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Air temperature thresholds to evaluate snow melting at the surface of Alpine glaciers by T-index models: the case study of Forni Glacier (Italy)

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Abstract

The glacier melt conditions (i.e.: null surface temperature and positive energy budget) can be assessed by analyzing meteorological and energy data acquired by a supraglacial Automatic Weather Station (AWS). In the case this latter is not present the assessment of actual melting conditions and the evaluation of the melt amount is 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 273.15 K.

In this paper, to detect the most indicative threshold witnessing melt conditions in the April–June period, we have analyzed air temperature data recorded from 2006 to 2012 by a supraglacial AWS set up at 2631 m a.s.l. on the ablation tongue of the Forni Glacier (Italian Alps), and by a weather station located outside the studied glacier (at Bormio, a village at 1225 m a.s.l.). Moreover we have evaluated the glacier energy budget and the Snow Water Equivalent (SWE) values during this time-frame. Then the snow ablation amount was estimated both from the surface energy balance (from supraglacial AWS data) and from T-index method (from Bormio data, applying the mean tropospheric lapse rate and varying the air temperature threshold) and the results were compared. We found that the mean tropospheric lapse rate permits a good and reliable reconstruction of glacier air temperatures and the major uncertainty in the computation of snow melt is driven by the choice of an appropriate temperature threshold. From our study using a 5.0 K lower threshold value (with respect to the largely applied 273.15 K) permits the most reliable reconstruction of glacier melt.

1 Introduction and study aims

Melting processes at glaciers occur when surface temperature is equal to 273.15 K and the surface energy budget is positive (e.g. Hock, 2005; Senese et al., 2012a). It is however very difficult assessing these conditions, in particular whenever a supraglacial Au-

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tomatic Weather Station (AWS) is not located and running 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 Days models e.g. Braithwaite, 1985; Cazorzi and Dalla Fontana, 1996; Hock, 1999; Pellicciotti et al., 2005). The degree days amount during the ablation period have naturally to be calculated for any point of the glacier surface. The estimation of distributed degree days amount from 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 used meteorological station features a strong elevation difference with respect to the studied glacier. Unfortunately this condition often occurs as meteorological stations are mainly located close to urbanized areas which are at bottom of mountain valleys and only a small number of glaciers are equipped with AWSs. The availability of a supraglacial AWS is also very useful in order to assess presence and persistence of snow cover. These information are particularly useful in the case of late spring/early summer time (April–June) at the glacier ablation zone in order to establish in detail if snow is at the melting point and how long this phenomenon occurs.

A further very important issue in the application of T-index models is the air temperature threshold adopted for melting conditions: generally a daily average value of 273.15 K is used (Braithwaite, 1985; Hock, 2003; Bocchiola et al., 2010). This assumption neglects the fact that melting does not necessarily occur only when daily average temperature exceeds 273.15 K, and there can be days featuring a negative average temperature value but experiencing a fraction of the time (from a few to several hours) with positive air temperature (thus driving melt). Moreover the surface energy balance can be positive also with negative air temperature (Kuhn, 1987). Then the choice of an appropriate air temperature threshold is fundamental to detect the actual melting days and to evaluate the melt amount.

Within this context the aim of this paper is to investigate the relationship between degree days amount and melting processes considering a 7 year period of measures on the Forni Glacier which is the largest Italian valley glacier (Fig. 1). It is widely debrisfree, even if darkening phenomena are shown (Diolaiuti and Smiraglia, 2010; Diolaiuti et al., 2012). The measures were performed both by means of a supraglacial AWS (named AWS1 Forni, see Citterio et al., 2007; Senese et al., 2012a, b) and by field surveys (i.e. snow pits and ablation stakes). The goal of the research is to contribute better understanding the use of T-index models focusing on the air temperature threshold. Moreover we aim at evaluating the performances that can be achieved using meteorological stations located outside the glacier to reconstruct supraglacial air temperature conditions.

2 Data and methods

The analyses presented in this paper are based on data collected in the 2005–2012 period:

1. daily average air temperature records (T_{AWS}) collected by a supraglacial AWS, the AWS1 Forni at 2631 m a.s.l., and by a meteorological station located at Bormio, a village at 1225 m a.s.l. and about 20 km far 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 K km^{-1}, the resulting temperature values are indicated T_{B} from here).

2. Hourly air temperature, relative humidity, wind speed, air pressure, solar and infrared radiation (both incoming and outgoing) data collected by the AWS1 Forni.

3. Snow pits annually performed nearby the AWS1 Forni.

The AWS1 Forni (Fig. 1) was set up on the glacier melting tongue on 26 September 2005. It was developed in the framework of the SHARE (Stations at High Altitude for Research on the Environment) program and data are quality checked and validated according to the SHARE protocol and available to all the scientific community upon request. This dataset is quite uninterrupted (from 26 September 2005 up to now) with very few gaps (3.05 % of the total period). In this study the time frame from 1 October 2005 to 31 December 2012 is analysed. The Bormio meteorological station is managed by the Lombardy Regional Agency for Environmental Protection (ARPA Lombardia), which takes care data validation and disseminates the data through a dedicated web site. The snow pit data have been provided by personnel from the Centro Nivometeorologico di Bormio of ARPA Lombardia according to the AINEVA protocol. The pits were annually dug at the end of the accumulation period (April–May), only in 2007 no surveys were performed.

The snow and ice melting is assessed from surface energy budget (Melt from Energy Budget, M_{EB}, calculated from AWS1 Forni data). The net energy (R_{S}) available for heating the surface and melting snow and/or ice is calculated following Senese et al. (2012a):

$$R_{\mathrm{S}} = \mathrm{SW}_{\mathrm{net}} + \mathrm{LW}_{\mathrm{net}} + \mathrm{SH} + \mathrm{LE} \tag{1}$$

where $\mathrm{SW}_{\mathrm{net}}$ and $\mathrm{LW}_{\mathrm{net}}$ correspond to the net radiation (shortwave and longwave, respectively), 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 neglected since no temperature sensors were located in the snowpack and in the ice surface layer.

The melt amount (M_{EB}, $\mathrm{kg\,m^{-2}}$ or mm w.e.) was obtained from:

$$M_{\mathrm{EB}} = \begin{cases} -\frac{R_{\mathrm{S}}}{L_{\mathrm{m}}}, & T_{\mathrm{S}} = 273.15\,\mathrm{K} \text{ and } R_{\mathrm{S}} > 0\,\mathrm{W\,m^{-2}} \\ 0, & T_{\mathrm{S}} < 273.15\,\mathrm{K} \text{ or } R_{\mathrm{S}} \leq 0\,\mathrm{W\,m^{-2}} \end{cases} \tag{2}$$

where L_{m} is the latent heat of melting ($3.34 \times 10^{5}\,\mathrm{J\,kg^{-1}}$). Whenever the surface temperature (T_{S} derived from outgoing LW data acquired by the AWS1 Forni) is at 273.15 K and R_{S} is positive, the melt amount (M_{EB}) is quantified. The obtained results are considered reliable and indicative of the glacier actual melt since in a previous paper (Senese et al., 2012a) the melt amount derived from energy budget computations has been compared to the melt amount measured on the field at a selection of ablation stakes located nearby the AWS1 Forni. These two dataset resulted strongly correlated (less than 3 % of difference between modelled cumulative melt and measured cumulative one) thus supporting the application of energy budget computation to assess the actual melt amount. Besides to M_{EB} we calculated also other two mass loss amounts: (i) melt occurred with 3 driving Conditions (M_{3C}) which corresponds to the snow ablation during days featuring positive energy balance, surface temperature of 273.15 K, and albedo (α, from here) > 0.4:

$$M_{3C} = \begin{cases} -\frac{R_S}{L_m}, & T_S = 273.15\,\mathrm{K} \text{ and } R_S > 0\,\mathrm{W\,m^{-2}} \text{ and } \alpha > 0.4 \\ 0, & T_S < 273.15\,\mathrm{K} \text{ or } R_S \leq 0\,\mathrm{W\,m^{-2}} \text{ or } \alpha \leq 0.4 \end{cases} \tag{3}$$

(ii) Melt evaluated only considering the Positive Energy Budget (M_{PEB}) which is estimated neglecting glacier surface temperature and conditions:

$$M_{PEB} = \begin{cases} -\frac{R_S}{L_m}, & R_S > 0\,\mathrm{W\,m^{-2}} \\ 0, & R_S \leq 0\,\mathrm{W\,m^{-2}} \end{cases} \tag{4}$$

The snow melting is also assessed by a T-index model ($M_{T\text{-}INDEX}$) following Braithwaite (1985):

$$M_{T\text{-}INDEX} = \begin{cases} \sum T \cdot \mathrm{DDF}, & T > T_t \\ 0, & T \leq T_t \end{cases} \tag{5}$$

where T_t corresponds to the air temperature threshold (K) adopted by the model and DDF to the degree-day factor ($\mathrm{mm\,K^{-1}\,d^{-1}}$). The applied temperature data were T_B.

The snow Degree-Day Factor (sDDF) was found considering the degree days amount and the Snow Water Equivalent (SWE) values estimated from snow pits performed nearby the AWS1 Forni. The presence of snow or bare ice was deducted from albedo data (from AWS1 Forni) and then the length of the snow coverage period. In fact, the SWE was considered completely melted when the albedo becomes lower than 0.4. Finally the sDDF was calculated as:

$$\mathrm{sDDF} = \frac{\mathrm{SWE}}{\mathrm{DD_{glacier}}} \tag{6}$$

where $\mathrm{DD_{glacier}}$ is the sum of Degree Days (from T_B data) in the time frame between a snow pit survey and the occurrence of ice albedo. Moreover we also considered different air temperature thresholds.

We chose Bormio temperature record since this village is less affected by thermal inversion than other stations located nearby and inserted in the ARPA Lombardia meteorological network. By comparing T_B data with data actually measured by the AWS1 Forni (Fig. 2) a high correlation value results as well ($r = 0.91$), with a root mean square error of the modelled temperature slightly over 3 K. Moreover the slope coefficient of the linear regression between measured and modelled temperatures at the AWS1 Forni site turns out to be very close to 1 (see Fig. 2).

In order to detect the most suitable daily temperature threshold (T_t) to adopt in the T-index model for quantifying glacier melting in the April–June period, we considered hourly M_EB values (obtained from AWS1 Forni data) and studied how long ablation occurred in each day (number of hours per day). Then we sorted these data according to temporal length classes (0, 4, 6, 12 and 24 melting hours per day). For each class we calculated the mean, maximum and minimum values of daily average air temperature from T_AWS and T_B data. These temperature data represent possible thresholds to be applied to calculate degree days driving snow melt. We performed several attempts of running the T-index model by applying the different temperature threshold values and the obtained melt amounts ($M_\mathrm{T\text{-}INDEX}$) were compared with the ones from energy budget computation (M_EB) thus permitting to select the most suitable and performing threshold values.

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3 Results

3.1 Melting from energy balance

Melting at the AWS1 Forni site estimated from the energy balance is shown in Fig. 4. M_{EB} was obtained considering only hours characterized by null (273.15 K) surface temperature and positive energy budget. The time window of our analysis is scheduled according to the hydrological year (i.e. at Mid-latitudes from 1 October of the year x to 30 September of the year $x+1$). It results a total M_{EB} of −37.5 m w.e. over a 7 year period.

Supraglacial albedo data permit to detect snow cover presence ($\alpha > 0.4$) during days featuring both positive energy balance and surface temperature of 273.15 K. The occurrence of these three criteria (ranging from 69 to 108 days per year) allows calculation of M_{3C} (light grey bars in Fig. 3) which is found not negligible with a melt amount from 17.6 % to 29.2 % of the total annual value. In general the ice melting period (dark grey bars in Fig. 3) results longer (with an average value of 100 days per hydrological year) than the M_{3C} time frame (89 days per year mean value) with the unique exception of the hydrological year 2009/2010 (88 and 101 days for ice and snow, respectively).

In order to assess the importance of the condition concerning glacier surface temperature, we also performed a test calculating ablation (M_{PEB}) only from positive energy balance data during April–June period (91 days long) and not considering glacier surface temperature. The results were compared with M_{EB} values (Table 1). Totally a M_{EB} for the April–June period over the time window 2006–2012 of −12.72 m w.e. is calculated. This value differs from the M_{PEB} which results equal to −13.43 m w.e.

The quite wide range of variability of our results suggests further analyses. In fact, the April–June M_{EB} corresponds to ca. 1/3 of the total M_{EB} (Table 1). Focusing on this period we found the most intense ablation occurred in 2011 (−2.26 m w.e. contributing for 43.5 % with respect to the total M_{EB} for that year) and the minimum was found in 2008 (−1.55 m w.e., 31.0 % of the annual value).

3.2 Daily air temperature thresholds witnessing glacier melting in the April–June period

To choose the most suitable daily air temperature threshold (T_t) to detect melting days in the April–June period and to evaluate the corresponding melting amount by T-index model we analysed T_{AWS} and T_B data (see Table 2).

Days without melting (0 M_{EB} hours per day, 3rd column in Table 2) resulted occurring over 4.9 % of the total time frame (April–June over a 7 year long period). On the other hand, days featuring continuous and uninterrupted melting (24 M_{EB} hours per day, 8th column in Table 2) cover 3.3 % of the total time. The cumulative melt occurred over these 21 days is equal to −0.77 m w.e. and it represents only the 6.0 % of the total loss. These days are characterized by daily air temperature at AWS1 Forni always positive with a daily mean value of 278.6 K, the maximum of daily average data equal to 282.1 K and the minimum of daily average values of 275.5 K. T_B data over the same time frames are characterized by a mean daily average of 279.8 K, a maximum of daily average of 284.6 K and a minimum daily temperature of 274.7 K.

Days with at least 12 M_{EB} hours (7th column in Table 2) occurred on the 47.3 % of the total analyzed time and they represent the 73.3 % of the whole ablation (cumulative M_{EB}: −9.30 m w.e.).

Days with at least 6 M_{EB} hours (6th column in Table 2) occurred on the 83.8 % of the total analyzed time and they represent the 97.7 % of the whole ablation (cumulative M_{EB}: −12.43 m w.e.).

Then the largest part of the melt resulted occurring on days with at least 6 M_{EB} hours thus suggesting to consider temperature data calculated for this class as suitable T_t. In particular the minimum value of the average daily temperature calculated with at least 6 M_{EB} hours per day (268.6 K and 268.1 K considering the T_{AWS} and T_B data, respectively) were applied to detect the actual melting days. The first threshold was applied to T_{AWS} data and permitted to select 586 melting days describing the 99.4 % (−12.64 m w.e.) of the total M_{EB}. Considering T_B data, the threshold of 268.1 K permitted to detect 601 melting days giving a cumulative M_{EB} of −12.66 m w.e. equal to 99.5 % of the total.

From our results it is also clear that the use of the 273.15 K as temperature threshold drives an underestimation of ablation. In fact, this value applied to the AWS1 Forni temperature data allows to detect 421 melting days (66.1 % with respect to the total time frame) equal to a cumulative M_{EB} of −11.39 m w.e. (89.5 % with respect to the total melt). The same threshold applied to the T_B data allowed to select 481 melting days giving a M_{EB} of −12.00 m w.e. (94.3 % with respect to the total value).

In both cases the application of 273.15 K threshold does not represent the most suitable and exhaustive solution and an underestimation up to 10 % of the total M_{EB} in the April–June period can occur.

3.3 Melt calculation from T-index model

Besides the calculation of snow and ice melting by means of the energy balance, the snow daily melting rate at the AWS1 Forni site was also calculated by applying the T-index model ($M_{T\text{-}INDEX}$). T_B data represent the input values to calculate the degree days sum driving snow ablation. We focused on melting in the April–June period from 2006 to 2012.

Different temperature thresholds (T_t) estimated from T_B data were used: the most common and applied value (273.15 K), the minimum of daily average temperature calculated for days featuring at least 6 M_{EB} hours (268.1 K) and the minimum daily average temperature calculated for days featuring 24 M_{EB} hours (274.7 K). By comparing the cumulative $M_{T\text{-}INDEX}$ curves (Fig. 4) a similar trend is evident but the total amount of melting over the 7 year long period results quite different depending on the applied T_t value: from −6.81 m w.e. (threshold 274.7 K) to −8.23 m w.e. (threshold 268.1 K).

The cumulative M_{3C} in the same period results −8.23 m w.e. thus underlying that the temperature threshold that better explains magnitude and variability of snow melting corresponds to the minimum of daily average temperature calculated for days featuring at least 6 M_{EB} hours (268.1 K).

4 Discussions

During April–June at the AWS1 Forni site all the snow coverage has completely melted; in fact, from 2006 to 2012 the M_{3C} over the April–June time frame is found −8.23 m w.e. corresponding to the 97 % of the annual M_{3C} and to the 65 % of the April–June M_{EB} (see Table 1). This latter results equal to −12.72 m w.e., thus underlying that also a not negligible amount of ice has melted. On the one hand, the knowledge of both T_S and α allows the calculation of M_{3C} amount thus permitting to distinguish between ice and snow melt and evaluating their respective contribution to the whole loss at the glacier tongue. In fact, when we computed the April–June mass loss neglecting T_S and α, the ablation we found (M_{PEB}) results equal to −13.43 m w.e. thus underlining an overestimation (+5.6 % with respect to the M_{EB} over the same period). Then at least the knowledge of glacier surface temperature is really important to avoid misestimation of the melt amount and whenever also α is known the computation of ice and snow contribution to the total melt is possible. On the other hand T_S and α are available only on a small number of glaciers where supraglacial AWSs have been running thus suggesting to look for different strategies in order to assess the snow melt amount. The most diffuse and simple method is the T-index approach based on data acquired outside the studied glacier. Then in this study to compute the degree days amount driving glacier melt we used 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 K km^{-1}).

To validate this temperature reconstruction we made a comparison among modelled air temperature values (T_B) with air temperature actually measured at the AWS1 Forni (T_{AWS}). It resulted a strong agreement between the two records of data ($r = 0.91$) suggesting that it is possible to perform a reasonable reconstruction of supraglacial daily average air temperature starting from meteorological data acquired down valley also using a mean tropospheric vertical gradient as lapse rate. Nevertheless this result could depend on the small distance (ca. 20 km) between Bormio village and Forni

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Glacier. But on other glaciers the assessment of a local daily vertical gradient could be needed to reconstruct supraglacial air temperature and degree days amount from data acquired by weather stations located far and farer from the glacier site.

From our analysis results that the major uncertainty in computing the degree days amount at the glacier surface and then in assessing snow melt is given by the choice of an appropriate air temperature threshold (T_t). The modelled snow melt largely varies: from −6.81 m w.e. applying a threshold of 274.7 K to −8.23 m w.e. using a value of 268.1 K. Then T-index models show a high sensitivity to T_t changes.

To assess the most suitable temperature threshold, we firstly analyzed hourly M_{EB} values (obtained from AWS1 Forni data) in the April–June period to detect if ablation occurs and how long this phenomenon takes (number of hours per day). Then we sorted these data according to temporal length classes (0, 4, 6, 12 and 24 melting hours per day). For each class we calculated the mean, maximum and minimum values of daily average air temperature from T_{AWS} and T_B data. Moreover we also evaluated the cumulative M_{EB} for each temporal length class to evaluate its weight with respect to the total ablation. The largest part of the melting (97.7 % of the whole ablation) resulted occurring on days featuring at least 6 M_{EB} hours thus suggesting to consider the minimum average daily temperature value calculated for this class as a suitable temperature threshold (268.6 K and 268.1 K considering the T_{AWS} and T_B data respectively). These data were applied to detect the actual melting days. The first threshold was applied to air temperature data from AWS1 Forni and permitted to select 586 melting days describing the 99.4 % (−12.64 m w.e.) of the total M_{EB}. Considering T_B data, the threshold of 268.1 K permitted to detect 601 melting days giving a cumulative M_{EB} of −12.66 m w.e. equal to 99.5 % of the total.

Then we ran a simple T-index model using as input data T_B and varying the temperature threshold (273.15 K, 268.1 K and 274.7 K). The cumulative $M_{\text{T-INDEX}}$ curves we obtained in the April–June period (Fig. 4) show a similar trend but the total amount of snow melting over the 7 year long period results quite different. The cumulative M_{3C} (witnessing only snow melt) in the same period results −8.23 m w.e. and this values is

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also obtained applying as threshold 268.11 K to T_B data. These results suggest to use as T_t the minimum of daily average temperature calculated for days featuring at least 6 M_{EB} hours. This value permits to better explain magnitude and variability of snow melting (Fig. 4).

As regards the temperature threshold largely reported in the literature dealing with T-index model (273.15 K e.g. Braithwaite, 1985; Hock, 2003), our tests indicate that it drives an underestimation of snow melt (ca. 17 % with respect to the value obtained from M_{3C} which represents the actual snow melt). Moreover in the case the main purpose should be only the detection of the melting days and not the assessing of the melt amount, the application of the 273.15 K threshold drives an underestimation as well. With this threshold 481 melting days are detected against 601 melting days selected by applying the 268.1 K threshold to T_B data.

Our findings results in agreement with van den Broeke et al. (2010) who modelled the ablation at the Greenland ice sheet. They found an about 5 K lower threshold value by observing the cumulative distribution of daily average temperature for days with melt at three AWSs. From their study this value resulted to allow also an appropriate calculation of snow and ice degree-day factors. In fact applying the common 273.15 K threshold they obtained non-sense degree-day factor values.

Some attention has to be spent on the snow DDF (see Eq. 6) values. The snow DDFs we found, ranging from 2.0 to 5.8 mm d^{-1} K^{-1}, are in agreement with findings in other studies (see Table 3): Hock (2003) reported snow DDF values ranging from 2.5 mm d^{-1} K^{-1} (Clyde, 1931) to 11.6 mm d^{-1} K^{-1} (Kayastha et al., 2000) and Braithwaite (2008) suggested values from 3.5 to 4.6 mm d^{-1} K^{-1}. Moreover the snow DDFs we found result always minor than the ice DDFs we evaluated (they resulted 5.6, 3.6 and 6.7 mm d^{-1} K^{-1} with T_t 273.15 K, 268.1 K, 274.7 K, respectively) and this is in agreement with the literature dealing with the application of T-index models for computing ice and snow melt (see the overview by Braithwaite, 2011 and the considerations on the different magnitude of ice and snow DDFs reported by van de Broeke et al., 2010).

With the 268.1 K threshold the snow degree-day factor (Table 3) results lower than the ones derived applying the other two thresholds. This value (2.0 mm d^{-1} K^{-1}) resulted comparable in magnitude with the ones reported by van de Broeke et al. (2010) applying a threshold of 268 K to Greenland data and also these authors found smaller snow DDF value occurring with a T_t 5 K lower than the 273.15 K value.

5 Conclusions

The most suitable way to evaluate the actual snow melt amount is to calculate M_{3C}, the melt from energy budget computations considering both null surface temperature and albedo major than 0.4. Nevertheless this approach is applicable only whenever a supraglacial AWS is running thus giving information on T_s and α. Otherwise the snow melt can be estimated by applying T-index methods. The main limits in such approaches are due to the need of reconstructing air temperature at the glacier surface from data acquired outside the glacier and choosing a suitable air temperature threshold for computing the DD amount. Then we performed further investigations to contribute to this topic.

Firstly we started evaluating the actual glacier melt. We applied a point energy balance model (following Senese et al., 2012a) at the AWS1 Forni site on the glacier ablation tongue and we found that a not negligible annual snow melt (M_{3C}) occurs. In the 7 year period 2005–2012 it ranges from 17.6 % to 29.2 % of the total annual (ice and snow) ablation (M_{EB}).

Our data also indicate that during April–June at the AWS1 Forni site all the snow coverage disappears due to melting processes: from 2006 to 2012 the April–June M_{3C} is found corresponding to the 66.59 % of the April–June M_{EB}.

Secondly in order to apply a T-index model we reconstructed air temperature conditions at the glacier surface starting from data 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 K km^{-1}). This approach resulted a reasonable reconstruction of supraglacial daily average air temperature starting from meteorological data acquired down valley also using a mean tropospheric vertical gradient as lapse rate.

Then our analysis indicates that the major uncertainty in computing the degree days amount at the glacier surface and then in assessing snow melt is given by the choice of an appropriate air temperature threshold (T_t). In fact, ablation does not occur only with air temperature higher than 273.15 K since it is determined by the surface energy balance and this latter is only indirectly affected by air temperature (Kuhn, 1987).

Thirdly, to assess the most suitable temperature threshold, we analyzed hourly M_{EB} values (obtained from AWS1 Forni data) in the April–June period to detect if ablation occurs and how long this phenomenon takes (number of melting hours per day: 0, 4, 6, 12 and 24). The largest part of the melting (97.7 % of the whole ablation) resulted occurring on days featuring at least 6 M_{EB} hours thus suggesting to consider the minimum average daily temperature value calculated for this class as a suitable temperature threshold (268.1 K). This value was applied to detect the actual melting days permitting to select 601 days giving a cumulative M_{EB} of −12.66 m w.e. equal to 99.5 % of the total.

Finally we ran a simple T-index model using as input data the temperatures measured at Bormio and shifted to the glacier elevation and varying the temperature threshold (273.15 K, 268.1 K and 274.7 K). The cumulative M_{3C} (which witnesses actual snow melt) in the same period results −8.23 m w.e. and this value is also obtained applying as threshold 268.11 K. These results indicate as the most suitable T_t the minimum of daily average temperature calculated for days featuring at least 6 M_{EB} hours. This value (in agreement with findings by van den Broeke et al., 2010 who studied the Greenland ice sheet) permits to better explain magnitude and variability of snow melting and avoids most of the sampling problem in the application of the positive T-index models, such as the calculation of snow and ice degree-day factors. Then probably the choice of a 268 K value as air temperature threshold for computing degree days amount could be generalized and applied not only on Greenland glaciers but also on Mid latitude and Alpine ones like the Forni Glacier.

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Table 1. For each hydrological year the following data are shown: cumulative annual M_{EB} value (2nd column), cumulative M_{EB} during April–June (3rd column), cumulative M_{3C} during the snow melting period (5th column), cumulative M_{PEB} during April June (7th column) and percentages with respect to the annual M_{EB} value (4th, 6th and 8th column respectively). All melting amounts are in m w.e.

Hydrological year	Annual M_{EB}	Apr–Jun M_{EB}	Apr–Jun M_{EB} % with respect to the annual M_{EB}	Annual M_{3C}	M_{3C} % with respect to the annual M_{EB}	Apr–Jun M_{PEB}	Apr–Jun M_{PEB} % with respect to the annual M_{EB}
2005/2006	−5.6	−1.91	34.1 %	−1.15	20.5 %	−1.98	35.4 %
2006/2007	−5.5	−2.08	37.7 %	−1.00	18.2 %	−2.11	38.4 %
2007/2008	−5.0	−1.55	31.0 %	−0.84	16.8 %	−1.85	36.9 %
2008/2009	−5.6	−1.68	29.9 %	−1.61	28.8 %	−1.73	30.9 %
2009/2010	−5.6	−1.62	29.0 %	−1.54	27.5 %	−1.74	31.1 %
2010/2011	−5.2	−2.26	43.5 %	−1.37	26.4 %	−2.33	44.8 %
2011/2012	−5.0	−1.63	32.5 %	−0.96	19.2 %	−1.69	33.9 %
TOT	−37.5	−12.72	33.9 %	−8.47	22.6 %	−13.43	35.8 %
MEAN	−5.4	−1.82	33.9 %	−1.21	22.57 %	−1.92	35.8 %

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Table 2. Number of days and daily temperature values (mean, maximum and minimum of the average data) in the April–June period considering different temporal length classes of M_{EB} hours. The air temperature data are recorded by AWS1 Forni (T_{AWS}) and from Bormio meteorological station. These latter data are shifted to the glacier elevation by applying the mean tropospheric lapse rate (T_B). Underlined values are the ones chosen as possible T_t in the T-index model.

	M_{EB} hours						
Hours per day	All	0	< 4	≥ 4	≥ 6	≥ 12	24
Number of days	637	31	32	574	534	301	21
% with respect to the total studied period	100.0 %	4.9 %	5.0 %	90.1 %	83.8 %	47.3 %	3.3 %
Cumulative M_{EB} (m w.e.)	−12.72	0.00	−0.07	−12.65	−12.43	−9.30	−0.77
Mean average Daily T_{AWS} (K)	274.7	266.0	268.8	275.6	275.9	277.8	278.6
Max of average Daily T_{AWS} (K)	284.3	269.1	275.0	284.3	284.3	284.3	282.1
Min of average Daily T_{AWS} (K)	262.5	262.5	265.8	266.0	268.6	272.0	275.5
Mean average Daily T_B (K)	276.4	267.7	270.2	277.2	277.6	279.4	279.8
Max of average Daily T_B (K)	286.9	275.7	276.9	286.9	286.9	286.9	284.6
Min of average Daily T_B (K)	264.1	264.1	266.8	267.5	<u>268.1</u>	268.9	<u>274.7</u>

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Table 3. Mean degree-day factors for snow melting from the literature and from our results.

	Snow DDF ($mm\,d^{-1}\,K^{-1}$)	
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:		
$T_t = 273.15$	3.9	
$T_t = 268.1$	2.0	
$T_t = 274.7$	5.8	

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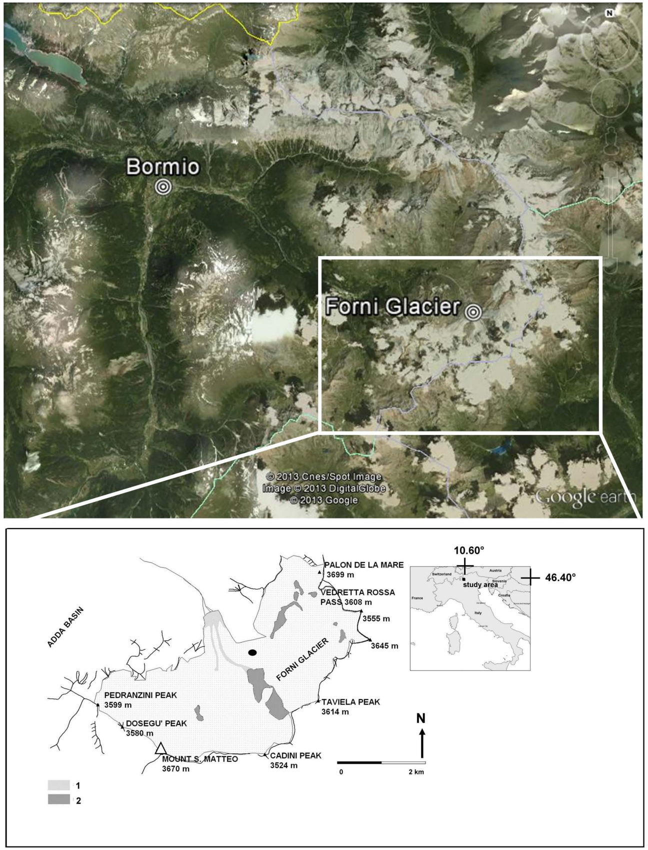

Fig. 1. On the top the location of Bormio (a village at 1225 m a.s.l.) and Forni Glacier (Google Earth© raster base) and in the lower picture the location of the AWS1 Forni (black dot, WGS84 coordinates: 46°23′56.0″ N and 10°35′25.2″ E, geodetic elevation: 2631 m a.s.l.). In the map the light grey areas (1) are used to mark supraglacial debris coverage and the dark grey zones (2) indicate rock exposures and nunataks.

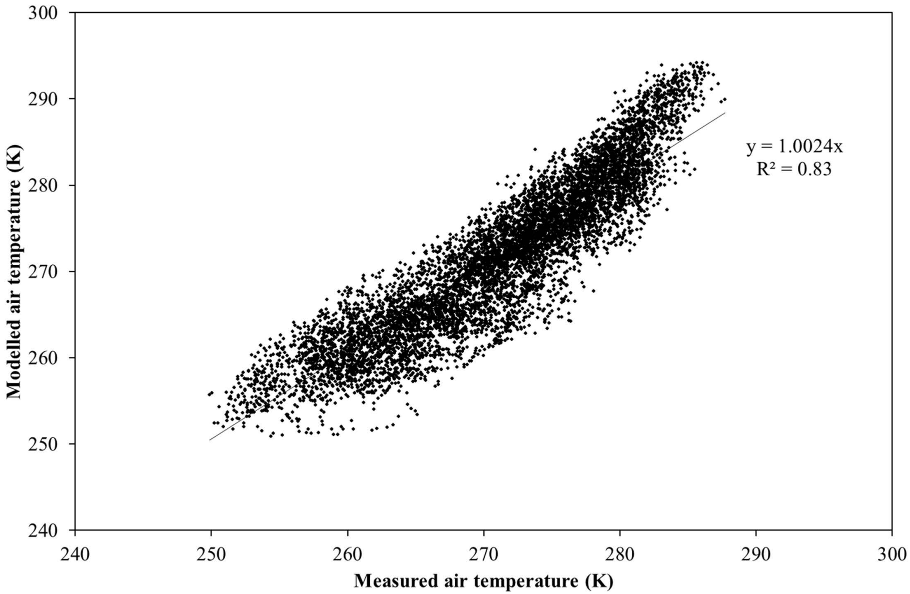

Fig. 2. Hourly temperatures recorded by the AWS1 Forni (T_{AWS}) during 2010 (x axis) vs. the modelled ones (T_B, y axis) derived from Bormio data shifted to the AWS1 Forni elevation through the application of the mean tropospheric lapse rate.

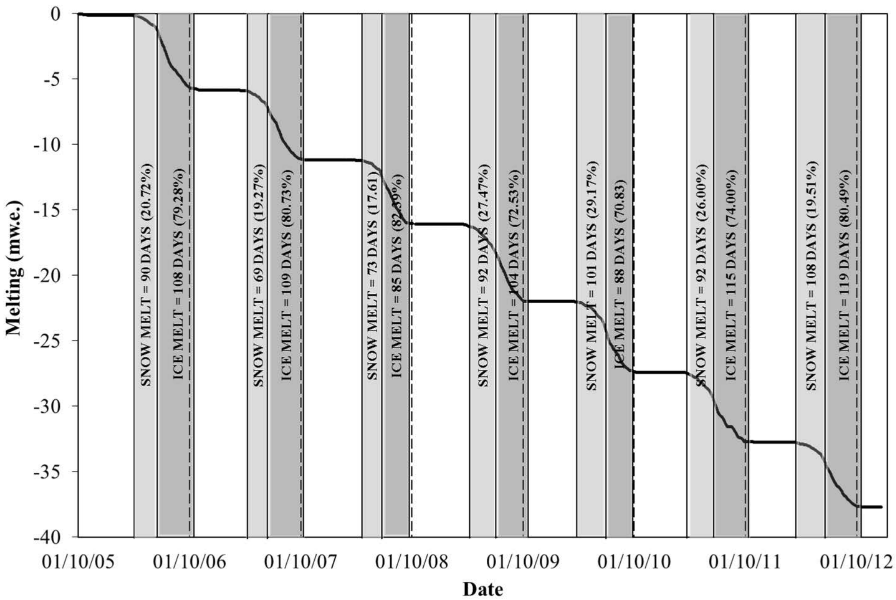

Fig. 3. Cumulative melting amount (M_{EB}) over the 7 year period from October 2005 to December 2012. The dotted lines mark the beginning of the hydrological year (1 October). In some cases ablation continues also in a few days of October and albedo values remain lower than 0.4. In light grey the time frames with snow melting (M_{3C}) and in dark grey the ice melting periods are shown.

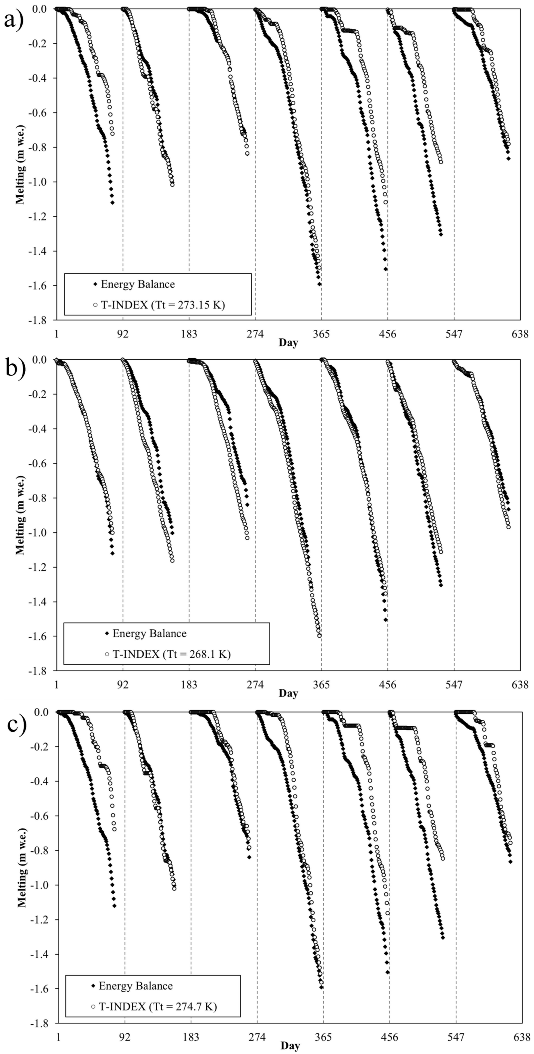

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Fig. 4. From April to June 2006–2012 snow melting rate are shown. With black dots are shown the results from the energy balance (April–June M_{3C}). White dots represent the results from T-index model ($M_{\text{T-INDEX}}$) by applying different temperature thresholds to T_B data: 273.15 K **(a)**, 268.1 K **(b)** and 274.7 K **(c)**. The x axis indicates the progressive number of the record concerning only April–June data.