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RESEARCH ARTICLE

An experimental method for evaluation of the snow albedo effect on near-surface air temperature measurements

Chiara Musacchio | Graziano Coppa | Andrea Merlone

Istituto Nazionale di Ricerca Metrologica (INRiM), Torino, Italy

Correspondence
Chiara Musacchio, Istituto Nazionale di Ricerca Metrologica (INRiM), Torino, Italy.
Email: c.musacchio@inrim.it

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Among the many effects influencing the accuracy in near-surface air temperature measurements (t_{air}), solar radiation plays a key role. While numerous technical solutions have been developed to protect temperature sensors from direct solar radiation, few studies are available to evaluate the warming due to reflected radiation. Changes in surface albedo influence the measurement results of t_{air} and, in the case of sensors positioned above a snow-covered surface, this effect is amplified due to the larger amount of radiation reflected. As a task of the European project MeteoMet, a design for a metrological experimental setup and associated measurement method was studied, to quantify errors in temperature records when thermometers in solar shields and compact automatic weather stations are positioned above snow-covered soil. An operative model was developed to minimize quantities of influence and uncertainties, while the experimental protocol proposed guidance on instruments required, sensor characterization, field experiment installations and site characteristics. The procedure described can be implemented by users without specific metrological skills: staff of hydro-meteorological agencies with commonly used equipment and technicians of manufacturing companies can easily perform the measurements, characterize the instruments and evaluate the total maximum effect in terms of temperature increase and a correction factor or curve for specific typologies of instruments. The work presented is part of wider activities aimed at completing the calculation of an uncertainty budget on near-surface air temperature measurement.

KEYWORDS
air temperature, albedo, environmental metrology, measurement uncertainty, MeteoMet, siting influence

1 | INTRODUCTION

Temperature is one of the key essential climate variables and one of the most important measured quantities in meteorology. Near-surface air temperature data have been collected for more than a century and now form the basis of scientific knowledge on climate trend. Techniques to measure air temperature constantly evolve in time and established guidelines are adopted to improve data accuracy. Performances of meteorological thermometers have improved with time and now top-quality instruments are equipped with platinum resistance sensors and high-level reading and recording electronics. Many efforts have also been made to minimize the effect of influential quantities on measurement results, with the aim of reducing measurement uncertainty. Solar radiation is one of the main factors introducing significant deviations between sensor readings and true air temperature, and techniques to protect the sensors from its direct influence have been adopted almost since the beginning of meteorological observations. Shields designed to avoid direct solar radiation reaching the sensing element evolved from Stevenson screens to modern "pagodas" and naturally or mechanically ventilated solar shields. Many different solutions to reduce heat transfer to the temperature sensors due to direct Sun radiation have been evaluated and compared in the literature (Aoshima *et al.,* 2010; Lacombe *et al.,* 2011) in numerous activities of the Commission for Instruments and Methods of Observation (CIMO) of the World Meteorological Organization (WMO). Such initiatives are widely reported for the effect of direct radiation, but efforts regarding the effect of reflected radiation, in terms of an increase in the temperature measured by thermometers mounted in different screens, are not documented in the literature. The albedo, as the fraction of reflected radiation at the ground surface, causes the air temperature to change due to heat transfer (radiation and convection) directly influencing the quantity to be measured. Radiation reflected by snow-covered surfaces generates an amplified effect for this phenomenon. When reflected radiation warms the air, the value of the near-surface air temperature (t_{air}) changes. This factor is a well-known effect in atmospheric physics and it is not under investigation in the present work. Here the work is instead concentrated on the effect of the reflected radiation on the sensor response, in terms of deviations from the t_{air} values due to instrument and shield characteristics. The problem of the albedo effect on near-surface air temperature can therefore be included as a part of the wider discussion on the calculation of the uncertainty budget on air temperature measurement as planned in the roadmap of the Consultative Committee for Thermometry of the International Committee for Weights and Measures and also requested by WMO and the Global Climate Observing System expert teams.

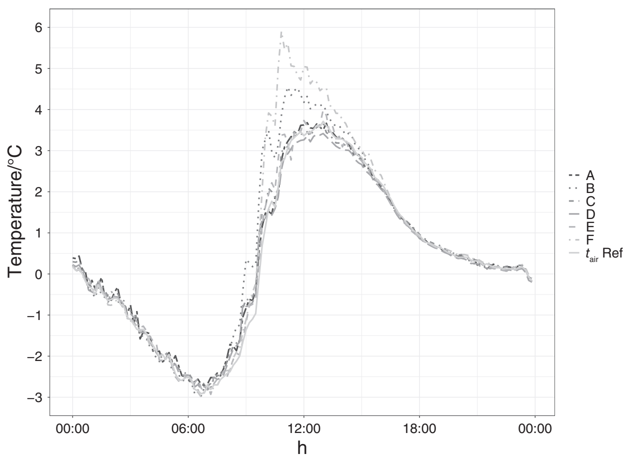

FIGURE 1 Near-surface air temperature data measured above a snow-covered surface from meteorological thermometers from different manufacturers and of different kinds (marked with letters A to F). Values come from a one-day acquisition and are plotted as a function of local time. The plot also features air temperature values recorded with a reference thermometer at the same site, at the same time, but not exposed to backward radiation (t_{air} Ref). In daytime, the recorded values differ due to the effect of the reflected radiation. During the night, the values are in agreement within the calibration uncertainty. Data are corrected for the effect of direct radiation from previous characterizations in the absence of snow

Temperature sensors used in automatic weather stations and atmospheric thermometers are supposed to record the actual air temperature: This is an assumption that in practice is only partially true, since sensors are not in perfect adiabatic conditions with the medium due to the many factors causing heat transfer to (and from) the sensor. Heat is mainly transferred from air to the sensor, through the instrument structure, by convection inside the shield. An extra amount of heat can be added by radiative effect and by conduction through any points of contact between the sensor and the structure of the shield. The amount of extra heating (or cooling) recorded is therefore associated with several factors: technical solutions adopted by manufacturers in designing the instruments, how the sensors are mechanically and thermally coupled with the other parts of the instrument, the level of protection of the screen from solar radiation, the shape of the inner air flow and the kind of natural or forced ventilation adopted, the material and ageing of the "pagodas" and screen. In widely used instruments such as compact automatic weather stations or thermometers equipped with radiation shields, even in the case of ventilated shields, the sensor measuring t_{air} can also be subjected to heat radiated backwards from the soil surface that is related to the albedo.

This effect is enhanced in conditions of high albedo such as from snow-covered terrain (Huwald *et al.,* 2009), and its magnitude depends upon different construction features and typologies of sensors. During the Metrology for Meteorology and Climate Conference (Merlone *et al*., 2015b), it was reported by meteorological operators that, when a snow-covered surface reflects the Sun's radiation towards meteorological stations, different instruments under the same conditions record different t_{air} values, even though they are calibrated and positioned in close proximity, where it is therefore assumed that the local air temperature is not different.

Starting form identical conditions of the quantities of influence, differences are mainly related to the behaviour of the screening or coupling part of the instrument, but also to the material of the sensor.

All these components could react in a different way to radiation and in particular to radiation reflected from the soil.

2 | THE OBSERVED PHENOMENON

An example of the effect investigated here is reported in the plot in Figure 1. It shows t_{air} values recorded by air temperature measurement instruments from different manufacturers, all of them being thermometers hosted in various typologies of solar shields, placed 2 m above snow-covered ground on a sunny day with low wind. It is clearly evident that, during the night, measured data are in reasonable agreement within the calibration uncertainty, while when the Sun rises and shines on the snow surface the sensors record different temperatures. The phenomenon is clearly visible in the plot in the time interval 0900 to 1500 with a maximum around 1100.

The phenomenon observed in daytime is shown not to have a constant magnitude, since it depends on other atmospheric conditions and quantities of influence, such as the total radiation and clouds' presence, precipitation (such as rain in warmer periods), wind speed, the duration of daytime. Although this deviation is not reproducible, it affects daily maximum records and in some circumstances it generates repeated deviations from the true value of t_{air} thus affecting both climate records and meteorological observations. This is reported in Figure 2 as 5 day averages of the differences Δt_m between the reading of different sensors positioned over snow-covered soil with respect to a reference "true air temperature value," recorded with a thermometer not exposed to backward radiation, positioned nearby. In this case, the effect studied here is clearly evident as well, causing significant differences during daytime with respect to the acceptable noisy behaviour around zero relative differences during dark hours.

The metrological method proposed is addressed at understanding, evaluating and including the phenomenon in t_{air} measurements and associated uncertainty. This work was developed within the numerous metrological activities of the European project MeteoMet—Metrology for Meteorology (Merlone *et al*., 2015a, 2018). The purpose of the work is to propose an experimental method for evaluation of the difference between readings of sensors exposed to reflected radiation from snow-covered surfaces with respect to natural soil, in the same site/area, and its inclusion in the overall t_{air} measurement uncertainty budget.

3 | A *PRIORI* ASSUMPTIONS FOR THE EVALUATION OF UNCERTAINTIES ON NEAR-SURFACE AIR TEMPERATURE MEASUREMENTS OVER A SNOW-COVERED SURFACE

A model has been created to give guidance on how to quantify the albedo effect on instrument readings and to prepare an experimental procedure to evaluate it.

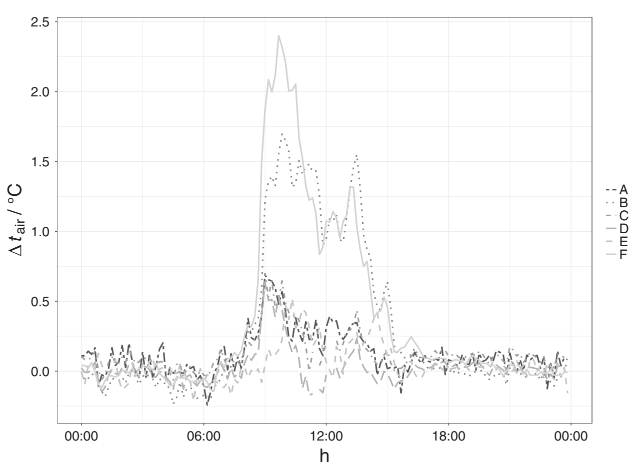

FIGURE 2 Differences between temperature values recorded by sensors positioned above a snow-covered surface and the reference t_{air} as averages over 5 days. Sensors are marked with letters A to F

The backward radiation reflected from a snow-covered surface is investigated here in its effect on the sensor reading, with respect to the same air temperature without the presence of snow. Therefore, in this model, the albedo effect is evaluated as a relative value in terms of temperature differences between two identical sensors measuring the same air temperature but positioned over different grounds, one covered by snow and the other over natural soil, at the same site. This temperature difference Δt can be evaluated for couples of sensors and represents the uncertainty component to be associated with t_{air} measurement when instruments are positioned on a snow-covered area and sensors' responses are influenced by reflected radiation:

$$\Delta t = t_a(t_{air}) - t_b(t_{air})$$

where Δt is the difference in the temperature readings t_a and t_b of two identical sensors, with sensor "a" positioned above a snow-covered surface and sensor "b" above natural soil, and t_{air} is the reference "true value" of the air temperature. Here the "true value" of the temperature is the value of the near-surface atmospheric air temperature recorded in the same place at the same time by a thermometer not exposed to any radiative effect. Technically this is the measurand of interest in the data series, which cannot be measured without associated correction and uncertainty in the case of snow presence and associated backward extra heat transfer to the thermometers. Only non-contact sensors can retrieve this value, but the overall uncertainty and technical features of such sensors are still not yet developed enough to be economically and scientifically competitive with contact thermometers.

Due to the very different response of the many typologies of shields and sensors from different manufacturers to quantities of influence and to the albedo effect itself, the method proposed here is addressed at giving guidance to detect the maximum temperature difference and the conditions causing this largest albedo effect. A correction curve is not suggested since it cannot be metrologically validated due to the many contributing factors such as wind, total and reflected radiation, temperature, condensation and turbulence. On the contrary, detecting the maximum absolute value, under the following guidance, can give robust information on the performances of sensors and shields and on the reliability of values in a network of identical stations.

An experimental setup, implemented to perform such an evaluation, needs to respect the conditions and to evaluate possible deviation from the assumptions by including measurements of further parameters and possible non-symmetries in the siting characteristics and in the effect of the influencing quantities on the main measurements and sensors.

The main assumption of the model is that temperature (t_{air}) is the same for both sensors. In this model, this assumption is taken as valid, while for an experimental evaluation the following considerations must be taken into account. The two sensors must be positioned on a flat surface, with no obstacles such as those defined by the WMO CIMO guide #8 (WMO-CIMO, 2014), e.g. road vicinity, trees, buildings. The two sensors must also be positioned in close proximity in order to consider the ground characteristics as constant in terms of shaded area, slope and composition.

If an obstacle is present, the two sensors must be at the same relative distance to the obstacle, the same siting conditions. In principle, the presence of the obstacle affects both the value of t_{air}, with a change of d (positive or negative), and at the same time the sensors' response by an amount e (negligible, positive or negative). Based on previous experience (Huwald *et al.,* 2009; Merlone *et al.*, 2015b), and from ongoing experiments on siting effect evaluations, it is expected that in normal siting conditions the larger effect is due to d. Here, under normal conditions, it is intended that the instruments are positioned on a flat surface, with obstacles at not less than 20 m from the measuring point, with 20 m the mutual distance between the two measuring points. At 20 m, recent studies not yet published on the effect of the presence of obstacles on t_{air} showed influences of less magnitude than the albedo effect (Figures 1 and 2). Moreover, this assumption reduced the influence since it affected both instruments, becoming a second order influencing quantity.

It follows that:

$$t_{air} \rightarrow t_{air} + d$$

$$t_a(t_{air}) \rightarrow t_a(t_{air}) + e_a$$

$$t_b(t_{air}) \rightarrow t_b(t_{air}) + e_b$$

Since the two sensors are identical and are kept in the same siting conditions, $e_a = e_b$, and so it follows that:

$$\begin{aligned}\Delta t &= [t_a(t_{air}+d)+e] - [t_b(t_{air}+d)+e] \\ &= t_a(t_{air}+d) - t_b(t_{air}+d)\end{aligned}$$

The experimental investigation requires the evaluation of $e_a = e_b$ in order to include and correct the temperature records from possible differences between the two factors, not in line with the theoretical assumption here adopted by the model.

From the assumption and conditions, it is expected that d will not be large enough to cause a nonlinear response in the commonly used sensors, based on thermocouples, resistance thermometers, thermistors or capacitive sensors. It follows that:

$$t_a(t_{air}+d) - t_b(t_{air}+d) = t_a(t_{air}) + t_a(d) - t_b(t_{air}) - t_b(d)$$

Since d is not a function of the snow cover, is of reduced amplitude and influences both sensors in the same way, due to the previous assumption, and since it is also assumed that the two identical sensors measure the same value for the same air temperature d, it can be stated that:

$$t_a(d) = t_b(d)$$

Under the previous assumptions, the albedo effect does not change its amplitude in the presence of obstacles at more than 20 m and similar distances from the measuring point. This synthetic conclusion is part of the information useful to propose an experimental guideline for the evaluation of the albedo as described in Section 5.

3.1 | Evaluating Δt on site

Systematic differences can arise from the instruments and from the effect of environmental conditions due to the site: (a) intrinsic differences between the sensors in stable and laboratory controlled conditions (Δt_{instr}); (b) intrinsic differences between the air temperature in site conditions, thus including possible effects arising from the site characteristics such as non-symmetric distances between possible obstacles like trees, water sources, roads, buildings (Δt_{site}).

In the procedure, a preliminary characterization of the sensors in a laboratory is requested to quantify and correct for the systematic differences between each pair of sensors. This characterization must be such as to give a numerical correction for recorded data, as reported in the indications in Section 5.4.

The distribution of Δt is expected to be strongly asymmetric since the albedo effect acts as an anomalous heating of the sensor. It is therefore expected that the largest values are positive temperature differences between sensors over snow and those over natural soil:

$$t_a - t_b > 0 \rightarrow \Delta t > 0$$

At night, if t_{air} is above 0°C, then the soil could become warmer with respect to the snow-covered area where all the heat is dissipated in the snow-melting phase transition. This is not an effect considered here since in natural conditions the soil is covered by snow; thus the air is actually exposed to lower temperatures. This effect acts on the measurand and it is only a side aspect of the proposed experiment design and not a quantity representative of the investigated effect.

4 | VARIABLES/CONDITIONS AND QUANTITIES INFLUENCING Δt

As described in Section 3, the model requires that the air temperature is the same in both measurement positions and that any potential obstacle and different siting conditions are supposed to have the same influence on the sensor readings.

Nevertheless, several phenomena and ambient conditions influence the albedo effect dependence of sensor readings and consequently have an influence on the magnitude of Δt. In general, and in this study, the main factors can be identified in a simplistic summary as follows:

- snowpack thickness (h)
- snow condition (s)
- solar radiation (SR)
- wind condition (W)
- humidity (Rh)

It is worth stressing that these phenomena also change the temperature of the air, but this is not the effect, nor the quantity under investigation. In principle, even when t_{air} does not change, the above quantities will change the heat transferred to the sensor and its adiabatic equilibrium with the surrounding fluid (the air), thus affecting the measurement results. With the above assumption, it can be stated that:

$$\Delta t = \Delta t(h, s, W, \mathrm{SR}, \mathrm{Rh})$$

In this study, the effect of each of the quantities is considered in the following.

4.1 | Wind (W)

When wind blows, the instrument and sensor are continuously kept under a forced convective effect that normally prevails in radiative and contact phenomena. With air moving outside, and thus being forced to move also inside the instrument, the sensor is continuously rinsed by air and its readings are closer to the temperature of the moving air.

It is therefore expected that $\Delta t(W)$ is an inverse function of the wind speed W. Therefore, the Δt value has its maximum at zero wind and this is the case that will deliver maximum information. Moreover, in the modelling phase it is not possible to evaluate this relationship since it is too strong relative to the instrument features. It is therefore assumed that:

$$\max\{\Delta t(W)\} = \Delta t(0)$$

4.2 | Snowpack thickness (h)

Following the CIMO guide no. 8 (WMO-CIMO, 2014), it is assumed, and the experiment is built accordingly, that the sensors are 2 m above ground, on a flat surface. Obviously, this model does not consider the case of the snow thickness being greater than 2 m, thus completely covering the sensors. It is expected that, from the absence of snow to a certain height under the sensor, the albedo effect increases with increase in snow thickness. This assumption is not valid for the whole height (0–2 m), since it is expected that when the snow level is too close to the sensor a convective extra cooling and even some contact contribution from the pole and the hanging structure can overcome the radiative effect. This is expected to be more evident in the case of low radiation. Moreover, above a certain height the air temperature is different due to local gradients and stratification. In this case, the assumption that t_{air} is the same for the two sensors is not true and this case will not be considered in this model and experiment. A limit can be set in snow deposition height to distinguish these cases.

The experimental results contribute to validating the model in this case and define a suggested threshold limit, in terms of minimum distance between the sensor and the snow, below which the measurements lose significance. Wind can influence this aspect and reduce this inverse phenomenon, partially or completely restoring the same t_{air} value. In this model, mutual effects are not taken into account due, again, to their dependence on instrument characteristics.

The model assumption is therefore that $\Delta t(h)$, the relationship between the albedo effect and the snow thickness, is here considered only for heights lower than the limit when the relationship $t_a > t_b$ is still valid. On a rigorous basis, this assumption requires that $\Delta t(h)$ is considered only for heights lower than the limit when the difference $t_a - t_b$ stops growing, i.e. the limit when the derivative $t_a - t_b$, a function of height, is zero:

$$\max\{\Delta t(h)\} = \Delta t(h = h_{\lim})$$

where

$h_{\lim} = h|_{\mathrm{d}(t_a - t_b)(h)/\mathrm{d}h = 0}$

This assumption can be experimentally evaluated to calculate eventually a correction function due to the effect of snow thickness on the temperature records. In this case, $\Delta t(h)$ will strongly depend on the instrument characteristics and other influencing quantities, such as wind and humidity, and can appear even as a function with more than a single maximum value. This analysis would require the evaluation of $\mathrm{d}(t_a - t_b)(h)/\mathrm{d}h$ by means of accurate measurements of different snow thicknesses, together with all other quantities involved. Since this work aims at detecting the maximum value of $t_a - t_b$, this analysis will be omitted in the experimental implementation protocol but will be considered for possible inclusion in further recommendations to users and to manufacturers.

4.3 | Incident solar radiation (SR)

A higher quantity of incident radiation for a fixed value of reflected radiation fraction results in a higher albedo effect.

Considering that solar radiation depends on cloud coverage and solar zenith angle, including night and day alternation, maximum values for Δt will be found for cloudless conditions and during daytime. Sensor couples will have to be positioned in close proximity, of the order of some 10 m, in order to assume that the Sun's radiation is as identical as possible for both instruments. The incident radiation can occasionally be different at the two measuring points, due to asymmetric shadows from clouds or mountains at sunset or dawn. Two radiometers positioned close to the two temperature sensors are needed then in the experimental evaluation to check for these conditions. The post-processing of the data will take into account the occurrence of the conditions evaluating both the site and the values of the incident solar radiation and the data associated with these occurrences will not be considered as useful to evaluate the albedo effect.

4.4 | Snow condition (s)

Albedo due to a snow-covered surface is dependent on snow conditions. Several influencing factors change the effective value of the reflectance of the surface. Many parametrization models have been used to study snow albedo for climatic purposes (Landsberg and Van Mieghem, 1976; Stephen, 1982; Berry, 1996; Pedersen and Winther, 2005). The present work is not intended to deal with a deep analysis of snow conditions but the following aspects are taken into account:

- absorption caused by impurity decreases albedo;
- snow melt decreases albedo;
- snow grain size affects albedo values.

In general, the principle to be considered for the present model is that fresh snow has a higher albedo, so the time passed from the last snowfall (T_s) can be used as a proxy for the qualitative quantity s. It is therefore assumed that maximum values of Δt can be found when $T_s \rightarrow 0$:

$$\max[\Delta t\{s(T_s)\}] = \Delta t\{s(0)\}$$

This consideration will be taken into account for the evaluation of on-site measurements in the data analysis process.

4.5 | Humidity (Rh)

Humidity reduces the amount of visible solar radiation reception, and reduces radiation energy. Absorption and scattering phenomena, related to humidity, can cause a reduction of radiation reflected by the surface but also influence incident solar radiation and air temperature. The relation between relative humidity and the albedo effect depends on complex phenomena including the scattering of aerosol particles and absorption properties of the atmosphere (Zdunkowski and Liou, 1976; Nessler *et al.*, 2000).

Moreover, the influence of humidity on the value Δt should be strictly related to the radiation fraction reflected by the snow surface, which warms up the sensor. Since these scattering effects are proportional to the air column, for the purpose of this model, having considered a maximum height of only 2 m, the effect of this small portion of air is negligible. Nevertheless, relative humidity as an influencing quantity on contact thermometry sensors should be monitored in on-site measurements independently from this specific purpose, since it gives information on sensor condensation and icing.

It is assumed that this method identifies conditions that maximize the albedo effect. It will be taken into account that, in principle, low humidity conditions are expected to be correlated with higher albedo. In this model, it is assumed that air humidity is not significantly different at the two measuring points, and so the relative effect on the dependence of albedo radiation from the humidity level is negligible in evaluating temperature differences. It is in any case suggested that a hygrometer be included in the experimental setup, to monitor humidity and to understand the possible dependence of the extra warming of the thermometers in the post-processing data analysis.

5 | EXPERIMENTAL GUIDANCE

Bearing in mind the assumptions and considerations of the model, a general guideline can be proposed for the realization of an experiment for the evaluation of the albedo effect. The experiment is designed to be easily implemented by users without high metrological skills: staff of hydro-meteorological agencies with routine equipment can perform the measurements to characterize the instruments involved in their networks. In the same way, manufacturers can include this information in their product datasheet or plan actions to reduce it if discovered to be too large. The main assumption is to consider relative measurements, so that the sensor readings are not taken as absolute values but used to evaluate the difference of readings between two identical sensors placed in the same experimental site but over different ground conditions. This also reduces the need for calibration and the associated uncertainty.

5.1 | Equipment

For investigation of the albedo effect on temperature sensors inside solar shields, two identical instruments are required, equipped with the same kind of thermometers and shields and sharing a single datalogger, to reduce to the minimum the uncertainty introduced by the equipment. Two albedometers are suggested, to measure both direct and reflected total radiation at the two measuring points. They need not be of very high quality and are needed only for measuring the total radiation value, independently from the spectral distribution, since different instruments can react differently due to their construction solutions. The two radiometers can give full information on associating the maximum temperature bias recorded by the thermometers to the corresponding radiation fluxes. To economize the costs, even a single radiometer, facing downwards, can be involved for measuring the only reflected radiation above the snow-covered surface. A hygrometer and an anemometer should be present since they measure quantities influencing the magnitude of the investigated effect. A rain gauge is also suggested, and a solid precipitation gauge can be added but is not strictly necessary. Snow thickness must be measured to check the height conditions as prescribed by the model.

5.2 | Principles of installation

Three points of interest will have to be identified as shown in Figure 3. A central point is used to host the instruments for the "ancillary" measurements: anemometer, hygrometer (or thermohygrometer), dataloggers, transmitter and, if any, a power source. This positioning is proposed to reduce to a minimum the instrumental impact at the other two points, hosting the two instruments under test. The two external measurement points, identified as "a" and "b" in the scheme, are equipped with the temperature sensors under test and radiometers for incident and reflected radiation. The measurement point "a" will have to be kept free of snow for the duration of the experiment.

5.3 | Site

For the experiment, a place with good characteristics in terms of instrument siting must be found and selected. Obviously, the site identified for the field measurement needs to be in an area with seasonal snow coverage. Sites with historical records of snow cover duration of more than 2 months are preferred. Days of snow cover should last for a minimum of some weeks, to allow meeting the weather conditions creating the maximum albedo effect: days with clear sky and absence of wind and precipitation should be enough to associate some statistics to the measurements.

The site needs to be a flat surface of at least 50 m radius covered with natural and low vegetation (<10 cm) representative of the region and without the presence of obstacles (buildings, trees, roads, rivers). In the case of obstacles in the immediate vicinity of the area, the instruments should be positioned to be symmetric with respect to the obstacle and care to minimize Δt_{site} must be taken.

The place should have easy access to allow maintenance, controlling the snow conditions and removing the snow from a portion of the surface, and downloading data in the case of absence of a remote connection. Power supply by electric line is preferred.

5.4 | Characterization

To detect the amplitude of the albedo effect, the method prescribes that the relative difference between the sensors in the same conditions must be null, thus corrected for systematic instrumental and environmental conditions.

A preliminary laboratory study must be performed on the temperature sensors, to evaluate the possible systematic differences Δt_{instr} between the two sensors exposed at the same temperature. As the aim of the experiment is the investigation of differences in output values from the instruments with or without snow on the surface below them, there is no need to ensure accurate absolute temperature measurement values. For this reason, calibration is recommended but not strictly necessary if the differences are evaluated over the whole temperature range expected to be encountered on the site.

Tests on sensors must initially be performed in the laboratory, under controlled stable temperature conditions or slowly changing, to check for possible different dynamics. Acquisition frequency must be set to the same order as the one adopted in the field: 10 min is a reasonable time interval. The temperature homogeneity of the chamber or laboratory must be below the sensor resolution, to avoid excessive uncertainty in the characterization phase. The planned duration of the preliminary test on the sensors must include repetition of the test changing the spatial configuration and relative position of the sensors.

The difference Δt_{instr} in laboratory conditions is obtained as:

$$t_a(t_{\text{air}}) - t_b(t_{\text{air}}) = \Delta t_{\text{instr}}$$

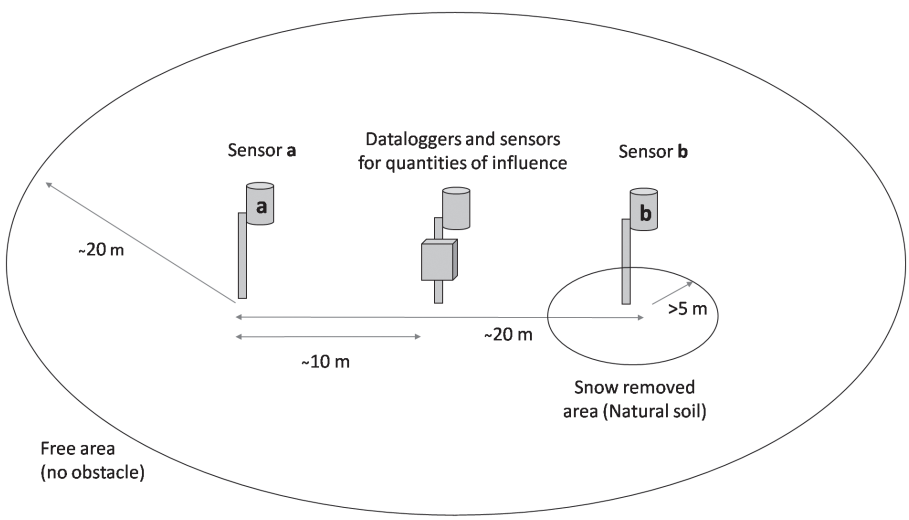

FIGURE 3 Scheme of the experimental installation

On-site measurements will then be corrected for Δt_{instr} obtaining $t_{a\ corr}$ and $t_{b\ corr}$, and corrected values are proposed to be:

$$t_{a\ corr} = \text{mean}(t_a; t_b) - \Delta t_{instr}/2$$

$$t_{b\ corr} = \text{mean}(t_a; t_b) + \Delta t_{instr}/2$$

A characterization of the differences recorded by the two instruments must be performed with snow presence on both measuring points, to check for possible systematic temperature record differences Δt_{site} to be evaluated and included as corrections in post-processing:

$$\Delta t_{site} = t_{a\ corr} - t_{b\ corr}$$

The repeatability of Δt_{site} can change significantly during the experiment, due to seasonal changes in the site conditions, such as vegetation on trees, shadows from surrounding mountains, sunshine duration and Sun angle. Non-symmetries can occur in the case of variable wind direction and speed; shadow can cover one measuring point at a time. All these facts must be taken into account when evaluating the amplitude of Δt_{site}.

The work can be minimized by considering that the analysis aims at detecting values and conditions that maximize the values of Δt.

Δt_{site} is expected to be dependent upon the quantities of influence. For this reason, the value of Δt_{site} that will be used for correcting the readings must be recorded in the same conditions as those generating the maximum value for Δt such as maximum Sun radiation, absence of wind and other possibly identified factors. The difference Δt_{site} is considered as a systematic effect due to the measurement site characteristics. It includes instrumental effects and must be used as a correction for measured records. In any case, the maximum Δt_{site} must be corrected removing spikes and outliers to produce a significant statistical value, to be used as uncertainty.

6 | DATA ANALYSIS PROCEDURE

Normally, for field experiments such as instrument intercomparisons or characterizations, the amount of data easily becomes large due to the prolonged acquisition period, over months and seasons, because significant amounts of data must be available for appropriate statistical analysis. The phenomenon investigated here is expected to have a highly dynamic behaviour: for this reason, an acquisition time of 10 min or less is required to capture the temperature rise with significant resolution and sensitivity. Data analysis should be focused on evaluating the maximum albedo effect on the involved instruments in terms of temperature differences between the two measuring points taking into account all the considerations in Section 4.

It seems inappropriate to suggest correcting functions for the dependence of Δt from the quantities of influence identified in Section 4, due to their nature. A low value of Δt can be recorded due to the concurring effects of different quantities but it is impossible at the moment to associate a correction as a multi-parameter function with a complete uncertainty evaluation. The data records should be analysed carefully as several cases can be generated, as reported in the example of 2 weeks of acquisition in Figure 4. At night, the absence of the phenomenon is evident. In the cases grouped in box 1, the effect is quite well measurable, of the order of more than 2°C with maximum values associated with daytime, higher radiation and the maximum differences of reflected radiation. In the case of box 2, an interesting phenomenon is recorded: although the reflected radiation is

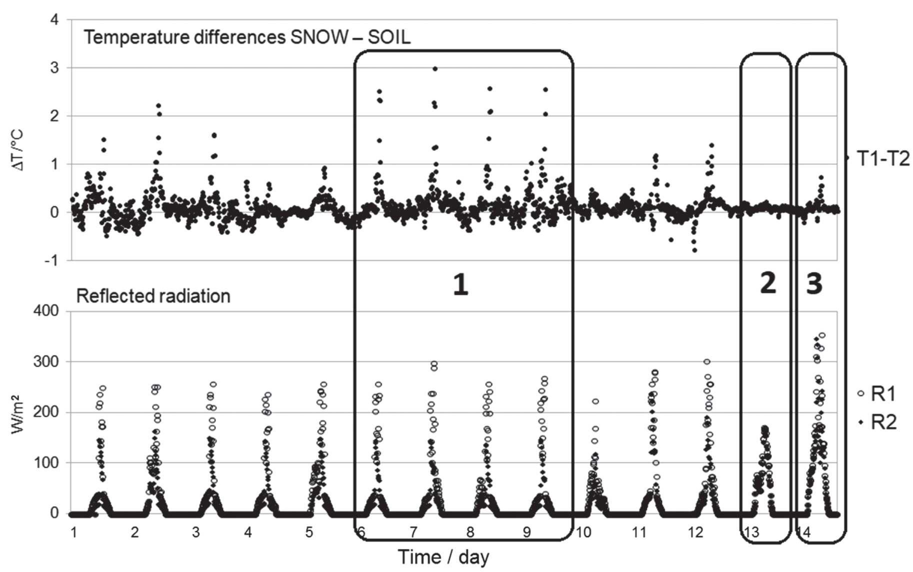

FIGURE 4 Example of data recorded during 2 weeks. Top: Temperature differences T1, T2 between the coupled sensors, with T1 being the temperature recorded by the sensor positioned above the snow-covered surface and T2 the sensor on natural soil. Bottom: Reflected radiation R1 measured at the position of the sensor T1 (snow) and at the sensor over natural soil, R2

significantly higher than at night time, since the difference in radiation levels is almost negligible the effect on the temperature records falls within the statistical noise around zero. In the case of box 3, the total reflected radiation is very high, meaning a clear sky sunny day, but with lower differences between the two measuring points: the associated temperature difference does not reach the same level as in the cases of box 1. Since it is expected that general statistical noise is present in the temperature differences physically due to such concurring effects, a reflected radiation threshold can also be defined to save time from data analysis and better identify days when the effect is more evident. This is why a correction function is not recommended; instead, a statistical analysis and grouping in ranges of temperature difference can have a more significant meaning. According to the guide to the expression of uncertainty in measurement (GUM, 2008) the uncertainty in the differences can be evaluated as type A from the statistical occurrence of the values and as type B from the instrumental and environmental contributions evaluated and corrected as in the characterization, Section 5.4. The experiment proposed here can last for just one snow season if weather conditions fully represent the mix of variability of all meteorological quantities.

7 | CONCLUSIONS

In this work, a model and an experimental method were studied to evaluate the effect of reflected radiation on sensors in the solar shield, measuring near-surface air temperature, in the case of the presence of snow. The model gives guidance on how to set up an experiment based on two identical sensors one positioned 2 m above snow-covered soil and the other positioned above soil without the presence of snow but at the same time and on the same site. The effect under investigation is based on evaluating Δt as a difference of the sensor readings and is considered as an overheating of the sensor due to reflected radiation hitting the shield from below. This model aims to identify the condition depending on several influencing parameters that maximize Δt and calculate the maximum value of the variable. A procedure for an on-field measurement campaign is proposed and devised to obtain measured data, which will be used to validate and integrate the model.

This model can be used for evaluating the performances of instruments by manufacturers and users. It does not require specific skills, nor expensive systems not normally available in hydro-meteorological agencies. The results delivered by the experiments can give valuable information and recommendations to manufacturers and users. Manufacturers can perform such tests on their products in order understand the occurrence of this effect on their instruments, to investigate technologies to minimize the effect, and to evaluate and declare its maximum magnitude in the commercial datasheets. Users can also make this evaluation, to add an uncertainty component in their air temperature records in the case of snow and high Sun radiation, in terms of the maximum values recorded. A possible adoption of correction curves by manufacturers or users for a specific equipment will need to take into account a quantitative analysis of the effect of such influencing quantities on the selected device, but since the correction curve cannot be fully associated with the uncertainty on the contribution of each influencing quantity its adoption is not encouraged. In both cases, an improvement in the quality of metadata associated with the data product is envisaged.

The experimental setup proposed and the associated measurement method are intended to quantify the maximum deviation from accurate temperature values due to the presence of snow under an air temperature measuring instrument, such as thermometers in solar shields and compact automatic weather stations. This procedure is of general scope and can be adopted to check and evaluate possible different behaviours and deviations among different typologies of sensors from different manufacturers. The maximum value obtained is recommended to be considered as an uncertainty component to be added to the temperature record in the case of snow presence. This experimental model can also be implemented for adopting a correction curve to be applied to data series in post-processing, associating metadata information on snow conditions, as retrieved from the radiometer records, and including a more robust characterization of the wind effect. In this case, the two albedometers mentioned in Section 5.1 are required: a best-fit interpolating curve linking the differences recorded by the two temperature sensors to the reflected radiation differences recorded by the two albedometers can be calculated. This curve will include the evaluation of the minimum limit from which the reflected radiation becomes an influencing quantity.

The value of the effect is proposed to be included as an uncertainty component in general studies on uncertainty associated with near-surface air temperature measurements. It is also recommended that future initiatives on data quality and identification of reference grade measurements, such as the Global Climate Observing System Surface Reference Network, consider this aspect and perform an appropriate characterization of instrumentation involved to quantify the effect investigated.

This work, motivated by the need to develop a protocol for practical evaluation of the phenomenon and effect described here, has formed the basis for designing experimental campaigns. In the framework of the MeteoMet project, a long lasting field experiment was set up, involving a representative number of different instruments, in different typologies and from different manufacturers following the guidance of the method presented, and data were collected over the seasonal period. Results are being analysed and will be subject of a later paper.

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ORCID

Chiara Musacchio https://orcid.org/0000-0001-7473-3678

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