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# AN ABLATION MODEL FOR DEBRIS-COVERED ICE: THE CASE STUDY OF VENEROCOLO GLACIER (ITALIAN ALPS)

**ABSTRACT**: BOCCHIOLA D.(*), SENESE A.(**), MIHALCEA C.(**), MOSCONI B. (**), D'AGATA C.(**), SMIRAGLIA C.(**) & DIOLAIUTI G. A., *An ablation model for debris-covered ice: the case study of Venerocolo Glacier (Italian Alps).* (IT ISSN 0391- 9838, 2015).

We developed a simple model to estimate ice ablation under a debris cover. The ablation process is modelled using energy and mass conservation equations for debris and ice and heat conduction, driven by input of either i) debris surface temperature or ii) radiation fluxes, and solved through a finite difference scheme computing the conductive heat flux within the supra-glacial debris layer. For model calibration, input and validation, we used approximately bi-weekly surveys of ice ablation rate, debris cover temperature, air temperature and solar incoming and upwelling radiation during for Summer 2007. We calibrated the model for debris thermal conductivity using a subset of ablation data and then we validated it using another subset. Comparisons between calculated and measured values showed a good agreement (RMSE = 0.04 m w.e., r = 0.79), thus suggesting a good performance of the model in predicting ice ablation. Thermal conductivity was found to be the most critical parameter in the proposed model, and it was estimated by debris temperature and thickness, with value changing along the investigated ablation season. The proposed model may be used to quantify buried ice ablation given a reasonable assessment of thermal conductivity.

KEY WORDS: Debris-covered glaciers, Ice ablation, Heat conduction, Venerocolo Glacier, Italian Alps.

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**RIASSUNTO:** BOCCHIOLA D.(*), SENESE A. (**), MIHALCEA C.(**), MOSCONI B. (**), D'AGATA C. (**), SMIRAGLIA C. (**) & DIOLAIUTI G. A., *Un modello di ablazione del ghiaccio per ghiacciai coperti da detrito: applicazione al caso di studio del Ghiacciaio del Venerocolo (Alpi Italiane).* (IT ISSN 0391-9838, 2015).

In questo articolo presentiamo un modello di fusione da applicare in condizioni di ghiaccio coperto da detrito (i.e.: *buried ice*) come si ritrova sui ghiacciai neri (i.e.: *debris-covered glaciers*) presenti nelle principali catene montuose glacializzate del Pianeta. Il processo di ablazione è modellato utilizzando le equazioni di conservazione dell'energia e della massa e la conduzione del calore. L'input principale per quantificare (attraverso il calcolo delle differenze finite) il flusso di calore conduttivo attraverso lo spessore detritico è: i) la temperatura superficiale del detrito o ii) la radiazione assorbita. Per la calibrazione del modello e la sua validazione sono stati impiegati set distinti di dati di campo di ablazione, temperatura del detrito e parametri meteorologici (temperatura dell'aria e radiazione solare in entrata e riflessa) acquisiti durante campagne di rilevamento svolte nell'Estate 2007. Il confronto fra l'ablazione modellata e misurata ha evidenziato una buona capacità del modello nella descrizione dell'ablazione (RMSE = 0.04 m w.e., r = 0.79). Le analisi svolte hanno evidenziato come la conduttività termica sia il parametro più critico del modello e come questa possa essere stimata dalla temperatura e dallo spessore del detrito sopraglaciale, dati che si modificano nel corso della stagione ablativa. Il modello proposto può pertanto venire utilizzato per quantificare la fusione del ghiaccio coperto da detrito se sono disponibili quantificazioni locali della conducibilità termica.

TERMINI CHIAVE: Ghiacciai neri, Ablazione glaciale, Conduzione del calore, Ghiacciaio Venerocolo, Alpi.

## INTRODUCTION

Water cycle of alpine glaciers is of utmost importance for the Alpine environment, as well as for water resources and water management planning in temperate regions (Barnett & *alii*, 2005). While snow cover extent, duration and dynamics influence vegetal and animal biota in Alpine areas (*e.g.* Keller & *alii*, 2005; Kulakowski & *alii*, 2006), freshwater availability from the cryosphere during Spring and Summer regulates hydrological cycle of Alpine basins, and influences Alpine ecosystems development (*e.g.* Beniston & *alii*, 2003). Water budget of the cryosphere is driven, on the one side, by snow cover forming during winter, and by its redistribution by gravity and wind (*e.g.* Wagnon & *alii*, 2007), and on the other side, by energy budget of snow and ice, leading to evaporation and ablation (*e.g.* Oerlemans, 2001; Lehning & *alii*, 2002; Oerlemans & Klock, 2002; Hock, 2005; Senese & *alii*, 2012; 2014; Gambelli & *alii,* 2014). Ice ablation mechanism may be further complicated by the presence of supraglacial rock debris, *i.e.* for debris covered glaciers (*e.g.* Diolaiuti & *alii*, 2004; Mihalcea & *alii*, 2006; Nicholson & Benn, 2006; Brock & *alii*, 2007; Mihalcea & *alii*, 2008a; Mihalcea & *alii*, 2008b; Soncini & *alii*, 2014), where debris cover is increasing due to macrogelivation and rock degradation processes, stronger and more effective lately (Huggel & *alii*, 2005; Chiarle & *alii*, 2007; Gruber & Haeberli, 2007; Deline & Kirkbride, 2009; Kellerer-Pirklbauer & *alii*, 2008; Diolaiuti & *alii*, 2009; Diolaiuti & *alii*, 2012a;b; Pelfini & *alii*, 2012).

On debris-covered glaciers, rock debris mantles the largest part of the ablation area (Benn & Evans, 2010), thus influencing short and long term variations (Smiraglia & *alii*, 2000; Diolaiuti & *alii*, 2003a; Diolaiuti & *alii*, 2009). Debris-covered glaciers are common in alpine environments, such as the Himalaya and Karakoram (Diolaiuti & *alii*, 2003b; Hewitt, 2005; Mayer & *alii*, 2006; Mihalcea & *alii*, 2008a; Bocchiola & *alii*, 2011; Soncini & *alii*, 2014), the Peruvian Andes and the Southern Alps of New Zealand (Kirkbride & Warren, 1999; Benn & *alii*, 2004; Kirkbride, 2010), and also in European and Italian Alps (Diolaiuti & *alii,* 2005*;* Mihalcea & *alii*, 2008b; Bocchiola & *alii*, 2010). To assess the water budget of glaciarized basins where debris-covered glaciers are located, the description of supraglacial debris presence and distribution and the calculation of its impact on ice melting are fundamental (Østrem, 1959; Nakawo & Young, 1981; Mattson & *alii*, 1993; Nakawo & *alii*, 2000; Han & *alii*, 2006; Nicholson & Benn, 2006; Brock & *alii*, 2010; Reid & Brock, 2010; Shukla & *alii,* 2010). Empirical relationships between supraglacial debris thickness and ice-melt rates have been analyzed in numerous studies (Han & *alii*, 2006; Nicholson & Benn, 2006; Brock & *alii*, 2010; Reid & Brock, 2010; Shukla & *alii*, 2010; Bocchiola & *alii,* 2010*; 2011;* Lejeune & *alii,* 2013).

Debris layer depth, whenever thicker than a specific and local threshold (the "critical thickness" *sensu* Mattson & *alii*, 1993) reduces magnitude and rates of ice melt. Critical debris thickness depends upon thermal conductivity of rock, grain size, porosity and water content, and should be evaluated locally (e.g. Kayastha & *alii*, 2000; Mihalcea & *alii*, 2006). Also, rock thermal conductivity and albedo control buried ice ablation rate.

Thick debris layers insulate the underlying ice, and the surface energy flux is mainly used to increase debris temperature, with only a residual conductive heat flux reaching the ice-debris interface. Albeit the most important parameter influencing ice ablation is debris thickness (*DT* henceforth), other debris properties such as porosity (depending on grain size), water content (humidity), and lithology affect heat conduction through the debris mantle (Mattson & *alii*, 1993). While *DT* may be estimated *e.g.* using remote sensing data (Mihalcea & *alii*, 2008a;b), thus making possible to assess debris coverage on wide glaciers without direct investigations, porosity and humidity can be evaluated only through dedicated field experiments, and the extrapolations of the collected data is quite complicate, especially in the case of wide and thick supraglacial covers.

A few models (either physically or empirically based) have been developed over the last three decades to calculate buried ice ablation (among others, Nakawo & Young, 1981, Nakawo & Takahashi, 1982). More recently, Han & *alii* (2006) modelled ice ablation under debris layers thicker than 0.5 m, by mimicking heat conduction through the debris, using surface temperatures as input data. Nicholson & Benn (2006) developed an energy balance model for calculating buried ice melt on a daily basis, explicitly considering debris properties to calculate ablation in both wet and dry debris conditions. The model developed by Reid & Brock (2010) uses debris thermal properties to calculate both surface temperatures and ice melt, depending upon meteorological variables. This model was also applied by Fyffe & *alii* (2014), who distributed melt to the whole surface of the Miage Glacier (Mont Blanc, Italy). A recent work by Brock & *alii* (2010) suggested that throughout debris-covered glaciers complex heat exchange processes occur, so that meteorological data gathered close to the debris surface are necessary to apply energy balance models. Analogously, the paper by Lejeune & *alii* (2013) introduced a model (developed starting from the well-known CROCUS snow pack model) to evaluate the melt from debris-covered glaciers applicable also whenever a snow layer is present at the glacier surface, driven by local meteorological variables acquired through an automatic weather station (AWS).

The main limit of such models lays within their operational use, e.g. on glaciers located in remote areas, where the installation and the maintenance of automatic weather stations is unfeasible, and AWSs may be run for short periods (*e.g.* one or two ablations seasons, Mihalcea & *alii*, 2006; 2008a; Reid & Brock, 2010; Fyffe & *alii*, 2014).

Therefore, physically based ablation models for debris-covered glaciers that do not entirely depend upon local AWS data are desirable, to predict both short-term melt rate in response to meteorological conditions, and long-term glacier ablation regimes.

The work presented here is in fulfillment of the CARIPANDA project, funded by the Cariplo Foundation of Italy, aimed to investigate water resources distribution scenario (2007-2050) for the Adamello glacierized Park, in the Central Italian Alps. The paper presents a study on seasonal ablation from the 0.82 $km^2$ Venerocolo Glacier, with more than 50% of its surface covered by a continuous debris layer, making buried ice ablation the focus of our model (Bocchiola & *alii*, 2010). Purpose of the work is modeling the ice ablation at thaw with a numerical model describing full mass and energy conservation equations on the debris-covered surface of the glacier, to capture ablation patterns within the glacier catchment.

We developed and tested an ablation model, that can be driven by either i) debris surface temperature, or ii) radiation data, and calculates total ablation, debris temperature at different depths, energy fluxes at the atmosphere-debris and debris-ice interfaces, and thermal conductivity. Surface debris temperature data may indeed be available from direct measurements (e.g. through thermistors and/or from outgoing longwave radiation measuring devices, e.g. Mihalcea & *alii*, 2006; Brock & *alii*, 2010), remote sensing investigations (e.g. surface kinetic temperatures from ASTER, Mihalcea & *alii*, 2008a;b), and incoming solar radiation and debris thickness input data (higher radiation and thicker debris lead to higher debris surface temperatures; see Mihalcea & *alii,* 2006; 2008a;b; Mayer & *alii*, 2010; Minora & *alii*, 2015). Accordingly, we prefer to have two options to drive the ablation model, including via debris surface temperature that may be available without direct measurements (thus making the model applicable to glaciers without AWSs running at their surface). Furthermore, when future projections of ablations are required, e.g. for hydrological projections within ice fed catchments, we could use as input data meteorological values projected by global circulation models, GCMs (e.g. Bocchiola & *alii*, 2011; Groppelli & *alii*, 2011). Based upon data from a field campaign carried out during late Spring and Summer 2007, with installation of an AWS, ablation stakes and debris temperature gauges, the model is setup and tested during the melt season.

## STUDY SITE

The Venerocolo Glacier (fig. 1, 46°10'N, 10°29'E) is located in the Adamello Group (Lombardy), and nested within the protected area of the Adamello Natural Park (Baroni & *alii*, 2004; Maragno & *alii*, 2009; Coppola & *alii*, 2012). This area displays Alpine climate, with cold winter and moderate summer temperature, considerable solar radiation, and high frequency of clear sky conditions, especially during winter. Snowfall is frequent from October to May, and snow cover generally persists in time until July at the highest altitudes.

Average annual precipitation in the Park area is about 1300 mm (Bocchiola & Diolaiuti, 2010). Several glaciers dwell within the Park area: among others Adamello, the widest glacier of Italy (~18 km$^2$), and several smaller glaciers featuring different shape, size and morphology (Maragno & *alii*, 2009). The Venerocolo Glacier (fig. 1a, b, c) has NW aspect and an area of 0.82 km$^2$ (Smiraglia & Diolaiuti, 2015), approximately 50% covered by rock debris. The glacier is located on the North side of Mount Adamello, and it developed its debris cover only recently (last 50 years), becoming now the first studied debris-covered glacier within the Central Alps of Italy. The minimum glacier elevation is 2560 m a.s.l. (2007 data), and the maximum is 3017 m a.s.l..

The glacier basin reaches its maximum at 3539 m a.s.l. (Adamello Peak). On Venerocolo, the extension of supraglacial debris is likely associated with stronger rock degradation and more frequent macrogelivation processes following glacier shrinkage, over the last decade frequently observed in other mountain ranges in the Alps (Deline & *alii*, 2008; Kellerer-Pirklbauer & *alii*, 2008; Diolaiuti & *alii*, 2009). Supraglacial debris on Venerocolo is mainly made by tonalite and granodiorite (common lithologies in the Adamello Group) and it covers almost the entire glacier ablation area, with depth ranging from a few mm to 1 m (average *DT* 15 cm, e.g. Bocchiola & *alii*, 2010).

Grain size ranges from a few millimeter (pebbles and small stones) to several meters (boulders and large blocks). The role played by the debris cover in reducing Venerocolo ice ablation is likely important. The mean measured surface albedo (henceforth $\alpha$, which we found ranging from 0.20 to 0.35) is higher, compared to other debris covered glaciers (0.07, 0.14 for Larsbreen Glacier in Norway and Belvedere Glacier in Italy, respectively, Nicholson & Benn, 2006; ca. 0.12 at the Miage Glacier in Italy, Brock & *alii*, 2010). This is due to the properties of tonalite and granodiorite, both displaying lower thermal conductivity, and higher reflectance, than metamorphic rocks (*e.g.* crystalline schists), or sedimentary rocks, more common throughout other debris-covered glaciers. The NW aspect, jointly with debris lithology and thickness, influences the surface energy balance and the dominating meteorological conditions.

Recently the area change of Adamello glaciers was studied, among others by Maragno & *alii* (2009), who found an area reduction of -19% during 1983-2003. The smaller glaciers (i.e. area < 1 km$^2$, 91% of the total glacier number and 10% of total glacier area) showed the strongest retreat (-39% of the initial area). Venerocolo Glacier reduced its area from 1.68 to 1.25 km$^2$, i.e. -25% (1983-2003), and more recently to 0.82 km$^2$, i.e. -34% (2003-2007).

Venerocolo ablation tongue retreated by -3.9 m/y during 1951-2002 (unpublished data). The rate of retreat increased most lately (i.e. ca. 1982-2002), reaching -6.7 m/y. Trends (1965-2007) of meteorological data within the area were investigated by Bocchiola & Diolaiuti (2010), who found increasing temperature, and unchanged total precipitation, but with decreasing snow cover, especially during 1980-1990. Diolaiuti & *alii* (2012) demonstrated that within the six main glacier groups of Lombardy region, including Adamello group, recent (1976-2005) increase in Spring and Summer temperatures, and decreased snow cover at thaw led to enhanced melting of glaciers of any size (*i.e.* up to 20 km$^2$). Meltwater discharges from the Venerocolo Glacier were studied and modeled by adopting a simple degree day approach for calculating ice melt (Bocchiola & *alii*, 2010). The melt factors therein were evaluated against debris cover thickness by using an empirical data driven approach, and the results indicate that half of the spring and summer flows in the catchment area derive from ice and snow ablation. However, investigation of energy fluxes and ice ablation using an energy balance approach was never carried out throughout the Venerocolo Glacier.

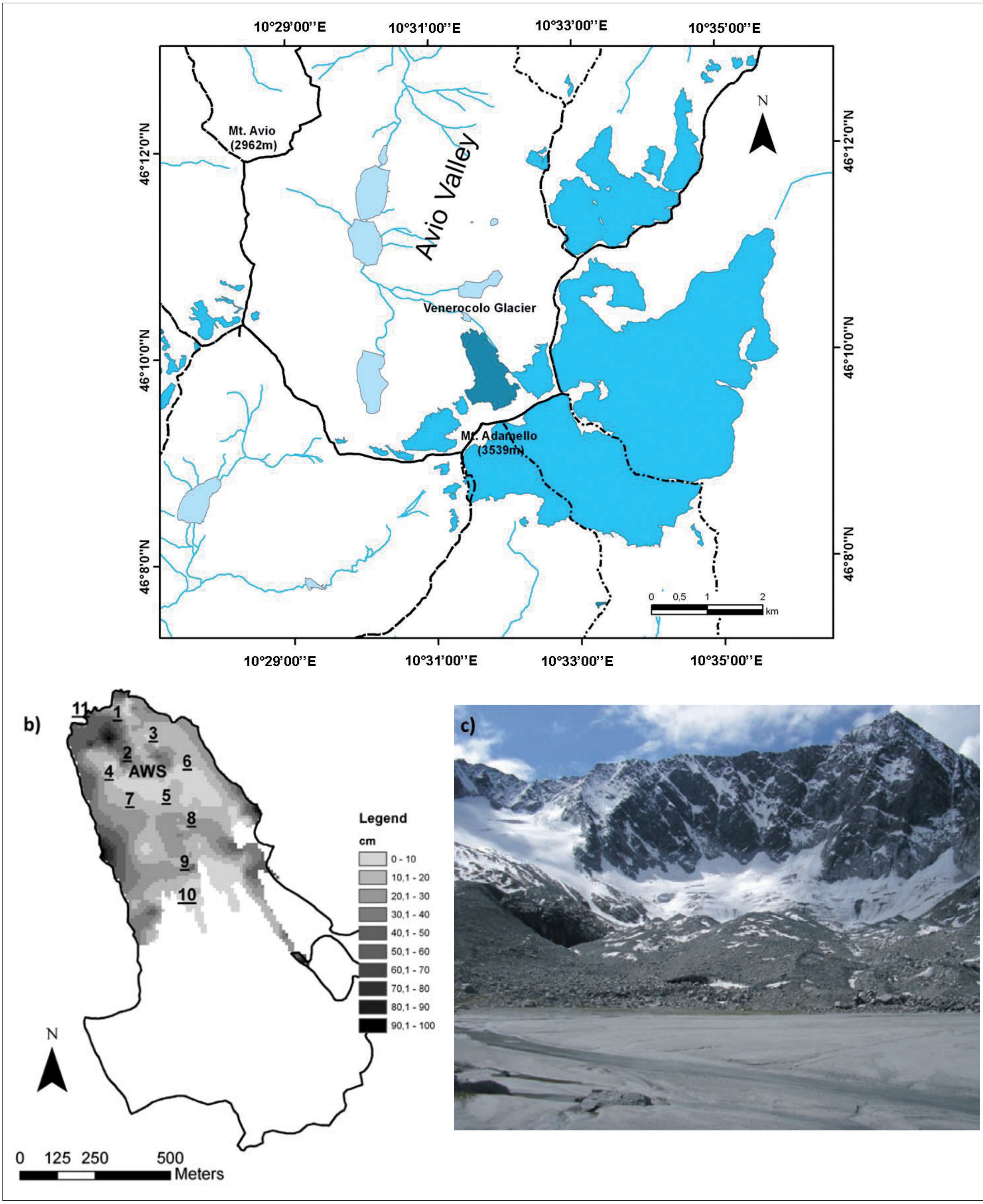
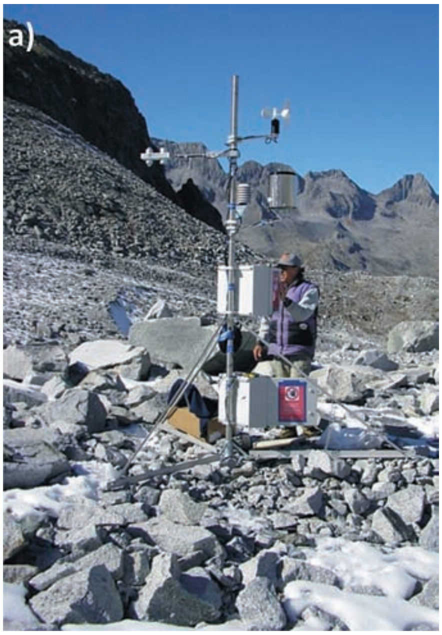



FIG. 1 - Study site. a) The Adamello Group. b) Stakes and AWS position on the Venerocolo Glacier. Underlined stake numbers indicate stakes with more complete database, used in the study. The debris-covered area is shown. With a grey scale are reported the different debris thicknesses. c) The Venerocolo Glacier situated on the north side of Adamello Peak (3538 m a.s.l.).



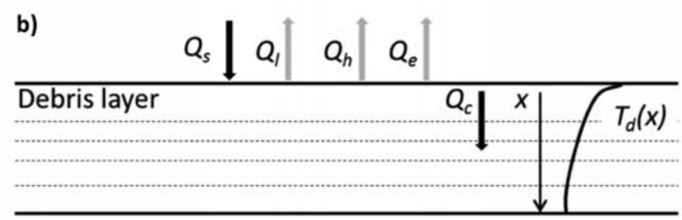




FIG. 2a) - The Automatic Weather Station (AWS) located during the 2007 ablation season at the debris-covered surface of Venerocolo Glacier (2621 m a.s.l.). b) Ablation model design. $T_d$ is debris temperature along $x$ vertical direction. See Eq. (1) for explanation of energy fluxes.

## DATA AND METHODS

### FIELD DATA

During Summer 2007 we performed a field campaign on the Venerocolo Glacier. An AWS (fig. 1b, 2a) was installed on July 27$^{th}$ 2007 at the debris-covered glacier tongue, at 2621 m a.s.l., to record (every ten minutes) liquid precipitation, air temperature, air pressure, wind speed and direction, incoming and outgoing radiation (short and longwave fluxes) data. The station was then removed on October 11$^{th}$ 2007. On June 13$^{th}$ 2007 eleven ablation stakes were drilled into the ice to evaluate ice melt with different debris thickness (fig. 1b) and altitude (i.e. from 2500 m to 2700 m a.s.l.).

The stakes were distributed according to one longitudinal and two cross profiles on the debris-covered area. They were monitored from June 13$^{th}$ 2007 to October 11$^{th}$ 2007. Since in some cases ablation stakes went broken due to ice flow, and occurrence of rock debris avalanches at the glacier surface, for our analysis we used ablation data from 8 stakes, which we found most reliable (fig. 1b).

The point surface debris temperature was measured (every 10 minutes) by thermistors and data loggers (further details of the method can be found in Mihalcea & *alii*, 2008b), close to the ablation stakes. The sensor tips were attached to flat rock surface (0.02 m thick, 0.10 x 0.10 m), at 0.02 m below the debris surface. The data recorded at this depth are normally considered the indicative of point surface temperature, and used within several international protocols to study permafrost and frozen ground (see Osterkamp, 2003; Guglielmin, 2006; Guglielmin & *alii*, 2008). We used point data because our model calculates heat flux and buried ice melt at single sites. As reported above, the glacier area is approximately 50% covered by rock debris. Measurements of *DT* were performed by direct excavation, digging into the rock debris until glacier ice surface, trying to keep one side of the pit undisturbed for measuring debris layer properties (thickness, grain size, water content). Debris excavation was performed at each stake site and at other 417 points along cross and longitudinal profiles spread all over the glacier surface. The point data were then interpolated by applying a geo-statistical software (namely Surfer®), so obtaining an estimated 1 m resolution debris cover map. The glacier DEM was kindly made available by the Lombardy Region (ITT Department). We found out that 74% of the rock debris coverage features a $DT < 0.30$ m, and only 6% of the rock debris has $DT > 0.50$ m (see Bocchiola & *alii*, 2010).

### A SIMPLE BURIED ICE MELT MODEL

A simple model to calculate ice ablation under a debris layer was developed and applied to the Venerocolo Glacier. The model simulates internal temperatures and ice melt every 10 minutes, by mimicking heat conduction within the debris. We considered a debris coverage composed by flat and parallel layers with variable temperature (debris surface temperature, henceforth $T_d$). The assumption of a simple debris coverage (i.e.: made by flat and parallel layers) is surely a simplification, but in our case it is close to reality. Indeed, our experiments revealed quite constant conditions (moisture, grain size) with only actual changes in debris depth. Probably this is due to the gentle slope, the dominant lithology and the small size featured by the Venerocolo Glacier. Likely, upon wider, steeper and more complex debris-covered glaciers this assumption may need further discussion.

The variation of debris temperature (*$dT_d(x)$*) is analysed only in the vertical direction (i.e., $x$ = debris depth) at each point where the model is applied, and debris properties (i.e.: temperature, thermal conductivity, density and heat capacity) only vary along $x$. Three components generally describe a debris layer: i) the air fraction, ii) the water content and iii) the rock debris fraction. In our study, we considered an unsaturated debris layer, and water content always at the liquid state.

The position (in depth, along the $x$ axis) of the air/water interface is assumed constant, since it is difficult to predict its position over time. Two layers are modeled with respect to this separation surface. The first layer, the upper one is made by debris with pores filled by air, and the second layer is the lower one with water filled pores. First, we considered the energy balance equation at the debris surface (e.g. Nicholson & Benn, 2006) as:

$$Q_s + Q_l + Q_h + Q_e + Q_c = 0 \tag{1}$$

with $Q_s$ net shortwave radiation flux, $Q_l$ net longwave radiation flux, $Q_h$ net sensible heat flux, $Q_e$ net latent heat flux, $Q_c$ conductive heat flux within the debris, all in [W m$^{-2}$]. All terms are positive towards the debris surface. We here neglected the effect of heat flux due to precipitation, which however is normally small (*e.g.* Reid & Brock, 2010). The net shortwave radiation flux is expressed as

$$Q_s = S(1-\alpha) \tag{2}$$

with $S$ incoming (solar) shortwave radiation [W m$^{-2}$], and $\alpha$ is albedo [.]. The net longwave radiation flux is calculated as

$$Q_l = (L - Q_m) = \left(L - \varepsilon\sigma T_d^4\right) \tag{3}$$

with $L$ incoming (atmospheric) longwave radiation flux [W m$^{-2}$], $Qm$ longwave emission flux by the debris surface at temperature $T_d$, obtained from Stefan-Boltzman equation, with $\sigma = 5.67 \times 10^{-8}$ W m$^{-2}$ K$^{-4}$, and $\varepsilon$ emissivity [.] from debris surface. Sensible heat flux depends mostly from debris ($T_d$) and air ($T_a$) temperature [K], as

$$Q_h = \rho_0 \frac{P}{P_0} c_a U_w \frac{k_*^2}{[\ln(z/z_0)]^2}(T_d - T_a) \tag{4}$$

with $\rho_0$ density of air at standard sea-level pressure [1.29 kg m$^{-3}$], $P$ air pressure at the site [Pa], $P_0$ standard air pressure at sea level [$1.013 \times 10^5$ Pa], $c_a$ air specific heat capacity [1010 J kg$^{-1}$ K$^{-1}$], $U_w$ wind speed [m s$^{-1}$], $k_*$ is Von Karman's constant [0.42], $z$ height of air temperature probe [m] and $z_0$ debris roughness length [0.01 m].

Calculation of latent heat flux $Q_e$ is done similarly to $Q_h$, but requires measurements of relative air humidity (*e.g.* Nicholson & Benn, 2006; Reid & Brock, 2010), which we did not carry out. Reid & Brock (2010) investigated the relative importance of the terms in Eq. (1) in mimicking correctly air temperature and ice melt, finding that removal of the term $Q_e$ leads to small loss of accuracy in their case study area (Miage Glacier, Mont Blanc group, western Italian Alps), and they concluded that on Alpine glaciers this term may be neglected, at least preliminarily. The same suggestion comes from Lejeune & *alii* (2013), who applied the CROCUS-DEB model considering zero the latent heat flux. They stated than on the largest part of the time (dry conditions) this term is negligible. Heat transport $Q_c$ through the debris layer is here modelled as dependent on the temperature gradient and to the thickness of the exchange surface (*i.e.* according to Fourier heat conduction law).

$$Q_c = \lambda_d \frac{dT_d(x)}{dx} \tag{5}$$

with $\lambda_d$ [W m$^{-1}$ K$^{-1}$] thermal conductivity. To solve Eq.5, debris temperature data are required. Due to the difficulties in obtaining representative $T_d(x)$ values for the entire debris-covered surface, most published models only calculate ice melt at a small number of experimental sites (e.g. Nicholson & Benn, 2006). In addition, when $T_d$ measurements are not available, the surface energy fluxes need to be calculated (Eq. 1-4).

Assuming all heat flux to occur by conduction, and thermal conductivity to be constant with depth, this method uses time series of vertical temperature profiles within the debris to determine the apparent thermal diffusivity of the debris ($\lambda_0$, m$^2$ s$^{-1}$) using a one-dimensional thermal diffusion equation (see also Conway & Rasmussen, 2000; Nicholson & Benn, 2006):

$$\frac{dT_d(x)}{dt} = \lambda_0 \frac{d^2T_d(x)}{dx^2} \tag{6}$$

with $t$ time [s]. The thermal diffusivity ($\lambda_0$) is the debris capacity to accumulate heat and it can be obtained from the ratio between debris layer thermal conductivity and debris density and specific heat capacity. In our study, we used an apparent mean thermal diffusivity independent from $x$ and constant along the vertical profile. In this way, Eq. 6 can be rewritten as:

$$\lambda_d \frac{d^2T_d(x)}{dx^2} = \left[\rho_d c_p(1-n_d) + \rho_w c_w n_d\right]\frac{dT_d(x)}{dt} \tag{7}$$

with $c_d$ and $\rho_d$ are the specific heat capacity and density of the debris, $n_d$ is the debris porosity and $c_w$ and $\rho_w$ are the specific heat capacity and density of the void filler within the debris. When the energy fluxes as from Eq. (1-7) are known, and particularly $Q_c$, one can estimate ice melt. If ice temperature $T_i$ [K] is fixed at melting point [$T_m$ = 273.15 K], and $Q_c$ is entirely used to melt an ice layer with latent heat of melting $\lambda_i$ [ca. 334000 J kg$^{-1}$] and mass density $\varrho_i$ [≈900 kg m$^{-3}$], the cumulated ice melt $I_m$ [m w.e.] is

$$I_m = \sum_{i=1}^{t} \frac{Q_c}{\lambda_i \rho_i} \tag{8}$$

TABLE 1 - Main parameters of the ablation model, and adopted values.

| Parameter | Value | Source |
|---|---|---|
| Albedo [.] | 0.35 | Measured, highest value |
| Stefan-Boltzmann constant σ [W m$^{-2}$ K$^{-4}$] | 5.67×10$^{-8}$ | Literature |
| Debris emissivity [.] | 0.98 | Literature |
| Granite density $\rho_d$ [kg m$^{-3}$] | 2700 | Literature |
| Water density $\rho_w$ [kg m$^{-3}$] | 1000 | Literature |
| Ice density $\rho_i$ [kg m$^{-3}$] | 900 | Literature |
| Granite specific heat capacity $c_p$ [J kg$^{-1}$ K$^{-1}$] | 790 | Literature |
| Water specific heat capacity $c_w$ [J kg$^{-1}$ K$^{-1}$] | 4186 | Literature |
| Air specific heat capacity $c_a$ [J kg$^{-1}$ K$^{-1}$] | 1010 | Literature |
| Latent heat of ice melting $\lambda_i$ [J kg$^{-1}$] | 334×10$^3$ | Literature |
| Water saturated debris thickness $DT_s$ [m] | 0.035 | Observed, average value |
| Debris porosity $n_d$ [.] | 0.625 | Observed, average value |
| Von Karman's constant $k_*$ [.] | 0.42 | Literature |
| Thermal conductivity $\lambda_d$ [Wm$^{-1}$K$^{-1}$] | 0.615 | Estimated, average value |

Field measurements over short periods at the Venerocolo Glacier during the 2007 ablation season showed that $T_i$ is constantly close to melting point (273.15 K). To evaluate the energy fluxes in Eq.(1) according to their expression in Eq.(2-7), one needs debris temperature, which appears everywhere but in Eq.(2). Otherwise, $T_d$ can be back calculated by fulfilling Eq.(1), via iterative calculation, when all other variables and parameters are either measured or known (*e.g.* Nicholson & Benn, 2006). Here, we implemented an executable (C$^{++}$®) to numerically solve Eq.(1) through a finite difference scheme, based on a data driven approach. We used an implicit forward derivative scheme to warrant stability of the solution (full description reported in Malgarida, 2008). The stability of the system is assessed by von Neumann analysis. The model set up was chosen in C$^{++}$® to reduce computational time and to warrant portability. The ablation model can then be used in two different data driven modes depending on the available data: i) debris temperature driven mode, MT, and ii) energy fluxes driven mode, MR. In fact, a few short-term studies have investigated the energy balance of debris-covered snow and ice (Brock & *alii*, 2010; Reid & Brock, 2010; Fyffe & *alii*, 2014). Conversely, empirical degree-day approaches are normally the most used (e.g., Mihalcea & *alii*, 2006; 2008a;b; Singh & *alii*, 2006; Hagg & *alii*, 2008; Minora & *alii*, 2015) owing to limited data availability in remote mountain locations and poor knowledge of key processes.

In the MT mode, the model requires debris surface temperature data ($T_d$), debris thickness ($DT$), and thermal conductivity ($\lambda_d$). In the MR mode, the model requires as input data the net short wave and long wave radiation fluxes ($Q_s$ and $Q_l$, respectively), air temperature ($T_a$), debris thickness ($DT$), and thermal conductivity ($\lambda_d$).

The model provides as outputs the vertical debris temperature variation at 10 equally spaced points in the debris layer (independently from debris thickness) ($T_d(x)$), the surface temperature ($T_d$), the conductive heat flux ($Q_c$), the partial ice ablation in the time step ($l_i$), every 10 minutes, and the total ablation during the analyzed period.

The model calculates ice melt whenever positive energy flux occurs, corresponding to the downward flux from debris surface to ice (273.15 K). Refreezing processes during night are neglected, and when the conductive heat flux is negative ablation is set to 0. When using the simulated radiative flux, the model requires slope angle and albedo. Otherwise, it uses a default albedo value of 0.35 (we selected for the model the highest measured albedo value at the Venerocolo Glacier).

In Table 1 are listed the constant and variables used in the model. The tonalite and granodiorite rock properties are similar to those ones featured by granite. Therefore, in this study we considered the granite properties, namely rock density and heat capacity. In both modes, the model requires debris thermal conductivity, $\lambda_d$. In literature, the thermal conductivity can be implicitly estimated by thermal resistance of debris layer (i.e. ratio between layer thickness and thermal conductivity, see Nakawo & Young, 1982), or by vertical thermal diffusivity (using a one-dimensional thermal diffusion equation) and volumetric heat capacity (Conway & Rasmussen, 2000; Nicholson & Benn, 2006). In our study, to estimate $\lambda_d$ under a data driven approach, we used ice ablation data gathered as reported above.

## RESULTS

### METEOROLOGICAL AND DEBRIS TEMPERATURE DATA

Meteorological data collected at the Venerocolo Glacier surface in summer 2007 by the AWS were analyzed, since they drive the surface energy balance. To estimate the energy available for buried ice melting, debris temperatures measured by thermistors were analyzed as well. During the ablation season 2007, air temperature ($T_a$) averaged 277.6 K, and liquid precipitation (*P*) amounted to 250 mm at the AWS station. Wind speed ($U_w$) was 1.7 m $s^{-1}$ on average. Our data showed a close agreement (correlation $r = +0.85$) between the incoming short wave radiation (*S*) and the surface debris temperature ($T_d$, measured at 2 cm depth according to Osterkamp, 2003; Guglielmin, 2006; Guglielmin & *alii*, 2008).

This correlation is partially due to the surface albedo, which we found to range from 0.20 to 0.35, thus giving about 65-80% of *S* retained by rock debris and used to increase its temperature $T_d$.

Surface values of $T_d$ influence $T_a$, since the debris layer surface releases long wave radiation flux $Q_m$, warming the air layer nearby the rock surface (fig. 3a). Therefore, the conductive heat flux in the debris layer and ice ablation therein are less sensitive to $T_a$ variation, but mainly influenced by debris properties and incoming solar radiation flux, differently from debris-free glaciers. Measurements of $T_d$ (gathered as reported at 0.02 m below the surface to avoid direct sun radiation and then temperature overestimation) displayed maximum values of $T_d$ as high as 303.15 K during daytime, and as low as 273.15 K during night (fig. 3a,b). A snowfall event on the glacier was detected at the end of ablation season 2007 (September 18$^{th}$-20$^{th}$) when $T_d$ dropped close to 273.15 K, and $Q_m$ was much lower than expected (fig. 3a). Also $T_a$ data dropped below freezing. Melt of the snow layer was tracked by analysis of $T_d$ pattern, clearly increasing as snowmelt proceeds (fig. 3b). The correlation between $T_d$ and *DT* on the Venerocolo Glacier ($r = +0.7$) is smaller than in other debris covered glaciers (Mihalcea & *alii*, 2008a;b). This may be due to the narrow range of debris thickness as observed throughout Venerocolo. From our experiments, debris is thinner than 10-15 cm for the largest part of the glacier area. During the ablation season, debris redistribution is large, thus further minimizing differences among different glacier sectors. Debris redistribution is mainly driven by differential ablation processes occurring at high rates when debris depth is thin, and higher whenever debris depth is thinner than the critical value. Conversely, throughout wider debris covered glaciers, like the Miage in the Alps (Diolaiuti & *alii*, 2009; Mihalcea & *alii*, 2008a) or the Baltoro in the Karakoram (Mihalcea & *alii*, 2008b; Mayer & *alii*, 2006), supraglacial debris cover shows a wide debris depth variability, ranging from a few millimeters in the upper glacier sectors to several meters at the tongue, thus carrying a more complex pattern of debris temperature and energy budget, and magnifying the correlation between $T_d$ and *DT* (Mihalcea & *alii*, 2006; 2008a; 2008b). On large debris covered glaciers, the areas where debris is thicker are affected by slower ablation rates (Diolaiuti & *alii*, 2009), thus avoiding a strong debris redistribution and transport, and then maintaining a wide spatial variability of debris depth. Further on, the low albedo featured by the main lithology dominating the Venerocolo (i.e.:

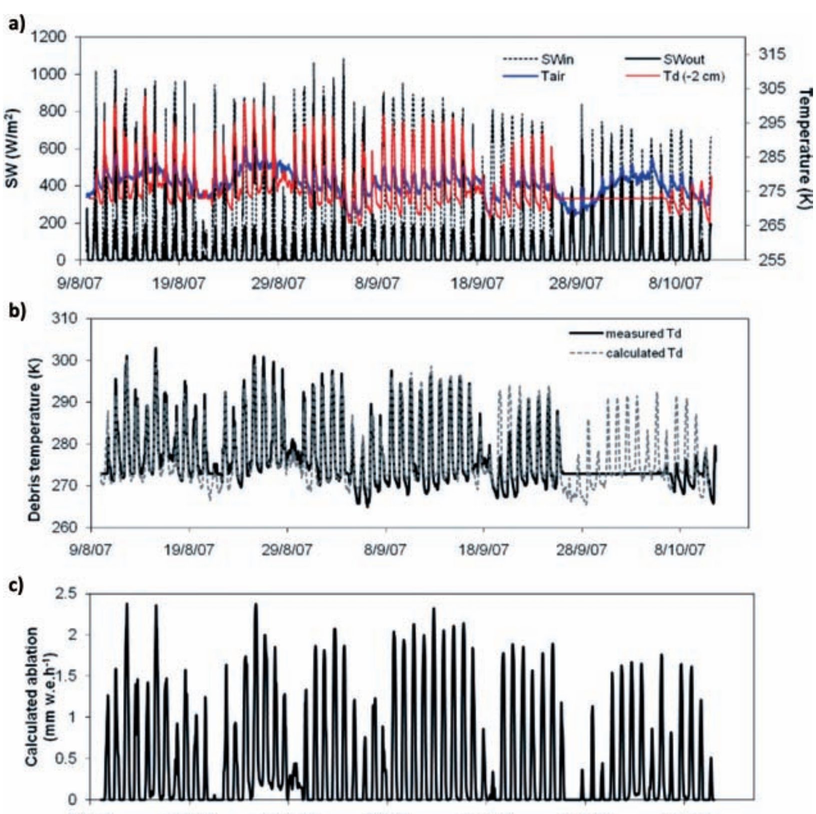



FIG. 3a) - Incoming short wave $SW_{in}$, and outgoing long wave $SW_{out}$ radiation, $T_a$ and surface debris temperature $T_d$ for the 2007 ablation season. b) Model output data: calculated and measured debris surface temperatures; and c) Modelled ablation derived from surface energy flux input data.

tonalite) and the glacier aspect towards NW may provide lower average surface debris temperatures than throughout other debris covered glaciers.

## Ablation model

### *Thermal conductivity*

A key role in the ablation model (i.e. in the ablation process) is played by debris thermal conductivity $\lambda_d$. While surface debris temperature $T_d$ and debris thickness *DT* can be measured or estimated on site, the spatial and temporal variability of $\lambda_d$ is unknown. Debris cover displays a variety of structures, with different thermal characteristics, changing during the ablation season, and $\lambda_d$ is not a priori constant in time. The value of $\lambda_d$ is influenced by debris properties, such as thickness, rock type (density, specific heat capacity), porosity of the solid matrix, and water content. Specific measurements of debris properties (grain size, layer geometry, water content) were performed for a few sites on the Venerocolo Glacier, but $\lambda_d$ could not be directly investigated.

We decided here to obtain representative values of $\lambda_d$ by back calculation, solving Eq.(1-8) for known (i.e. measured) values of ice ablation. A bisection method was applied. The model was fed with a minimum and a maximum value of $\lambda_d$ as drawn from the available literature. Then, the model was used to iteratively calculate ice ablation by varying $\lambda_d$, and evaluate the absolute error (%) between calculated and observed cumulated ablation $I_m$

$$err = \left| 1 - \frac{I_{m,sim,j}}{I_{m,oss,j}} \right| \tag{9}$$

with $I_{m,oss}$ and $I_{m,sim}$ observed (during the field surveys) and simulated total ice melt at stake *j*, respectively. A best value of $\lambda_d$ was obtained by iteratively minimizing *err* at each stake, considering ablation periods when debris properties were constant (*i.e.* constant values of *DT* during field surveys). So doing, we obtained a set (*i.e.* for different stakes and different periods, depending upon *DT*) of values of $\lambda_d$, reported in figure 4 for each stake, and variable in time according to different debris thickness. This analysis displayed variable values of $\lambda_d$, with an average $E[\lambda_d]= 0.615$ W m$^{-1}$ K$^{-1}$ for the considered period.

The $\lambda_d$ pattern shown in figure 4 displays a noticeable variability, with a maximum $\lambda_d$ of 1.09 W m$^{-1}$ K$^{-1}$, and a $\lambda_d$ minimum of 0.11 W m$^{-1}$ K$^{-1}$, both recorded at stake 3. Maxima are mainly observed in the first days of August, and the minima during the end of September 2007. These values are within the range of previous direct measurements (0.85 to 2.6 W m$^{-1}$ K$^{-1}$; see Nakawo & Young, 1982; Conway & Rasmussen, 2000) and of estimations from physical constants for typical debris forming materials (0.47 to 1.97 W m$^{-1}$ K$^{-1}$; Nicholson & Benn, 2006). Generally, the thermal conductivity of the debris varies with mineralogy, porosity, moisture content and thickness (Suzuki, 2010). As previously shown, mineralogy and porosity can be considered constant over Venerocolo Glacier, and then we focused on the other two parameters. Our data show that, even if *DT* did not vary so much, small changes in debris thickness influence noticeably $\lambda_d$: a 20% change in *DT* leads to a 30-50% variation of $\lambda_d$. However, this is not the unique driving factor of $\lambda_d$, since we found higher values of $\lambda_d$ during periods with higher inputs of energy, *i.e.* $Q_s$, feeding back in higher ablation rates and then in larger water amount in the debris layer. In fact, an increasing debris water content at the debris-ice interface, as given by enhanced melting, provides higher $\lambda_d$. These results are similar with findings by Brock & *alii* (2010). In fact, they reported $\lambda_d$ values ranging from 0.71 to 1.37 W m$^{-1}$ K$^{-1}$. They explained this variability as dependent on debris thickness. This could be due to greater heat transfer by convection in the larger openwork clast layer normally present in thicker covers.

### *Debris temperature*

The ablation model mimics the vertical profile of debris temperatures by using as input either surface measured $T_d$ (MT mode) or the surface energy fluxes, and air temperature (*i.e.* $Q_s$, $Q_l$, $T_a$, MR mode). In figure 3b we report a simulation carried out using MR mode. We report the debris surface temperature $T_d$ as provided by the model, against its measurements from the thermistors, at stake 5. This stake is nearby the AWS, where energy fluxes $Q_s$, $Q_l$ and air temperature $T_a$ were measured. A reasonable correspondence is seen between modelled and measured $T_d$. We then modelled debris surface temperatures at the other stakes, where we observed a slight overestimation. This was likely due to inaccuracies in the use of the energy fluxes measured at the AWS site, that is relatively far. In figure 5 we report a 3D temperature profile as provided by the model (MR mode) within the debris cover, down to 0.10 m depth, at stake 5 for two days (July 31$^{st}$, August 1$^{st}$ 2007).

The model was able to predict the diurnal temperature variation at the surface, and along the debris column at 10

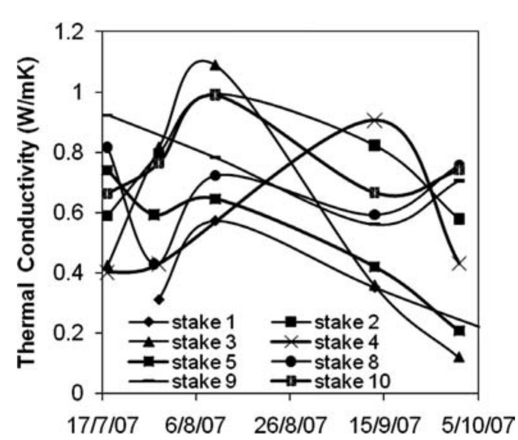



Fig. 4 - Thermal conductivity variation at 8 stakes during the 2007 ablation season.

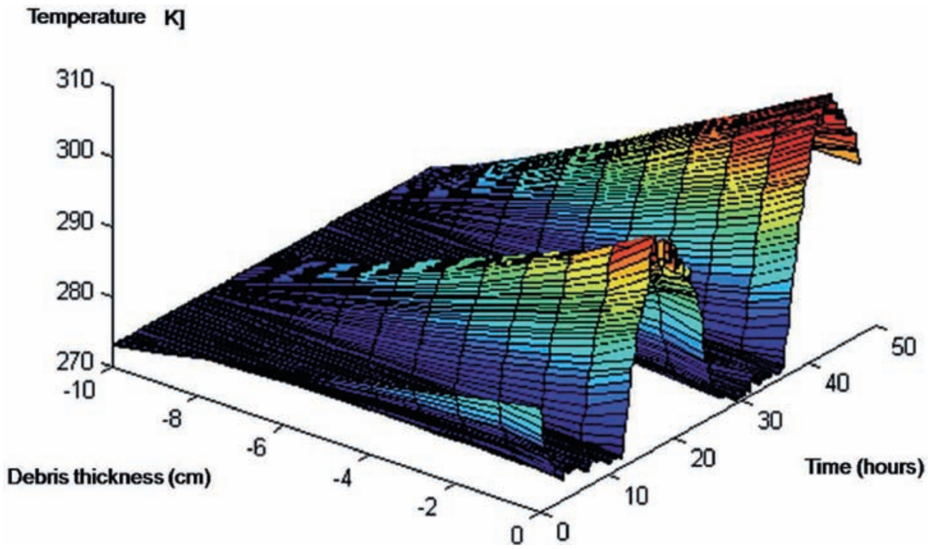



FIG. 5 - Variability of the modeled debris temperatures (3D) at stake 5 for two days (July 31st, August 1st 2007).

depths. A maximum value is found of 293.15 K and the minimum close to 273.15 K. In figure 6 we report the vertical profile of modelled debris temperature at different hours during the day, averaged during June 13-October 2007 at stake 5 (see Reid & Brock, 2010).

Figure 6 displays low temperatures profiles during the morning, when surface temperature is lower than at the debris-ice contact (melting point). Around 12:00 a.m. an increasing energy input at the surface occurs, driving increasing conductive heat flux, and warmer debris temperature in the afternoon. The observed patterns overlap well those found in other studies (Nicholson & Benn, 2006; Reid & Brock, 2010).

*Ice melting estimation*

We tested the model performance (MR mode) in calculating cumulative ice ablation $I_m$ during August-

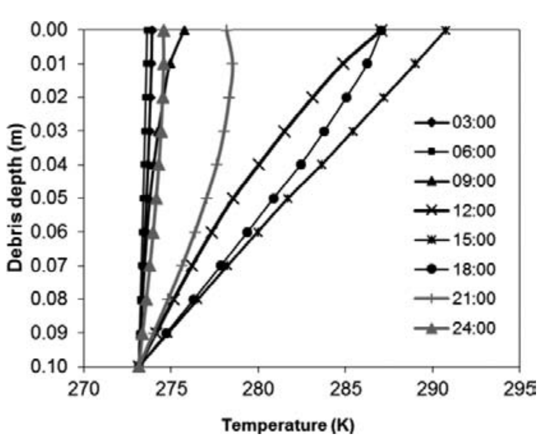



FIG. 6 - Modelled debris temperature at different hours during the day, averaged during June 13 - October 2007 at stake 5 (see Reid & Brock, 2010).

October 2007 (fig. 3c). To do so we selected 8 stakes with most complete observations, and we compared the model output $I_m$ with respect to its counterparts measured at each stake (Tab. 2). The energy fluxes, $Qs$ and $Q_l$ measured by the AWS were used as input data, and the model was used to calculate ablation during 34 days (10 August - 13 September 2007). Comparisons between calculated and measured values showed a good agreement (RMSE = 0.04 m w.e., r = 0.79), thus suggesting a good performance of the model in predicting ice ablation in MR mode (Table 2).

At stake 5, we modelled a total ablation $I_m$ of 0.676 m w.e. over 62 days, in a good agreement with the measured cumulative ice ablation of 0.625 m w.e. (with a slight overestimation of 0.05 m w.e.). This inaccuracy could be due to the snowfall event occurred at the end of September as reported (fig. 3a). In fact, our model is not able to take into account the occurrence of a snowfall, and then it is not implemented with a module for the snow melting. Therefore, in those days the available energy was spent to melt the snow covering the debris, and not the underlying ice. Then this results in a slight overestimation of buried ice ablation. In this case, $T_d$ data would probably be more suitable as input for the model (*i.e.* MT mode), because ice melting is calculated therein by pure heat conduction through rock debris. However, generally either measured or modeled meteorological variables are available for the purpose of ice ablation estimation, and MR mode is more easily applicable.

At stakes 9 and 10 (the highest and the farthest from the AWS) the difference between measured and calculated $I_m$ is about 10%, whereas for stakes closer to the AWS the differences are lower than 5%. This error may be mainly due to some assumptions we made, mainly taking wind speed and longwave and shortwave fluxes constant on the whole glacier surface, since they were actually measured only at the AWS site.

TABLE 2 - Modelled and measured total ice ablation and thermal conductivity at 8 stakes (debris thickness *DT* and elevation *E*) from 10th August to 13th September 2007. The energy flux is used as input data for calculating ablation (MR mode).

| Stake | Elevation [m a.s.l.] | DT [m] | Measured ablation [m w.e.] | Calculated ablation [m w.e.] | Measured thermal conductivity [W m$^{-1}$ K$^{-1}$] | Calculated thermal conductivity [W m$^{-1}$ K$^{-1}$] |
|---|---|---|---|---|---|---|
| 1 | 2581 | 0.06 | 0.455 | 0.438 | 0.35 | 0.37 |
| 2 | 2600 | 0.11 | 0.480 | 0.454 | 0.82 | 0.90 |
| 3 | 2595 | 0.078 | 0.470 | 0.435 | 0.56 | 0.52 |
| 4 | 2590 | 0.082 | 0.545 | 0.520 | 0.54 | 0.61 |
| 5 | 2621 | 0.065 | 0.525 | 0.510 | 0.42 | 0.44 |
| 8 | 2661 | 0.10 | 0.465 | 0.482 | 0.59 | 0.56 |
| 9 | 2689 | 0.065 | 0.495 | 0.566 | 0.56 | 0.45 |
| 10 | 2700 | 0.07 | 0.555 | 0.612 | 0.67 | 0.56 |

In figure 7 the model is tested to reproduce the well-known chart showing ablation (y axis) *vs* debris thickness (x axis) by Østrem (1959). The considered time window is from 10th August to 13th September 2007. In this test we considered thermal conductivity constant ($\lambda_d$ = 0.44 W m$^{-1}$ K$^{-1}$, average value at stake 5, see fig. 4), to mask the possible effect of seasonal changes of $\lambda_d$.

We analyzed output data calculated for stake 5 (the measured value is reported as a triangle in the chart, instead the black squares indicate the ablation value calculated varying debris thickness), the closest to the AWS, at 2621 m a.s.l. An exponential curve is obtained plotting the calculated ablation values vs the debris thicknesses, in agreement with the trends observed in other studies for increasing debris cover thickness (*e.g.* Mattson & *alii*, 1993; Mihalcea & *alii*, 2006; Nicholson & Benn, 2006; Reid & Brock, 2010). There is a substantial agreement between our modeled data and the ones reported by Nicholson & Benn (2006), and by Mattson & *alii* (1993), even if melt rates on the Venerocolo Glacier are generally lower. This is due to the different type and structure of supraglacial debris and to the peculiar glacier settings (i.e.: elevation, aspect, slope) with respect to those investigated in the mentioned studies. Our model does not display a plateau (i.e. a local maximum) in the ablation rates occurring with very thin debris thicknesses. The value of *DT* giving highest ablation is specific for each glacier, and depends on lithology, grain size and porosity. Debris thicker than this threshold gives decreasing ablation values, until it reaches a buried ice melt rate equal to the one of bare ice (and the corresponding debris depth is known as "critical debris thickness", Mattson & *alii*, 1993). Then, further increasing debris depth gives decreasing buried ice melt rates, until a stable minimum (generally for debris layer thicker than 0.40-0.50 m or so). Notice however that maximum ice melt rate may occur for very thin debris layers, so finding of this maximum value using an energy balance model may not be appropriate, and ablation is always found to increase in practice (*e.g.* Reid & Brock, 2010). In Bocchiola & *alii* (2010) we reported investigation of melt factors for the Venerocolo glaciers using the same data as here (namely, ice ablation and temperatures). We experimentally found maximum ablation (*i.e.* the maximum melt factor) for *DT* = 0.02 m. However, ablation could not be measured for lower values of *DT* (besides *DT* = 0 m for bare ice), so we can infer little in this sense. An extensive survey of debris thickness *DT* on the Venerocolo with subsequent interpolation (see Bocchiola & *alii*, 2010), showed that approximately 10% of the debris-covered area cover displays *DT* < 0.05 m, and 3% of the debris covered area or so has *DT* < 0.02 m.

Thus, ablation as provided by our model, albeit possibly inaccurate for small values of *DT*, should still be representative for most of the glacier debris covered area.

In figures 8a,b, we report the measured *vs* simulated ice melt for all the 8 stakes. Our model reproduces $I_m$ (121 days) with acceptable accuracy when applying different $\lambda_d$ values as resulting from the analysis above.

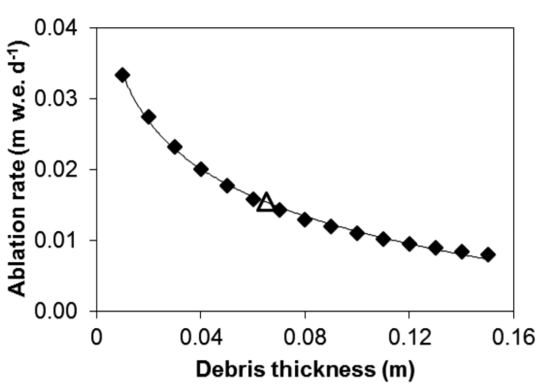



FIG. 7 - Modelled ice ablation (at Stake 5, 2621 m.a.s.l.) with different debris thickness. The triangle indicates the measured ablation rate.

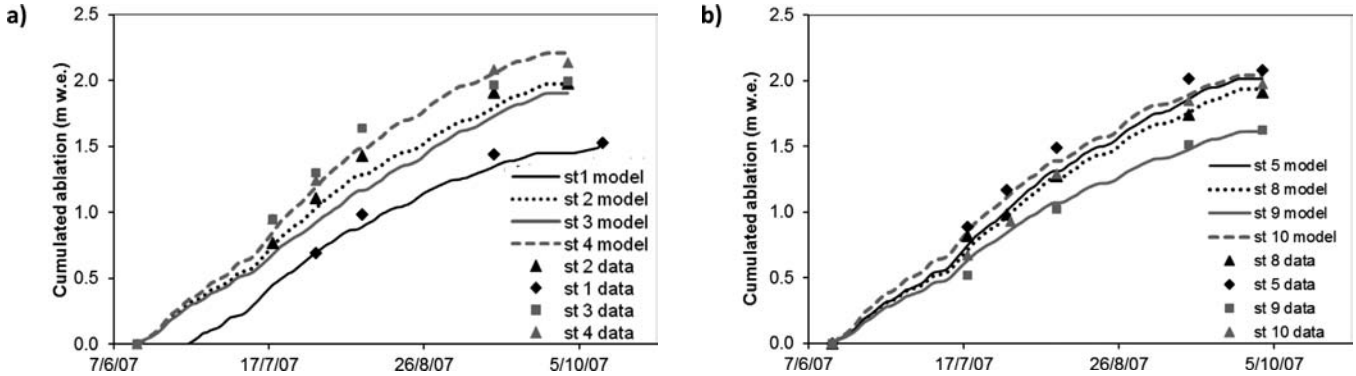



FIG. 8 - Modelled and observed ice ablation at different stakes for a period of 121 days. a) Stakes 1-4 b) Stakes 5, 8-10.

## DISCUSSION

Our model was tested on the Venerocolo Glacier, since it represents an interesting test site due to its small size and homogeneous coverage features (mainly rock debris type), allowing collection of field data in some selected representative points. Simple and efficient models to describe buried ice ablation are particularly required in view of the enlarging supraglacial debris coverage observed recently (Deline & *alii*, 2008; Kellerer-Pirklbauer & *alii*, 2008; Diolaiuti & *alii*, 2009). Moreover, in some glacierized regions like Karakoram, debris covered glaciers are already largely diffused, and their contribution to meltwater production is utmost (Mayer & *alii*, 2006; Hewitt, 2005). Our energy balance based model was developed for calculating buried ice melt using in input either meteorological (MR mode) or $T_d$ (MT mode) data, the former more easily available than the latter. We developed this model making some assumptions, which make simpler and wider model applicability. The first is that the interfacial debris-ice temperature was fixed to melting point preventing in this way nighttime refreezing of the buried ice; this assumption was made considering both our data from thermistors and logger at the Venerocolo debris-covered glacier and from other debris-covered glaciers we studied on the Italian Alps (Brock & *alii*, 2010; Mihalcea & *alii*, 2008a). Field data suggested that refreezing during nighttime is negligible whenever actual, and not strongly influencing the melt amount. This assumption was also made by previous authors, e.g. Reid & Brock (2010) and Nicholson & Benn (2006) who found on alpine debris-covered glaciers negative debris temperatures at the ice/debris interface only in Winter. Those of ablation models were run for temperate glacier in the Summer, when the ice surface remained at the melting point, thus supporting this assumption. Refreezing may need to be accounted for if the model was run over the Winter or shoulder periods.

Second, the estimation of turbulent fluxes (sensible and latent heat fluxes) was simplified in our model and only the sensible heat flux was calculated (Eq.4). Surface latent heat flux was neglected following e.g. Nicholson & Benn (2006), and Lejeune & *alii* (2013), and the loss of accuracy therein should not be large. Energy flux due to precipitation was also considered negligible. Other studies (Reid & Brock, 2010) demonstrated the total ablation is less sensitive to heat flux due to precipitation. Moreover, during the summer season 2007 precipitation occurred only during short periods and gave a small total amount (~250 mm).

Third, our model is not able to account for snow cover on the debris, being thus mostly usable in Summer. However, our model was conceived especially for estimation of buried ice melt, which is largest in Summer. In case of summer snowfall, a snow layer may develop or not, depending on the thermal state of the debris. When the debris temperature is below the melting point, a snow cover may develop on top of the debris. For higher debris temperatures, development of a snow cover depends on the balance between the heat content of the debris and the falling snow. From Venerocolo data, only one snowfall event occurred in the study period and in late September (i.e.: end of ablation season), thus suggesting that for the largest part of the melting time our model is suitable. Future improvements to take into account snow melt will be necessary, but the model is already usable for ice melt during warm season.

Our model presents further simplifications, *i.e.* mainly debris thermal properties and only standard meteorological data were used ($Q_s$, $Q_l$, $T_a$, $U_w$). Compared for instance to the model proposed by Han & *alii* (2006), our model can run with meteorological data as inputs to calculate ice melt when debris temperature are not available. Moreover, by using a simplified energy balance calculation (net radiation flux, air convection and surface emission), the model can be applied to different debris-covered sites and to site not equipped with an AWS (Nicholson & Benn, 2006; Brock & *alii*, 2010; Reid & Brock, 2010). This model is also suitable for further developments (i.e.: a distributed approach) and to be applied on other debris-covered glaciers located in remote areas with limited available field data. Finally, the model could be used to predict future ice ablation trends starting from solar radiation and air temperature data, made available by Global Climate Models (GCMs).

A critical parameter to assess ice ablation is thermal conductivity $\lambda_d$, which has to be accurately estimated. The model was run here in MT mode to find $\lambda_d$ values minimizing the melting error (i.e.: difference between measured and modeled values of $I_m$). In figure 9 we report a sensitivity analysis carried out to test the suitability of the model in calculating buried ice ablation over the whole summer period (121 days) when using different values of $\lambda_d$. For this purpose, we used different values of $\lambda_d$. The model was run in MT mode, and $\lambda_d$ was iteratively changed with steps of 0.05 W m$^{-1}$ K$^{-1}$ in the range 0.2-0.8 W m$^{-1}$ K$^{-1}$, as from our analysis above (fig. 4).

Stake 1 showed a low value of $\lambda_d$ (0.35 W m$^{-1}$ K$^{-1}$, possibly due to tonalite clasts' size, generally larger than 0.20 x 0.20 m). There, strong differences between measured and modeled ablation were found changing the best fit $\lambda_d$ value, with changes up to 120% for $\lambda_d$ = 0.8 W m$^{-1}$ K$^{-1}$.

In general, values of $\lambda_d$ reasonably close to the best fit one (*i.e.* ±20% or so), delivered an estimation error somewhat linearly changing (*i.e.* ± 20% or so).

We also investigated the chance of finding an unique (i.e. a most suitable) value of $\lambda_d$ to be applied to the whole glacier surface. This attempt was made to find a practical solution applicable on debris-covered glaciers located in remotes areas, where point wise ablation estimation is not feasible (Hewitt, 2005; Kirkbride & Warren, 1993; Mihalcea & *alii*, 2008a). The $\lambda_d$ value which minimizes the difference between measured and modeled ablation at all the analyzed stakes is $\lambda_{d,av}$ = 0.615 W m$^{-1}$ K$^{-1}$.

When $\lambda_{d,av}$ was used (fig. 10), the $I_m$ modelling error ranged from 30% to 50% (reaching up to 1 m at stake 1). However, averaging all the stakes, an error of 0.03 m is found. This indicates that use of a constant, valid on average $\lambda_d$ value may affect ablation data at single stake locations, but the impact may be negligible if only an average ablation value is required, say for hydrological investigation (e.g. Bocchiola & *alii*, 2010).

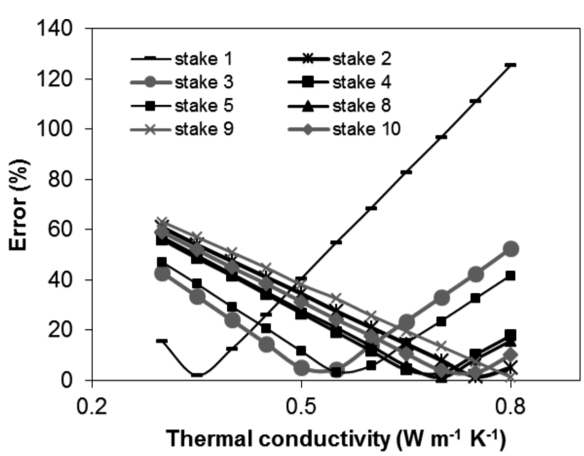



FIG. 9 - Error (%), difference between calculated and measured total ablation by varying the thermal conductivity values.

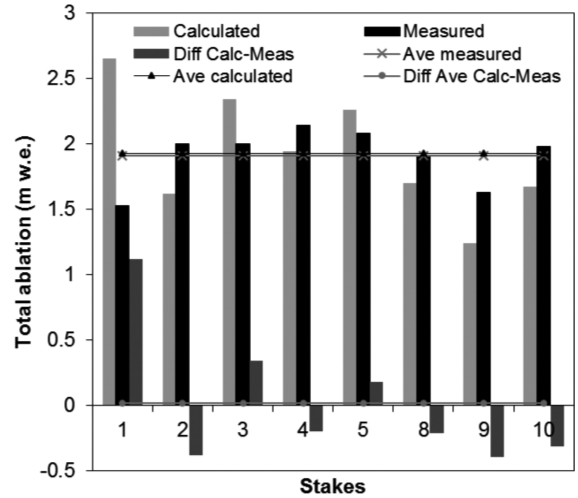



FIG. 10 - Total ablation (m w.e.). Measured melt, calculated melt and difference between calculated and measured melt at each stake. Average value of measured melt, and average value of calculated melt using $\lambda_d$ = 0.615 W m$^{-1}$ K$^{-1}$ also reported.

In the available literature on debris-covered glaciers, several authors apply constant (in space and time) values of $\lambda_d$ since it is quite difficult to predict its temporal and spatial variability (Brock & *alii*, 2010; Reid & Brock, 2010). Reid & Brock (2010) found $\lambda_d$ independent from debris thickness at the Miage Glacier, and they calculated an average value of 0.94 W m$^{-1}$ K$^{-1}$, which is higher than the mean one we calculated for the Venerocolo Glacier (0.615 W m$^{-1}$ K$^{-1}$). As stated above, our analysis shows that during an ablation season on the Venerocolo debris-covered Glacier $\lambda_d$ experienced noticeable changes, thus affecting ablation calculation at point sites. Also *DT* was affected by high variability, and both parameters are crucial and should be accurately determined.

To improve the ablation models, thermal conductivity calculation should consider the thermal properties of the debris layer, not constant with depth: porosity, moisture, aerodynamic roughness. Using a constant $\lambda_d$ to model ablation is a sub-optimal solution, and it should take into account $\lambda_d$ variation, not only at different sites, but also along the debris layer column. To implement in the model a $\lambda_d$ varying with debris depths is not easy, and more experiments are necessary to analyze the $\lambda_d$ pattern.

## CONCLUSIONS

The application of ice ablation models to debris-covered areas represents a challenge in view of the increasing debris coverage at glaciers' surface worldwide, and of the subsequent changes in glacier energy budget. Our simple model predicted with acceptable accuracy total ice ablation, internal debris temperature and positive heat flux at the debris-ice contact. The total ice ablation ranged between 2.00-2.65

m w.e., during 121 days in the ablation season 2007. The model may use as input data meteorological measurements ($T_a$, $Q_s$, $U_w$) from the nearby synoptic meteorological stations running for longer periods. Our analyses indicated that on the Venerocolo Glacier debris thickness and thermal conductivity $\lambda_d$ are affected by spatial and temporal variability, and $DT$ and $\lambda_d$ variations up to 100% were measured during the 2007 ablation season.

Use of a constant $\lambda_d$ value on debris-covered glaciers is often preferred, as it is quite difficult to predict its temporal and spatial variations (Brock & *alii*, 2010; Reid & Brock, 2010). Nevertheless, our results indicate that the use of a constant $\lambda_d$ can affect considerably the calculation of ice ablation, and the energy balance models used to estimated buried ice melt rates should consider values of $\lambda_d$ varying with depth, temperature, etc., especially when a distributed approach is required. The proposed model is reasonably simple and can be applied on other debris-covered glaciers featuring debris cover thicker than 0.01 m, and where a few meteorological parameters are available (either measured or calculated). The model time step of 10 min, and the spatial resolution of 11 steps are good for short time periods (one ablation season) and for single site measurements. Further model development may consider variable debris cover characteristics (water content, stratification, slope and aspect), trying also to reduce temporal and spatial resolution along the debris column. This latter feature is desirable to reduce the computation time for calculating melt over longer periods. Eventually, the model proposed here may be used confidently enough to simulate ice ablation on debris-covered glaciers, say for hydrological conjectures, or to predict future ice ablation trends under climate change scenarios.

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