Geogr. Fis. Dinam. Quat.
37 (2014), 15-22, 8 figg.

DOI 10.4461/GFDQ.2014.37.2

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DISTRIBUTION OF THE SURFACE ENERGY BUDGET: PRELIMINARY ANALYSIS ON THE INCOMING SOLAR RADIATION. THE CASE STUDY OF THE FORNI GLACIER (ITALY)

ABSTRACT: GAMBELLI S., SENESE A., D'AGATA C., SMIRAGLIA C. & DIOLAIUTI G., *Distribution of the surface energy budget: preliminary analysis on the incoming solar radiation. The case study of the Forni Glacier (Italy).* (IT ISSN 0391-9838, 2014).

This study represents a contribution to distribution of the surface energy budget of the Forni Glacier (Ortles-Cevedale Group, Upper Valtellina, Italy). The analyses are based on data acquired at S. Caterina Valfurva (a village in the glacier valley at 1768 m ellipsoidal elevation WGS84) by an Automatic Weather Station (AWS) installed and managed by the Lombardy Agency for the Environment («ARPA Lombardia»). We focus on the two most important meteorological parameters affecting surface energy budget: air temperature (T) and incoming shortwave radiation (SWin). Data collected from the ARPA AWS are used to evaluate these parameters at the glacier surface during the meteorological summer 2009 (from 1st June to 31st August 2009) and then the computations are validated through comparison with data recorded by an AWS installed at the surface of Forni Glacier tongue («AWS1 Forni», 2669 m ellipsoidal elevation WGS84). The analysis of the distributed air temperature data enabled identification of the lowest value (–11.9°C), found at the Mount S. Matteo peak (3669 m) on 22nd June at 8:00 pm, and the highest value (+16.1°C), recorded at the glacier terminus (2497 m) on 23rd July at 2:00 pm. The seasonal temperature amplitude (Tmax-Tmin) was 28°C. The hottest week was 20th-26th July 2009 and the coldest was 1st-7th June 2009. Regarding daily SWin distribution, the maximum value (406.9 Wm^{-2}) was recorded on 13th June and the minimum (28.5 Wm^{-2}) on 6th June. From the analysis of hourly SWin values we could distinguish between days with clear sky conditions and days with intense cloud cover. Weekly mean SWin data showed the greatest value (327.1 Wm^{-2}) from 20th-26th July 2009 and the lowest (207.8 Wm^{-2}) from 22nd-28th June 2009. Furthermore, in analysing SWin it is critical to take into account the problem of shading. Using the Hillshade tool of ArcGIS, which takes into account only the slope and the aspect of each grid cell neglecting the surrounding topography effect, we compiled 66 shadow maps. Finally this study represents a first approach in modelling the distributed incoming solar radiation. In fact the considered driving factors are the elevation, the slope and the aspect of each grid cell. The next step will consist in taking into account the surrounding topography and the actual atmosphere conditions as well.

KEY WORDS: Air temperature, Incoming solar radiation, Distributed energy budget, Ortles-Cevedale Group, Alpine glaciers.

RIASSUNTO: GAMBELLI S., SENESE A., D'AGATA C., SMIRAGLIA C. & DIOLAIUTI G., *Distribuzione del bilancio energetico superficiale: analisi preliminare della radiazione solare incidente. Il caso del Ghiacciaio dei Forni, Valtellina (gruppo Ortles-Cevedale).* (IT ISSN 0391-9838, 2014).

Questo studio è un contributo al calcolo del bilancio energetico superficiale distribuito del Ghiacciaio dei Forni (Gruppo Ortles-Cevedale, Alta Valtellina, Italia). Siamo partiti da dati registrati da una stazione meteorologica automatica (AWS) di ARPA Lombardia installata a Santa Caterina (una frazione del comune di Valfurva (SO), poco lontana dal Ghiacciaio dei Forni, a 1768 m quota ellissoidica WGS84). Ci si è concentrati sui due parametri meteorologici più importanti per il calcolo del bilancio energetico: la temperatura dell'aria (T) e la radiazione ad onda corta entrante (solare o SWin). Per distribuire questi due parametri si è partiti dai dati raccolti dalla AWS dell'ARPA durante l'estate meteorologica 2009 (1 giugno - 31 agosto 2009). I valori calcolati per la superficie del ghiacciaio sono stati validati mediante confronto con i dati registrati dalla AWS1 Forni (2669 m quota ellissoidica WGS84), la stazione meteorologica automatica installata nel 2005 sulla lingua d'ablazione del ghiacciaio. Le analisi sulla distribuzione della temperatura dell'aria per l'intero periodo hanno permesso di identificare il valore minore (–11.9°C), sulla cima del Monte S. Matteo (3669 m), il 22 giugno 2009 alle ore 20:00, e il valore maggiore (+16.1°C), stimato alla fronte glaciale (2497 m) il 23 luglio 2009 alle ore 14:00. L'escursione termica stagionale (Tmax-Tmin) è risultata pari a 28°C. La settimana più calda è risultata quella dal 20 al 26 luglio 2009 e la più fredda dall'1 al 7 giugno 2009. Riguardo la distribuzione della radiazione solare giornaliera il valore massimo (406.9 $W m^{-2}$) è stato raggiunto il 13 giugno e quello minimo (28.5 $W m^{-2}$) il 6 giugno 2009. Dai valori orari di SWin è stato possibile distinguere le giornate con cielo terso da quelle con intensa copertura nuvolosa. I valori settimanali medi di SWin hanno mostrato il massimo (327.1 $W m^{-2}$) dal 20 al 26 luglio e il minimo (207.8 $W m^{-2}$) dal 22 al 28 giugno 2009. Nell'analisi

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This work summarizes the main results of the MS Thesis in Natural Sciences of Sara Gambelli which was the recipient of the 2011 Award of the Italian Glaciological Committee (CGI) for the best thesis dealing with glaciological topics. The authors acknowledge ARPA Lombardia (Lombardy Agency for the Environment) which kindly provided meteorological data. The research was developed in the framework of the SHARE STELVIO project. Share Stelvio is a research project supported by Lombardy Region and managed by EvK2CNR Committee and FLA, Lombardy Foundation for the Environment. The AWS1 Forni is part of the SHARE network. SHARE (Stations at High Altitude for Research on the Environment) is an international project developed and managed by EvK2CNR Committee. The authors are grateful to ITT of Lombardy Region which kindly provided the 2007 Digital Elevation Model (DEM).

della SWin è inoltre molto importante tenere in considerazione il problema dell'ombreggiamento. Grazie all'utilizzo dello strumento Hillshade di ArcGIS, che considera solo la pendenza e l'esposizione di ogni cella trascurando l'effetto della topografia circostante, sono state realizzate 66 mappe descriventi l'ombra alla superficie del ghiacciaio. Questo lavoro rappresenta quindi un primo approccio per la modellazione distribuita della radiazione solare in cui i fattori considerati sono l'elevazione e l'ombreggiamento dovuto a esposizione e pendenza locale. Successivamente sarà necessario considerare anche la topografia circostante e le condizioni reali dell'atmosfera.

TERMINI CHIAVE: Temperatura dell'aria, Radiazione solare incidente, Bilancio energetico distribuito, Gruppo Ortles-Cevedale, Ghiacciai alpini.

INTRODUCTION

Glaciers are sensitive indicators of Climate Change. Numerical glacier models estimate the sensitivity of alpine glaciers and provide tools for evaluating the closely related responses of ecosystems and water resources in glacierized regions of the world.

Understanding the impact of climate change is also important because mountains have a socio-economic relevance, particularly for tourism and water resources (Beniston, 2003). Climatic processes, operating at a range of spatial and temporal scales, drive energy exchanges at the glacier surface which control meltwater production and runoff (Hannah & *alii*, 2000).

Since the glacier surface differs from the surroundings, it is really an interesting environment to be studied, especially in terms of energy budget and its seasonal and interannual variability (Oerlemans, 2005). For these reasons, it is clear that field measurements of meteorological parameters on glaciers are very useful. Nevertheless a general problem in testing and calibrating a mass-balance model is the scarcity of data describing meteorological conditions and energy fluxes at the glacier surface (Senese & *alii*, 2012a). Temporally longer and more complete datasets are needed and they can be obtained only from supraglacial permanent automatic weather stations (AWSs).

On the Italian Alpine glaciers, length variation and mass-balance measurements started, respectively, in 1895 at Forni Glacier (Lombardy) and in 1967 at Careser Glacier (Trentino) (Smiraglia, 2003). In spite of this long tradition in field surveying in Italy, it was not possible to measure meteorological data and energy fluxes directly at the glacier surface until the installation of the first permanent Italian AWS («AWS1 Forni») which was set up on the ablation area of the Forni Glacier (Upper Valtellina, Ortles-Cevedale group, Stelvio National Park, Lombardy Alps), at 2669 m (ellipsoidal elevation WGS84) on 26th September 2005 (Citterio & *alii*, 2007; Diolaiuti & *alii*, 2009; Senese & *alii*, 2010; Senese & *alii*, 2012a; 2012b). In fact, in the past, all the Italian glacial AWSs were located on rock exposures, nunataks or buildings (such as mountain huts) thus making the recorded data representative of high mountain atmospheric conditions and not of the actual glacier surface conditions.

Most supraglacial AWSs are located on accumulation basins, due to the higher stability of these areas; very few are installed on ablation zones because the intense melting rate during the summer season causes instability. Moreover, crevasses and supraglacial morphology change considerably during the summer, making maintenance of the stations difficult.

For this reason it is highly important to optimize models able to reconstruct meteorological conditions at the glacier surface starting from data acquired by AWSs located outside glaciers. In fact these latter are more diffuse and have been running since long time thus assuring longer records of data. Supraglacial AWSs in this context are crucial in enabling validation of meteorological reconstructions obtained from synoptic weather stations located outside glaciers, thus supporting application of the formulae and models developed to other glaciers where no supraglacial AWSs are available.

The aim of this research is to contribute to the spatial distribution of the surface energy budget of the Forni, the widest Italian Valley glacier (see fig. 1), based on data acquired by an AWS installed in a village not far from the glacier. The AWS, installed and managed by the Lombardy Agency for the Environment (ARPA Lombardia), is locat-

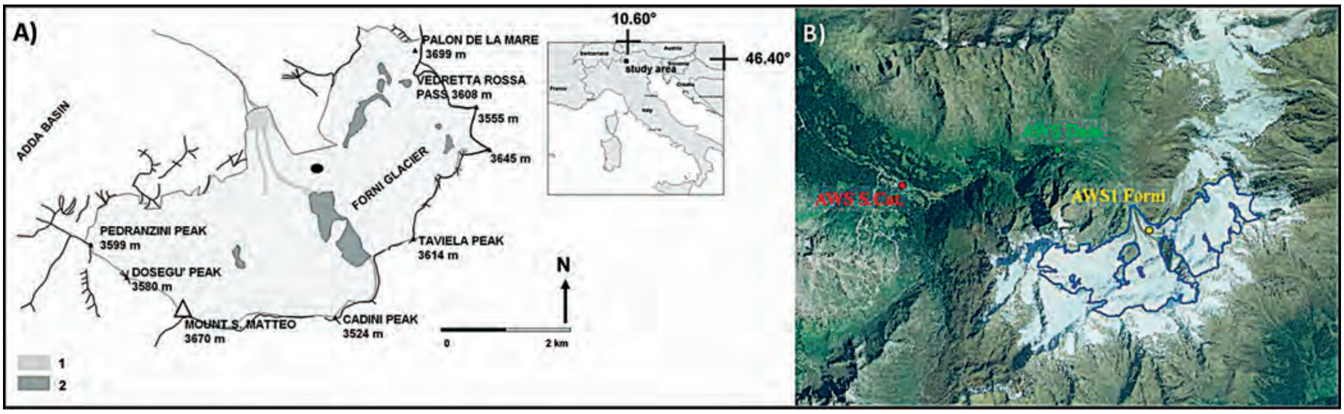


FIG. 1 - Location map: the Forni Glacier and the AWSs used in this study. The AWS1 Forni (black dot in A and yellow dot in B), the AWS S.Cat. (red dot in B) and the AWS Forni Dam (green dot in B). In fig. A the light grey areas (1) represent supraglacial debris coverage, while dark grey areas (2) indicate *nunataks* and rock exposures.

ed at S. Caterina Valfurva (1768 m ellipsoidal elevation WGS84). In particular we focus on the two most important meteorological parameters affecting energy balance: air temperature (T) and incoming shortwave radiation (SWin). The effects of shading and topography are also considered, obtained from the aspect and slope of each point.

In the recent literature dealing with glacier mass balance modelling there are some attempts performed on Italian Glaciers. Among the others Grossi & *alii* (2013) adopted a physically based modelling approach to the Mandrone Glacier (Adamello-Presanella mountain group). In their study although the modelling outputs were still uncertain, mainly due to errors in precipitation measurements at high altitude and the hypotheses of the energy balance model adopted, verifications with point ablation measurements and satellite-derived snow cover were performed with satisfactory results.

Our modelling approach is based on data collected from the ARPA AWS set up in S. Caterina Valfurva («AWS S.Cat.») during the meteorological summer 2009 (1st June to 31st August 2009). Analysis validation is by comparison with data recorded by AWS1 Forni, an automatic weather station located at the glacier tongue surface (2669m ellipsoidal elevation WGS84) which has been running since September 2005 (Citterio et al., 2007).

The glacier size and geometrical features of the Forni (i.e. length, elevation range), as well as the presence of both the supraglacial and the ARPA AWSs (this latter being part of the synoptic regional weather network), make this site suitable for a study of energy budget distribution.

STUDY AREA, INSTRUMENTS AND DATA

The Forni Glacier, in the Ortles-Cevedale Group (Stelvio National Park, Upper Valtellina, Italy, 46.40° N, 10.60° E) is the largest Italian valley glacier, with a surface area of 11.34 km^2 (fig. 1). It has a northward down sloping surface and stretches over an elevation range of 2500 m to 3670 m a.s.l. From the surrounding mountains to the terminus, the glacier is about 3.5 km long, and the width, along three basins, is about 6 km. The glacier is surrounded by mountains reaching a height of 3700 m a.s.l., providing shade particularly to the southern and eastern sectors.

Since 2005 the first Italian permanent supraglacial AWS (AWS1 Forni) has been acquiring data on the main meteorological parameters on the Forni glacier; it is located at an ellipsoidal elevation of 2669m (WGS84 coordinates: 46° 23' 56.0" N, 10° 35' 25.2" E) about 800m from the glacier terminus (figs. 1 and 2B). The AWS is on the lower glacier sector, on the ablation area, at the base of the Eastern icefall. The AWS site minimizes topographical effects and is favourable to station safety (low probability of avalanches) (see Citterio & *alii*, 2007; Diolaiuti & *alii*, 2009; Senese & *alii*, 2010; 2012a; 2012b). Furthermore the ablation tongue is a strategic position from which to study the glacier energy budget because it enables measurement of winter accumulation and all meteorological parameters and energy fluxes which determine summer snow and ice melt (Bliss & *alii*, 2004; Oerlemans & *alii*, 2004). Over the last 7 years the AWS1 Forni has been checked several times without any problem being observed (Citterio & *alii*, 2007; Senese & *alii*, 2012a; 2012b).

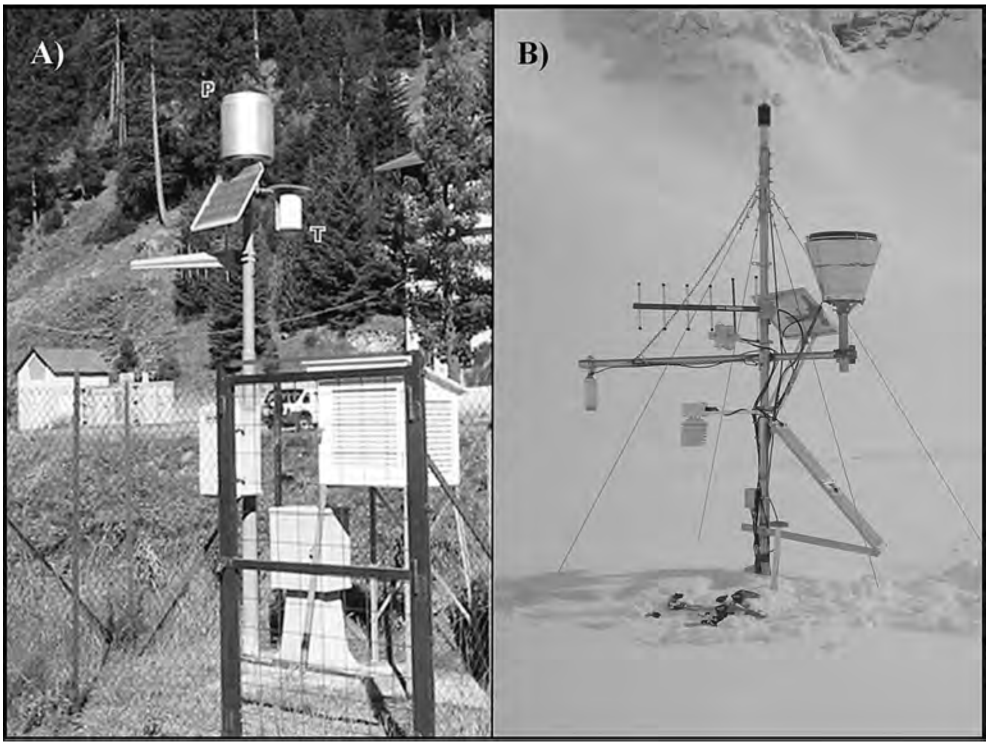


FIG. 2 - Automatic Weather Stations of S. Caterina Valfurva (A) and AWS1 Forni (B).

All the AWS1 Forni sensors comply with the qualitative standards recommended by the World Meteorological Organization (Diolaiuti & *alii*, 2009). The whole system is supported by a four-leg, 5 m high stainless steel mast standing directly on the ice surface, following the construction system proposed and tested by IMAU (Oerlemans, 2001). The AWS stands freely on the ice and it is perfectly suited to the dynamic conditions typical of glaciers.

AWS1 Forni is equipped with a LSI-Lastem 20-channel data logger (Babuc ABC), with 5 channels still free enabling future implementation with further sensors. The battery voltage over time is recorded by the data logger, so it is possible to control it during the data download. A 40W solar panel is installed on the mast to maintain battery power. The AWS1 Forni is equipped with sensors for measuring air temperature and humidity (naturally ventilated sensor), wind speed and direction, air pressure, incoming and reflected solar radiation in the 0.3-3 μm spectral range, far infrared radiation in the 5-50 μm spectral range from the sky and glacier surface, liquid precipitation (with a 1000 cm^2 unheated rain gauge), and snow level (a Campbell SR-50 sonic ranger is installed on the AWS mast, measuring only the accumulation and not ice ablation). Data points, sampled at 60-second intervals and averaged over a 30-minute time period for most of the sensors, are recorded on a flash memory card, combined to basic distribution parameters (maximum, minimum and standard deviation values). Since 2009 a radio link connected with a GSM modem has enabled remote data downloading and system checking.

Moreover in this study we also used data from two weather stations which are part of the ARPA Lombardia (Lombardy Regional Agency for the Environment) meteorological network: AWS Santa Caterina and AWS Forni Dam. The first ARPA AWS (WGS84 coordinates: 46° 24' 42.56" N, 10° 29' 40.26" E) is set up in S. Caterina Valfurva (a village at 1768m ellipsoidal elevation) (fig. 1A), 6.9 km from the AWS1 Forni. This AWS is equipped with sensors to measure air temperature, relative humidity, wind speed and direction, incoming shortwave radiation, liquid and solid precipitation (with a heated rain gauge) and snow level. Data is recorded every hour.

Moreover we also used data from Forni Dam AWS (WSG84 coordinates: 46° 25' 14.83" N, 10° 33' 19.49" E). This station is located at an ellipsoidal elevation of 2218m in the Forni Valley, at about 2 km from the glacier terminus. It measures only temperature, wind speed and precipitation (solid and liquid) but not the incoming shortwave radiation.

We used data from the Forni Dam and S.Cat. AWSs to calculate local lapse rates. These were applied to data acquired by AWS S.Cat. to reconstruct glacier conditions. The validation of our data modelling was made through comparison with actual supraglacial data acquired by AWS1 Forni.

METHODS

The Forni Glacier surface was described through data from the 2007 Lombardy Region Digital Elevation Model (DEM), which uses a 20 m spaced grid. The glacier surface was spread over 27,850 DEM points. The applied DEM was obtained by Lombardy Region analysing aerial photos acquired in 2007 summer (i.e. Flight TERRA Italy 2007, CGR). All the data was processed using a GIS software (ArcMap).

Firstly we calculated hourly lapse rates by comparing data from the three AWSs during summer 2009 (1^{st} June to 31^{st} August 2009). Data from AWS1 Forni was compared with data from AWS Forni Dam and then with data from AWS S.Cat. The datasets were markedly correlated, supporting the subsequent analyses.

Temperature was distributed using a local lapse rate (Γ) obtained by comparing AWS S. Cat. and AWS1 Forni:

$$T_{point} = \Gamma * \Delta h + T_{S.Cat} \qquad (1)$$

where Δh is the altitude difference between each DEM point and the AWS S.Cat.

By applying this formula we obtained hourly temperature values for all DEM points over the 2009 summer. Then by analysing the hourly data, the minimum and maximum temperature values and daily range (Tmax-Tmin) for each point were found. The same analysis was performed considering daily and weekly average values thus evaluating both the hottest and the coldest week.

The solar incoming radiation was distributed by applying a formula proposed by Oerlemans (2001):

$$SWin_{\ point} = SWin_{\ S.Cat} * [a + (2.4 * 10^{-5} * \Delta h)] \qquad (2)$$

where Δh is the altitude difference between each DEM point and the AWS S.Cat and $SWin_{\ S.Cat}$ is the solar radiation measured at S. Caterina.

The value of a was found by comparing the radiation values calculated at the elevation of the AWS1 Forni using the formula above, with data acquired by the AWS1 Forni. The strongest agreement among measured and modelled values was found with a value of a equal to 1.025.

In this way hourly SWin values in absence of shading and then daily and weekly data were calculated for each point.

From the SWin data it was possible to distinguish days with clear sky conditions from those with intense cloud cover.

Using GIS data processing, 13 weekly maps and 3 monthly maps, for temperature and SWin, both distributed, were computed.

For a more correct spatial distribution of SWin it is important to take into account the forcing factors, such as i) cloudiness, ii) surrounding topography and iii) local shading.

i) The solar radiation can be affected by scattering and reflection due to the cloud cover that reduces the actual amount received by the surface. The SWin modelled over the Forni Glacier (eq. 2) embraces the actual atmosphere featured at Santa Caterina Valfurva. Indeed due to the vicinity of the village to the glacier, we can assume that the meteorological conditions of the two sites are almost the same. In this way the solar radiation distributed over the glacier encountered the decreasing cloud effect.

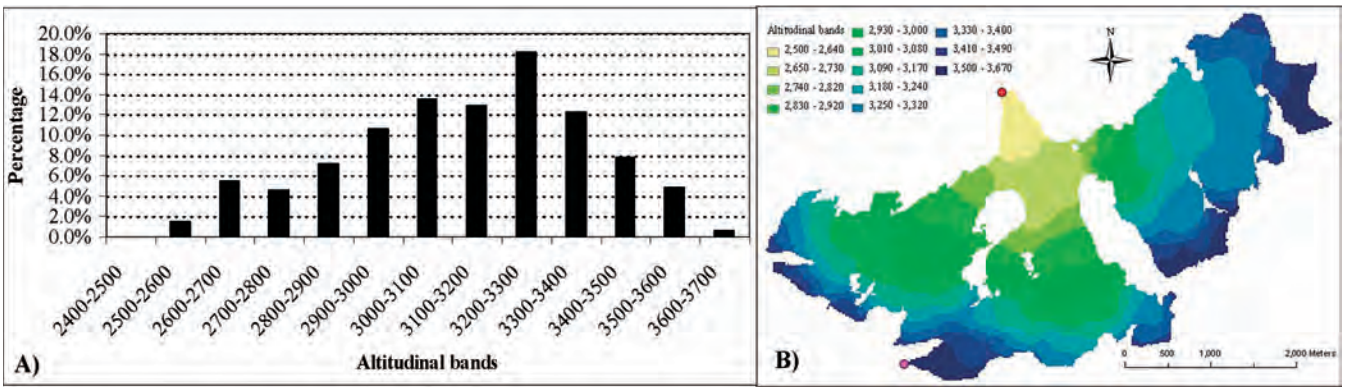


FIG. 3 - Percentage spatial distribution (A) and map (B) of Forni Glacier according to altitudinal bands. The red point marks the area where we calculated the maximum temperature value and the pink dot indicates the zone with minimum temperature value during summer 2009.

ii) Moreover on the one hand the radiation can be increased by multireflection due to the surrounding snow covered topography. On the other hand this latter can intercepts the solar beams reducing SWin.

iii) Finally another factor is the cell features (i.e. slope and aspect): for instance a very sloped area facing to North receives less radiation than a flat one.

As a preliminary study, we examined the shading due to only the last factor using the *Hillshade* tool of ArcGIS. In particular the hypothetical illumination of a surface was estimated by setting a position for a hypothetical light source and calculating the illumination values of each cell in relation to 8 neighbouring cells. Then the solar elevation and azimuth angles (depending on the latitude, season and time of the day; Oke, 1987) and the slope and aspect of each cell are estimated for determining the final hillshade value. This latter ranges from 0 (i.e. a totally shaded cell) to 255 (i.e. a completely illuminated one). Finally the percentages of illuminated and shaded glacier areas were calculated and the shading maps were elaborated.

RESULTS

The distribution in altitudinal bands of the Forni Glacier is shown in the histogram below (fig. 3A) and by a map of the Forni Glacier in ArcMap (fig. 3B): it shows that the bulk of the glacier area is found between 3200 m and 3300 m.

For every month, the hourly lapse rate is averaged to obtain the daily trend. As expected, lapse rate results lower during night time (minimum value generally at 6:00 am, –0.004 K/m in June and -0.003 K/m in July and August) and higher during daylight (maximum value of –0.012 K/m at 3:00 pm in August, of –0.010 K/m at 3:00 in July and –0.010 K/m at 6:00 pm in June) (fig. 4).

Concerning distributed air temperature data for the entire period analyzed, the lowest value (–11.9°C) was recorded at S. Matteo (3669 m) on 22nd June at 8:00 pm (dark pink point in fig. 3B), and the highest value (+16.1°C) at the glacier terminus (2497 m) on 23rd July at 2:00 pm (red dot in fig. 3B). The seasonal temperature amplitude (Tmax-Tmin) is therefore 28°C. The hottest week is 20th-26th July and the coldest is 1st-7th June.

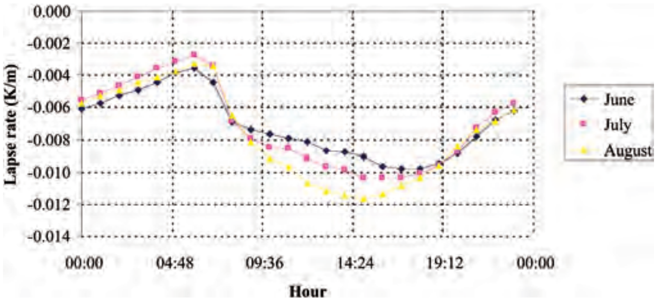


FIG. 4 - Hourly lapse rate between AWS S.Cat and AWS1 Forni averaged over the whole summer period 2009.

The maximum temperature was recorded at an unsurprising time (immediately after noon), while the minimum value seems more unusual (in the evening and not before dawn). To check against the occurrence of errors in data gathering, during summer 2009 minimum values both for S. Caterina Valfurva and AWS1 Forni were calculated and they were found to be, as expected, at 6:00 am of 1st June and at 3:00 pm of 19th July, respectively.

A possible explanation can be found in the lapse rate trend: the minimum temperature at S. Caterina corresponds to the minimum lapse rate. However, in the evening a maximum lapse rate reduces the calculated temperature, resulting in minimum values for the whole glacier surface.

In our analysis, to simplify computations we ignored the occurrence of heat islands (e.g. rock outcrops, medial moraines and nunataks).

Analysing the daily SWin values calculated for all the glacier points, the maximum value (406.9 Wm^{-2}) was recorded on 13th June, and the minimum (28.5 $W m^{-2}$) on 6th June. Analysing the daily trend, this lowest value is due to atmospheric conditions: in fact in the graph (fig. 5B) very low values are shown. In general, from hourly SWin values it is possible to distinguish days with clear sky conditions, characterized by higher values (fig.

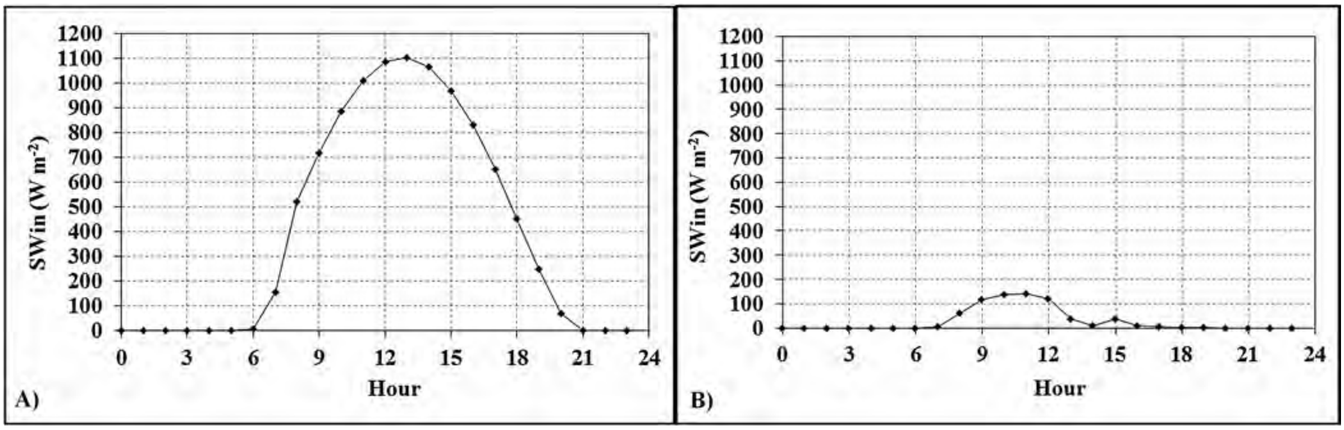


FIG. 5 - Example of graphs representing a day with clear sky conditions, 13th June (A), and a day with intense cloud cover, 6th June (B), during summer 2009.

5A) and regular radiation behaviour (i.e.: increasing up to noon and decreasing to sunset), from days with intense cloud cover which reduces the incoming radiation thus giving low SWin values and irregular behaviours (fig. 5B).

Moreover weekly values show the greatest value (327.1 Wm^{-2}) on 20th-26th July and the lowest (207.8 Wm^{-2}) on 22th-28th June.

A series of temperature and SWin spatial distribution maps were created, 13 for weekly and 3 for monthly data. These show how spatial distribution of both parameters reflects the distribution by elevation belts. By comparing the maps we can also identify a small warmer island where less radiation occurs on some weeks, in the western basin, under the S. Giacomo peak, due to the sheltering effect of a small valley, and a little colder island where more radiation is found, on the eastern basin, between Taviela and Pejo Peaks, due to an exposed promontory (fig. 6).

Regarding the shading due to slope and aspect we report the results of four indicative days representing the period studied (1st June, 1st July, 1st August and 31st August 2009). Averaging the values of these 4 days, the percentage of illuminated glacier (i.e. value > 0) results equal to 33% at 6:00 am and 100% at noon. In particular at 6:00 am of 1st June and 1st July the illuminated glacier area is 46%, on 1st August 31% and on 31st August 8%.

It is possible to validate these results using SWin data recorded by AWS1 Forni, collected from 6:00 am to 8:00 pm. In the shading map, at 6:00 am, AWS1 Forni is not in full light yet but greater than 0 SWin data are recorded by the station (e.g. only 37.3 Wm^{-2} for 1st June): this is due to atmospheric scattering. Moreover solar radiation measurements are overestimated during spring (due to the multipath effect of the snow/ice covered walls surrounding the glacier) and underestimated in cases of shading (due to aspect and topography). Further evidence shows that the western basin is illuminated first: this is because the Forni Glacier has a north to south aspect (figs. 7 and 8).

DISCUSSION AND CONCLUSIONS

The glacier surface is characterized by different physical properties than the surroundings (e.g. different albedo or air temperature and humidity), so it is very important to measure the energy exchanges directly at the glacier surface. However installing a permanent AWS on a glacier is not always possible, especially due to the complex surface

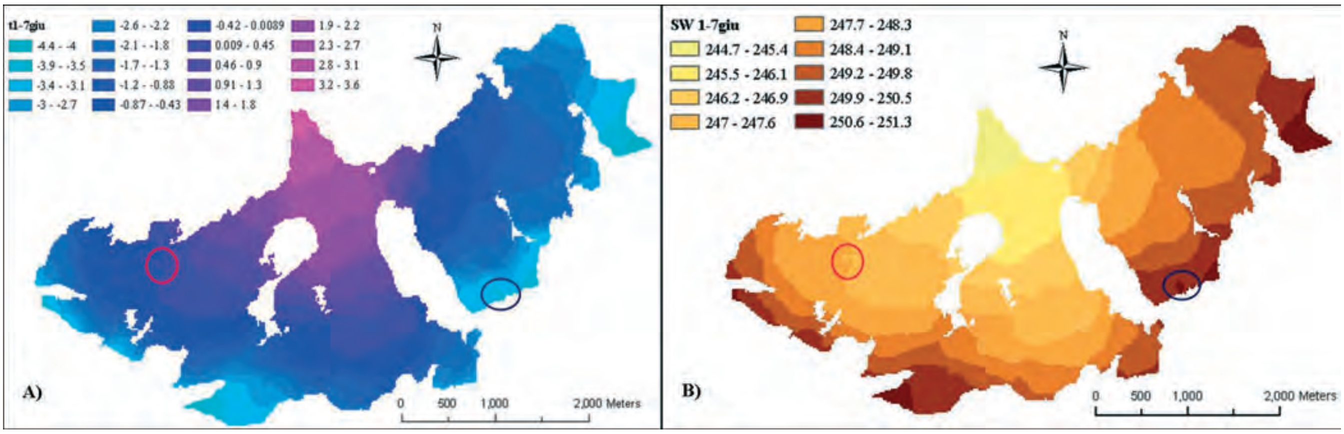
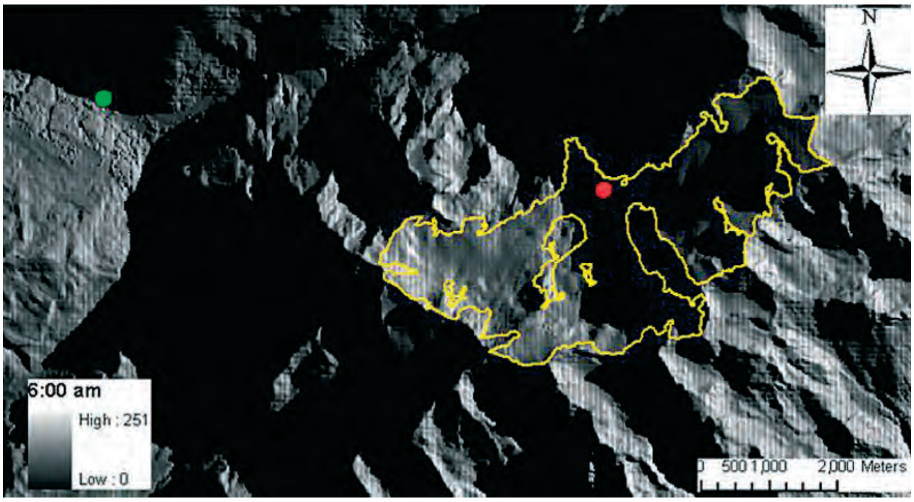


FIG. 6 - Example of maps representing temperature (A) and SWin (B) weekly distribution on Forni Glacier. Red circle marks the warmer island and the blue one indicates the colder island.

FIG. 7 - A shading map of 1st June 2009 at 6:00 am. The red point represents the AWS1 Forni, the green point AWS S.Cat. and the yellow line is the glacier boundary.



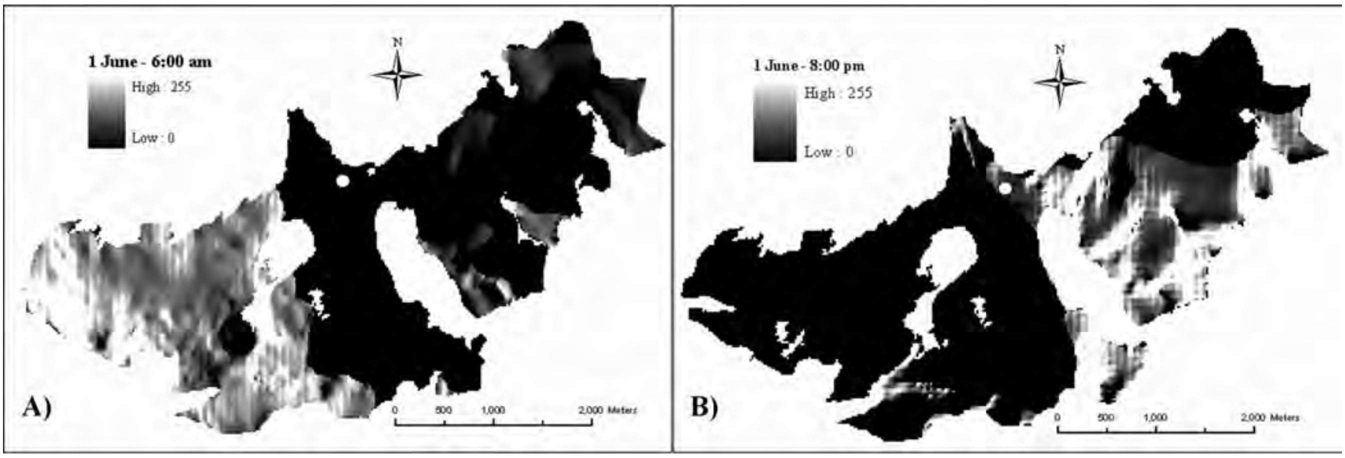


FIG. 8 - Shadow maps of Forni Glacier extrapolated by the Hillshade function of ArcGIS: 1st June 2009 at 6:00 am (A) and at 8:00 pm (B). The white point indicates the AWS1 Forni.

morphology, so it is crucial to calculate the lapse rate for the most significant meteorological parameters affecting the energy budget, such as air temperature and incoming solar radiation. On the contrary regarding albedo variability it is necessary to further investigate the surface features (i.e. fresh snow, compacted snow, dust-covered snow, bare ice and buried ice) which influences the amount of the absorbed solar radiation.

As a preliminary study, we investigate the gradients of air temperature and incoming shortwave radiation and then these parameters are distributed over the whole Forni Glacier surface. In particular, the relationship between glacier energy balance and meteo-climate variables measured by a synoptic station not influenced by the glacier are considered. In fact, the AWS S.Cat. is located near the glacier, but not directly on its surface, so its data allowed us to describe an alpine microclimate not influenced by the glacier boundary layer. For this reason we applied a local lapse rate (modelled from AWS S.Cat and AWS1 Forni dataset) and not the mean tropospheric one.

Regarding the air temperature during summer 2009, the points where the highest (+16.1°C) and lowest (–11.9°C) values were found seem correct. Our results represent the first «simple» approach to distribute the energy budget of the Forni Glacier. To simplify our calculations we ignored the debris covered areas affecting the glacier surface (the medial moraines, see Smiraglia, 1989) and the rock outcrops and nunataks which have become more extensive over recent decades (see Diolaiuti and Smiraglia, 2010). Nevertheless the results show reliable trends and patterns of air temperature and solar radiation, thus supporting this first simple attempt.

Analysis of the daily trend of SWin confirms that this parameter is useful in reconstruction of atmospheric conditions and in distinguishing days with clear sky conditions, characterized by higher values, from days affected by intense cloud cover which reduces the incoming radiation.

The two small islands observed both for temperature and for radiation are evidence of the considerable influence of topography and morphology on local micro meteorology.

In the analysis of SWin it is vital to take account of shading effects. In fact, in a shadowed zone solar radiation is only diffuse and not direct. This analysis is performed by the Hillshade tool of Arcmap. Hourly hillshade values deliver a more correct distribution of SWin over the whole glacier. Moreover the obtained shadow maps allow us to confirm the accuracy of AWS1 Forni, which records SWin values from 6:00 am to 8:00 pm. They are thus a useful tool to check accuracy, precision and any overestimation of radiation values calculated.

In the future, to enable a more complete, in-depth and comprehensive analysis it will be important to consider the debris covered zones, nunataks and rock outcrops, since they have different thermal properties. It will therefore also be necessary to consider the thickness and distribution of supraglacial rock debris.

Furthermore, to apply a full energy distribution model to the whole glacier surface, the albedo, net longwave radiation and turbulent fluxes also need to be distributed. In this way it will be possible to quantify ice losses at the end of each ablation season (September). In particular the albedo variability in space and time can be evaluated estimating the influence of the dust and fine and sparse debris (which decreases the ice reflectivity) and of the rain (that washes out the finer sediment above glacier ice surface increasing the albedo). Then, considering also winter accumulation, it will be possible to calculate the whole glacier mass balance. In this way we will extend our knowledge of the evolution of the Forni Glacier and it will be possible to forecast glacier changes according to different climate scenarios.

Moreover, the improvement of meteorological data modelling from records acquired by the AWSs located outside alpine glaciers where supraglacial AWS are also running (thus enabling data validation), could help future works on remote areas where no instruments and sensors are available at the glacier surface.

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(Ms received 15 February 2013; accepted 15 November 2013)