
$T_t = -1.0\,°C$	409	67.8 %
$T_t = +0.5\,°C$	353	58.5 %
$T_t = +2.3\,°C$	203	33.7 %

suitable threshold is the value $-7.2\,°C$. This value permits detecting early melt which generally does not result in an actual diminishment of the snowpack but does drive other processes changing the snow's properties (i.e., water percolation and refreezing phenomena, heat exchanges along the snowpack, etc.).

4.4 Daily air temperature thresholds associated with actual snow ablation

The same analyses performed to identify the air temperature thresholds witnessing the snow melting season were carried out to detect the beginning of the actual snow ablation (i.e., when refreezing phenomena become negligible and the melt processes cause a decrease in the volume of the snowpack) as well (see Table 4).

Days without melting (0 M_{3C} h d^{-1}; third column in Table 4) occurred over 1.1 % of the total time frame and days featuring snow ablation (at least 1 M_{3C} h d^{-1}; fourth column in Table 4) cover 98.9 % of the total time with a total ablation of -3.73 m w.e. These days are characterized by a daily mean value of $+3.3\,°C$, the maximum daily average is $+8.9\,°C$ and the minimum daily average $-6.6\,°C$.

Days with continuous and uninterrupted melting (24 M_{3C} h d^{-1}; tenth column in Table 4) represent 6.4 % of the whole ablation (cumulative melt from M_{3C}: -0.24 m w.e.) and occurred over 2.9 % of the total analyzed time.

Days with at least 6 M_{3C} h (seventh column in Table 4) represent 99.2 % of the whole ablation (cumulative melt from M_{3C}: -3.69 m w.e.) and occurred over 93.4 % of the total analyzed time.

Days with at least 4 M_{3C} h (sixth column in Table 4) represent 99.8 % of the whole ablation (cumulative melt from M_{3C}: -3.72 m w.e.) and occurred over 97.1 % of the total analyzed time.

As found when analyzing the conditions dominating the initial phases of the melting period, during the actual snowmelt season the largest part of the ablation proved to occur on days with at least 4–6 M_{3C} h. Then we considered possible thresholds for the minimum daily air temperature calculated for days featuring at least 4–6 M_{3C} h during the actual snow ablation period (Table 4). The suitability of these thresholds for computing snow ablation amount was evaluated by applying a T-index approach (see Sect. 4.6).

4.5 Estimation of supraglacial daily air temperature from data acquired outside the studied glacier

To compute the degree-day amount driving snowmelt we shifted the daily air temperature values measured at Bormio (1225 m a.s.l.) to the AWS1 Forni site elevation (2631 m a.s.l.) applying the mean tropospheric lapse rate ($-6.5\,°C\,km^{-1}$). To validate this temperature reconstruction we made a comparison among modeled daily air temperature values (T_B) with air temperatures actually measured at the AWS1 Forni (T_{AWS}) from 2006 to 2012 (Fig. 4, black dot). It showed a strong agreement between the two data records ($r = 0.94$) with a root mean square error (RMSE) of the modeled temperature equal to 2.64 °C. Considering only the snowmelt period (i.e., February–June), the RMSE value is 2.37 °C (Fig. 4, white dot). Moreover, the slope coefficient of the linear regression between measured and modeled temperatures at the AWS1 Forni site turns out to be very close to 1 (see Fig. 4). These findings suggest that it is also possible to perform a reasonable reconstruction of the supraglacial daily average air temperature starting from meteorological data acquired down valley using a mean tropospheric vertical gradient as lapse rate.

4.6 Calculation of actual snow ablation using the T-index model

The calculation of snow ablation amount by means of the T-index model ($M_{T\text{-INDEX}}$) was performed by applying the air temperature thresholds (T_t) found in Table 4. The T_B data represent the input values needed to calculate the total degree days driving snow ablation. We focused on melt periods from 2006 to 2010 (Fig. 5). We analyzed a period shorter than the whole data set (2006–2012) because for the last 2 years, snow pits were not dug at the end of the accumulation season, thus making it impossible to validate the snow depth records obtained from sonic ranger measurements. For this reason, we preferred to make our analysis cover a shorter time frame, but one featuring validated and crosschecked snow depth and SWE data.

The following thresholds were applied: the most common and applied value (0 °C; Fig. 5a), the minimum daily average temperature calculated for days featuring at least 4–6 M_{3C} h ($-4.6\,°C$; Fig. 5b), the minimum daily average temperature calculated for days featuring at least 12 M_{3C} h ($-1.0\,°C$; Fig. 5c), the minimum daily average temperature calculated for days featuring at least 18 M_{3C} h ($+0.5\,°C$; Fig. 5d), and

Table 4. Number of days and daily temperature values (mean, maximum and minimum of the average data) during an actual snow ablation period from 2006 to 2010 (i.e., the time frame between the beginning of the diminishment of the snow depth indicated by sonic ranger data and bare ice exposure derived from albedo values) considering different temporal length classes of M_{3C} hours per day. The air temperature data are recorded by AWS1 Forni (T_{AWS}). The bold values are the ones chosen as possible T_t in the T-index model for estimating actual snow ablation.

Actual snow ablation	M_{3C} hours								
Hours per day	All	0	≥ 1	< 4	≥ 4	≥ 6	≥ 12	≥ 18	24
Number of days	272	3	269	5	264	254	149	64	8
Percentage with respect to the total studied period	100.0 %	1.1 %	98.9 %	1.8 %	97.1 %	93.4 %	54.8 %	23.5 %	2.9 %
Cumulative SWE (m w.e.; value from the sonic ranger records, the distribution over the length classes is evaluated through M_{3C} computation)	−3.73	0.00	−3.73	−0.01	−3.72	−3.69	−3.05	−1.30	−0.24
Percentage with respect to the total cumulative SWE (m w.e.)	100.0 %	0.0 %	100.0 %	0.2 %	99.8 %	99.2 %	82.0 %	34.9 %	6.4 %
Mean average daily T_{AWS} (°C)	+3.2	−2.9	+3.3	−1.4	+3.4	+3.4	+4.4	+4.4	+5.7
Max. of average daily T_{AWS} (°C)	+8.9	+0.9	+8.9	+1.9	+8.9	+8.9	+8.9	+8.9	+8.9
Min. of average daily T_{AWS} (°C)	−6.6	−5.5	−6.6	−6.6	**−4.6**	**−4.6**	**−1.0**	**+0.5**	**+2.3**

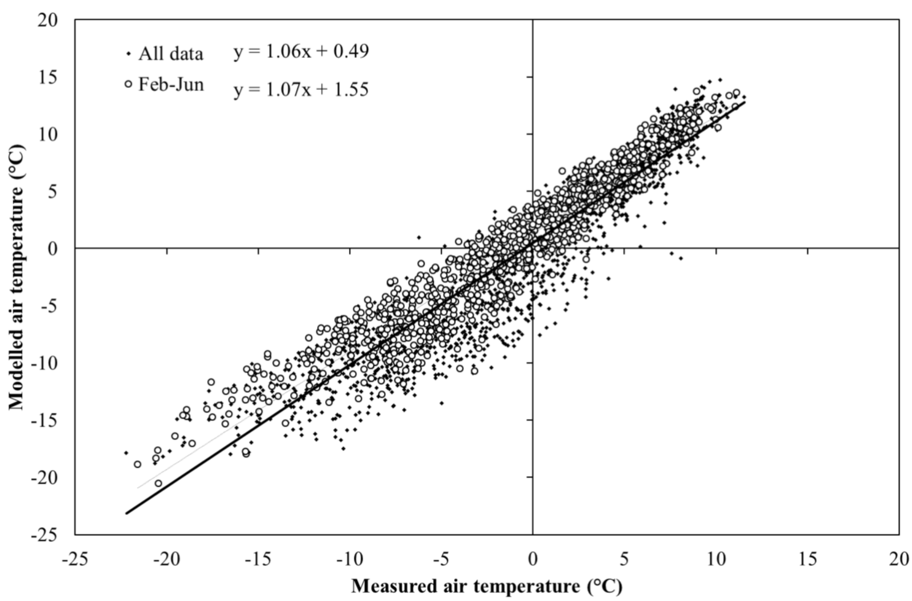

Figure 4. Daily temperatures recorded by the AWS1 Forni (T_{AWS}) from 2006 to 2012 (x axis) vs. the modeled ones (T_B, y axis) derived from Bormio data shifted to the AWS1 Forni elevation through the application of the mean tropospheric lapse rate.

the minimum daily average temperature calculated for days featuring 24 M_{3C} h (+2.3 °C; Fig. 5e).

We found that the snow ablation obtained with the threshold of +0.5 °C more closely corresponded to the measured SWE value compared to the other T_t values (Table 5). A good agreement was also found with the most common and applied threshold (0 °C).

Therefore, whoever needs to evaluate the actual snowmelt amount (SWE) without any further considerations on the persistence and duration of melt processes over time has to apply

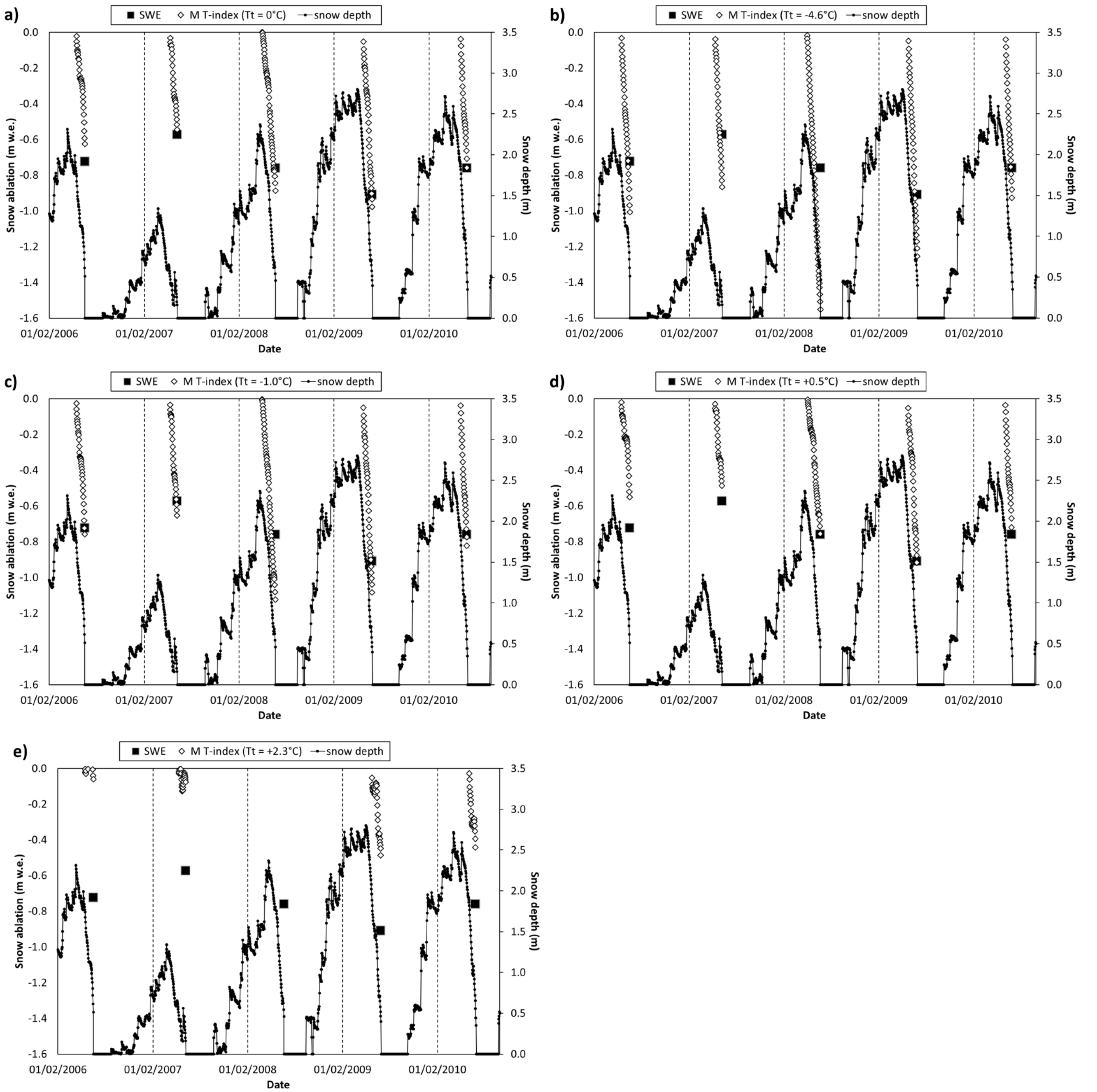

Figure 5. Comparison between snow ablation measured by sonic ranger (SWE) and estimated by T-index approaches from 2006 to 2012. The results from the T-index model ($M_{T\text{-INDEX}}$) were obtained by applying different temperature thresholds to T_B data: 0 °C **(a)**, −4.6 °C **(b)**, −1.0 °C **(c)**, +0.5 °C **(d)** and +2.3 °C **(e)**. The trend of the snow depth measured by sonic ranger is shown as well.

an air temperature threshold of about 0 °C otherwise there is a risk of overestimation.

5 Discussion

In this study we used daily air temperature values measured at Bormio (1225 m a.s.l.) and shifted to the AWS1 Forni site elevation (2631 m a.s.l.) applying the mean tropospheric lapse rate (−6.5 °C km^{-1}). We chose the Bormio temperature record since an analysis of the 2006–2012 data set shows that this town is not affected by thermal inversion, unlike other stations located nearby and included in the ARPA Lombardia (2014) meteorological network (e.g., the AWS at Santa Caterina Valfurva at 1730 m a.s.l., and the one located

Table 5. The total amount of snow ablation during the actual snow ablation season over the 2006–2010 period measured by sonic ranger (SWE) and calculated by the T-index considering different daily air temperature thresholds (T_t).

	Snow ablation (m w.e.)
SWE	−3.73
$M_{T\text{-INDEX}}$ ($T_t = 0\,°C$)	−3.79
$M_{T\text{-INDEX}}$ ($T_t = -4.6\,°C$)	−5.61
$M_{T\text{-INDEX}}$ ($T_t = -1.0\,°C$)	−4.44
$M_{T\text{-INDEX}}$ ($T_t = +0.5\,°C$)	−3.43
$M_{T\text{-INDEX}}$ ($T_t = +2.3\,°C$)	−0.93

at the dam of the Frodolfo stream at 2180 m a.s.l.). Santa Caterina Valfurva and the Frodolfo dam AWSs are found to be affected by thermal inversion for about 9 and 1 % of the analyzed period, respectively.

The modeled daily temperatures were found in agreement with the measured data set thus suggesting that the meteorological data acquired down valley and the mean tropospheric vertical gradient as lapse rate give the possibility to perform a reasonable reconstruction of the supraglacial daily average air temperature. Nevertheless this result could depend on the small distance (ca. 20 km) between Bormio and the Forni Glacier. In fact, whenever temperature data are acquired by weather stations located farther and farther from the glacier site, the assessment of a local daily vertical gradient could be needed to reconstruct the supraglacial air temperature and degree-day amount.

From our analyses, it appears that the greatest uncertainty in computing the degree-day amount at the glacier surface and then in assessing snowmelt is represented by the choice of an appropriate air temperature threshold (T_t).

Our results suggest that in cases where the main purpose is only to detect the occurrence of snow melting and not to assess the actual snow ablation amount, the application of the 0 °C threshold does not represent the most suitable and exhaustive solution, and may give rise to an underestimation of up to 40 % of the total melting days in the February–June period. Conversely when the main aim is to assess the snow ablation amount, the most suitable threshold is closed to 0 °C (Table 5).

Our findings are in agreement with van den Broeke et al. (2010), who modeled the ablation at the Greenland ice sheet. They found a threshold value that was about −5 °C by observing the cumulative distribution of daily average temperatures for days with melt at three AWSs. From their study this value proved also to allow for an appropriate calculation of snow and ice degree-day factors. In fact, applying the common 0 °C threshold, they obtained meaningless degree-day factor values.

Table 6. Mean degree-day factors for snow melting from the literature and from our results.

	sDDF ($mm\,d^{-1}\,K^{-1}$)	
De Quervain (1979)	4.2	
Van de Wal (1992)	2.8	
Hock (1999)	3.2	
Hock (2003)	5.1	
Braithwaite (2008)	3.5	(1) Winter balance
Braithwaite (2008)	4.6	(2) Winter balance plus precipitation
Braithwaite (2008)	4.1	(1) and (2) combined
Our results (actual snow ablation)		
$T_t = 0\,°C$	4.3	
$T_t = -4.6\,°C$	2.3	
$T_t = -1.0\,°C$	3.6	
$T_t = +0.5\,°C$	4.6	
$T_t = +2.3\,°C$	7.1	

Another issue to be considered is the opportunity to analyze SWE on 1 April, the date largely considered the most indicative of the cumulative SWE in high mountain environments of the midlatitudes. Surely this is a suitable date for performing snow pits in order to assess the whole glacier accumulation amount (see Bohr and Aguado, 2001) but this date is not always the best one for starting the melting computation. In fact, our tests revealed that M_{3C} computed from 1 April gave a total snow ablation of 1.15 in 2006, 1.00 in 2007, 0.84 in 2008, 1.61 in 2009 and 1.54 in 2010. The actual ablation derived from sonic ranger depletion curves was instead 0.72 in 2006, 0.57 in 2007, 0.76 in 2008, 0.91 in 2009 and 0.76 in 2010 with a mean overestimation of the actual ablation of 65.1 %, thus suggesting that to use a fixed date for starting the snowmelt computation is not the most suitable solution and that a correct temperature threshold can help in detecting the most appropriate time window of analysis indicating the starting time of snow melting processes.

Finally, some attention has to be given to the snow DDF (see Eq. 8) values. The sDDF values we found, ranging from 2.3 to 7.1 $mm\,d^{-1}\,°C^{-1}$, are in agreement with findings in other studies (see Table 6): Hock (2003) reported sDDF values ranging from 2.5 (Clyde, 1931) to 11.6 $mm\,d^{-1}\,°C^{-1}$ (Kayastha et al., 2000) and Braithwaite (2008, 2011) suggested values from 3.5 to 4.6 $mm\,d^{-1}\,°C^{-1}$.

With a lower temperature threshold the snow degree-day factor (Table 6) proves lower than the ones derived by applying higher thresholds. The value obtained with T_t of −4.6 °C (2.3 $mm\,d^{-1}\,°C^{-1}$) is comparable in magnitude with the ones reported by van de Broeke et al. (2010) applying a threshold of −5 °C to Greenland data. These authors also found smaller snow DDF values occurring with a T_t 5 °C lower than the 0 °C value.

6 Conclusions

Our analysis underlines the fact that, in spite of the early beginning of the snowmelt processes at the glacier surface (which the analyzed time frame shows occurring from February to March), the actual snow ablation takes place only later, thus requiring different strategies for the correct detection of both of these phenomena. In particular, to detect the first occurrence of the snowmelt a suitable strategy is to look for days featuring a minimum daily air temperature of at least $-4.6\,°\mathrm{C}$ (the 94.4 % of the total melting days). Instead, to assess the snow ablation amount, the best solution is to take a T-index approach based on a temperature threshold of $+0.5\,°\mathrm{C}$. These values were found by analyzing both energy and meteorological data acquired by a supraglacial AWS located on the melting tongue of the widest Italian valley glacier, although the same approach can be applied to temperature data sets acquired by meteorological stations located outside glaciers (thus extending the applicability and replicability of our analysis) by using a general temperature lapse rate of $-0.65\,°\mathrm{C\,km^{-1}}$, which we found to provide a reliable temperature reconstruction. Our analysis also underlines the fact that the correct energy amount driving snowmelt is the one computed considering three constrictions: albedo higher than 0.4, null surface temperature and positive energy budget. In particular, an overestimation of up to 18% resulted from neglecting null surface temperature (M_{PEB}) and of up to 52 % if albedo was not considered (from M_{EB} energy data until 30 June).

Moreover, T_{S} and α are available only on a small number of glaciers where supraglacial AWSs have been in operation, thus suggesting that it is necessary to look for different strategies in order to assess the snow ablation amount. The most diffuse and simple method is the T-index approach based on data acquired outside the studied glacier. This method yields a reliable reconstruction whenever a correct air temperature threshold is adopted.

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