The non-woven geotextiles as strategies for mitigating the impacts of climate change on glaciers

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Keywords: non-woven geotextile; snow melt mitigation; Dosdè Est Glacier; Presena Ovest Glacier.

Abstract

During the past decades, there have been attempts to offset melt at glacier ski resorts. The most important method is active glacier protection, largely based on the use of geotextiles to preserve snow cover and reduce its melt. Until 2008, a scientific evaluation of the efficiency of glacier covering strategies had never been carried out in Italy, although strategies for snow melt reduction were already in place.

In this study, we show the results from three experiments carried out on Dosdè Est Glacier (Cima Piazzi Group, Lombardy) and Presena Ovest Glacier (Adamello-Presanella Group, Autonomous Province of Trento). The first experiment was set up in 2008 at 2800 m a.s.l. on Dosdè Est Glacier with the aim of verifying the applicability and the effectiveness of these geotextile covers on non-groomed snow. The second test was carried out in 2010 by covering most of Presena Ovest Glacier with the aim of verifying the applicability and the effectiveness of geotextile covers on groomed snow and of investigating the involved radiative processes.

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The last experiment was set up in 2012 at 2765 m a.s.l. on Presena Ovest Glacier and it was aimed at evaluating which materials and properties are able to reduce snow/ice melt more effectively. Tested materials included commonly used polypropylene and polyester and poly-lactic acid (fully biodegradable) with different combinations of mass per unit area and thickness. We found that these non-woven geotextiles are able to reduce snow/ice melt up to 69% compared to the uncovered glacier surface, mainly thanks to an increase in albedo by about 50% compared to ice. The material with the best performances is composed of polypropylene with a mass of 500 g/m^2 per unit area and a nominal thickness of 3.70 mm.

1. Introduction and study aims

Present climate change affects glaciers worldwide (Zemp, 2008; Paul et al., 2004; 2007). Most alpine glaciers have experienced a more or less continuous mass loss since the end of the Little Ice Age (ca. 1850, Grove, 1988; Zemp et al., 2008) and over recent years this phenomenon has been intensifying (Citterio et al., 2007; Diolaiuti et al., 2012). In addition, Italian glaciers lost 30% of their area, from 526.88 km^2 in the 1960s to 369.90 km^2 in the past decade (Smiraglia et al., 2015).

Currently, summer ski activities occur only on a small selection of Alpine glaciers in Europe, depending on climatological conditions (e.g. precipitation and wind), the presence of infrastructures and facilities like ski-lifts, and the availability of snow cats to manage ski routes. Nevertheless, these glaciers play a non-negligible role for the economy of local communities and they are used for training by the national ski teams during the summer season, ensuring the continuity of their preparation to face national and international winter competitions. During the past decades, there have been attempts to offset the melt on these glaciers. On some glaciers, the managers of the ski routes and the local administrations decided to forbid ski activities during the warmest summer months (i.e. July and August). Since this strategy did not prove sufficient to reduce human impacts, other methods were developed and tested. Mass balance management can be performed by means of glacier covers, grooming, water injection, snow-farming, snow production and relocation (Olefs and Fischer, 2008; Olefs and Obleitner, 2007; Olefs and Lehning, 2010; Fischer et al., 2016).

The most effective method is glacier covering, largely based on the use of special blankets (geotextile) to preserve snow cover and reduce its melt (Olefs and Fischer, 2008).

Until 2008, a scientific evaluation of the efficiency of active glacier protection strategies had never been carried out in Italy, although strategies for snow melt reduction were already in place (e.g. covering the base of the ski lift pylons with special blankets) at some glacier ski resorts.

Since then, researchers at the University of Milan have carried out three experiments with non-woven geotextiles in different contexts, on both groomed and non-groomed snow. Unlike woven geotextiles (where the weaving is meant to provide a high load capacity, but a low porosity, which makes the geotextile impermeable), non-woven geotextiles are manufactured by bonding materials together, either through chemical processes or heat, needle punching or other methods, which allows for better drainage. The first test, performed in 2008 on Dosdè Est Glacier (Cima Piazzi Group, Lombardy), focused on the efficiency and applicability of non-woven geotextiles. In summer 2010, a second test was performed on Presena Ovest Glacier (Adamello-Presanella group, Autonomous Province of Trento) to investigate the involved radiative processes and to assess the effects of the geotextiles on the albedo. A third experiment was carried out on this glacier in summer 2012, aimed at detecting which geotextile is most efficient at reducing snow and ice ablation through a comparative analysis.

2. State of the art

Modern techniques for reducing snow and ice melt are based on pilot studies performed in the past: a prominent example is represented by studies performed by Louis Agassiz. In 1841, in the tenth chapter of the first book about glaciology, Louis Agassiz (Swiss biologist, zoologist, paleontologist and glaciologist) described how icy paths were sprinkled with sand or chaff and the ice was able to last longer beneath the sand cover than in the surroundings. Moreover, these paths turned out to be at higher elevation compared to the ground as the sand protected the underlying black ice from evaporation and melting.

Artificial ablation reduction methods have received little attention in the past as snow mostly created problems rather than being useful to humans (Olefs, 2009). Additionally, compared to other natural surfaces, snow has a rather high shortwave reflectivity, which is difficult to increase further. Different types of artificial (aqueous or urethane foams, plastic sheets) and natural (sawdust) coverings were tested in the 1960s and 1970s for Arctic operations to increase the stability of roads and runways (Grove et al., 1963; Herrmann and Stehle, 1966) or in recent times to guarantee the seasonal storage of snow for cooling applications (Skogsberg, 2005). Most of the techniques were aimed either at increasing the albedo and/or decreasing thermal conductivity to reduce the energy available for melting the underlying snow or ice surface (Olefs, 2009). In Japan, attempts were made to create artificial glaciers out of perennial snow patches by increasing accumulation using snow fences and decreasing ablation with different cover materials. In these experiments, nets were placed on the snow surface to reduce wind velocity and therefore turbulent heat exchange (Higuchi, 1973).

Such approaches are partly based on observations of natural processes where active glacier protection is a well-known phenomenon (Olefs, 2009). The natural modification of snow and ice ablation is related to the surface deposition of debris-like material (sand, gravel, rocks), dust or volcanic ash. Depending on the material properties (e.g. thermal conductivity or thickness), their presence leads to differential ablation through the modification of the energy balance at the snow or ice surface (Bocchiola et al., 2015). For rock or debris cover, well-known structures like glacier tables or dirt cones evolve from the glacier surface if the material has a small areal extent. Important consequences on the glacier mass balance are observed for larger, debris-covered ice areas. Debris increases the ablation for thicknesses of less than around 2 cm owing to a discontinuous layer of scattered particles with low albedo. However, thermal insulation dominates for larger thicknesses with a continuous layer and the ablation is subsequently reduced, with melt reduction between 35% and 85% for debris thicknesses of 0.1 m and 0.4 m, respectively (Nicholson and Benn, 2006; Mihalcea et al., 2006).

Dust layers (e.g. from the Sahara) are regularly observed in the Alps (Azzoni et al., 2018); they are generally very thin and therefore tend to accelerate ablation by about 10% to 20%, whereas volcanic ash, when thick enough, was observed to reduce melt rates in New Zealand (Slaughter, 1969; Brock et al., 2007). Drake (1981) noted that thick dust covers, low solar radiation and high wind speed delay melt, whereas the inverse is required to observe accelerated melt rates.

One of the first studies on the intentional reduction of ice and snow ablation at glacier ski resorts is that by Olefs and Obleitner (2007) where both numerical models and field tests supported the application of special blankets to reduce glacier melt. More recently, Fischer et al. (2016) summarized the research they performed at Austrian glacier ski resorts. They reported that in the uppermost parts of the glaciers, the preservation of ice by covering the glacier works well to retain the track connection between ropeway mountain stations and the glacier surface over multi-year periods. In areas near the glacier terminus, the continuous combination of additional snow load and glacier cover helps to preserve the remaining ice body where, without mass balance management, the glacier would retreat rapidly. However, the applicability of glacier covers is limited by altitude: Olefs and Lehning (2010) showed that at lower altitudes sensible heat fluxes become more important compared to shortwave radiation making the method less effective.

In the context of mass balance management, this paper provides new data and reports the findings from three Italian experiments. To our knowledge, these are the only experiments available to evaluate and discuss the use of geotextiles on glaciers in the southern Alpine sector.

3. Study areas

Our first test was performed on Dosdè Est Glacier (46° 23’ 26” N, 10° 13’ 05” E, Fig. 1), one of the main glaciers of the Piazzi-Dosdè Group (Italian Alps). This glacier is about 0.71 km^2 wide, and it ranges from 2580 to 3220 m a.s.l. It has a North-Westerly aspect (350°) and a mean slope of 22° (data from 2007, Smiraglia and Diolaiuti, 2015). Soncini et al. (2015) reported a yearly mean mass balance of about -1 m w.e. between 2009 and 2014. This glacier is not part of a ski resort, and represents a Site of Community Importance (SCI) designated under the EU Habitats directive (92/43/EEC).

Dosdè Est Glacier is the most studied glacier of the Piazzi-Dosdè Group; its tongue has retreated by about 400 m over the past 50 years (about 30% of its total length in the second half of the 20th century). This trend is similar to the one shown by other Italian glaciers (see Citterio et al., 2007), although the terminus retreat rates depend upon glacier size. The retreat rate of Dosdè Est from 1970 to the present is -24 m/y, higher than between 1955 and 1970 when it averaged -14 m/y.

The second focus of the study is Presena Ovest Glacier (46° 13' 23" N, 10° 34' 54" E), part of the Adamello-Presanella Group (Autonomous Province of Trento, Italy, Fig. 1), and located within the river basin of Vermigliana-Noce-Adige. The area of this glacier is about 0.25 km^2 and the altitudinal range is between 2690 and 2990 m a.s.l.; the glacier has a North-Westerly aspect (348°) with a mean slope of 22° (data from 2011, Smiraglia and Diolaiuti, 2015). It is part of the SCI (92/43/EEC) named "Ghiacciaio dell'Adamello". The terminus, monitored by the Society of Tridentine Alpinists (SAT), experienced a retreat of more than 50 m between 1990 and 1999. In 1961, the glacier had an area of 0.82 km^2 with a maximum length of 1200 m and a width of 1100 m (Comitato Glaciologico Italiano, 1961). The glacier shrank to almost 0.68 km^2 in 1987 (data from PAT) and 0.75 km^2 at the beginning of 1990 (data from SAT, see Bombarda, 1996). Recent studies revealed a surface of 0.33 km^2 in 2003 (data from PAT). This value refers to Presena Ovest Glacier only, which is now completely separated from a smaller body (0.08 km^2) named "Corno di Lago Scuro". In 2011, Presena Ovest and Corno di Lago Scuro had an area of 0.25 km^2 and 0.04 km^2, respectively (Smiraglia and Diolaiuti, 2015). Snow accumulation comes from direct solid precipitation with little contribution from snow avalanches, owing to the lack of surrounding high rock walls. In fact, during less favorable years, snow melts away completely at the end of the summer, in spite of the north-westerly aspect of the glacier.

This glacier is part of a ski resort and ski activities are practiced from 1^{st} November to 30^{th} June. During the warmest summer months, skiing is forbidden to save at least part of the glacier snow. In spite of this practice, the local administration observed severe ice thinning in the middle of the glacier, which could prelude a fragmentation event. Therefore, in summer 2008 the Autonomous Province of Trento decided to apply an active glacier protection strategy and to investigate the best method for preserving glacier ice on Presena Ovest.

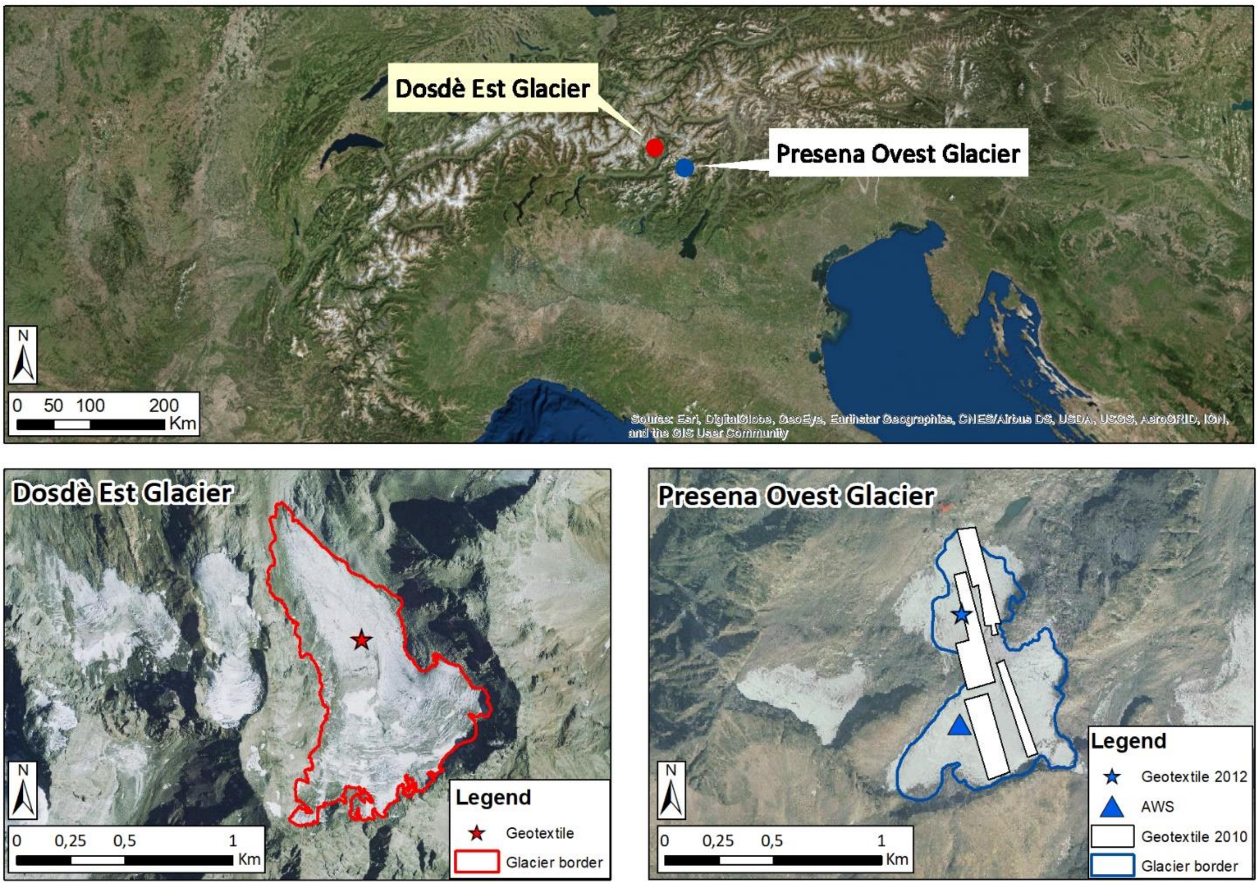

Fig. 1: Location map of the study sites (on the top), and pictures of Dosdè Est Glacier (on the left) and Presena Ovest Glacier (on the right) where the position of the geotextiles is shown.

4. Materials and Methods

4.1 The first experiment: Dosdè Est Glacier

On Dosdè Est Glacier, activities started on 15 May 2008 with the installation of a non-woven geotextile 150 m^2 wide (Table 1) at an elevation of 2800 m a.s.l (Fig. 1) to evaluate the reduction in snow and ice melt under natural conditions (i.e. no addition of freshwater, no snow grooming by means of snow cats). This non-woven geotextile was made of polyester and polypropylene (ICE PROTECTOR 500 ©). It is a thermal stabilizer and it absorbs UV rays, preventing them from reaching the underlying snow. Thus, snow melt is reduced by means of a thermal barrier at the atmosphere-snow interface. In addition, the chosen material is free from toxic substances and it is thermally disposable.

The ICE PROTECTOR 500 © roll (55 m long and 4.85 m high) was transported onto the glacier by helicopter on May 14^{th}. Before the installation, the snow thickness was measured at various sites by means of a manual snow probe and the average value was 2.20 m (2.50 m considering only the installation area). In addition, a snow pit was dug at 2800 m: a density ranging from 400 to 600 kg m^{-3} was measured and a total snow water equivalent (SWE) of 1.29 m w.e. was estimated. Detailed information about snow pits is reported by Senese et al. (2018). After the analysis of snow properties, the non-woven geotextile was laid out manually. Owing to its permeability, the non-woven geotextile absorbs the water film that covers the snow crystals and thus it naturally sticks to the snowpack. As katabatic winds can occur on Alpine glaciers (i.e. up to 140 km/h from the accumulation basin to the glacier terminus, see Senese et al., 2012a), to keep the blanket in a stable position, 36 rock blocks were placed on its border and fixed by means of static tape. To limit the influences of these rocks on glacier albedo, they were inserted into bags made from the same geotextile. At the end of the installation procedure, the whole surface looked white and homogenous (Fig. 2). During summer 2008, the area was regularly visited to provide maintenance, to measure the snow density and thickness beneath the geotextile and the thickness variations of unprotected snow/ice. The geotextile was removed on 4 October 2008.

Site	**Year**	**Manufacturer**	**ID Geotextile**	**Chemical composition**	**Mass per unit area**	**Thickness (mm at 2kPa)**
Dosdè	2008	Landolt	ICE PROTECTOR 500 ©	Double-bedded Polypropylene / Polyester (PET/PP)	500 g/m^2	3.80
Presena	2010	TenCate	TOPTEX GLS 340	Polypropylene (PP)	340 g/m^2	4.00
Presena	2012	Edilfloor	COVERICE 340	Polypropylene (PP)	340 g/m^2	3.20
Presena	2012	Edilfloor	COVERICE 340BIO	Poly-lactic acid (PLA)	340 g/m^2	3.00
Presena	2012	Edilfloor	COVERICE 340PET	Polyester (PET)	340 g/m^2	3.00
Presena	2012	Edilfloor	COVERICE 500	Polypropylene (PP)	500 g/m^2	3.70
Presena	2012	Edilfloor	COVERICE 500D	Double-bedded Polypropylene (PP)	500 g/m^2	4.40
Presena	2012	Edilfloor	SI400	Polypropylene (PP)	400 g/m^2	3.80

Tab. 1: Details of the non-woven geotextiles tested on Dosdè Est and Presena Ovest glaciers.

Fig. 2: The ICE PROTECTOR 500 © on Dosdè Est Glacier: the installation on 14/05/2008 (left), the differences between the unprotected glacier surface and the area covered by the geotextile on 19/08/2008 (right).

4.2 The second experiment: Presena Ovest Glacier

On 28 June 2010, a non-woven geotextile (TOPTEX GLS 340 ©, produced in Linz, Austria, see Table 1) was installed along the main flowline of Presena Ovest Glacier, covering 76400 m^2 which is about 30% of the total glacier area. The aim of this experiment was to understand the effects of non-woven geotextiles on glacier radiative fluxes and albedo (Fig. 3). The geotextile was placed on snow previously compacted by snow cats, thus with a higher initial density than natural snow at the same elevation. It was removed on 14 September. Before the installation, snow pits were dug following the AINEVA protocol (Senese et al., 2018) by personnel from the Autonomous Province of Trento (PAT), with the aim of evaluating the snow density and its features and of quantifying snow accumulation. The snow/ice ablation rate was measured every 15 days by means of ablation stakes drilled into the ice both along the geotextile borders and at specific sites in unprotected areas of the glacier at the same elevation.

To measure glacier radiative fluxes and albedo, two automatic weather stations (AWSs) were installed. The first AWS (measuring shortwave and longwave incoming and outgoing radiation) was located on the non-woven geotextile (named $AWS_{geotextile}$), while the second AWS (named $AWS_{glacier}$) was placed in a different area of the glacier, without artificial covering and with similar aspect and elevation as the site covered with the non-woven geotextile. At the second AWS, all meteorological and radiative parameters were measured. The radiative fluxes at the covered and unprotected glacier surface were compared by means of four components radiometer sensors (Kipp & Zonen, CNR1, Fig. 4), measuring shortwave (range: 0.3-3 µm) and longwave (range: 5-50 µm) radiation, both incoming and outgoing. With these sensors, we also estimated the albedo, defined as the broadband hemispherically averaged reflectance in approximately the spectral range 0.3-3 µm and depending on solar elevation, cloudiness, presence of liquid water, crystal structure, surface conditions and the presence or absence of impurities (rock debris, dust, organic matter, etc.) (Azzoni et al., 2016). This parameter can range from 0 (all the incoming flux is absorbed by the surface) to 1 (all the incoming flux is reflected). It is estimated as the ratio of outgoing shortwave radiation (SWout) to incoming shortwave radiation (SWin). The CNR1 radiometer sensor installed on the automatic weather station $AWS_{geotextile}$ (Fig. 4a) was set up at 1.5 m above the non-woven geotextile surface and the acquired dataset spanned from the end of July to the beginning of September 2010. The second radiometer (Fig. 4b) was installed on the $AWS_{glacier}$ located outside the glacier area covered with the non-woven geotextile, at 2900 m a.s.l., and far from nunataks affecting the energy fluxes and air temperature. In addition to the CNR1 radiometer, the $AWS_{glacier}$ was equipped with sensors for measuring air temperature, relative humidity, wind speed and direction, atmospheric pressure, liquid precipitation, and snow depth (Table 2). The battery (100 Ah and 12 V) was charged by means of a solar panel (40 W). The whole system was supported by a three-leg, 5 m high stainless steel mast standing on the ice surface according to the construction and setting used by researchers of the University of Milan (Senese et al., 2012a). The $AWS_{glacier}$ stood freely on the ice and adjusted to the melting surface during summer. The height of each instrument above the surface was chosen in agreement with the recommendations by the World Meteorological Organization. Unlike the other Italian Alpine supraglacial AWSs (Senese et al., 2012a), the $AWS_{glacier}$ was set up in an area with intense anthropic activities (skiers, snow cats, etc.); its location was therefore a good compromise between representativeness of typical glacier conditions and the need to minimize the risk for skiers.

Snow and ice melt were assessed from the surface energy budget. The net energy (R_S) available for heating the surface and melting snow and/or ice was calculated following Senese et al. (2014):

$$R_S = SWnet + LWnet + SH + LE \quad (1)$$

where SWnet and LWnet correspond to the net radiation (shortwave and longwave, respectively) calculated as the difference between the incoming and the outgoing fluxes, and SH and LE to the sensible and latent heat fluxes. All the fluxes (W m^{-2}) were defined positive when directed towards the surface. The conductive heat flux at the surface was not considered since no temperature sensors were located in the snowpack and in the ice surface layer. Whenever surface temperature (calculated from outgoing LW radiation) is at 0°C and R_S is positive, the energy is used to melt snow and/or ice. The total melt (M, m w.e., water equivalent) can then be computed as:

$$M = \frac{R_S}{L_m \cdot \rho} \quad (2)$$

where L_m is the latent heat of melting (3.34×10^5 J kg^{-1}) and ρ is the density of water. This approach was validated by Senese et al. (2012b) against field measurements. The data sets obtained from the energy balance approach and field measurements appeared to be strongly correlated (a difference of less than 3% between the modeled and measured cumulative melt), which supports the usefulness of the energy budget approach in assessing the actual melt.

Fig. 3: Geotextile cover on Presena Ovest Glacier in summer 2010 (TOPTEX GLS 340 ©).

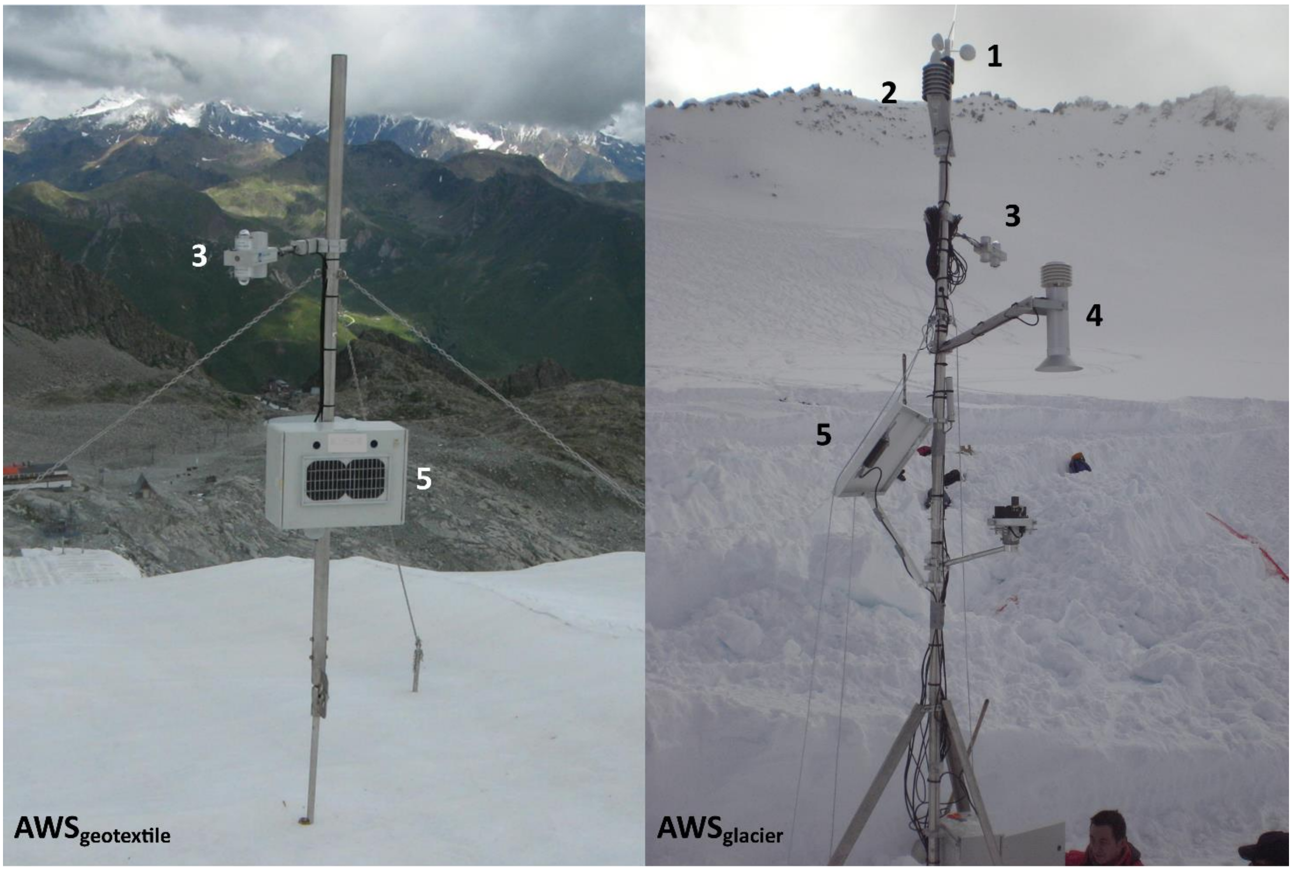

Fig. 4: On the left the $AWS_{geotextile}$ above the geotextile and on the right the $AWS_{glacier}$ on the unprotected glacier area on Presena Ovest Glacier. The sensors are labelled with numbers: wind speed and direction (1), air temperature and relative humidity (2), CNR1 (3), snow level (4), and solar panel (5).

Number in Fig. 4	Variable	Range	Accuracy	Recording rate	Sensor	Manufacturer
1	Wind Speed	0 - 50 m s^{-1}	±1%	60 min	Anemometer	LSI-Lastem DNA022
1	Wind Direction	0° - 360°	±1%	60 min	Anemoscopic	LSI-Lastem DNA022
2	Air Temperature	–30 - +70 °C	±0.001°C	60 min	Naturally ventilated thermohygrometer	LSI-Lastem DMA570
2	Relative Humidity	0 - 100 %	±1%	60 min	Naturally ventilated thermohygrometer	LSI-Lastem DMA570
3	Solar Radiation	0.3 - 3 µm	±5%	60 min	Net radiometer	Kipp and Zonen CNR-1
3	Longwave Infrared Radiation	5 - 50 µm	±5%	60 min	Net radiometer	Kipp and Zonen CNR-1

Table 2: Characteristics of the sensors installed at the $AWS_{geotextile}$ and $AWS_{glacier}$.

4.3 The third experiment: Presena Ovest Glacier

During summer 2012, new tests were carried out on Presena Ovest Glacier, specifically aimed at detecting the most efficient type of geotextile for preserving the snow pack and for reducing magnitude and rates of snow and ice melt. For this purpose, we performed a comparative analysis testing different non-woven geotextiles on the same glacier, at the same elevation (2765 m a.s.l.) and under the same conditions. We compared five non-woven geotextiles (COVERICE, Table 1 and Fig. 5) with different chemical composition (polypropylene - PP, polyester – PET, and poly-lactic acid - PLA), diverse mass per unit area (from 340 to 500 g m^{-2}) and various thicknesses (from 3.00 to 4.40 mm at 2kPa). The PLA geotextile is obtained from polymerization of lactic acid derived from dextrose extracted from corn; thus, it is fully biodegradable and we refer to it with the "BIO" suffix. In addition, we analyzed the polypropylene geotextile commonly used by PAT and Società Impianti of Presena Glacier (SI 400 in Table 1). The five geotextiles were placed in the lower part of the glacier (46° 13' 30.20" N, 10° 34' 50.76" E) at 2765 m a.s.l. on 26 June. As in the previous experiment, glacier snow was previously compacted by snow cats. Each sample consisted in two parcels of 60 m^2 (with a total area of 600 m^2) joined by means of a VELCRO® Brand VELLOC® tape, with a limited overlapping of 1-2 cm and a reduced installation time compared to the traditional method, which uses heat welding and has an overlapping width of 30 cm.

The aim of the third experiment was to understand how chemical composition and mass per unit area affect the protective effectiveness of the geotextile and modulate the ablation rate of the covered snow/ice. For these purposes, we recorded thickness and density of the snow five times from the end of June to the middle of September by digging snow pits. In addition, during each field survey, we measured the incoming and outgoing solar radiation by means of a net radiometer (CNR4, Kipp&Zonen, Fig. 6) with a recording rate of 1 minute at each geotextile type. A tripod was used to raise the net radiometer for short periods (at least 10 min for each measurement) above the geotextile surface. Previous studies demonstrated that the height of the sensor above the surface has a negligible influence on the albedo if the surface is homogeneous (Azzoni et al., 2016) as in the case of a geotextile. The acquired radiation data were used for deriving surface albedo, as the ratio of outgoing shortwave radiation (SWout) to incoming shortwave radiation (SWin).

The energy available for melting depends not only on the absorbed radiation but also on the conductive heat flux through the geotextile. This flux can be quantified by measuring the surface temperature, which was continually monitored by means of PT100 thermistors (Tinytag Plus 2, with a recording rate of 10 minutes, Fig. 6) from 27 June to 12 September. The thermistors were installed underneath each geotextile, parallel to the snow surface, in order to measure the actual temperature at the geotextile-snow interface without direct solar radiation influence. At the end of the summer, the differences in height between protected and unprotected surfaces were measured.

Fig. 5: The blue rectangle shows the position of the five COVERICE non-woven geotextiles on Presena Ovest Glacier in 2012.

Fig. 6: Examples of measurements carried out in summer 2012 on Presena Ovest Glacier: the CNR4 radiometer (left and top right), a PT100 thermal probe used for monitoring surface geotextile temperature (bottom right).

5. Results and discussion

5.1 The first experiment: Dosdè Est Glacier

At the moment of installation, snow covered by the ICE PROTECTOR 500© had an area of 150 m^2, a thickness of 1.29 m w.e. (quantified via the snow pit) and thus a volume of 193.8 m^3 w.e. After one month (14 June 2008), the effects of the geotextile were already evident, as the protected area was on average 0.30 m higher than the surrounding surfaces (Fig. 7). On 23 of July, the unprotected snow was completely melted and thus the ice mass losses were monitored by means of ablation stakes. By then, the covered material was composed of compacted snow and ice. From 23 July to the end of the season, the ice ablation rate ranged between 1.7 and 4 cm w.e. day^{-1} (at 2850 m and 2650 m, respectively). The last survey was carried out on 4

October and the mean elevation difference between the covered and the natural surface was 1.90 m (Fig. 7). In particular, the ice depth was 1.15 m (with a density of 917 kg m^{-3}). The remaining snow layer on top had a density of 750 kg m^{-3} corresponding to compact snow (Fig. 8).

Fig. 7: The effectiveness of the non-woven geotextile ICE PROTECTOR 500 © on Dosdè Est Glacier: on 14th June 2008 (left) and on 4th October 2008 (right).

During the ablation season, the depth of the protected snow/ice ranged between 1.29 m w.e. (at the end of the accumulation period) and 0.56 m w.e. (in October), thus corresponding to 43% of the initial thickness (Fig. 8). In addition, the ICE PROTECTOR 500 © prevented ice melting, which was 1.05 m w.e. (i.e. 1.15 m of ice) in the unprotected areas. Total ablation was thus 2.34 m w.e. and 0.73 m w.e. over the unprotected and protected areas, respectively, and the ICE PROTECTOR 500 © reduced total melting processes by 69% and snow ablation by 43%.

While the initial shape of the covered snow was a rectangular parallelepiped, the final shape resembles a trapezoidal solid, as more melting occurred towards the sides, which were gradually covered by the geotextile (see Fig. 7). The volume of preserved water was calculated by dividing the trapezoidal solid in two: the top solid, made of snow, with an upper surface area of 37 m^2 and a volume of 21 m^3 w.e; the bottom one, made of ice, with an upper surface area of 90 m^2 and a volume of 95 m^3 w.e. (see Fig. 8). The total volume of the solid was 116 m^3 w.e. or 116000 liters.

The efficiency of the geotextile used on the Dosdè Est Glacier is slightly smaller than that reported in other studies performed on European glaciers (e.g. Olefs and Fischer, 2008; Fischer et al., 2016). The difference is probably caused by factors modulating the local energy balance such as albedo variability, local climatic conditions (determining the length of the ablation season and melt rates) or topographic effects. The lack of compaction by snow cats of snow covered with geotextiles on Dosdè Est Glacier could also have a minor impact. In fact, in our experiment the non-woven geotextile was placed on natural snow at the end of the accumulation season, and the glacier was not part of a ski resort. Thus, the initial snow density was only related to the natural process of deposition and metamorphism, which reduces the air content in the snow pack and increases density. In contrast, at glacier ski resorts, snow pack density is increased by the action of snow cats, which mechanically compact snow, and by fresh water injection, which by freezing produces ice layers in the snow pack, slowing down melt (Olefs and Fischer, 2008). Thus, our results only derive from the efficiency of the geotextile, which is a heat stabilizer, a UV absorber, and whose albedo is high and stable. In fact, the geotextile reflectivity appeared constant and similar to that of snow in June. Conversely, the bare ice albedo of the unprotected area was approximately 0.31 at the end of the ablation season (measured by the automatic weather station installed on the glacier surface, Senese et al., 2012a), corresponding to an energy absorption of 69% and to higher snow/ice melt rates.

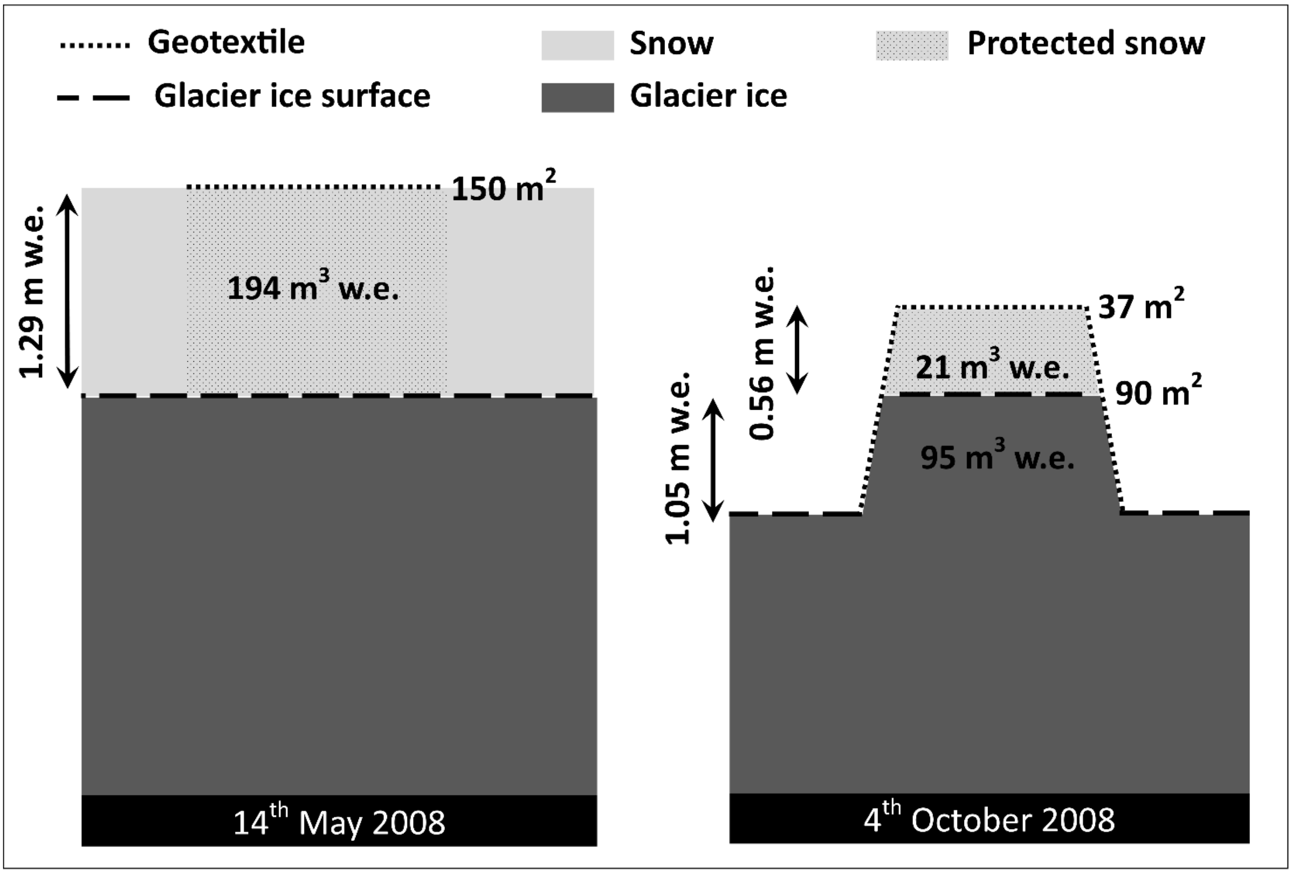

Fig. 8: Schematic drawing showing the effectiveness of the ICE PROTECTOR 500 © non-woven geotextile on Dosdè Est Glacier. Snow and ice are represented by light and dark grey, respectively. Dotted lines denote the geotextile cover and dashed lines the glacier ice surface and then the snow-ice interface.

5.2 The second experiment: Presena Ovest Glacier

In the second experiment**,** besides evaluating the effectiveness of non-woven geotextiles in reducing snow/ice melt, we also assessed how the geotextile modifies radiative exchanges between atmosphere and glacier surface.

Point measurements of SWE undertaken by PAT over the glacier on 18 March 2010 showed an average of 2.22 m w.e. (ranging between 1.64 and 3.25 m w.e.). Distributed SWE was estimated via interpolation through a combination of inverse distance weighting and an altitudinal gradient (0.16 m w.e. every 100 m in height, calculated from field observations). The total SWE was estimated by PAT as 728000 m^3 w.e. On 21 June (one week before the geotextile installation), SWE was measured again and an average of 1.41 m w.e. was found (range: 0.84-2.68 m w.e.). The altitudinal gradient was recalculated as 0.34 m every 100 m in height and total SWE was 462000 m^3 w.e. Thus, a total snow melt of 266000 m^3 occurred under natural conditions (i.e. no geotextile covers), corresponding to an average snow melt of 0.81 m w.e. (ranging from 0.49 m w.e. at the higher elevations to 1.11 m w.e. at the lower elevations). On 26 September, no residual snow was present, except for the areas covered by the geotextile, where the mean residual snow layer was 0.72 cm w.e., or approximately 54000 m^3 w.e. Comparing the mean SWE at the time of installation (1.41 m w.e.) with final SWE, the geotextile leads to a reduction in snow melt by 49%. Besides, the geotextile also helped to preserve the underlying ice.

After assessing the efficacy of the geotextile (49% reduction in snow melt), we compared radiative fluxes acquired by the radiometer at the $AWS_{geotextile}$ and at the $AWS_{glacier}$ (Figs. 9 and 10). As the geotextile has a different albedo (α) and emittance of outgoing longwave radiation (LWout) compared to the glacier surface, we analyzed both variables as well as net radiation (i.e. SWnet + LWnet, see Fig. 10). The mean geotextile albedo was 0.64, higher than the unprotected snow-covered glacier surface (i.e. 0.43, Fig. 9). In addition, once the snow was completely melted at the $AWS_{glacier}$ site, the mean ice albedo was 0.21. Therefore, solar radiation absorbed by the geotextile was 36% of the incoming flux, while the glacier surface absorbed 57% on average (up to 79%). This difference was caused by the geotextile properties: the stable pure white color reduces absorption of incoming solar radiation. Conversely, during melting processes the unprotected snow surface was progressively covered by fine debris and water, which decreased the albedo down to values typical of glacier ice (i.e. 0.30 and lower, Cuffey and Paterson, 2004). In comparison, the study of Schaufelferner, Olefs and Lehning (2010) reported a lower increase in daily mean albedo on the geotextile relative to the unprotected surface (0.69 vs. 0.59 in 2005 and 0.65 vs. 0.58 in 2006). Regarding outgoing longwave radiation, the unprotected glacier surface emits a lower flux compared to the geotextile for 59% of the period of observation. Unlike outgoing fluxes, the incoming shortwave and longwave radiation datasets show a similar trend over both the geotextile and the unprotected glacier area, due to the vicinity of the two sites. Considering net radiation (SWnet + LWnet), at the $AWS_{glacier}$ a total value of 410.28 MJ m^{-2} was measured, higher than the one measured at the geotextile (197.10 MJ m^{-2}). Therefore, the geotextile effect consists in enhancing reflection of solar radiation (i.e. SWout), thus limiting the absorbed net radiation (i.e. SWnet + LWnet). These different radiative behaviors could affect snow/ice melt. However, the albedo and LWnet of a material are not the only important parameters to assess the effectiveness of a geotextile (Olefs and Fischer, 2008). In fact, beside radiative fluxes, other physical processes play a role in modulating the geotextile effect: latent and sensible heat flux and thermal insulation (Olefs and Lehning, 2010).

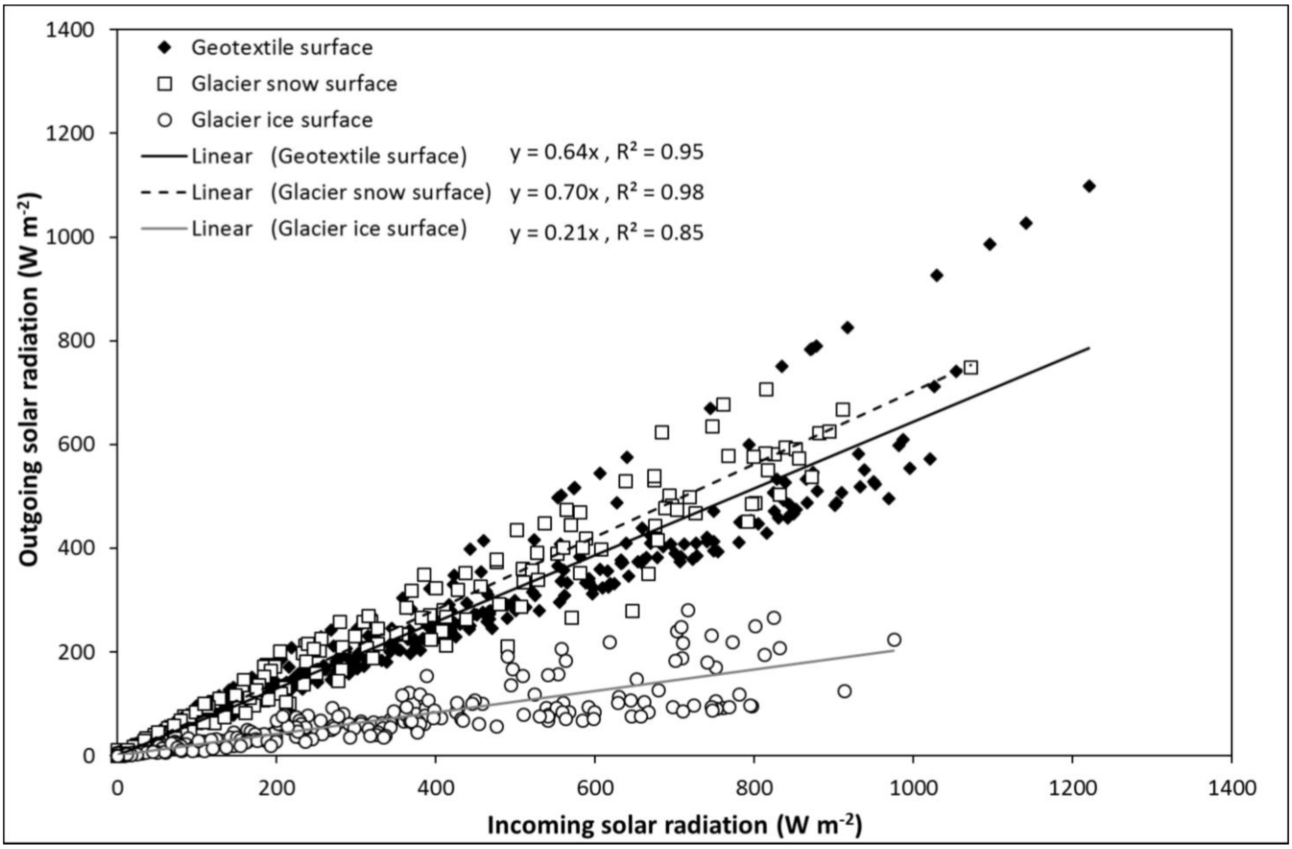

Fig. 9: Comparison between hourly albedo values calculated at the $AWS_{geotextile}$ and at the $AWS_{glacier}$ from 31 July to 1 September 2010.

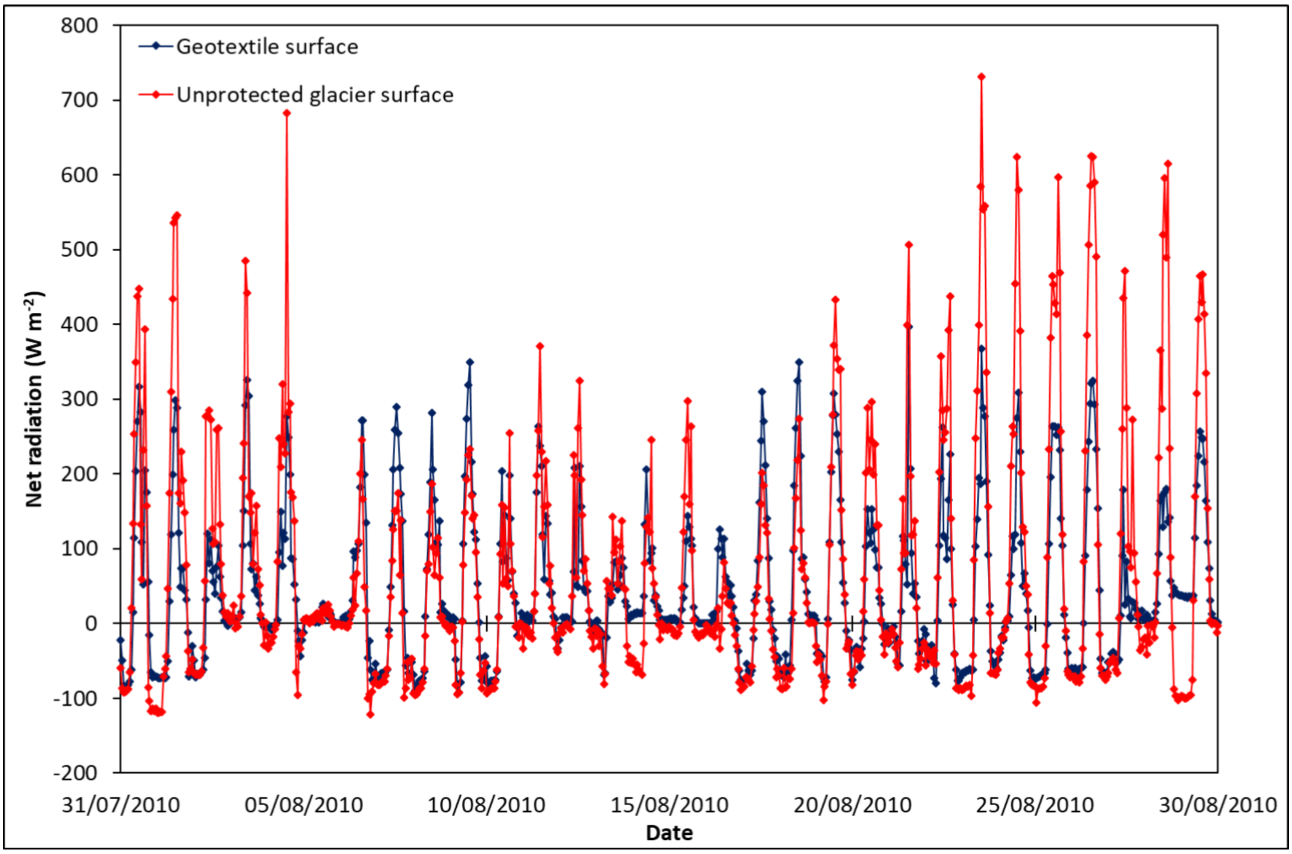

Fig. 10: Hourly net radiation (SWnet + LWnet) measured at the $AWS_{geotextile}$ and at the $AWS_{glacier}$.

Fig. 11: The effectiveness of the non-woven geotextile TOPTEX GLS 340 © on the Presena Ovest Glacier at the end of July 2010.

5.3 The third experiment: Presena Ovest Glacier

The positive results we obtained from these two experiments on Dosdè Est and Presena Ovest Glaciers suggested performing further tests for evaluating which non-woven geotextile is most efficient at preserving the snow pack and at reducing magnitude and rates of snow and ice melt. During summer 2012, a comparative analysis was performed on Presena Ovest Glacier by testing 5 different COVERICE geotextiles with different chemical composition, mass per unit area and thickness. In this experiment, we focused on thermal (Fig. 12) and optical (Fig. 13) properties of the geotextiles.

The trend of the daily mean temperatures at the snow-geotextile interface (Fig. 12) suggests that this parameter depends on air temperature, incoming solar radiation and geotextile thermal properties. COVERICE 340 BIO showed in general a higher temperature and COVERICE 500 a lower temperature compared to the other geotextiles, although some oscillations occurred.

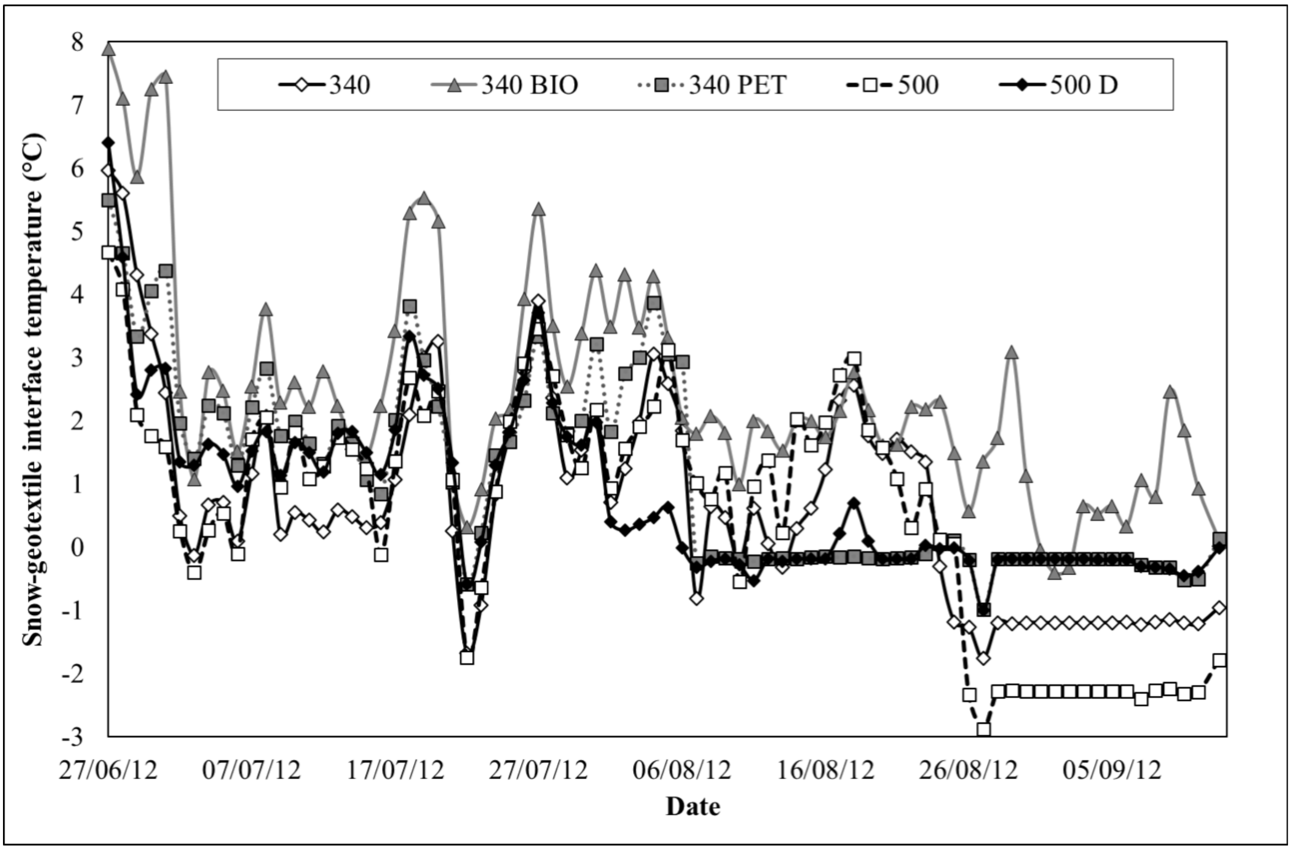

Fig. 12: Daily mean surface temperature (at the snow-geotextile interface) measured underneath the geotextiles from June 27 to September 12 2012.

The albedo was found to decrease with time regardless of the type of geotextile (Fig. 13). This is caused by the deposition of fine particulate (dust) that makes the surface darker and thus less reflective. The lowest values were recorded on 20th September 2012, at the end of the experiment. These results are in agreement with findings by other researchers, showing a gradual increase in light-absorbing particles over the glacier surface during the ablation season (Wiscombe and Warren, 1980; Aoki et al., 2006; Azzoni et al., 2016). Until mid-August, the geotextile with the highest albedo is COVERICE 500 D, then COVERICE 500 shows the maximum values, although not considerably higher than COVERICE 500 D. Averaging all the data, the COVERICE geotextiles with higher albedo are in order: 500, 500 D, 340, 340 PET, and 340 BIO. Considering instead only the last measurement (on 20th September 2012) the sequence is: 500, 500D, 340 PET, 340, and 340 BIO. As regards the geotextiles with a mass of 340 g/m^2 (Table 1), the polyester one (340 PET) shows similar values as the polypropylene one but higher values than the 340 BIO. However, all the COVERICE geotextiles show a higher albedo than old snow and higher than the SI 400 geotextile (also used during the previous season), which suggests a noteworthy effectiveness in reflecting solar radiation and in decreasing the absorbed energy. Old-snow albedo ranged between 0.27 and 0.46, which is slightly lower than the values reported by Hartmann (2010), i.e. 0.35-0.65. Snow on the Presena Ovest Glacier is groomed and moved several times during the winter/spring season and the glacier is used for skiing; all these activities make the snow less reflective than typical old snow.

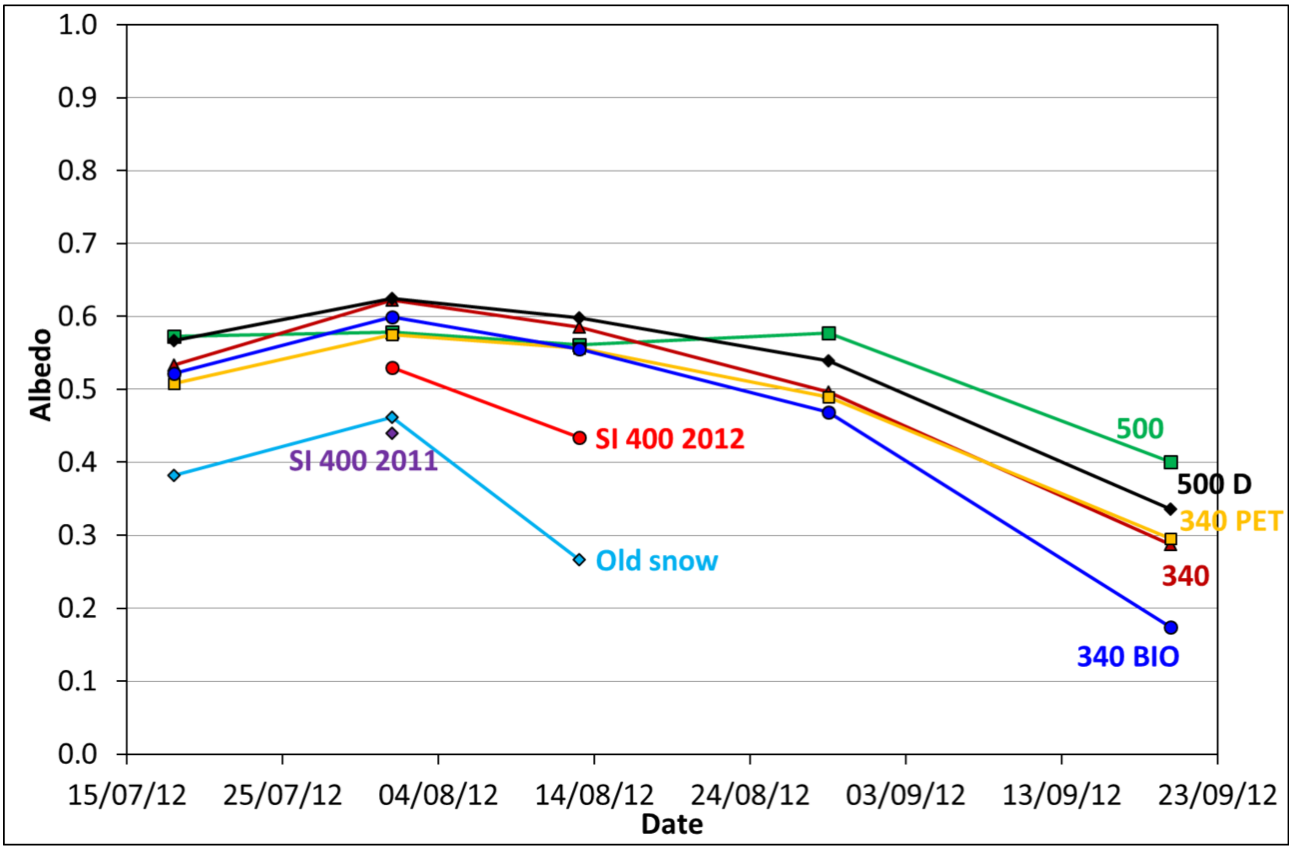

Fig. 13: Daily mean albedo measured at each non-woven geotextile from the beginning to the end of the experiment on Presena Ovest Glacier in 2012.

6. Feasibility analysis

Based on the positive results on Dosdè Est Glacier, active glacier protection can be applied even on natural glacier snow, without the need for mechanical treatments (i.e. snow cats) and/or freshwater injection. However, the cost of geotextiles and manpower requirements are a serious limit to the replicability of this strategy to mitigate ablation on wider natural glacier surfaces. For example, in 2009 and 2010 approximately € 130,000 (about € 1/m² for geotextiles lasting about three years) was spent on the purchase of the geotextiles for covering the Presena Ovest Glacier and € 100,000 per year on manpower (data from PAT). Two teams of six workers each take an average 10-15 days to remove the geotextiles from the surface and rewind them with the help of snow cats and a special machine designed and created specifically to facilitate recovery operations. At the end of the summer season, all the geotextiles are removed from the surface of the glacier and stored in a warehouse ready to be reused in the following year. The geotextiles are theoretically relocated to the surface of the glacier every year, but in practice the recovery operations are rather difficult and, owing to their cold and frozen surface, the geotextiles often break, so it is often necessary to partially replace them with new ones. In addition, during the summer season, the surface of the geotextiles can be darkened by natural dust deposition, reducing the albedo and making it necessary to replace them even if they are still intact. In fact, unlike on the glacier surface, dust deposited over the geotextile can not be washed out because the geotextile acts like a blanket and thus absorbs water and impurities. Similar results were found by Olefs and Lehning (2010) who reported that the performance of worn-out material is reduced due to a lower albedo. While the use of geotextiles involves rather high costs, at glacier ski resorts the above figures have to be compared with a likely cost of almost € 300,000 (data from PAT) to produce artificial snow for replacing melted snow. Further still, the production of artificial snow requires one of the most important natural resources, i.e. water. Outside glacier ski resorts, the size and the weight of the geotextile become important and might require using helicopters at least twice each season (i.e. for the initial installation and for removal at the end of the ablation season) if glaciers are located in remote areas. This entails further costs and emissions of greenhouse gases, which are unlikely to be justifiable in such a setting.

6. Conclusions

Since 2008, research has been carried out on the applicability and efficiency of strategies for mitigating climate change impacts on Italian Alpine glaciers. Two sites were selected to perform dedicated field tests. The first site is Dosdè Est, where the applicability and the effectiveness of mitigation strategies were tested on natural snow. Here, a small parcel of the glacier surface (about 150 m^2) was covered by means of a non-woven geotextile for the whole ablation season. The geotextile (ICE PROTECTOR 500 ©) was found to reduce snow ablation by 43% and snow/ice melt processes by 69%. These results are very impressive if we consider that snow was not previously compacted by snow cats and no fresh water was added to produce ice layers. We performed two other tests on a second study site, Presena Ovest, a glacier ski resort that has been active for a long time. On this glacier, we firstly investigated the energy fluxes at the glacier surface covered by the geotextile (TOPTEX GLS 340 ©) and we compared this dataset with one obtained from an unprotected glacier parcel, located at the same elevation and with similar slope and aspect. The mean albedo on the protected area was 0.64, about 50% higher than on the uncovered glacier area. Thus, from 31 July to 1 September 2010 the geotextile decreases the absorbed solar radiation up to 45% and net radiation (SWnet + LWnet) by about 52% (from 410.28 MJ m^{-2} at the $AWS_{glacier}$ site to 197.10 MJ m^{-2} at the geotextile). The albedo can be considered the most important among the geotextile properties for melt reduction, as it is higher than over unprotected snow surfaces and quite stable over the melting season. Based on these results, we performed the third experiment, which was also carried out on Presena Ovest Glacier. Here we performed a comparative analysis using different geotextiles during one ablation season (i.e. summer 2012) and comparing both the quantity of snow preserved at the end of the ablation season and the main features of the geotextiles (in particular albedo). We covered previously groomed glacier snow, thus with a higher initial density than natural snow at the same elevation. By analyzing SWE and meteorological data, we found the COVERICE 500 (a polypropylene geotextile with a mass per unit area of 500 g/m^2 and a nominal thickness of 3.70 mm) to be the most efficient, as it reduced snow ablation by 73%. It also featured the highest albedo values (with a mean of 0.54) and the lowest temperatures just underneath the geotextile (with a mean of 0.6°C). This might be the result of the higher mass per unit area, which makes surface reflectivity more stable. Beside optical and thermal properties, these results might also be caused by the different structure of the COVERICE 500.

In summary, in the most neuralgic areas of glacier ski resorts (rock outcrops, ski-lift tracks, ski-lift pylons, and glacier margin, Olefs and Lehning, 2010), the use of special blankets (non-woven geotextiles) allows reducing melt by about 60%. Whenever heavy snowfalls occur during winter, by installing these non-woven geotextiles it is possible to gain glacier mass, increasing the height of the snow surface. Therefore, this method can significantly reduce the maintenance of ski resort infrastructures, contributing to a more sustainable management. Glacier coverage with geotextiles has non-negligible costs (i.e. materials, transport, installation and maintenance) and is therefore applicable only on small glacier sectors and for limited periods (a few years with seasonal use only). Furthermore, our tests show that non-woven geotextiles can efficiently protect natural snow (without water addition and not subjected to grooming) as well, which suggests that geotextiles could be used on natural glacier surfaces. However, the monetary and environmental costs to protect significant glacier areas are prohibitive for likely all cases.

Acknowledgement

This research was carried out within a project funded by Sanpellegrino Levissima S.p.A. and one funded by Edilfloor S.p.A.; early career researchers involved in the study were supported by the DARA (Department of Regional Affairs and Autonomies) of the Presidency of the Council of Ministers of the Italian Government through the GlacioVAR project (PI Guglielmina Diolaiuti). We thank M. Folatti (Provincia di Sondrio) for giving permission to work in the Dosdè Est Glacier area. The Autonomous Province of Trento (PAT) kindly supported data analysis and hosted the $AWS_{glacier}$ on the surface of the Presena Ovest Glacier, thus making it possible to study a southern Alpine glacier. We also thank Consorzio Adamello Ski for the logistical support on Presena Ovest Glacier. We are also grateful to Gian Pietro Verza, Roberto Chillemi, Adriano Greco, Angelo Lunghi, Emanuela Bianchi, Davide Bavera, Gabriele Ruggiero, Matteo Fiorelli and Carlo Guarneri for their fundamental technical assistance in the field.

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