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Comitato Glaciologico Italiano
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We focus here on modelling the meteorological parameters most influencing snow/ice melting over an alpine glacier. Specifically, we consider shortwave and longwave downward radiation, and air temperature. We set up and test a methodology for their accurate distribution at the glacier surface, which can be applied whenever: i) supraglacial meteorological measurements are available or ii) weather data are acquired from a station quite close to the glacier. As a suitable site to test our approach we selected the Forni Glacier, in the Italian Alps, where an Automatic Weather Station (AWS) has been running since autumn 2005 thus giving a robust dataset for developing a field based modeling approach. First, we modelled and distributed the incoming solar radiation by taking into account actual atmospheric conditions, glacier topography and shading. Then, we modelled the incoming longwave radiation considering cloud-cover and air temperature. Third, we investigated a local lapse rate to depict the yearly variability of the vertical air temperature gradient, to assess the actual thermal conditions at different elevations. Finally, we compared the modeled values against data collected on the field. The results display that during the glacier ablation period (i.e.: May-September): i) our approach provides a good depiction of both point incoming solar and infrared radiation fluxes, ii) the spatial distribution of the incoming solar radiation we developed is satisfactory, iii) our tests suggest that the incoming longwave fluxes can be considered constant over the whole glacier ablation area thus neglecting its spatial distribution, and iv) the application of a local lapse rate provides a good distribution of air temperature at the glacier surface.

**Key Words:** Short- And Long-Wave Downward Radiation; Air Temperature; Ice And Snow Melting; Alpine Glaciers, Stelvio National Park

**Abstract:** A. Senese, M. Maugeri, S. Ferrari, G. Confortola, A. Soncini, D. Bocchiola & G.A. Diolaiuti. Modelling shortwave and longwave downward radiation and air temperature driving ablation at the Forni Glacier (Stelvio National Park, Italy). (IT ISSN 0391-9838, 2016)

Antonella Senese (**), Maurizio Maugeri (**), Stefano Ferrari (**), Gabriele Confortola (**), Andrea Soncini (**), Daniele Bocchiola (**), Guglielmina Diolaiuti (*)

**MODELLING SHORTWAVE AND LONGWAVE DOWNWARD RADIATION AND AIR TEMPERATURE DRIVING ABLATION AT THE FORNI GLACIER (STELVIO NATIONAL PARK, ITALY)**

**Abstract:** A. Senese, M. Maugeri, S. Ferrari, G. Confortola, A. Soncini, D. Bocchiola & G.A. Diolaiuti. Modelling shortwave and longwave downward radiation and air temperature driving ablation at the Forni Glacier (Stelvio National Park, Italy). (IT ISSN 0391-9838, 2016)
Incoming longwave radiation, a review of models is given by Gueymard (1993), including the basic distribution parameters (minimum, mean, maximum, and standard deviation values). The portable station is equipped with a four component radiometer (CNR1, Kipp&Zonen, with an accuracy of ±5%), a waterproof box containing a data logger (E-log, LSI-Lastem), a 5 Ah battery, a 10W solar panel and a tripod to raise the net radiometer above the ice surface (fig. 2) for short periods (c. 20-30 min per measurement). The CNR1 net radiometer used here is similar to that used at the AWS1 Forni 2012a), including the basic distribution parameters (minimum, mean, maximum, and standard deviation values).

During summer 2011 and 2012 (30 June 2011, 4 July and 9 September 2012), field surveys were carried out at the Forni Glacier tongue, to collect a total sample of 18 radiative data. The portable station was equipped with a four component radiometer (CNR1, Kipp&Zonen, with an accuracy of ±5%), a waterproof box containing a data logger (E-log, LSI-Lastem), a 5 Ah battery, a 10W solar panel and a tripod to raise the net radiometer above the ice surface. Data points are sampled at 60-second intervals and averaged over a 30-minute time period for most of the sensors (see Senese & alii, 2012a), including the basic distribution parameters (minimum, mean, maximum, and standard deviation values).

The AWS1 Forni is powered by two solar panels (40 Watt) and a lead-gel battery (100 Ah). Data points are sampled at 60-second intervals and averaged over a 30-minute time period for most of the sensors (see Senese & alii, 2012a), including the basic distribution parameters (minimum, mean, maximum, and standard deviation values).
2.2. Incoming solar radiation model

To model the distributed incoming solar radiation at the Forni Glacier surface, we used four methods of increasing complexity, namely considering i) a flat and ideal exo-atmospheric surface (i.e. we calculated radiation taking into account astronomical and geographical factors only, thus neglecting atmospheric absorption and orography, Iqbal, 1983; Allen & alii, 2006; Wang & alii, 2006), ii) a sloped exo-atmospheric surface (i.e. we considered slope and aspect too, Garner & Ohmura, 1968; Duffie & Beckman, 1980; Hunter & Goodchild, 1997; Allen & alii, 2006), iii) a sloped exo-atmospheric surface in a complex orographic system (i.e. we evaluated the shading too), and iv) a complex surface (from iii) in an actual atmosphere (i.e. we also considered meteorological conditions, and the multireflection from the surrounding surfaces, Hock & Noetzli, 1997; Gueymard, 2001). We describe here the algorithms we applied to distribute the global radiation.

i) The approach proposed by Iqbal (1983) was used to estimate the daily exo-atmospheric solar radiation ($SW_{0\text{-point}}$) received by a flat surface:

$$SW_{0\text{-point}} = I_0 \cdot E_0 \cdot k \cdot \int_{w_{sr}}^{w_{ss}} \cos(\theta) \cdot \mathrm{d}h$$  (1)

where $I_0$ is average solar irradiance at the mean Earth-Sun distance (1367 W m$^{-2}$), $E_0$ is an eccentricity factor (i.e. the correction due to the elliptical orbit of the Earth depending on the day of the year; Spencer, 1971), $\theta$ is the angle between the normal to the surface and the solar beam (Oke, 1987), $h$ is the hour angle (zero value at solar noon, negative during morning and positive during afternoon), and $k$ is a factor to express $SW_{0\text{-point}}$ in MJ day$^{-1}$. Finally, $w_{sr}$ and $w_{ss}$ are the sunrise and sunset hour angles, respectively (Allen & alii, 2006):

$$w_{ss} = \arccos(-\tan \Phi \cdot \tan \delta)$$  (2)

$$w_{sr} = -w_{ss} = -\arccos(-\tan \Phi \cdot \tan \delta)$$  (3)

where $\Phi$ is the latitude, and $\delta$ is the solar declination. Here, $w_{sr}$ and $w_{ss}$ have opposite values because the hour angle is the angular displacement of the sun, east or west of the local meridian. This is due to rotation of the Earth on its axis, at $2\pi/24$ radiant per hour: morning ($w_{sr}$) is assumed as negative and afternoon ($w_{ss}$) as positive. Finally, simplifying the approach proposed by Wang & alii (2006), the daily exo-atmospheric solar radiation received by a flat surface is:

$$SW_{0\text{-point}} = 2 \cdot I_0 \cdot E_0 \cdot k \cdot [(\sin \delta \cdot \sin \Phi) \cdot w_{ss} +$$

$$+ (\cos \delta \cdot \cos \Phi) \cdot \sin w_{sr}]$$  (4)

ii) For an inclined surface, we considered the angle between the normal to the surface and the solar beam, by expressing Eqn 4 according to Garner & Ohmura (1968) and Duffie & Beckman (1980) as:
where $S$ is the slope angle and $A$ is the aspect angle, both calculated according to Hunter & Goodchild (1997). The slope ranges from 0° (i.e. horizontal) to 90° (i.e. vertical). The aspect is related to the South, then 0° represents South, 90° East, -90° West, and ±180° North. To calculate $w_{sr}$ and $w_{ss}$ for an inclined surface we applied the method proposed by Allen & alii (2006). Also the auto-shading was estimated following the approach reported by Allen & alii (2006): when slopes are steep and northerly facing in northern latitudes or southerly facing in southern latitudes, the grid point may be shaded during all or portions of the day.

iii) To assess whether a grid point is affected by shading (i.e. the orography intercepts the hypothetical line linking this grid point to the Sun), we considered both Sun elevation angle ($\gamma_{\text{Sun}}$), and the angle between the mountain peak and the grid point ($\gamma_{\text{peak-point}}$):

$$\gamma_{\text{Sun}} = \arcsin[\cos(\alpha) \cdot \cos(\delta) \cdot \cos(\phi) + \sin(\phi) \cdot \sin(\delta)]$$

(6)

and

$$\gamma_{\text{peak-point}} = \arctan\left(\frac{h_{\text{peak}} - h_{\text{point}}}{\text{distance peak-point}}\right)$$

(7)

where $h_{\text{peak}}$ and $h_{\text{point}}$ are the mountain peak and grid point elevations, respectively, defined by the DEM (i.e. Digital Elevation Model). In particular, we searched for the $\gamma_{\text{peak-point}}$ value representing the highest obstructing angle along the grid-point-to-the-Sun direction for each hour of the day. In fact, almost every glacier point featured different values of $h_{\text{peak}}$, and these also varied with the solar azimuth. Hence, whenever $\gamma_{\text{Sun}} < \gamma_{\text{peak-point}}$, the grid point is affected by shading.

iv) To take into account the atmospheric absorption, we considered the ratio between the global radiation actually received by a surface measured by the AWS1 Forni ($SW_{T-AWS}$), and the modelled exo-atmospheric radiation received by the same surface ($SW_{0-AWS}$) (Gueymard, 2001):

$$SW_T = \frac{SW_{T-AWS}}{SW_{0-AWS}} \cdot SW_0$$

(8)

The $SW_{T-AWS}/SW_{0-AWS}$ ratio will vary from a maximum under clear-sky conditions to a minimum in overcast conditions. This ratio was calculated at the AWS1 Forni site, and the value was considered representative for the whole glacier surface (Escher-Vetter, 1980). The incoming solar radiation ($SW_{T-AWS}$) was measured at the radiometer installed at the AWS1 Forni, whereas the exo-atmospheric radiation ($SW_{0-AWS}$) was estimated according to Eqn 5, taking into account the slope of the surface where the meteorological station is located.

The AWS1 Forni is located on a valley glacier, and therefore it is potentially subject to topographic shading, while other parts of the glacier may still be in the sunshine. For this reason, the AWS1 Forni is considered in clear-sky and partially cloudy conditions at the time $t$:

$$SW_{T-\text{point}}(t) = 0.15 \cdot SW_{T-AWS}(t)$$

(12)

There is no direct radiation, but only diffuse radiation at both grid points. Diffuse radiation is assumed to be invariant over the area. Hence, global radiation at the grid point is set to measured global radiation.

D) Grid point is shaded and AWS is unshaded, in clear-sky and partially cloudy conditions at the time $t$:

$$SW_{T-\text{point}}(t) = SW_{T-AWS}(t)$$

(11)

There is no direct radiation, but only diffuse radiation at both grid points. Diffuse radiation is assumed to be invariant over the area. Hence, global radiation at the grid point is set to measured global radiation.

The $SW_{T-AWS}/SW_{0-AWS}$ ratio varies from a maximum under clear-sky conditions to a minimum in overcast conditions. This ratio was calculated at the AWS1 Forni site, and the value was considered representative for the whole glacier surface (Escher-Vetter, 1980). The incoming solar radiation ($SW_{T-AWS}$) was measured at the radiometer installed at the AWS1 Forni, whereas the exo-atmospheric radiation ($SW_{0-AWS}$) was estimated according to Eqn 5, taking into account the slope of the surface where the meteorological station is located.

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E) Grid point is shaded and AWS is unshaded, under overcast conditions at the time $t$:

$$\text{SW}_{T\text{-point}}(t) = \text{SW}_{T\text{-AWS}}(t)$$

(13)

where the diffuse radiation is 100% of the total radiation and the shading is irrelevant.

To evaluate the accuracy of the modelled solar data ($\text{SW}_{T\text{-point}}$), we compared the calculated values against shortwave radiation data measured on the field by the portable radiometer during summer 2011 and 2012 (18 sites). In high-mountain regions the temporal variability of cloudiness is very high, and it influences the $\text{SW}_{T\text{-AWS}}/\text{SW}_{0\text{-AWS}}$ ratio whenever this latter is evaluated with a high time resolution (e.g. every 5 minutes or higher). This phenomenon could affect partially our computations, since we derived the $\text{SW}_{T\text{-AWS}}/\text{SW}_{0\text{-AWS}}$ ratio from AWS1 Forni data (which recorded at thirty minutes interval), while our portable radiometer acquired data every 5 minutes in 2011, and every minute in 2012. In order to minimize such discrepancy we calculated the ratio considering the half-hourly minimum, mean and maximum solar values acquired by the AWS1 Forni.

2.3. Incoming infrared radiation model

In the available literature concerning the estimation of distributed ice melt using an energy budget, both the incoming and the outgoing infrared radiation are often taken constant in space (e.g. Hock & Noetzli, 1997). However, incoming longwave radiation depends on air temperature and humidity (varying over the glacier surface as well), on topographic reflection, and on spatial cloud-cover variations.

To investigate the suitability of a spatially constant value to describe at each time step the infrared radiation over the whole ablation surface of a glacier, we performed field measurements of incoming longwave radiation (i.e. $\text{LW}_{in}$) at different sites spread over the Forni Glacier tongue. The surveys were carried out with the portable radiometer (CNR1) during the ablation season in 2011 and 2012. We then compared these field measurements with the values recorded by the AWS1 Forni. In figure 3 two examples are shown: one in summertime 2011 (series with circles) and one in summertime 2012 (series with diamonds). As expected, the spatially distributed longwave measurements (black series, fig. 3) resulted in the range measured by the AWS1 Forni (white series, fig. 3). Hence, the assumption of spatially constant incoming longwave radiation may be taken as acceptable (as stated by Hock & Noetzli, 1997).

We also considered that mostly supraglacial AWSs are not equipped with a four component radiometer (i.e. a net radiometer measuring both up- and down-ward, and short- and long-wave fluxes) but only with a global solar sensor, thus limiting the evaluation of the radiation to the shortwave contribution, and neglecting the longwave one. We therefore sought for a method to model incoming longwave radiation, applicable also in sites where a longwave radiometer is not available. The solution we found the most suitable uses air temperature ($T_a$) and sky emissivity ($\varepsilon_s$) as main input data. In fact, in melt models, longwave irradiance is usually estimated from empirical relationships, based on standard meteorological measurements, exploiting the fact that longwave irradiance correlates well with air temperature and vapour pressure at screen level, usually at 2 m above the surface (Kondratyev, 1969).

The sky emissivity was calculated from cloudiness ($\varphi$, assessed from incoming solar radiation from the AWS1 Forni) and vapour pressure ($\varphi_v$, estimated from air temperature and relative humidity values from the AWS1 Forni). Hence, in order to model $\text{LW}_{in}$ a thermo-hygrometer and a global radiometer (both commonly-used sensors) are necessary. In fact, the incoming infrared component firstly depends upon cloudiness. As cloud observations are not available at the Forni Glacier (nor at other sides nearby), cloudiness was estimated from the measured incoming shortwave radiation dataset ($\text{SW}_{T\text{-AWS}}$) (Oerlemans, 2000). First, the daily global radiation ($W \text{ m}^{-2}$) for clear sky was estimated ($\text{SW}_{T\text{-CS}}$) by way of a sine-cosine function (fig. 4), adjusted on the daily measured data averaged from

![Fig. 3 - Comparison of LW_{in} data acquired at several glacier sites (black series) with LW_{in} values recorded in the same time frames by the AWS1 Forni (white series). The circles refer to measurements acquired on 30th of June 2011, and the diamonds on 9th of September 2012. On X axis time (hours) is reported, on Y axis LW_{in} values are indicated (W m^{-2}). The vertical bars show an error range of ± 5% of the measured value (error reported by Kipp&Zonen).](image)

![Fig. 4 - Clear sky envelope (SW_{T-CS}) defined for incoming solar radiation (truncated Fourier series at the second factor) and the actual daily mean values (SW_{T-AWS}) from 1st October 2005 to 31st December 2012.](image)
2006 to 2012 and interpolated through the truncated Fourier series at the second order below:

\[
SW_{T-CS} = 160.4 - 236.0 \cdot \cos \left( \frac{\text{day} \cdot 2\pi}{365} \right) + 27.3 \cdot \sin \left( \frac{\text{day} \cdot 2\pi}{365} \right) - 25.1 \cdot \cos \left( 2 \cdot \frac{\text{day} \cdot 2\pi}{365} \right) - 15.1 \cdot \sin \left( 2 \cdot \frac{\text{day} \cdot 2\pi}{365} \right)
\]  
(14)

where \(\text{day}\) is the Julian date. To assess the actual clear sky incoming solar radiation without overestimation as due to multiple reflection from snow covered surroundings, we considered the snow-free half-year (i.e. from 1 May to 30 September of every year, following Oerlemans, 2000). Year 2005 was excluded by this computation because the AWS1 Forni dataset starts from 26\(^{th}\) September 2005.

Then, the atmospheric transmissivity (\(\tau\)) depending on the cloud cover is defined by:

\[
\tau = \frac{SW_{T-AWS}}{SW_{T-CS}}
\]  
(15)

and then the cloudiness (\(n\)), based on the altitude, was estimated according to the approach proposed by Sauberer (1955) and Konzelmann & alii (1994):

\[
\tau = 1 - (0.41 - 6.5 \cdot 10^{-5} \cdot \text{altitude}) \cdot n - 0.37 \cdot n^2
\]  
(16)

with an altitude of the AWS1 Forni site of 2631 m a.s.l. (fig. 5). This relation was found analysing global radiation data from Austrian climate stations (Alps), thus it can be assumed representative for the Forni Glacier. On days when \(\tau\) exceeds 1, cloudiness is zero.

Once we estimated cloudiness, we took into account the effect of emissivity for clear (\(\varepsilon_{cs}\)) and overcast (\(\varepsilon_{cl}\)) sky. The latter can be considered constant and close to one (0.976 at 2310 m a.s.l., Greuell & alii, 1997), since clouds block long-wave radiation very effectively (Oerlemans, 2000). Otherwise, the clear-sky emissivity depends on the (lumped) concentration of greenhouse gases, and on vapour pressure (\(e_a\)) and air temperature (\(T_a\)) according to Konzelmann & alii (1994):

\[
\varepsilon_{cs} = 0.23 + b \left( \frac{e_a}{T_a} \right)^{1/b}
\]  
(17)

with \(b = 0.475\) (found by Oerlemans, 2001, at 2310 m a.s.l.). The values of \(e_a\) and \(T_a\) were those recorded by the AWS1 Forni. Then the total emissivity is:

\[
\varepsilon = \varepsilon_{cs}(1 - n^p) + \varepsilon_{cl}n^p
\]  
(18)

with \(p = 2\). Cloud emission is often calculated from observations of cloud cover, type and altitude. However, this information is rarely available in remote locations and it is subject to errors. Sicart & alii (2006) in the mountains of northern Canada, and Sedlar & Hock (2009) on a glacier in northern Sweden, showed that a rough estimate of atmospheric solar transmissivity from measurements of global radiation can be used as an acceptable index of cloud cover to parameterize cloud emissivity.

Finally, the incoming longwave radiation was assessed following the Stephan-Boltzmann law:

\[
LW_{in} = \varepsilon \cdot \sigma \cdot T_a^4
\]  
(19)

where \(\sigma = 5.67 \times 10^{-8} \text{ W m}^{-2} \text{ K}^{-4}\). The method was verified by comparison of the modelled data against the 7-year infrared flux dataset recorded by the AWS1 Forni (from 1\(^{st}\) October 2005 to 31\(^{st}\) December 2012).

### 2.4. Air temperature model

To assess the most suitable lapse rates applicable also in other periods, we considered i) long temperature records, ii) different measurement stations, and iii) general meteorological conditions (such as excluding thermal inversion). We processed 4 years of data (from 1\(^{st}\) January 2006 to 31\(^{st}\) December 2009) from Bormio (1225 m a.s.l.), Santa Caterina Valfurva (1730 m a.s.l.) and Frodolfo dam (2180 m a.s.l.) weather stations (nearby the Forni Glacier, fig. 1). We firstly calculated hourly series of lapse rates between the three surrounding weather stations and the AWS1 Forni, thus obtaining for each year 3 dataset of hourly data records, thus 12 sets of hourly lapse rate. Secondly to avoid thermal inversion to affect the data too much, only the warmest hours of the day (from 12 pm to 4 pm) were considered in the calculation of the daily average lapse rates.
Indeed in a previous study (Senese & alii, 2014) Santa Caterina Valfurva and the Frodolfo dam AWSs were found to be affected by thermal inversion for about 9% and 1% from 2006 to 2012, respectively. Thirdly, these 12 series of daily records were averaged, to obtain annual daily lapse rate. Finally, to smooth this record, a regression model was used (fig. 6). More precisely, we used a relationship between lapse rate ($\lambda$) and time ($\text{day}$), following a truncated Fourier series at the second order:

$$\lambda = -7.88 + 1.27 \cos\left(\frac{\text{day}-2\pi}{365}\right) + 0.45 \sin\left(\frac{\text{day}-2\pi}{365}\right) - 0.16 \cos\left(2\frac{\text{day}-2\pi}{365}\right) - 0.73 \sin\left(2\frac{\text{day}-2\pi}{365}\right)$$

(20)

where $\text{day}$ corresponds to the Julian date (1 = 1 January, 365 = 31 December). We evaluated the accuracy of this approach comparing the model output values with daily data measured by the AWS1 Forni during 2010.

2.5. Model validation

We used a number of descriptive statistics to validate shortwave and longwave radiation, and air temperature. We calculated bias ($BE$) as:

$$BE = \frac{1}{N} \sum(y - x)$$

(21)

where $N$ is sample size, and $y$ and $x$ are measured and modelled values, respectively. Secondly, we estimated the mean absolute error ($MAE$) as:

$$MAE = \frac{1}{N} \sum|y - x|$$

(22)

Third, the root mean square error ($RMSE$) was calculated as:

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

(23)

Finally, we calculated bias-removed root mean square error ($BRRMSE$) as:

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

(24)

3. RESULTS AND DISCUSSIONS

Figure 7 shows the spatial distribution of the exo-atmospheric solar radiation over the Forni Glacier during the spring and autumn equinoxes, and summer and winter solstices, considering real surfaces and neglecting the effects of shading by surrounding topography and atmospheric absorption. As expected, the day with the highest solar radiation is the summer solstice (with 41.9 MJ m$^{-2}$). The largest cumulative annual value (about 12000 MJ m$^{-2}$) is reached on a south-facing surface with a slope of 22.7°, while the smallest one (about 1350 MJ m$^{-2}$) is observed on a north-facing surface with a slope of 62.8°. Auto-shading conditions (estimated according to Allen & alii, 2006) occur for northerly facing slopes higher than 23.3°. Particularly, whenever the slope exceeds 70° auto-shading can occur every day. Generally, the northern part of the eastern basin features the most intense solar irradiation on the glacier. Here the slopes are moderate and the main aspect is south and south-west (fig. 7). The $SW_{T-AWS}/SW_{G-AWS}$ ratio measured at AWS1 Forni ranges from 0.1 to 1.3. Taking into account both cloudiness and multi-reflection, this well agrees with the range 0.2-1.2 found by Hock (1999).

Validation of our approach was performed by comparing the modelled incoming shortwave radiation against the one measured at 18 sites along the glacier tongue, during summer 2011 and 2012 (fig. 8). The model agrees well with observations (tab. 1), with an $r$ value of 0.97.

The estimated values of daily mean $LW_{in}$ were compared against those by the AWS1 Forni during 2006-2012 period (fig. 9). The model performance was evaluated during the actual glacier ablation period (i.e.: May-September in agreement with Oerlemans, 2000). In fact on the other months (i.e.: October-April) at the Forni Glacier accumulation prevails (Senese & alii, 2014), thus neglecting this latter period is acceptable since the main aim of our work is at modelling radiative components driving glacier melt. An acceptable agreement between the two datasets was found (tab. 1), although there was a significant share of points with $LW_{in}$ underestimated by the model. This can be due to neglecting the local topography, but probably the most important factor is poor cloudiness computation. Indeed, a low modelled longwave radiation is likely due to the presence of clouds, increasing the column-averaged temperatures and thus down-welling longwave radiation. Another source of errors is probably linked to the fact that the temperature of the lowest air layers over the glacier may be affected by the temperature of the glacier surface, which can cause, especially in summer, temperature inversions above the glacier. Therefore, in warm conditions, temperatures measured at glacier AWS may underestimate longwave irradiance as they may be more representative of the
Fig. 7 - Maps of daily exo-atmospheric solar radiation over the Forni Glacier during the spring and autumn equinoxes and summer and winter solstices, considering real surfaces and neglecting the effects of shading by surround topography and atmospheric absorption.

Fig. 8 - Measured and modelled incoming solar radiation during summer 2011 and 2012.

Fig. 9 - Modelled and measured daily incoming longwave radiation during May-September time frame from 2005 to 2012.
melting surface than of the air over the glacier (van den Broeke, 1996). In our case, the underestimation is found to be consistent with cloudy sky conditions. Indeed, comparing daily differences measured-modelled LW, (ΔLW) with cloudiness values (n), the 96.1% of ΔLW in values higher than 5 MJ m$^{-2}$ occurred with values of n higher than 0.8.

The approach presented in this paper can also be applied considering temperature as a function of elevation as described in Section 2.4, and applying some methodologies (see Shea & Moore, 2010) to extend the estimation of e over the entire glacier. We think, however, that the small vertical extent of the ablation area of the Forni Glacier (i.e.: from 2650 m a.s.l. to 3000 m a.s.l.) does not require such effort which instead has to be performed on widest mountain glaciers featuring a higher elevation extent.

Concerning air temperature, we shifted the daily air temperature values measured at Bormio (1225 m a.s.l.) to the AWS1 Forni site elevation (2631 m a.s.l.) applying the daily lapse rate (Eqn. 20). To validate this temperature reconstruction, we made a comparison between modelled daily air temperature values with air temperatures actually measured at the AWS1 Forni during 2010 (fig. 10). These two datasets result in agreement (tab. 1) with an r value of 0.95, but some points feature temperatures underestimated by the model. Nevertheless, the slope coefficient of the linear regression between measured and modelled temperatures is very close to 1 (fig. 10), thus suggesting that the approach is accurate enough. In a previous study (Senese & alii, 2014), we found that it was possible to perform a reasonable reconstruction of the supraglacial daily average air temperature at the AWS1 Forni starting from meteorological data acquired down valley using a mean tropospheric vertical gradient as lapse rate. Conversely, taking into account actual values of lapse rate (as the ones found in this study) allows a better distribution of air temperature over the whole surface of the glacier.

4. CONCLUSIONS

In the present study, we focus on modeling the meteorological parameters most influencing the snow/ice melting and on distributing them over a wide and representative alpine glacier, the Forni Glacier (Italian Alps, Stelvio National Park). In fact, in energy balance models the radiative components are the most important driving factors (Müller, 1985; Senese & alii, 2012a), while the air temperature is considered a proxy of ablation in T-index approaches (Braithwaite, 1995), thus requiring accurate reconstruction and distribution of data.

Firstly, the solar radiation was estimated taking into account astronomical and geographical factors and actual atmosphere conditions, secondly it was distributed considering slope and aspect of each glacier grid point, and shading due to the surrounding topography. The obtained solar radiation distribution was benchmarked against distributed solar radiation data measured during field campaigns in summer 2011 and 2012 (18 sites). The two datasets are in agreement with a RMSE of 0.095 MJ m$^{-2}$, thus suggesting that the proposed solar radiation model is suitable for the purpose. Then, we compared distributed measured longwave data (acquired by a portable net radiometer at several points at the glacier surface) to infrared values acquired simultaneously by the permanent supraglacial AWS installed at the surface of the Forni Glacier. The two records of data supported the assumption of spatially constant incoming longwave radiation may be taken as acceptable (as stated by Hock & Noetzli, 1997). Then we modelled daily infrared values from 2006 to 2012 (during May-September) and we compared the obtained data to the ones measured by the AWS Forni. It resulted only 12.3% of the samples featuring an underestimation larger than 5 MJ m$^{-2}$, and the underestimate not exceeding 8 MJ m$^{-2}$ thus supporting our approach. A higher measured incoming longwave radiation with respect to the modelled one is probably due to the presence of clouds, increasing the column-averaged temperatures and thus down-welling longwave radiation, and to the surrounding topography. Hence, the infrared model can be considered appropriate and the observed underestimation possibly negligible. Finally, the air temperature was estimated considering long temperature records (2006-2009 dataset), different mea-

![Fig. 10 - Modelled and measured daily air temperature during 2010 (the modeled series is derived from Bormio data shifted to the AWS1 Forni elevation through the application of estimated lapse rate, Eqn 20).](image-url)
surement stations (Bormio, 1225 m a.s.l., Santa Caterina Valfurva, 1730 m a.s.l., and Frodolfo dam, 2180 m a.s.l.), and general meteorological conditions (such as excluding thermal inversion). Then, the modelled daily lapse rate was applied to Bormio dataset and the obtained values were validated against those from the AWS1 Forni during 2010. Even in this case, the model agrees well with observations (RMSE = 2.76°C). Eventually, the present study provided some information concerning errors in modelling solar and infrared radiation and air temperature, useful for quantifying glacier melt rate. Moreover, it turned out that unlike solar radiation and air temperature, the longwave radiation can be considered constant over a glacier surface. In conclusion, for estimating these three parameters, we suggest that a supraglacial weather station measuring all meteorological data is not strictly necessary. In fact, air temperature can be modelled from data acquired far away the site: Bormio is about 20 km from the glacier terminus. The parameters that should be measured directly over the glacier surface (or at least very close to it) seem to be: i) the vapour pressure, considered in this study for estimating the clear-sky emissivity in the infrared model, and ii) the shortwave radiation. Hence, it seems enough a minimal configuration for a supraglacial weather station, equipped with a pyranometer measuring the incoming global solar radiation, and a thermo-hygrometer, for modelling of the three most important parameters driving the ice/snow melting.

In the near future, there will be more and more detailed DEM based on UAV reliefs (Fugazza & alii, 2015), thus allowing a more correct distribution of meteorological parameters. In addition, the next step of our research will be to use the parameterization presented in this study coupled with spatially distributed albedo derived from remote sensing (e.g. Fugazza & alii, 2016) for a more accurate description of the absorbed solar radiation at each glacier pixels. This last point is particularly important as the net radiation is certainly greater in recent times as a result of the darkening phenomena (Diolaiuti & Smiraglia, 2010), namely the increasing deposition of black carbon and dust on glacier surface which reduces albedo and increases melting (Azzoni & alii, 2016).

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