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ANTONELLA SENESE [1*], MICHELA LEIDI [1] & GUGLIELMINA DIOLAIUTI [1]

A NEW ENHANCED TEMPERATURE-INDEX MELT MODEL INCLUDING NET SOLAR AND INFRARED RADIATION

ABSTRACT: SENESE A., LEIDI M. & DIOLAIUTI G., *A new enhanced temperature-index melt model including net solar and infrared radiation.* (IT ISSN 0391-9839, 2021).

We proposed a new enhanced T-index model including net longwave radiation to evaluate glacier ice melt. We applied the methods for simulating ice melt at the Automatic Weather Station (AWS) site on the Forni Glacier (Italian Alps). The AWS has been continuously running since September 2005. We tested several models with increasing complexity (i.e. from the simplest degree-day to enhanced models including shortwave and longwave fluxes) in order to assess the best approach to be applied depending on the temporal resolution and to verify if the goodness of the calculation could depend also on the model type. We applied all models using measured meteorological data. We benchmarked the performance of each model against melt values estimated by means of the energy balance model. The results display that i) T-index features a high performance if applied at the seasonal scale, but the worst at daily and weekly resolution; ii) taking into account solar radiation seems to improve the models at a higher time resolution; iii) including the longwave input within the enhanced T-index model can be considered a simplification of the energy balance model and provides more accurate calculation of ablation depending on the time resolution.

KEY WORDS: Ice melting, T-index model, Enhanced T-index model, Forni Glacier, Italian Alps.

RIASSUNTO: SENESE A., LEIDI M. & DIOLAIUTI G., *Un nuovo modello di fusione di 'enhanced temperature-index' in cui vengono considerati anche la radiazione netta solare e infrarossa.* (IT ISSN 0391-9839, 2021).

In questo studio viene proposto un nuovo modello di fusione rispetto a quelli precedentemente usati e definiti "*enhanced T-index*". Nello specifico vengono presi in considerazione anche i flussi radiativi (sia solare che infrarosso) oltre alla temperatura dell'aria. Il sito scelto per l'esperimento è il Ghiacciaio dei Forni dove è attiva una stazione meteorologica automatica dal 2005 permettendo quindi l'applicazione di diversi modelli di fusione nel sito in cui è installata. I modelli testati sono caratterizzati da una complessità via via sempre maggiore, partendo dal più semplice, ovvero il T-index, arrivando a quelli definiti "enhanced" e che includono anche i flussi radiativi. Nello specifico ci si è focalizzati sull'efficacia dei modelli in base alla risoluzione temporale, applicandoli infatti a scala giornaliera, settimanale e infine stagionale. Per poter definire gli errori di ogni singolo modello si sono confrontati i valori di fusione del ghiaccio così ottenuti con quelli stimati grazie al bilancio energetico. I risultati mostrano che: i) il modello T-index fornisce risultati migliori a scala stagionale, ii) considerare anche la radiazione solare migliora le prestazioni dei modelli di fusione specialmente ad una risoluzione temporale maggiore, iii) includere la radiazione ad onda lunga nel modello sembra fornire risultati validi semplificando così il calcolo della fusione applicando il modello di bilancio energetico

TERMINI CHIAVE: Fusione del ghiaccio, Modello T-index, Modelli Enhanced T-index, Ghiacciaio dei Forni, Alpi Italiane.

INTRODUCTION

Although melt rates are fully described through the surface energy budget, glacier melt models based on the computation of the energy fluxes are not always applicable in mountain and Alpine areas, due to lack of input data. In fact, in high-mountain regions automatic weather stations (AWSs) measuring radiation fluxes are available at few locations, and often placed outside glaciers. Hence, temperature-index (T-index, also named degree-day) based models are widely used for computing snow and ice melt, given that air temperature is the most available meteorological variable (Braithwaite, 1995). Moreover, in the last decades several authors have developed enhanced T-index models, driven not only by air temperature (i.e. positive degree days), but by shortwave radiation as well (Hock, 1999; Cazorzi & Dalla Fontana, 1996; Pellicciotti & *alii*,

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2005). Such approaches generally allow to depict snow and ice melt accurately, and to distribute it spatially whenever a digital elevation model (DEM) of the glacier is available. Some of them take into account measured data (e.g. Pellicciotti & *alii*, 2005), making the need of solar radiation data possibly measured at the glacier surface to be the main limit of such enhanced models. Then, some methodologies have been developed to use modelled radiative input on glaciers where no AWSs are located (e.g. Cazorzi & Dalla Fontana, 1996; Pellicciotti & *alii*, 2005). Regarding the incoming solar flux, the approach proposed by Iqbal (1983) offers an extra-accuracy over more conventional approaches as reviewed by Gueymard (1993). In addition, satellite data can be also very useful (Manara & *alii*, 2020; Senese & *alii*, 2020). With respect to the incoming longwave radiation a review of models is given by Ellingston & *alii* (1991). Longwave radiation is usually estimated from empirical relationships with air temperature and vapor pressure (Plüss & Ohmura, 1997; Oerlemans, 2000; Klok & Oerlemans, 2002; Hock, 2005; Senese & *alii*, 2016), based on standard meteorological measurements (Kondratyev, 1969).

In this context, simple methods to model ice melt starting from easily available meteorological variables (like air temperature) are desirable. On the other hand, a simplified version of the energy balance model can be also useful. In fact, the energy balance is assumed to require less tuning, and thus to be more suitable for extrapolating mass-balance in both space and time but at the expense of a higher demand for input data (Machguth & *alii*, 2008). This paper presents the results of some tests we performed to evaluate ice melt at the automatic weather station site on the Forni Glacier (Italian Alps). More precisely, our main aims were as follows: i) to assess the reliability of different melt models simulating the different temporal behaviour of ablation; and ii) develop a new model of glacier ice melt simplifying the energy balance model and using the largely available input data (i.e. air temperature) and the easily derivable radiative fluxes, thus assuring model exportability.

Then, to reach the above reported goals we applied different T-index models, from an easiest one only considering temperature (e.g. Bocchiola & *alii*, 2018), to most recent and complex ones, which also consider solar radiation (e.g. Minora & *alii*, 2015; Senese & *alii*, 2018a) using measured meteorological data. An attempt was also made here, to provide improvement of these approaches by considering net longwave radiation as a further input thus making this proposed model a simplification of the energy balance model. A suitable site to develop our approach based upon field observations is given by the Forni Glacier (Stelvio National Park, Italian Alps, fig. 1), where since September 2005 an automatic weather station was continuously run (Senese & *alii*, 2016; 2018b), thus assuring a long sequence of meteorological and energy data.

FORNI GLACIER AND THE METEOROLOGICAL STATIONS

The Forni Glacier (10.5 km^2, data of 2016, Paul & *alii*, 2019) is located inside an extensive natural protected area (Stelvio National Park) and covers an elevation range from 2600 to 3670 m a.s.l.

In September 2005, a supraglacial meteorological station (AWS1 Forni; yellow triangle in fig. 1) was set up at the lower sector of the eastern tongue of this glacier (e.g. Senese & *alii*, 2012a). The WGS84 coordinates of AWS1 Forni were 46° 23' 56.0" N, 10° 35' 25.2" E, at an elevation of 2631 m a.s.l. A second station (AWS Forni SPICE, Senese & *alii*, 2018b) was set up in May 2014 close to AWS1 Forni. Due to the formation of ring faults (i.e. series of circular or semicircular fractures with stepwise subsidence), in November 2015 both AWSs were moved to the Forni Glacier central tongue (46° 23' 42.4" N and 10° 35' 24.2" E, 2675 m a.s.l., Senese & *alii*, 2018b, red star in fig. 1).

AWS1 Forni is equipped with sensors for measuring air temperature (T) and relative humidity (RH) housed in a naturally-ventilated radiation shield, wind speed and direction, air pressure, incoming and outgoing shortwave (SWin and SWout, respectively) and longwave (LWin and LWout, respectively) radiation, liquid precipitation by an unheated precipitation gauge, and snow depth. AWS Forni SPICE is equipped with a snow pillow and a barometer for measuring the snow water equivalent (SWE). All sensor and data logger specifications are detailed in Senese & *alii* (2012a; 2018b). Both AWSs are supported by four-leg stainless steel masts (5 and 6 m high, respectively) standing on the ice surface. The meteorological variables are sampled every 60 seconds and the acquired data are averaged every 60 minutes (snow depth - Campbell SR50, wind speed and direction, and air pressure), every 30 minutes (air temperature, relative humidity, solar and infrared radiation, and liquid precipitation) or every 10 minutes (snow depth - Sommer USH8, and SWE). All data are recorded in a flash memory card, including the basic distribution parameters (minimum, mean, maximum, and standard deviation values).

METHODS

We calibrated and validated all our computations using ice melt data estimated applying the energy balance model with data acquired by the AWS1 Forni. In previous studies (e.g. Pellicciotti & *alii*, 2005; Senese & *alii*, 2014), energy balance results were already used in empirical melt parametrization. In addition, this is supported by the fact that the melt amount derived from energy budget computations was validated by comparing it to field measurements at a selection of ablation stakes located near the AWS1 Forni (Senese & *alii*, 2012a; 2012b). A difference of less than 3% between the modelled cumulative melt and the measured cumulative one was found, thus suggesting to consider reliable and indicative the results obtained from energy balance model.

We decided to consider 2006-2011 data since already validated in previous studies (Gambelli & *alii*, 2014; Senese & *alii*, 2016; 2020). We divided the whole dataset in two subsets: even years (2006, 2008, and 2010) were used for calibrating the models and odd years (2007, 2009 and 2011) for validating them (tab. 1). We considered measured meteorological data as model input and not also derived values. In this way we assured that all found errors depend on

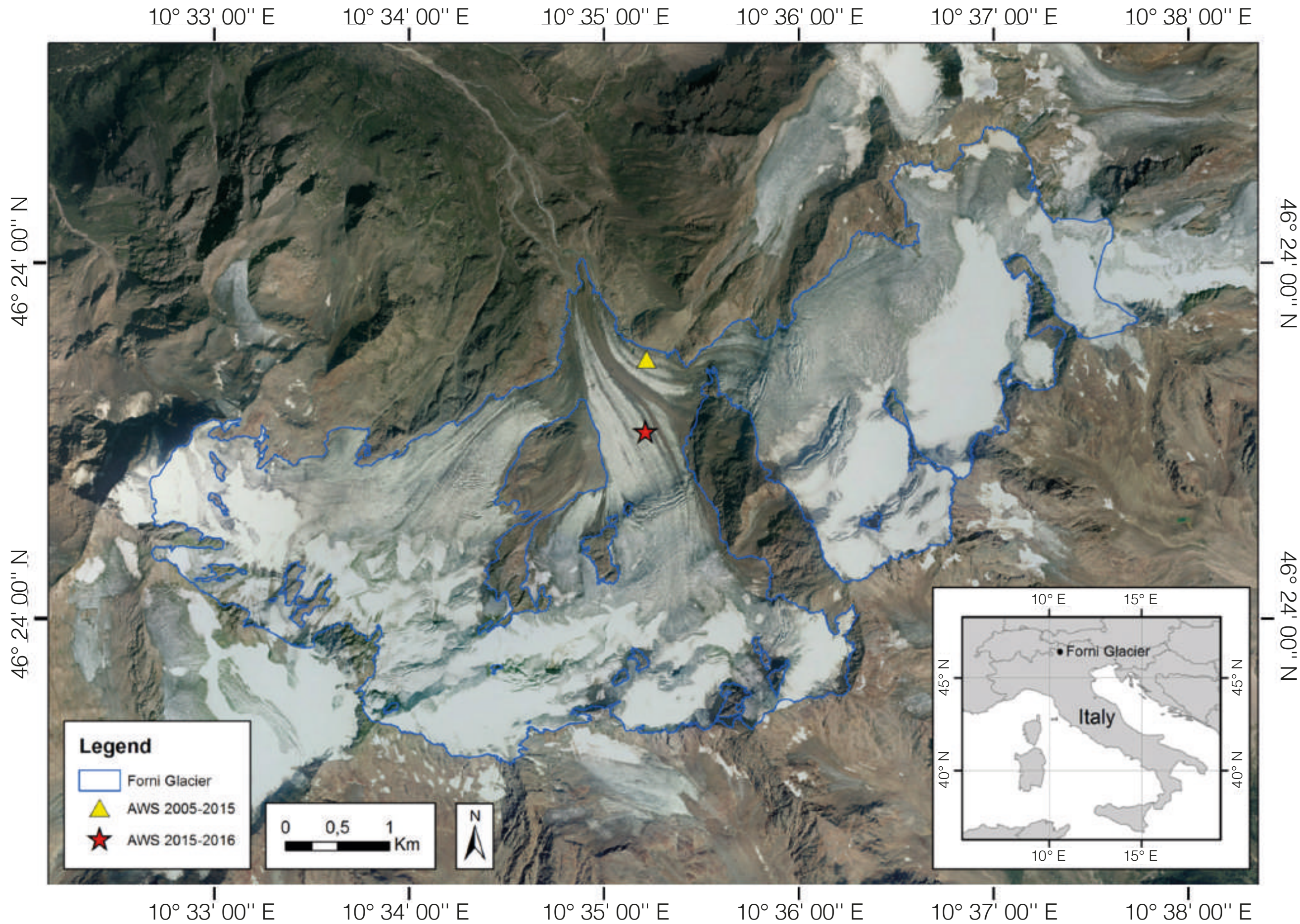

FIG. 1 - The Forni Glacier and the automatic weather station (AWS) sites.

the applied melt model and not on the methodologies used for deriving meteorological data. In addition, we considered different temporal resolutions: daily, weekly and seasonally.

We focused our study on the ice ablation seasons (tab. 1). Albedo data were used for investigating surface conditions and then distinguishing exposed-ice surfaces from snow-covered ones applying a threshold of 0.35 (Hartmann, 1994; Senese & *alii*, 2014).

TABLE 1 - Details of subsets in which is divided the whole dataset from 2006 to 2011. The beginning and the end of each ice ablation season are reported.

	Year	Beginning	End	N. days
Calibration	2006	18/06	03/10	108
Validation	2007	09/06	25/09	109
Calibration	2008	21/06	13/09	85
Validation	2009	29/06	10/10	104
Calibration	2010	29/06	24/09	88
Validation	2011	14/06	06/10	115

The ice melting (M, m w.e. per time step) assessed from the surface energy balance is calculated following Senese & *alii* (2012a, 2012b, 2014):

$$R_S = \left(SW_{in} - SW_{out}\right) + \left(LW_{in} - LW_{out}\right) + SH + LE \qquad (1)$$

$$M = \begin{cases} \dfrac{R_S}{L_m \cdot \rho_w} & T_S = 0°C \ \textit{and} \ R_S > 0 \ W \ m^{-2} \\ 0 & T_S < 0°C \ \textit{or} \ R_S \leq 0 \ W \ m^{-2} \end{cases} \qquad (2)$$

where R_S is the energy flux available for heating and melting the surface, SW_{in} and SW_{out} are the incoming and outgoing solar radiation fluxes, LW_{in} and LW_{out} are the incoming and outgoing longwave radiation fluxes, SH and LE are the sensible and latent heat fluxes, L_m is the latent heat of melting (33400 J kg^{-1}), ρ_w is the density of water (1000 kg m^{-3}) and T_S is the surface temperature (derived from LW_{out}). SH and LE are calculated by means of the well-known bulk aerodynamic formulas following Senese & *alii* (2012a):

$$SH = \rho_a \cdot c_p \cdot C_h \cdot V_{2m} \cdot \left(T_{2m} - T_S\right) \qquad (3)$$

$$LE = 0.622 \cdot \rho_a \cdot L_v \cdot C_h \cdot V_{2m} \cdot \frac{\left(e_{2m} - e_S\right)}{p} \qquad (4)$$

where ρ_a is air density (0.87 kg m^{-3}), c_p is the specific heat of dry air (1.006 kJ kg^{-1} $°C^{-1}$), C_h is the turbulent exchange coefficient (0.00127 ± 0.00030), V_{2m} is the wind speed value at 2 m, T_{2m} is the air temperature value at 2 m, T_S is the surface temperature, Lv is the latent heat of vaporization, e_{2m} is the vapor pressure value at 2 m, e_S is the vapor pressure value at the surface and p is the air pressure value at sensor level.

Then, the ice melting was quantified following different models. First, we applied the T-index model taking into account only air temperature (Braithwaite, 1995):

$$M = \begin{cases} T_1 MF \cdot T & T > 0°C \\ 0 & T \leq 0°C \end{cases} \quad (5)$$

where T_1MF is the temperature melting factor (m w.e. °C^{-1} per time step, tab. 2) calculated by regression model considering all together the calibration years. The empirical factors we found are in agreement with values reported in other studies that ranging from 0.0044 m w.e. day^{-1} °C^{-1} to 0.008 m w.e. day^{-1} °C^{-1} (e.g. Takeuchi & *alii*, 1996; Arendt & Sharp, 1999; Braithwaite, 1995; Hock, 1999; Pellicciotti & *alii*, 2005; Bocchiola & *alii*, 2011; Hock, 2003).

The second model we tested is based on the potential clear-sky incoming solar radiation ($SW_{in\text{-}cs}$), a modified version of the one proposed by Hock (1999):

$$M = \begin{cases} T_2 MF \cdot T + CSMF \cdot (1-\alpha) \cdot SW_{in-cs} & T > 0 \\ 0 & T \leq 0 \end{cases} \quad (6)$$

where T_2MF is the temperature melting factor (m w.e. °C^{-1} per time step, tab. 2), CSMF is the clear-sky radiation melting factor (m w.e. (W m^{-2})$^{-1}$ per time step, tab. 2), and α is the surface albedo (equal to 0.35 for glacier ice, see Senese & *alii*, 2012a). As cloud observations are not available at the Forni Glacier (nor at other sides nearby), $SW_{in\text{-}cs}$ is estimated by way of a sine-cosine function adjusted on the daily data measured by the AWS1 Forni and interpolated through the truncated Fourier series at the second order following Senese & *alii* (2016):

$$\begin{aligned} SW_{in-cs} = {} & 160,4 - 236,0 \cdot \cos\left(\frac{day\ 2\pi}{365}\right) + \\ & + 27,3 \cdot \sin\left(\frac{day\ 2\pi}{365}\right) - 25,1 \cdot \cos\left(2\frac{day\ 2\pi}{365}\right) + \\ & + 15,5 \cdot \sin\left(2\frac{day\ 2\pi}{365}\right) \end{aligned} \quad (7)$$

where day is the Julian date. This is an envelop of the measured values which allows to get an indication of the daily maxima (clear sky radiation) corresponding to each day of the year. To assess the actual clear-sky incoming solar radiation without overestimation as due to multiple reflection from snow-covered surrounding slopes, the snow-free half-year was considered only (i.e. from 1 May to 30 September of every year, following Oerlemans, 2000; Senese & *alii*, 2016). $SW_{in\text{-}cs}$ does not take into account the reduction of solar radiation due to actual atmospheric conditions (e.g. clouds), thus the need for additional meteorological input data is avoided (Hock, 1999). Compared to the easier T-index, this model allows to better investigate the spatial variability of melt rates due to local topography (such as slope, aspect and effective horizon), particularly in high mountainous regions. Furthermore, the clear-sky radiation allows to take better account of the temporal variability with respect to the air temperature. In addition to the methodology here applied, $SW_{in\text{-}cs}$ can be derived as a function of top-of-atmosphere solar radiation, an assumed atmospheric transmissivity, and topographic characteristics (Hock, 1999).

Then, we considered a multiplicative radiative model including the actual absorbed solar flux, according to Carturan & *alii* (2012):

$$M = \begin{cases} CMF \cdot (1-\alpha) \cdot SW_{in} \cdot T & T > 0°C \\ 0 & T \leq 0°C \end{cases} \quad (8)$$

where CMF is the combined melting factor taking into account both temperature and radiative flux (m w.e. °C^{-1} (W m^{-2})$^{-1}$ per time step, tab. 2), α is the surface albedo derived from solar fluxes acquired by the AWS1 Forni, SWin is the incoming solar radiation measured by the AWS1 Forni (W m^{-2}). Albedo is calculated as:

$$\alpha = \frac{SW_{out}}{SW_{in}} \quad (9)$$

The mean ice albedo is 0.23 (0.25 of median) with the minimum of 0.09 and the standard deviation of 0.15.

The combined melting factor reported by Carturan & *alii* (2012) is 0.00048 mm °C^{-1} W^{-1} m^2 h^{-1} for both snow and ice ablation. Cazorzi & Dalla Fontana (1996) applied a similar model and found for the snow a CMF ranging 0.016 to 0.024 mm °C^{-1} EI^{-1} h^{-1} (where EI is the energy input in J m^{-2}). Both values are correctly lower compared with the one obtained in this study. In fact, the snow melting factors are generally lower than the ones for ice (Hock, 2003).

As the previous model, the fourth one depends on the actual absorbed solar radiation but in this case it is an additive approach (as the one proposed by Pellicciotti & *alii*, 2005):

$$M = \begin{cases} T_3 MF \cdot T + RMF \cdot SW_{in} \cdot (1-\alpha) & T > 0\ °C \\ 0 & T \leq 0\ °C \end{cases} \quad (10)$$

where T_3MF (m w.e. C^{-1} per time step, tab. 2) and RMF (m w.e. (W m^{-2})$^{-1}$ per time step, tab. 2) are the temperature and the radiative melting factors, respectively. Even in this case, our melting factors are in agreement with the ones of other studies: 0.05 mm h^{-1} °C^{-1} and 0.0094 mm h^{-1} (W m^{-2})$^{-1}$ (Pellicciotti & *alii*, 2005), 0.00324 m day^{-1} °C^{-1} and 0.000079 m day^{-1} (W m^{-2})$^{-1}$ (Minora & *alii*, 2015).

Given that ablation depends upon the net energy available at the glacier surface, we tested a new model by simplifying the energy balance model (Eqs. 1 and 2). In particular, we added to the previous proposed algorithm the net longwave radiation (LW_{net}). In this way, turbulent fluxes of sensible and latent heat are slightly simplified by keeping them only dependent on the air temperature and lumping them together in one term:

$$M = \begin{cases} T_4 MF \cdot T + SLMF \cdot \left[(1-\alpha) \cdot SW_{in} + LW_{net}\right] & T > 0\ °C \\ 0 & T \leq 0\ °C \end{cases} \quad (11)$$

TABLE 2 - Calibrated parameters obtained for the ice melt model tested in this study.

Model	Melting factor	Daily	Weekly	Seasonally
T-index (Braithwaite, 1995) Eq. 5	T_1MF	0.0073 m w.e. day^{-1} °C^{-1}	0.0074 m w.e. week^{-1} °C^{-1}	0.0073 m w.e. season^{-1} °C^{-1}
Clear-sky-index (modified from Hock, 1999) Eq. 6	T_2MF	0.0055 m w.e. day^{-1} °C^{-1}	0.0059 m w.e. week^{-1} °C^{-1}	0.0058 m w.e. season^{-1} °C^{-1}
	CSMF	6.1 x 10^{-5} m w.e. day^{-1} (W m^{-2})$^{-1}$	4.9 x 10^{-5} m w.e. week^{-1} (W m^{-2})$^{-1}$	4.6 x 10^{-5} m w.e. season^{-1} (W m^{-2})$^{-1}$
Multiplicative radiative model (Carturan & *alii* (2012)) Eq. 8	CMF	3.81 x 10^{-5} m w.e. day^{-1} °C^{-1} (W m^{-2})$^{-1}$	4.00 x 10^{-5} m w.e. week^{-1} °C^{-1} (W m^{-2})$^{-1}$	28.3 x 10^{-5} m w.e. season^{-1} °C^{-1} (W m^{-2})$^{-1}$
Additive radiative model (Pellicciotti & *alii*, 2005) Eq. 10	T_3MF	0.0028 m w.e. day^{-1} °C^{-1}	0.0027 m w.e. week^{-1} °C^{-1}	0.0064 m w.e. season^{-1} °C^{-1}
	RMF	18.1 x 10^{-5} m w.e. day^{-1} (W m^{-2})$^{-1}$	18.8 x 10^{-5} m w.e. week^{-1} (W m^{-2})$^{-1}$	3.62 x 10^{-5} m w.e. season^{-1} (W m^{-2})$^{-1}$
LW-SW radiative model (this study) Eq. 11	T_4MF	0.0024 m w.e. day^{-1} °C^{-1}	0.0025 m w.e. week^{-1} °C^{-1}	0.0069 m w.e. season^{-1} °C^{-1}
	SLMF	24.3 x 10^{-5} m w.e. day^{-1} (W m^{-2})$^{-1}$	23.9 x 10^{-5} m w.e. week^{-1} (W m^{-2})$^{-1}$	2.00 x 10^{-5} m w.e. season^{-1} (W m^{-2})$^{-1}$

where T_4MF (m w.e. °C^{-1} per time step, tab. 2) and SLMF (m w.e. (W m^{-2})$^{-1}$ per time step, tab. 2) are the temperature and the shortwave-longwave radiative melting factors, respectively. The first term accounts for all the temperature-dependent fluxes, including turbulent and longwave radiation. Therefore, LW is considered twice (i.e. in the first and the second term) and by two different melt factors (i.e. T_4MF and SLMF). Generally, to calculate the ice melt from the energy budget, the net energy flux needs to be divided by the density of water and the latent heat of melting (see equation 2). Therefore, while the factor TMF represents a combination of parameters and variables, the factor SLMF should be equal to $1/(\rho_w{*}Lm)$, which is 25.87 x 10^{-5} m day^{-1} (W m^{-2})$^{-1}$, very similar to the ones found in this study (tab. 2).

All the melting factors are assumed sconstant in time and space (Hock, 1999) as the variability of melt rates in time and space is explained by the air temperature and radiative input (Cazorzi & Dalla Fonatana, 1996). Specifically, all the melting factors are calculated by means of regression model.

The statistics used to validate applied models against energy balance one are the bias error (BE), the mean absolute error (MAE), the Root-Mean-Square Error (RMSE), and the Bias-Removed Root-Mean-Square Error (BRRMSE) (Senese & *alii*, 2016):

$$BE = \frac{1}{N}\sum\left(y - x\right) \tag{12}$$

$$MAE = \frac{1}{N}\sum\left|y - x\right| \tag{13}$$

$$RMSE = \left[\frac{1}{N}\sum\left(y - x\right)^2\right]^{0.5} \tag{14}$$

$$BRRMSE = \left[\frac{1}{N}\sum\left(y - x - BE\right)^2\right]^{0.5} \tag{15}$$

where N is sample size, and y and x are measured and modelled values, respectively.

Regarding seasonal comparisons, as the sample size of both calibration and validation dataset is too small (only 3 values for each step), we applied the leave-one-out cross validation (LOOCV) (Senese & *alii*, 2018b). In this kind of cross-validation, the number of "folds" (repetitions of the cross-validation process) equals the number of observations in the dataset. In this way, we ensure independence between the data we use to estimate the melting factors and the data we use to validate ice melt models. In this case, the error was estimated dividing the standard deviation by the square root of the number of the considered melt values (6 values, Senese & *alii*, 2018b).

RESULTS AND DISCUSSION

We compared the energy balance ice melt values and the values obtained by means of the tested models (tab. 3, figs. 2-6). We performed the comparison during the validation periods (2007, 2009 and 2011). Depending on the time resolution, the performance of the approaches varies. In general, the enhanced T-index models using radiation fluxes seem more accurate in describing melt magnitude and rate compared to the classical degree-day model using exclusively air temperature. In fact, the T-index approach shows the highest BRRMSE if applied at daily (0.013 m w.e. day^{-1} corresponding to 32.65% of the daily mean melt, fig. 2a) and weekly scale (0.063 m w.e. week^{-1} corresponding to 22.18% of the weekly mean melt, fig. 2b). Whenever daily and weekly values are considered, the additive radiative approach is the most reliable (with a BRRMSE of 0.006 m w.e. day^{-1} corresponding to 15.32% of the daily mean melt, fig. 5a, and of 0.032 m w.e. week^{-1} corresponding to 11.33% of the weekly mean melt, fig. 5b). Instead, the T-index approach shows a lower error (but not the lowest one) at the seasonal scale (1.03%, fig. 2c). The LW-SW radiative approach driven by temperature, solar and infrared radiation (proposed in this study) has a BRRMSE of 0.007 m w.e. day^{-1} (corresponding to 17.32% of the daily mean melt, fig. 6a) and of 0.052 m w.e. week^{-1} (corresponding to 18.11% of the weekly mean melt, fig. 6b) thus improving T-index, Clear-sky-index and Multiplicative radiative approaches but resulting slightly less reliable than the additive radiative approach. Instead, if applied considering the whole season, the results are better compared to the ones obtained with the additive radiative approach (figs. 5c and 6c). Therefore, our model (Eq. 11) and the one proposed by Pellicciotti & *alii* (2005) (Eq. 10) are the most suitable approaches to predict ice melt and to depict variability over time, thus suggesting that considering measured radiation actually improves the calculation of ice melt via degree day approach.

TABLE 3 - Statistics obtained comparing ice melt (m w.e. per time step) modelled from energy balance and ice melt modelled using different temperature-index approaches in the validation periods.

	M ave	BE	%	MAE	%	RMSE	%	BRRMSE	%	LOOCV	%
T-index (Braithwaite, 1995) Eq. 3											
Daily	0.04	<0.001	-0.85%	0.010	25.30%	0.013	32.66%	0.013	32.65%		
Weekly	0.28	0.001	0.39%	0.047	16.63%	0.063	22.18%	0.063	22.18%		
Seasonally	4.05									0.042	1.03%
Clear-sky-index (modified from Hock, 1999) Eq. 4											
Daily	0.04	0.001	3.06%	0.009	22.53%	0.011	28.15%	0.011	27.98%		
Weekly	0.29	0.008	2.71%	0.037	12.86%	0.051	17.81%	0.051	17.60%		
Seasonally	3.98									0.023	0.58%
Multiplicative radiative approach (Carturan & *alii*, 2012) Eq. 6											
Daily	0.04	-0.007	-17.67%	0.011	27.22%	0.014	33.98%	0.012	29.03%		
Weekly	0.29	-0.039	-13.78%	0.056	19.43%	0.069	24.22%	0.057	19.91%		
Seasonally	4.05									0.095	2.35%
Additive radiative approach (Pellicciotti & *alii*, 2005) Eq. 8											
Daily	0.04	0.001	3.62%	0.005	12.09%	0.006	15.74%	0.006	15.32%		
Weekly	0.29	0.009	3.27%	0.026	9.21%	0.034	11.79%	0.032	11.33%		
Seasonally	4.05									0.037	0.92%
LW-SW radiative approach (this study) Eq. 9											
Daily	0.04	0.007	16.71%	0.008	19.87%	0.010	24.06%	0.007	17.32%		
Weekly	0.29	0.022	7.65%	0.038	13.39%	0.056	19.66%	0.052	18.11%		
Seasonally	4.05									0.033	0.81%

TABLE 4 - The standard error for the melting factors estimation.

	T_1MF	T_2MF	CSMF	CMF	T_3MF	RMF	T_4MF	SLMF
Daily	11.7×10^{-5}	32.2×10^{-5}	1.0×10^{-5}	0.1×10^{-5}	17.1×10^{-5}	0.7×10^{-5}	12.5×10^{-5}	0.6×10^{-5}
Weekly	18.1×10^{-5}	77.1×10^{-5}	2.4×10^{-5}	0.1×10^{-5}	67.4×10^{-5}	2.6×10^{-5}	36.9×10^{-5}	1.8×10^{-5}
Seasonally	8.3×10^{-5}	75.5×10^{-5}	2.2×10^{-5}	0.7×10^{-5}	147.8×10^{-5}	5.8×10^{-5}	52.2×10^{-5}	2.5×10^{-5}

Despite its wide application (e.g. Hock, 2003), the T-index model involves a simplification of complex physical processes which are more properly described by the energy balance of the glacier surface and overlying atmospheric surface layer (Pellicciotti & *alii*, 2005). Consequently, we found that T-index performances are better whenever applied at a coarse temporal resolution. This is in agreement with for example Kustas & *alii* (1994) and Lang (1986) reporting that T-index methods work well over longer time periods, but the accuracy decreases with increasing time resolution. Therefore, this approach is not appropriate for simulating the diurnal cycle of melt rate. Moreover, the spatial variations of melt rate across a glacier derived by T-index can only be simulated through changes in elevation associated with the air temperature lapse rate. In reality, melt varies spatially depending on the available surface energy budget that is controlled in a complex way by topographic features and surface conditions.

We assumed all the melting factors to be constant in time (in agreement e.g. with Hock, 1999) but in some studies they are repoprted to vary seasonally (e.g. Quick & Pipes, 1977; Gottlieb, 1980; Tangborn, 1984; Braun & *alii*, 1993). For this reason, we evaluated the error in estimating the melting factors obtained by the regression model since we used different years for calibration and then more than one ablation season (tab. 4). As found for the performances of the different approaches, also in this case the error magnitude varies depending on the temporal resolution. On the one hand, the errors associated to T-index decrease with coarser resolution, on the other hand with seasonally values the radiative approaches show the highest errors.

The advantage of implicitly considering the turbulent sensible and latent heat fluxes in the LW-SW radiative approach is due to the difficulty in measuring them. In fact, the turbulent fluxes can be measured by eddy-correlation techniques, but these require sophisticated instrumentation with continuous maintenance, which make them unsuit-

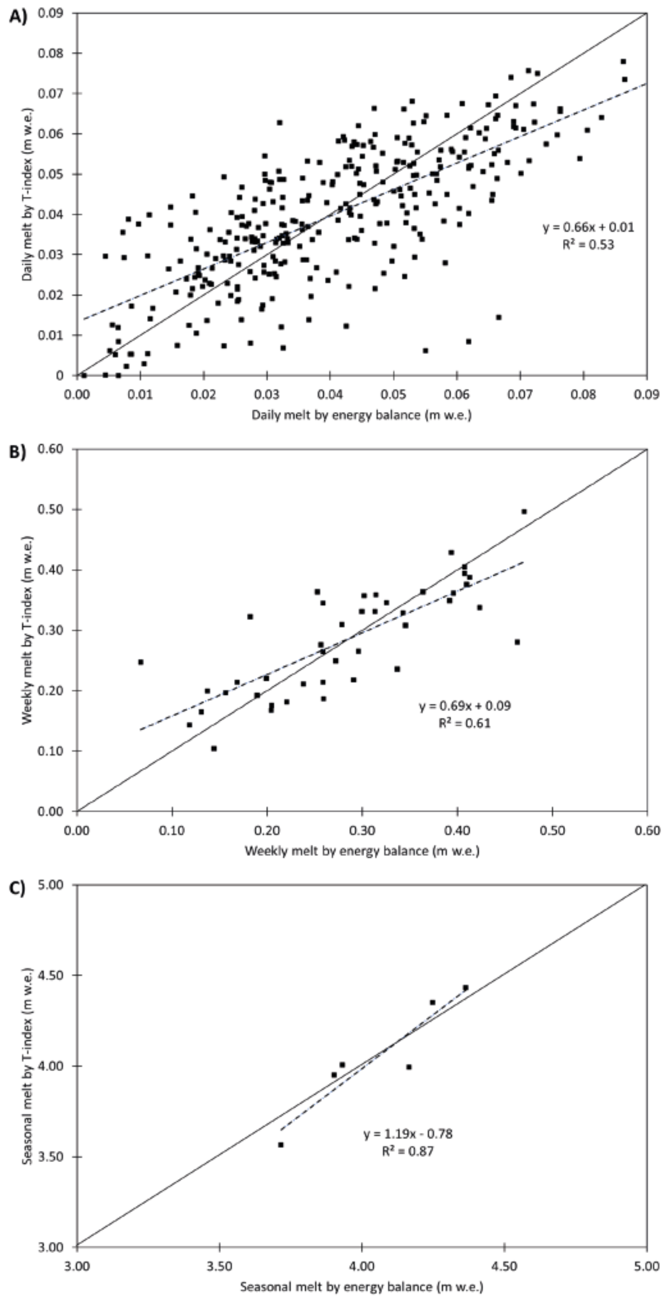

FIG. 2 - The comparison between the ice melt values modelled applying the energy balance and the ones obtained by means of the T-index at daily (A), weekly (B) and seasonal (C) time resolution.

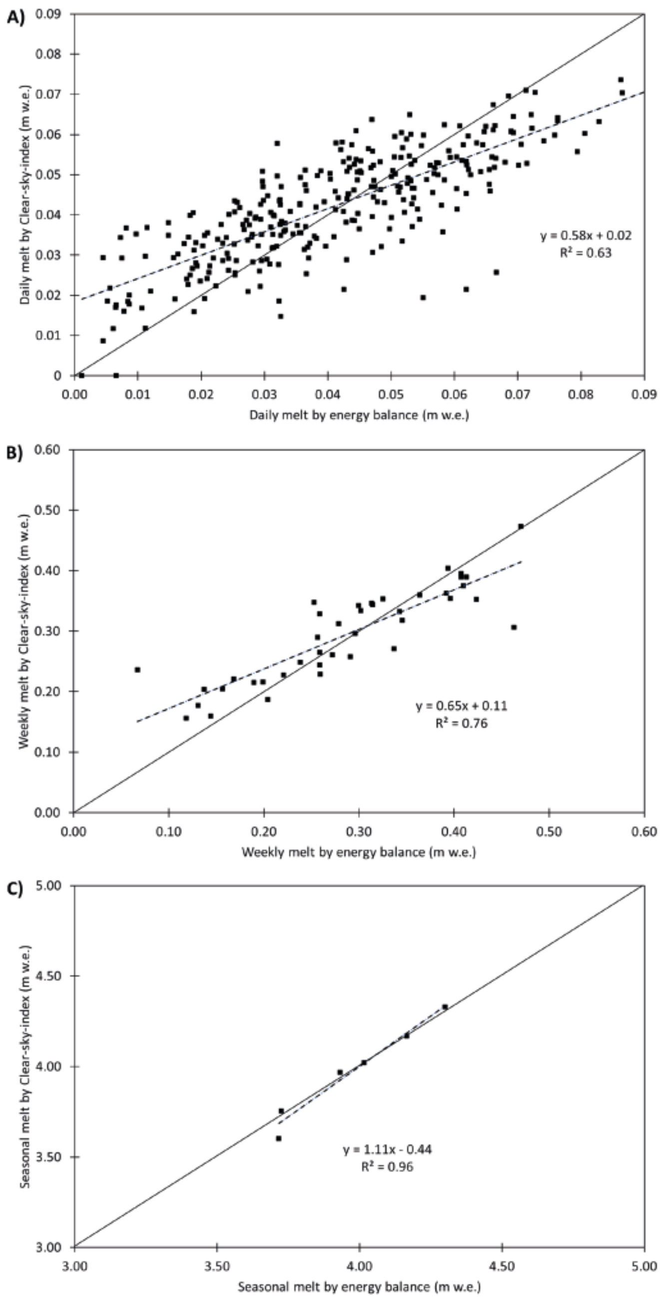

FIG. 3 - The comparison between the ice melt values modelled applying the energy balance and the ones obtained by means of the Clear-sky-index at daily (A), weekly (B) and seasonal (C) time resolution.

able for operational purposes (Hock, 2005). Consequently, such studies are rare and restricted to short periods of time (e.g. van der Avoird & Duynkerke, 1999). Therefore, the turbulent heat fluxes are often described by gradient-flux relations based on the theoretical work of Prandtl (1934) (e.g. Oerlemans & Grisogono, 2002). In addition, they can be calculated by means of bulk formulas (e.g. Denby & Greuell, 2000; Smeets & Van den Broeke, 2008) taking into account wind speed, temperature and humidity to be measured at only one height above the surface. If the air temperature can be easily measured or derived, wind speed generally entails more complex models since glaciers are generally located in area with high complex orography. For example, Song & *alii* (2007) applied an ARPS model that is a mesoscale, compressible, and nonhydrostatic numerical model with 1 km horizontal resolution and 40 vertical levels, making it to be clearly unsuitable for glacier melt quantification. Therefore, the turbulent fluxes are not so easy to derive and consequently a melt model based on a proxy can be more applicable.

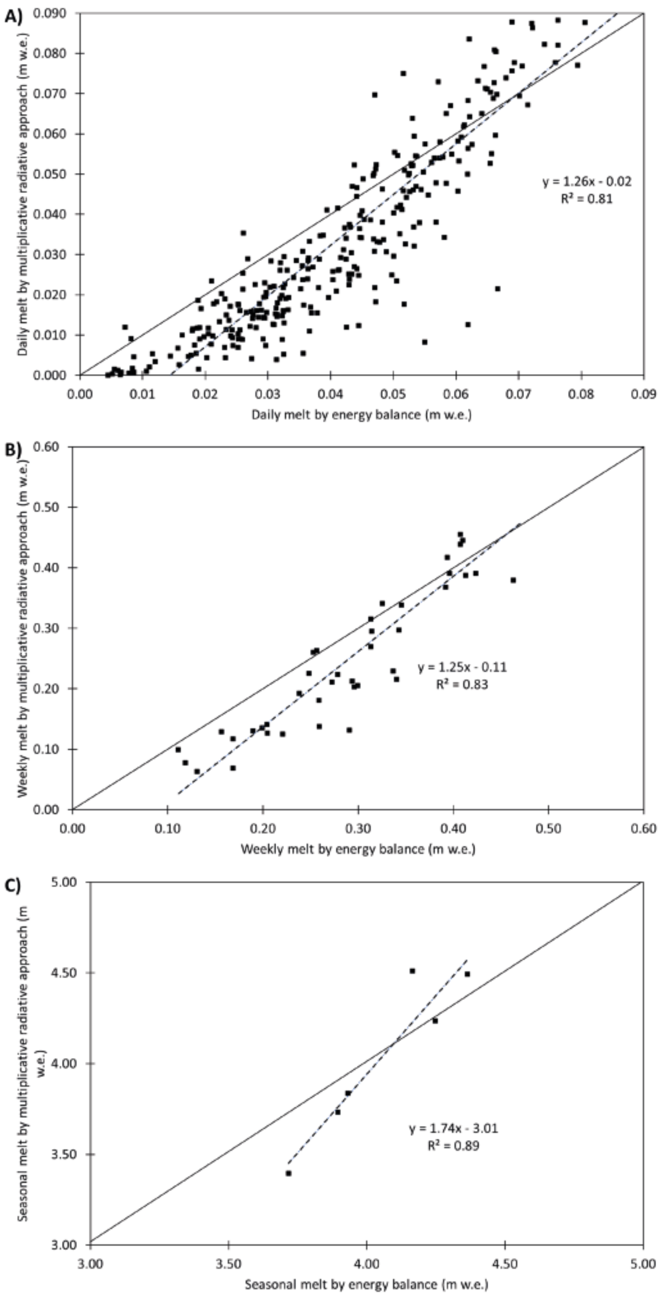

FIG. 4 - The comparison between the ice melt values modelled applying the energy balance and the ones obtained by means of the Multiplicative radiative model at daily (A), weekly (B) and seasonal (C) time resolution.

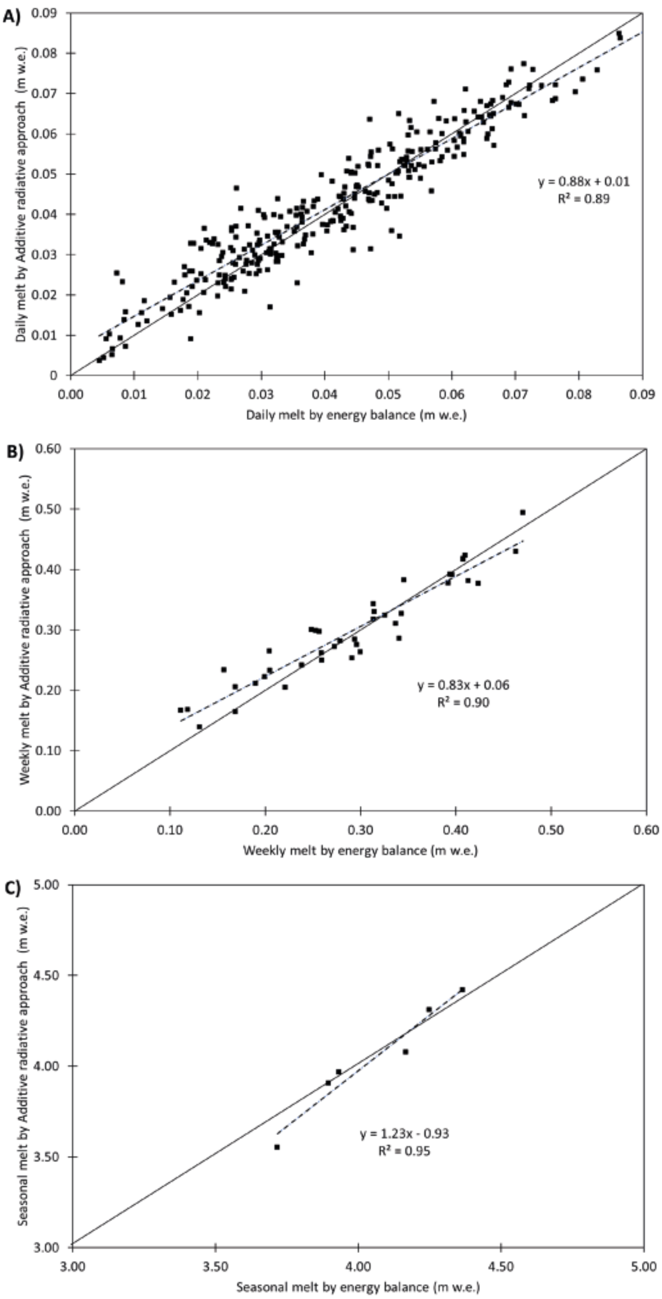

FIG. 5 - The comparison between the ice melt values modelled applying the energy balance and the ones obtained by means of the Additive radiative model at daily (A), weekly (B) and seasonal (C) time resolution.

CONCLUSIONS

In the present study we applied melt models of different complexity to predict temporal ice melting at the AWS site on the Forni Glacier (Italy). Further, we attempted at improve ice melt prediction by including the net longwave radiation as an input. The models including also radiation are more suitable at a higher time resolution than the classical T-index model, which on the contrary features its highest performance if applied at the seasonal scale. In fact, the T-index approach shows the highest BRRMSE if applied at daily and weekly scale (0.013 m w.e. day^{-1} and 0.063 m w.e. week^{-1}) but a low error at the seasonal scale (0.042 m w.e. season^{-1}).

Our enhanced T-index model, which is driven by temperature, solar and infrared radiation, quantifies with some more accuracy ice melt (about 18% of the daily and weekly mean ice melt amount), improving the approach introduced by Hock (1999) and Carturan & *alii* (2012). Instead, if compared with the model proposed by Pellic-

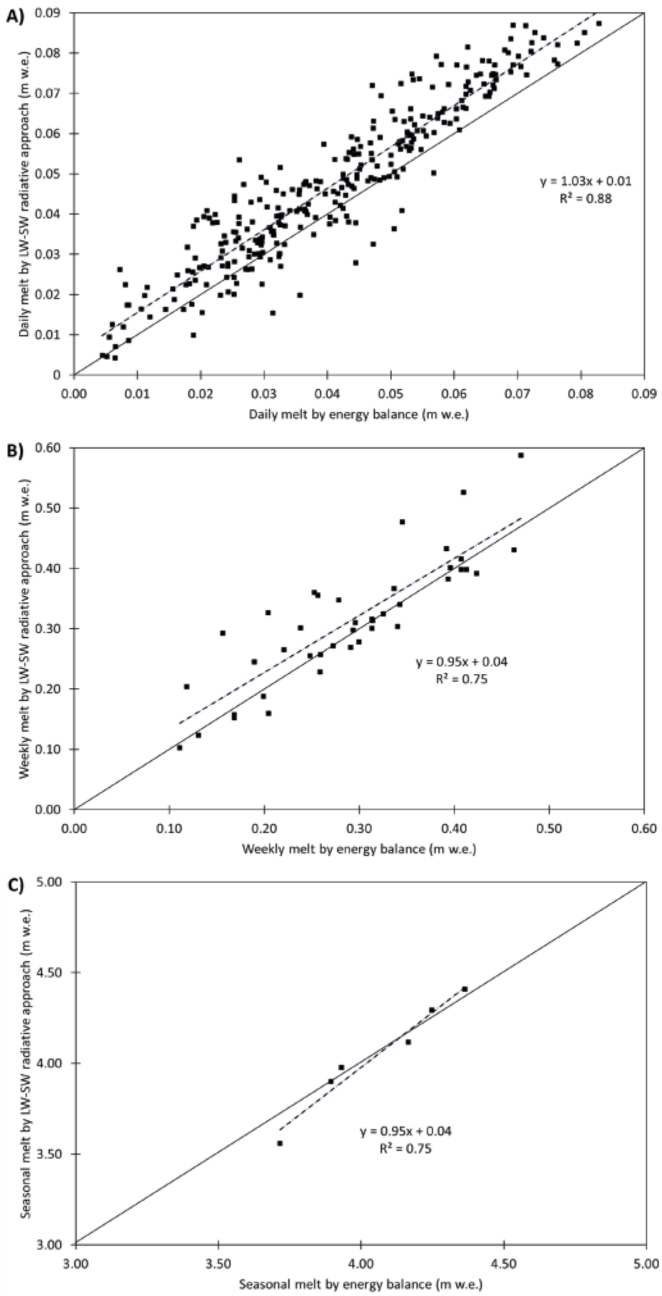

FIG. 6 - The comparison between the ice melt values modelled applying the energy balance and the ones obtained by means of the LW-SW radiative model at daily (A), weekly (B) and seasonal (C) time resolution.

ciotti & *alii* (2005), LW-SW radiative approach features slightly higher daily and weekly errors but a slightly lower seasonal error. Thus, it is suggested that upon the Forni Glacier radiation fluxes may explain part of ice melt temporal variability, and thus it should be better to consider all the radiative components to improve the degree-day approach for ice melt assessment at daily or weekly rime resolution. Eventually, the present study provided some information concerning errors in modelling ice melt depending on the time resolution and the available input, useful for quantifying glacier melt rate. Our melt approach displayed that use of both the radiative components may provide some gain in accuracy when estimating ice melting whenever wind speed and the other meteorological parameters necessary for deriving the turbulent fluxes are not available.

For implement model intercomparisons, we would take into account also modelled meteorological parameters (not only measured ones) or derived by satellite products. This could allow a better comparison with findings for example by Pellicciotti & *alii* (2005), which used modelled (and not measured) solar radiation.

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