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(Article begins on next page)

# Parameterization of shortwave, longwave and net radiation fluxes over the Hells Gate ice shelf (Antarctica)

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## Abstract

During the southern summer of 1997-1998, the XIII Antarctic scientific expedition organized by the PNRA took place at the Italian base of Terra Nova Bay. In this expedition, the team of IFA (CNR, now ISAC Roma) measured global shortwave radiation fluxes, temperature, humidity and pressure over the Hells Gate ice shelf. In the same period and at a very nearby site, the team of ISAO (CNR, now ISAC Bologna) measured the fluxes of incident and reflected shortwave radiations, upward and downward longwave radiations, and the albedo. In this work, the different components of the net radiation (incoming and outgoing shortwave and longwave) are calculated using the data collected by IFA with some parameterizations found in the literature. The results are compared with the observations performed by ISAO with the aim to verify the parameterizations, important for assessing the land surface process in Antarctica. The first results show periods and situations of good agreement and other situations in which the departure of calculated data from observations is not negligible. A discussion of these results is presented.

# 1 Introduction

The energy budget at the interface between bare soil and atmosphere can be expressed as:

$$R_n = L_e E + H + G \quad (1)$$

where  $R_n$  is the net radiation,  $L_e E$  is the latent heat flux,  $H$  is the sensible heat flux, and  $G$  is the heat flux entering into the surface through conduction. The net radiation can be broken down into several components:

$$R_n = S_n + L_n = S_{in} - S_{out} + L_{in} - L_{out} \quad (2)$$

where  $S_n$  is the shortwave net radiation,  $L_n$  the longwave net radiation,  $S_{in}$  the incoming shortwave radiation,  $S_{out}$  the outgoing shortwave radiation,  $L_{in}$  the incoming longwave radiation and  $L_{out}$  the outgoing longwave radiation.

Whenever possible, the net radiation flux should be measured as well and, at present, fairly reliable instruments are available for this purpose. However, in absence of direct measurements, net radiation can be estimated from its components. When the observation of these measurements are not available, the components can be obtained by theoretical methods or simple empirical formulae (parameterization).

In some previous work [1, 2] the attention has been focused on the evaluation of energy balance, while the aim of this work is to test some parameterizations of short and longwave radiation present in the literature. Some intercomparisons between measured and parameterized data will be presented and checked.

## 2 Experimental layout

Some measured data were collected by ISAO (CNR Bologna) in the site located in the position identified by the latitude-longitude coordinates: 74° 51' 3.7" S, 163°, 47', 2.8" E. The instruments were: a pyrradiometer Schenk model 8111 (range: 0.3-60 $\mu$ m), an albedometer Schenk model 8104 (range: 0.3-3 $\mu$ m), a pyrgeometer Eppley model PYR (range: > 3 $\mu$ m), and a pyrgeometer Everest model 4000.4GL. They allow to measure:

- the incident and reflected shortwave radiations and albedo (respectively  $S_{inM}$ ,  $S_{outM}$ ,  $\alpha_M$ );
- the downward and upward longwave radiations (respectively  $L_{inM}$ ,  $L_{outM}$ ).

In the site located in the position: 74° 52' 20.2" S, 163° 49' 6.4" E, the team of IFA (CNR, Roma) collected other data:

- the global shortwave radiation ( $S_{inR}$ ) by the Solarimeter Sitep (range: 0.4-1.1 $\mu$ m);
- the temperature of air and ice surface ( $T_a, T_s$ ) by the Thermometers Sitep (range: -30 - 70° C) at 5m and surface;
- the humidity ( $r_h$ ) by the Sitep hygrometer (range: 0-100%) at 5m;
- the pressure ( $p$ ) by the Sitep barometer (range: 800 - 1100 hPa).

The data measured by IFA team have been used to calculate the components of radiation ( $S_{in}, S_{out}, L_{in}$  and  $L_{out}$ ).

Two periods of this campaign, in which all instruments where operational have been selected. The first one ranged from 12<sup>th</sup> of January 1998 to 26<sup>th</sup> of January 1998 and the second one from 3<sup>rd</sup> of February 1998 to 18<sup>th</sup> of February 1998. They will hereafter be referenced as first and second period respectively.

## 3 Results

### 3.1 Incoming shortwave radiation

The measurements ranges of the two instruments, *i.e.* the Albedometer Schenk (0.3-3.0 $\mu$ m) and the Solarimeter Sitep (0.4-1.1 $\mu$ m), are different and have two non overlapping sub-ranges (0.3-0.4 $\mu$ m and 1.1-3.0 $\mu$ m). The incoming shortwave radiation has been parameterized, taking into account the missing range in the following way:

- 1) the solar elevation  $\gamma$  [3] has been computed using the input data: time, longitude and latitude;
- 2) the relative optical air mass ( $m$ ) [3] has been calculated as:

$$m = \frac{1 - \frac{z}{8000}}{\sin(\gamma)} \quad \text{if } \gamma > 10^0 \quad (3)$$

$$m = \frac{1 - \frac{z}{8000}}{\sin(\gamma) + 0.15(\gamma + 3.885)^{-1.253}} \quad \text{if } \gamma < 10^0 \quad (4)$$

where  $z$  is the altitude of the site;

3) the incoming shortwave radiation ( $S_{in}$ ) has been computed as:

$$S_{in} = S_{inR} + \frac{0.025 \cdot S_{inR}}{0.1 * m} \quad \text{if January} \quad (5)$$

$$S_{in} = S_{inR} + \frac{0.05 \cdot S_{inR}}{0.1 * m} \quad \text{if February} \quad (6)$$

where the coefficient 0.025 and 0.05 depend on the solar elevation.

The results are displayed in figs. 1(a) and 1(b). The fig. 1(a) is relative to the first period (from 12<sup>th</sup> to 26<sup>th</sup> of January) while the fig. 1(b) is relative to the second period (from 3<sup>rd</sup> to 18<sup>th</sup> of February). In abscissa the julian day is shown. The star points represent the measured data ( $S_{inM}$ ), the dashed line the measures collected by the solarimeter Sitep ( $S_{inR}$ ), the solid line the parameterized results ( $S_{in}$ ) and the dashdot line is the theoretical incoming radiation under clean sky ( $S_{inT}$ ), which is calculated according to [3] and [4]. It is noticeable that there is a good agreement between the measured and the parameterized data in both periods, and during clear and cloudy sky days.

In order to get a quantitative index, quantities named DIFF and BIAS have been calculated according to the relations:

$$DIFF = \frac{\sum_{i=1}^N [x_{par}(i) - x_{obs}(i)]}{N} \quad (7)$$

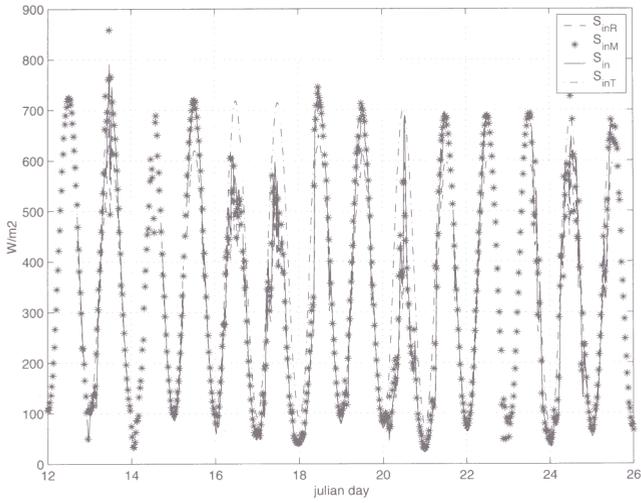
$$BIAS = \frac{\sum_{i=1}^N |x_{par}(i) - x_{obs}(i)|}{N} \quad (8)$$

where  $x_{par}$  is the parameterized value,  $x_{obs}$  the measured one and N the total number of data. In table 1, the values of DIFF and BIAS for the comparison between  $S_{in}$  and  $S_{inM}$  are reported. Considering that the instrumental precision of the Sitep solarimeter is  $\pm 15 \text{ Wm}^{-2}$ , it is clear that BIAS has the same order of the precision.

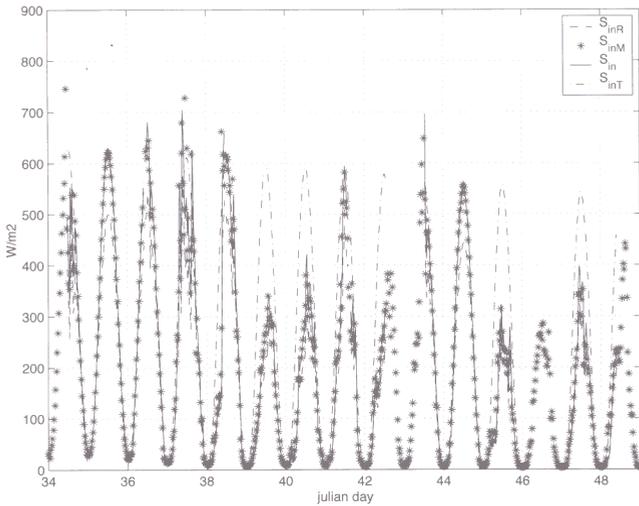
Table 1: Statistics about incoming shortwave radiation fluxes

Incoming shortwave radiation flux	DIFF	BIAS
$S_{in} - S_{inM}$ ( $\text{Wm}^{-2}$ )	-4	24

The theoretical incoming radiation under clean sky has been used to evaluate the cloudiness. In fact, as it can be seen by looking figs. 1(a) and 1(b), the 15<sup>th</sup>, 35<sup>th</sup>, and 45<sup>th</sup> julian days can be considered as clear sky days, because  $S_{inT}$  is almost equal to  $S_{inM}$ , while, during the other days, the presence of cloudiness is evident and cannot be neglected.



(a) Incoming shortwave radiation, January 1998.



(b) Incoming shortwave radiation, February 1998.

Figure 1: In the abscissa the julian days are reported. The star points refer to  $S_{inM}$ , the dashed line to  $S_{inR}$ , the solid line to  $S_{in}$  and the dashdot line to  $S_{inT}$ ; all values are expressed in  $Wm^{-2}$ .

### 3.2 Outcoming shortwave radiation

The relation between incoming and outcoming shortwave is:

$$S_{out} = \alpha \cdot S_{in} \quad (9)$$

where  $\alpha$  is the albedo of the surface.

As the antarctic soil is covered by snow, to reconstruct the albedo trend, two relations have been used:

1) Iqbal [5]:

$$\alpha_1 = \alpha' + (1 - \alpha') \exp \left[ -0.1\gamma - \frac{1 - \alpha'}{2} \right] \quad (10)$$

where  $\alpha'$  is the albedo at the maximum solar elevation and  $\gamma$  is the solar altitude. In these simulations, the values:  $\alpha'=0.8$  in January and  $\alpha'=0.62$  in February have been imposed;

2) Loth and Graf [6], Verseghe [7]:

$$\alpha_2(t) = \alpha_0(t) + \alpha_0^3(t) [1 - a_0(t)] F \quad (11)$$

$$\alpha_0(t) = \alpha + [\alpha_0(t - \Delta t) - a] \exp \left( -0.01 \frac{\Delta t}{3600} \right) \quad (12)$$

$$F = N^2 + \exp(\sin^2 \varphi) - 1.3N^2 \exp(\cos^2 \varphi) \quad (13)$$

where  $a=0.5$ ,  $N$  is the amount of clouds and  $\varphi$  the minimum between the actual sun elevation and  $\frac{\pi}{3}$ .

In the simulations, the values:  $\alpha = 0.6$ ,  $\alpha_0(0) = 0.72$  and  $\alpha_0(t) = 0.72$  (in case of snow) have been used. The main difference between the two parameterizations of albedo is that in the second parameterization the amount of clouds and the presence of snow are considered.

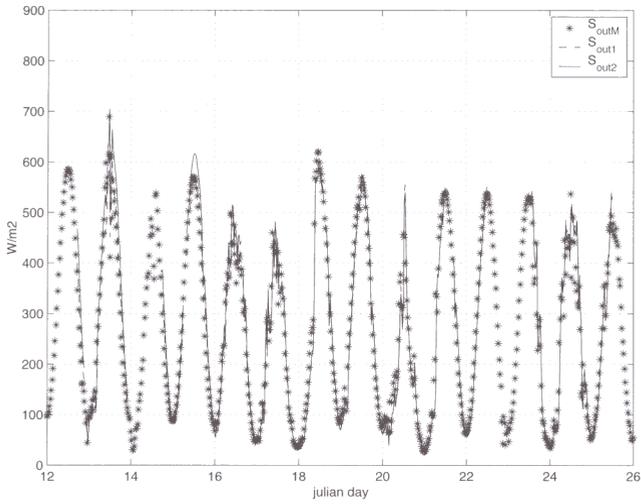
Then, the two values:

$$S_{out1} = \alpha_1 \cdot S_{in} \quad (14)$$

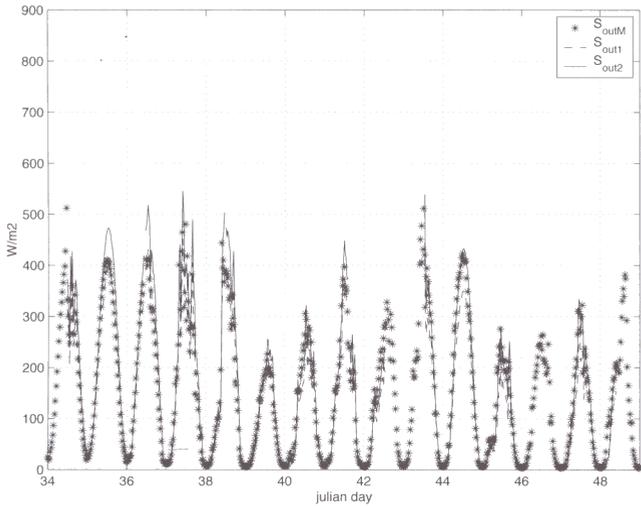
$$S_{out2} = \alpha_2 \cdot S_{in} \quad (15)$$

have been calculated and shown in figs. 2(a) and 2(b).

As in the previous figures, the star points represent the measured data ( $S_{outM}$ ), while  $S_{out1}$  is the dashed line and  $S_{out2}$  is the solid line, and in the abscissa there are the julian days. The agreement between the measured and parameterized data is good for both formulations, and BIAS (table 2) is similar to the one of incoming radiation. During the first period, eq. 10 generally behaves better (table 2). But, during the last snowy days, (from 45<sup>th</sup> to 47<sup>th</sup> julian days) the eqs. 11 - 13 show a better behaviour.



(a) Outcoming shortwave radiation, January 1998.



(b) Outcoming shortwave radiation, February 1998.

Figure 2: In the abscissa the julian days are reported. The star points refer to  $S_{outM}$ , the dashed line to  $S_{out1}$  and the solid line to  $S_{out2}$ ; all values are expressed in  $Wm^{-2}$ .

Table 2: Statistics about outgoing shortwave radiation fluxes

Outcoming shortwave radiation flux	DIFF	BIAS
$S_{out1} - S_{outM}$ $\left( \text{Wm}^{-2} \right)$	-8	28
$S_{out2} - S_{outM}$ $\left( \text{Wm}^{-2} \right)$	10	29

### 3.3 Incoming longwave radiation

The incoming longwave radiation is expressed by the product of two terms:  $L_{in-c}$ , the incoming longwave radiation under clean sky, and the cloudiness index:

$$L_{in} = L_{in-c} \cdot \text{cloudiness} \quad (16)$$

$L_{in-c}$  has been computed using a parameterization based on the law of gray bodies:

$$L_{in-c} = e_{ac} \sigma T_a^4 \quad (17)$$

where  $e_{ac}$  is the equivalent of the emissivity of atmosphere,  $\sigma$  the Stefan-Boltzmann constant (equal to  $5.67 \cdot 10^{-8} \text{WK}^{-4}$ ) and  $T_a$  the air temperature. For the parameterization of  $e_{ac}$ , three schemes have been used:

$$e_{ac} = 0.95 \left[ 1 - \exp \left( -e_a^{T_a/2016} \right) \right] \quad \text{Satterlund [8]} \quad (18)$$

$$e_{ac} = 0.6 \left( e_a^{0.08} \right) \quad \text{Stanley et al. [9]} \quad (19)$$

$$e_{ac} = 0.85 \cdot 10^{-5} T_a^2 \quad \text{Swinbank [10]} \quad (20)$$

The numerical coefficients have been slightly modified with respect to the original formulations to take into account the peculiar (snowy) surface in Antarctica. In fact, in the eq. 18 the original factor was 1.08, in eq. 19 it was 0.67, and in eq. 20 it was 0.92. For the parameterization of  $e_a$ , the usual equation:

$$e_a = \frac{r_h}{100} \cdot E \quad (21)$$

$$E = 6.112 \exp \left( 17.67 \frac{T_a - 273.15}{T_a - 29.65} \right) \quad \text{Garratt [11]} \quad (22)$$

has been used. In the previous relation,  $r_h$  is the relative humidity and  $E$  is the water vapour pressure at the saturation. The main difference between the three parameterizations given by eqs. 18 to 20 is that the first two formulae contain an explicit dependence from temperature and humidity, while the third one is depending only from temperature.

Finally, the parameterizations used to evaluate the cloudiness are:

$$cloudiness = 1.8 - 0.8 \frac{S_{in}}{S_{inT}} \quad \text{for parameterization (18) and (19)} \quad (23)$$

$$cloudiness = 1.93 - 0.93 \frac{S_{in}}{S_{inT}} \quad \text{for parameterization (20)} \quad (24)$$

adapted by Brutsaert [12] for antarctic conditions. These calculations can obviously be done only when  $S_{inT} \neq 0$ , then during daytime. For this reason, the nocturnal hours haven't been considered in this work; as the study refers to the Summer season, the number of radiationless nights was limited to few days in February.

The values of cloudiness obtained by eqs. 23 and 24 have been smoothed using a running average of fifth order. In the following  $L_{in1}$ ,  $L_{in2}$  and  $L_{in3}$  are defined as the incoming longwave radiations eq. 16 where  $e_{ae}$  has been computed using eqs. 18, 19 and 20 respectively.

The result of the parameterizations given by eq. 18 [8] is reported in figs. 3(a) and 3(b). As usual, the star points represent the measured data. In this case, the dashed line is the incoming longwave radiation under clean sky conditions and the solid line is the incoming longwave radiation with cloudiness. It is clear from these graphics that the cloudiness term is important, even if the agreement between measured and parameterized data is not perfect.

In figs. 4(a) and 4(b), the parameterization of incoming longwave radiation given by eq. 19 is represented. It can be observed that this equation has a behaviour similar to the 18.

The parameterization of incoming longwave radiation given by 20 is shown in figs. 5(a) and 5(b). In this case, the differences between observations and parameterizations are larger than in the previous two cases.

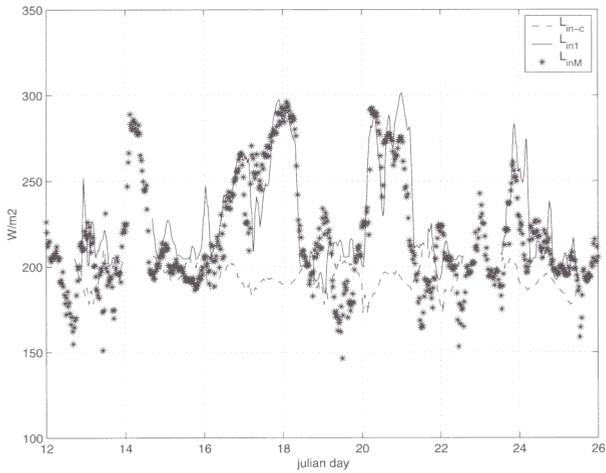
In table 3 the values of DIFF and BIAS for the comparison between  $L_{in1}$ ,  $L_{in2}$ ,  $L_{in3}$  and  $L_{inM}$  are reported. The numerical values confirm the qualitative conclusions inferred by graphics analysis above. The values of bias are smaller than the ones relative to the short wave radiation.

### 3.4 Outcoming longwave radiation

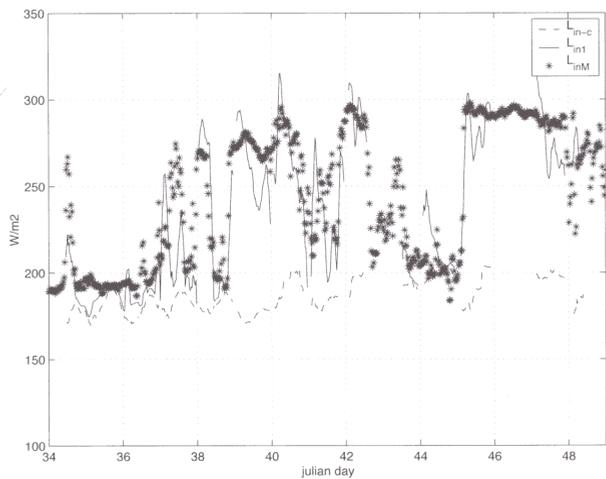
The outcoming longwave radiation ( $L_{out}$ ) is usually obtained using the law of gray body:

$$L_{out} = \varepsilon \sigma T_s^4 \quad (25)$$

where  $\varepsilon$  is the emissivity,  $\sigma$  is the Stefan-Boltzmann constant and  $T_s$  is the surface temperature. The value  $\varepsilon = 0.97$  reported in the literature [12] for

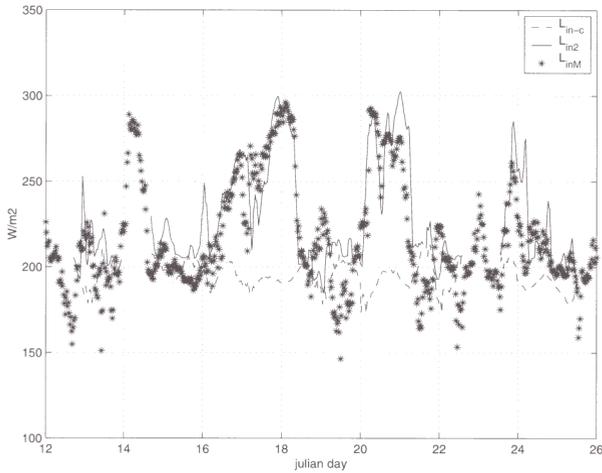


(a) Incoming longwave radiation from Satterlund (1979), January 1998.

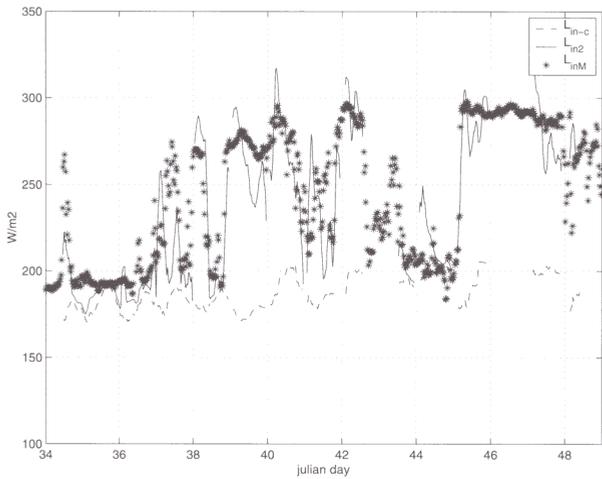


(b) Incoming longwave radiation from Satterlund (1979), February 1998.

Figure 3: In the abscissa the julian days are reported. The star points refer to  $L_{inM}$ , the dashed line to  $L_{in-c}$  and the solid line to  $L_{in1}$ ; all values are expressed in  $Wm^{-2}$ .

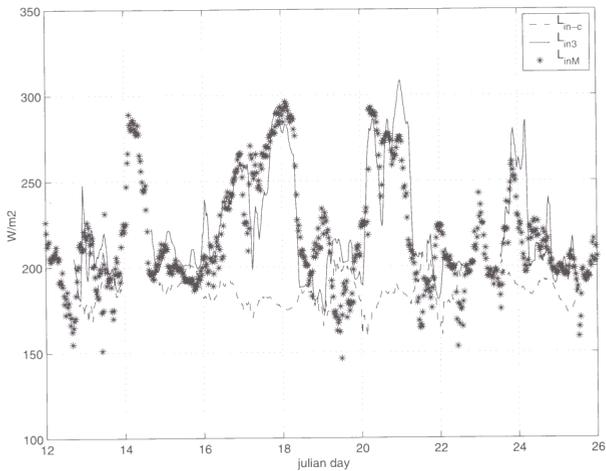


(a) Incoming longwave radiation from Stanley *et al.* [9], January 1998.

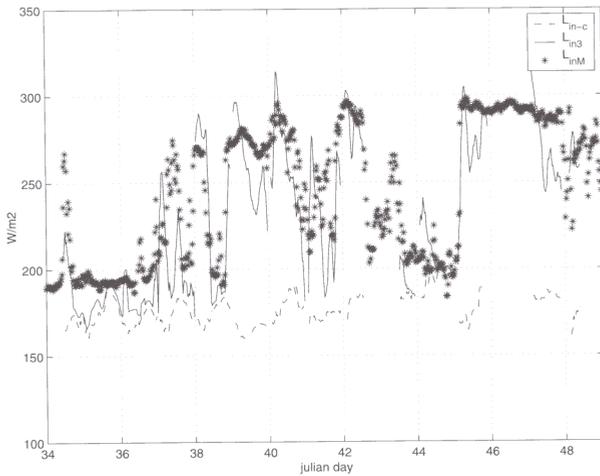


(b) Incoming longwave radiation from Stanley *et al.* [9], February 1998.

Figure 4: In the abscissa the julian days are reported. The star points refer to  $L_{inM}$ , the dashed line to  $L_{in-c}$  and the solid line to  $L_{in2}$ ; all values are expressed in  $Wm^{-2}$ .



(a) Incoming longwave radiation from Swinbank [10], January 1998.



(b) Incoming longwave radiation from Swinbank [10], February 1998.

Figure 5: In the abscissa the julian days are reported. The star points refer to  $L_{inM}$ , the dashed line to  $L_{in-c}$  and the solid line to  $L_{in3}$ ; all values are expressed in  $Wm^{-2}$ .

Table 3: Statistics about incoming longwave radiation fluxes

Incoming longwave radiation flux	DIFF	BIAS
$L_{in1} - L_{inM} \left( \text{Wm}^{-2} \right)$	1	17
$L_{in2} - L_{inM} \left( \text{Wm}^{-2} \right)$	2	17
$L_{in3} - L_{inM} \left( \text{Wm}^{-2} \right)$	-4	19

water and old snow has been imposed. The results of eq. 25 smoothed using a running average of fifth order, are reported in figs. 6(a) and 6(b). In this case, the intercomparison between parameterized and measured data shows the best agreement in the second period, while in some days of the first period (particularly in the julian days 18-20) while there are some evident disagreements. They can be due to the rise of surface temperature or to the inexact value assumed for  $\varepsilon$ .

In table 4 the DIFF and BIAS values for  $L_{out}$  are shown. It can be seen how the bias has the smallest value among all parameterizations used in this study.

Table 4: Statistics about outgoing longwave radiation fluxes

Outgoing longwave radiation flux	DIFF	BIAS
$L_{out} - L_{outM} \left( \text{Wm}^{-2} \right)$	4	10

### 3.5 Net radiation

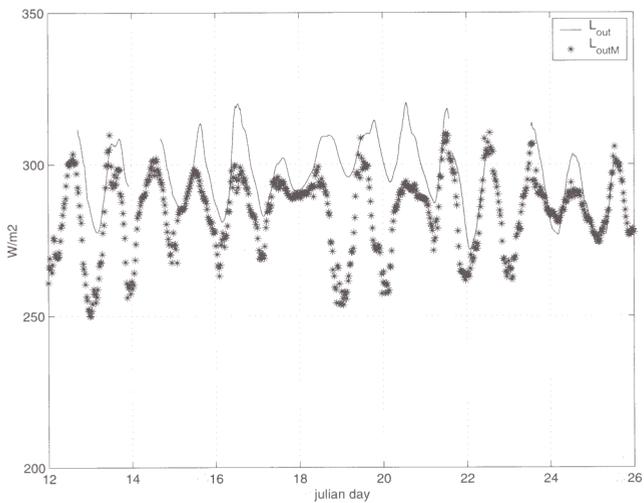
The net shortwave radiation has been evaluated as:

$$S_{net1} = S_{in} - S_{out1} \quad (26)$$

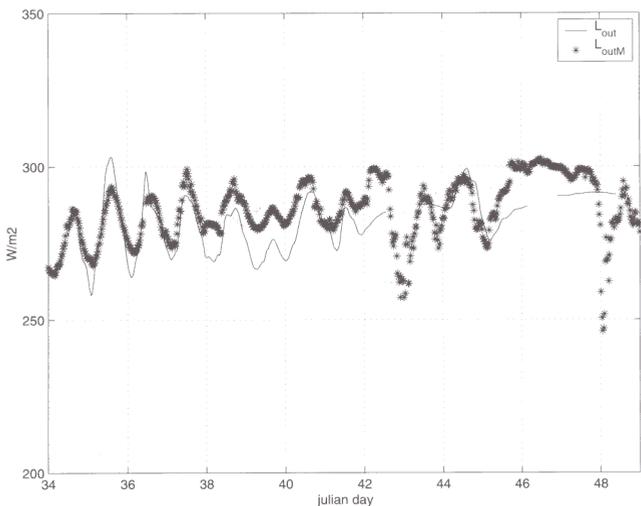
$$S_{net2} = S_{in} - S_{out2} \quad (27)$$

In figures 7a and 7b, the intercomparisons between eqs. 26 and 27 and observed data are shown. In the whole campaign  $S_{net1}$  seems closer to the observations with respect to  $S_{net2}$ , excepting in the last few days, when it snows.

The bias for the eqs. 26 and 27 is about  $20 \text{ Wm}^{-2}$ , smaller than the bias of the single values of incoming and outgoing shortwave radiations. This value is also similar to the accuracy of the sensors.

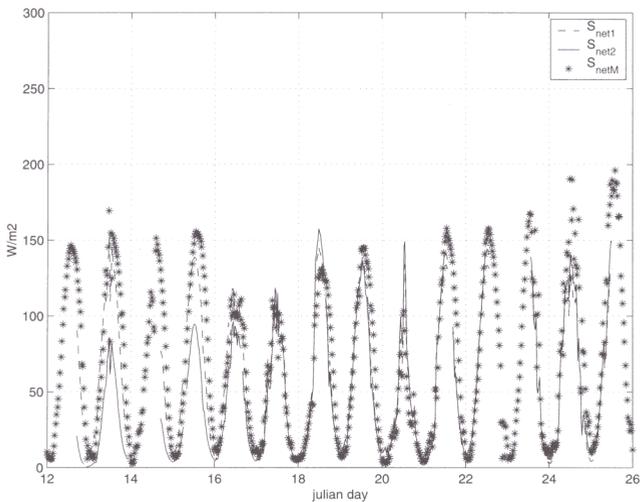


(a) Outcoming longwave radiation, January 1998.

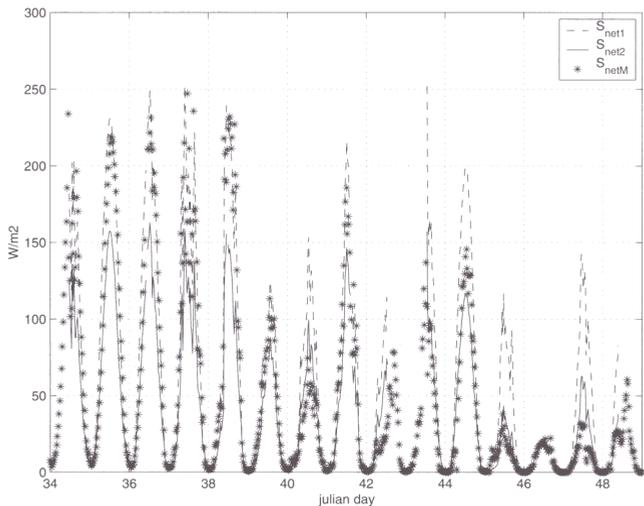


(b) Outcoming longwave radiation, February 1998.

Figure 6: In the abscissa the julian days are reported. The star points refer to  $L_{outM}$ , and the solid line to  $L_{out}$ ; all values are expressed in  $Wm^{-2}$ .

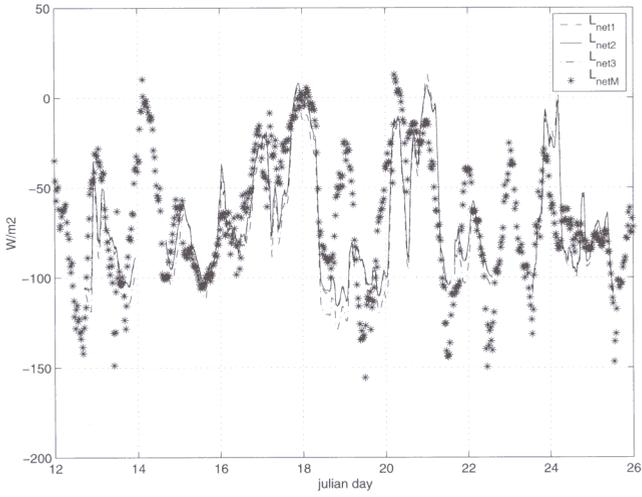


(a) Net shortwave radiation, January 1998.

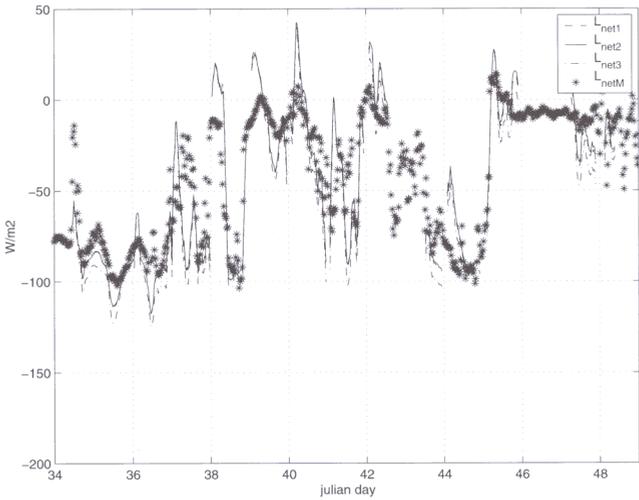


(b) Net shortwave radiation, February 1998.

Figure 7: In the abscissa the julian days are reported. The star points refer to  $S_{netM}$ , the dashed line to  $S_{net1}$  and the solid line to  $S_{net2}$ ; all values are expressed in  $Wm^{-2}$ .



(a) Net longwave radiation, January 1998.



(b) Net longwave radiation, January 1998.

Figure 8: In the abscissa the julian days are reported. The star points refer to  $L_{netM}$ , dashed line to  $L_{net1}$ , the solid line to  $L_{net2}$  and the dashdot line to  $L_{net3}$ ; all values are expressed in  $Wm^{-2}$ .

The net longwave radiations have been calculated as:

$$L_{net1} = L_{in1} - L_{out} \quad (28)$$

$$L_{net2} = L_{in2} - L_{out} \quad (29)$$

$$L_{net3} = L_{in3} - L_{out} \quad (30)$$

Figures 8(a) and 8(b) show the parameterizations of net longwave radiations referring to eqs. 28) - (30) respectively. Also in this case, the results were smoothed using a running average of the fifth order. The inspections of figs. 8(a), 8(b) and table 5 show that  $L_{net1}$  and  $L_{net2}$  are very similar and their accordance with the measured data is good; the bias is  $20 \text{ Wm}^{-2}$ .  $L_{net3}$  shows some differences from  $L_{net1}$  and  $L_{net2}$ , and its trend is worse than the ones of  $L_{net1}$  and  $L_{net2}$ , as evidenced by the larger bias.

Finally, the net radiation has been calculated using  $S_{net1}$  and  $S_{net2}$  for the shortwave radiation, but only  $L_{net1}$  for longwave radiation. The reason of this choice is that  $L_{net1}$  and  $L_{net2}$  are quite similar and they behave better than  $L_{net3}$ .

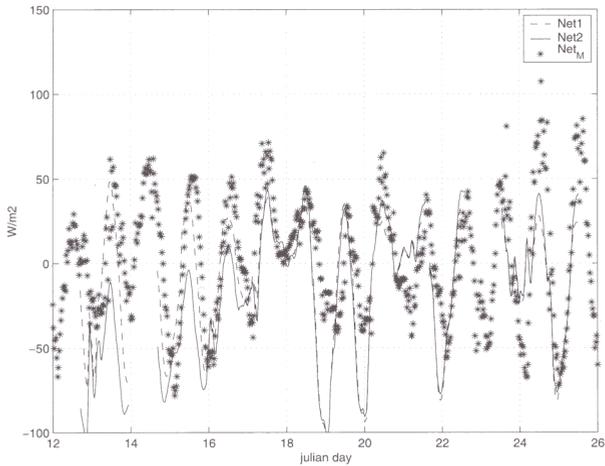
$$Net1 = S_{net1} + L_{net1} \quad (31)$$

$$Net2 = S_{net2} + L_{net1} \quad (32)$$

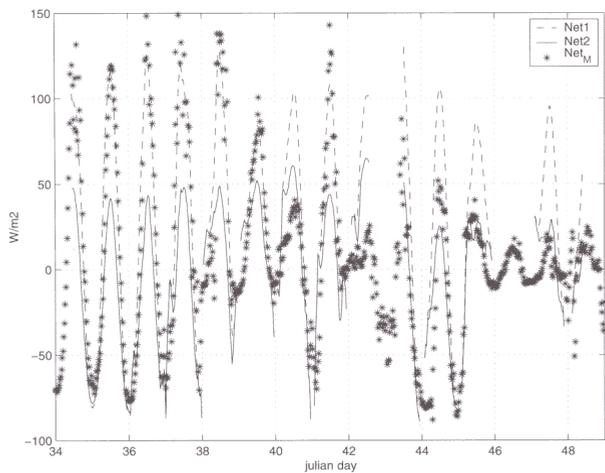
The results smoothed, using a running average of the fifth order, are represented in figs. 9(a) and 9(b). In these graphics, it is evident that Net1 is better than Net2 during the whole campaign, with the exception of the last days of February when weather conditions were snowy. This is also confirmed by the largest bias and difference (table 5).

Table 5: Statistics about net radiation fluxes

Net radiation flux	DIFF	BIAS
$S_{net1} - S_{netM} \left( \text{Wm}^{-2} \right)$	4	19
$S_{net2} - S_{netM} \left( \text{Wm}^{-2} \right)$	-14	20
$L_{net1} - L_{netM} \left( \text{Wm}^{-2} \right)$	1	20
$L_{net2} - L_{netM} \left( \text{Wm}^{-2} \right)$	2	20
$L_{net3} - L_{netM} \left( \text{Wm}^{-2} \right)$	-4	23
$Net1 - Net_M \left( \text{Wm}^{-2} \right)$	5.	27
$Net2 - Net_M \left( \text{Wm}^{-2} \right)$	-13	31



(a) Net radiation, January 1998.



(b) Net radiation, February 1998.

Figure 9: In the abscissa the julian days are reported. The star points refer to  $Net_M$ , dashed line to  $Net_1$  and the solid line to  $Net_2$ ; all values are expressed in  $Wm^{-2}$ .

## 4 Conclusions and perspectives

In this work, the different components in the net radiation (incoming and outgoing shortwave and longwave) have been calculated from observa-

tions (pressure, relative humidity, surface and air temperature and incoming shortwave radiation) and compared with the measured ones. The shortwave radiation has been parameterized using 2 schemes. In both cases the parameterization is able to reconstruct the measured data with a good approximation. The longwave radiation has been parameterized using 3 different schemes. These parameterizations are more critical than the ones for the shortwave radiation, because they depend strongly on the cloudiness. In this study, cloudiness was not observed and was obtained from the real shortwave radiation and the theoretical shortwave radiation in the case of absence of cloudiness. The availability of observations of cloud coverages and cloud types could improve the parameterizations of both short and longwave components. In spite of this problems, the larger bias has been obtained in the evaluations of the shortwave radiation. Every parameterization displayed a bias value not larger than  $30 \text{ Wm}^{-2}$ . Considering that the accuracy of instruments is of the order of  $15 \text{ Wm}^{-2}$ , it can be concluded that the use of the proposed formulations (adequately calibrated for the considered site) could allow to obtain data whose quality is only slightly lower than the one of the real observations.

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