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Effect of snow-covered ground albedo on the accuracy of air temperature measurements

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Abstract. Solar radiation is one of the main factors introducing significant deviations between thermometers reading and true air temperature value. Techniques to protect the sensors from direct radiative influence have been adopted almost since the beginning of meteorological observations. Reflected radiation from snow-covered surface can also cause extra warming to thermometers hosted in solar shields, not always optimized to protect the sensors from this further backward radiative heat transfer. This phenomenon can cause errors in near-surface temperature data series, with relevant impact on the quality of data records. The study here presented experimentally evaluates the effect of albedo radiation from snow-covered surface, on the accuracy of air temperature measurements. The investigation is based on evaluating temperature differences between couples of identical instruments positioned above ground covered by natural vegetation, being one in snow-free conditions and the other above snow-covered surface, at the same time in the same site in close vicinity. The work involved a representative number of different typologies of sensors and shields from different manufactures. A mountain site with appropriate field conditions, offering long-lasting snow presence to maximize data availability, was selected to host the experiment. Quantities of influence such as relative humidity, wind speed and direction, solar radiation (direct and reflected) were constantly measured. The effect was evaluated to range up to more than 3 °C for some typologies of sensors. Full data analysis is here reported, together with complete results. This main scope of this work is to report on an experimental estimation and method to evaluate and include this effect as a component of uncertainty in temperature data series for near-surface stations above snowy areas.

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1 Introduction

The World Meteorological Organisation (WMO) Commission for Climatology and the Global Climate Observing System (GCOS) are recommending study and definition of reference grade networks, installations and methods, to generate top quality data for climate studies (GCOS, 2019). A key requirement for a station taking part in a reference network is a documented measurement traceability and understanding of the total measurement uncertainty (Thorne et al., 2018). Consistent uncertainty calculation needs complete knowledge of the measurement system, the sensors calibration uncertainty, the characteristics of the site and the effects of environmental parameters such as wind, solar radiation and precipitation. Among the numerous observed Essential Climate Variables (ECV), atmospheric air temperature measurements have been collected for one and a half centuries. Such data series are the basis of scientific knowledge on local and global climate trends (Camuffo and Jones, 2002). Land-based stations are equipped with different kinds of thermometers whose performances have been constantly improved. Today, top quality instruments involve platinum resistance sensors and high-level reading and recording electronics. Many efforts have also been made to minimise the effect of quantities of influence on measurement results, with the aim to reduce the associated errors and measurement uncertainty. Solar radiation is one of the main factors influencing the instruments, causing significant deviations between the sensors reading and the real air temperature. Techniques to protect the sensors have been adopted almost since the beginning of meteorological observations. Shields to avoid direct solar radiation reaching the sensing element have been developed, from Stevenson screens (Stevenson, 1864) to modern "pagodas" and naturally or mechanically ventilated solar shields. Recent intercomparisons were organized by WMO (Lacombe et al., 2011) to evaluate the performances and differences among the numerous solutions adopted by manufacturers. While the practical/technical features offered by these shields are now optimized and prescribed (WMO, 2012), rarely their capability to protect the thermometers from backward radiation, reflected by the ground, is fully evaluated, taken into account in measurements and data series or documented in datasheets. This is proportional to the so called "albedo" which is the ratio of reflected radiation with respect to the direct radiation received by the ground that, in case of snow cover, is increased up to 95 % (Barry and Blanken, 2016). Like the direct radiation, this reflected component can cause extra warming of instruments, introducing errors in near surface temperature data series, with relevant impact on detected maximum values and anomalies. Such instrumental errors have different magnitudes depending on the equipment, and the technical solutions adopted in manufacturing thermometers and shields. This phenomenon is relevant in monitoring mountain climate, where the duration of snow cover is high (Nigrelli et al., 2018).

Only few studies can be found in literature evaluating the effect of albedo of snow-covered land on temperature sensors: among them the most significant work is the experiment from (Huwald et al., 2009) based on a very different approach and limited to a single typology of sensor and screen.

The task of the present work is to observe, measure and quantify the effect of extra heating on different kind of instruments positioned above snow covered land, in terms of deviations of sensors readings from actual temperature values. This work is the result of a study made in field conditions following a metrological protocol and experimental method, defined and reported in a previous study (Musacchio et al., 2019). The investigation is addressed at the evaluation of relative difference between the readings of pairs of identical sensors protected by solar shields as provided by manufacturers. One pair is positioned above snow-covered surface, while the other above grass-covered ground, in the same site, at the same time under equal environmental and topoclimatic conditions.

The problem of albedo effect on air temperature instruments, here studied, can be included as a part of the general study on assessing data quality and uncertainty in near-surface air temperature measurements. This wider subject is now being analysed and discussed by the WMO expert teams of the Commission of Climatology (CCl) and in the Commission of Instruments and Methods of Observations (CIMO) and is a key aspect in the creation of the Climate Reference Networks for the Global Climate Observing System (GCOS). The complete knowledge and evaluation of uncertainty budget components on air temperature measurement is also included in the roadmaps of scientific activities of the Working Group for Environment of the *Comité Consultatif de Thermométrie* (CCT - Consultative Committee for Thermometry) of the *Bureau International des Poids et Mesures* (BIPM - International Bureau of Weights and Measure) (CCT, 2017)

The activities here reported have been carried out in the framework of the MeteoMet project (Merlone et al., 2015a, 2015b, 2018), a funded joint research initiative of the European Metrology Research Project (EMRP) grouping a wide consortium of National Institutes of Metrology (NMIs), research institutes, universities and National Meteorological Hydrological Services (NMHSs).

2 Theoretical study and experimental method

The present work includes theoretical studies, the draft of an experimental protocol, collection of representative typologies of instruments (thermometers with shields and auxiliary equipment), their laboratory characterization, field installation, on-site measurement and data analysis.

The experiment here presented follows the prescriptions and assumptions proposed in (Musacchio et al., 2018) where a measurement protocol is presented following a theoretical study on the influence of various parameters such as wind speed and direction, snowpack thickness, incident solar radiation, snow conditions and humidity on air temperature measurements above snow-covered ground. In the cited work, the authors also give guidelines on the experiment design and the evaluation of uncertainty components, as well as laboratory characterisations of instruments and the ways to take into account all identified quantities of influence, both instrumental and environmental. Based on these considerations, for the realization of the field experiment, a measurement protocol was prepared, giving prescriptions on:

- design of the experimental set-up and definition of site requirements;
- evaluation of the quantities of influence;
- sensors characterization in laboratory and in field;
- evaluation of uncertainty components.

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2.1 Experimental set-up and site requirements

The "albedo effect" here investigated is the sensors overheating due to backward reflected radiation from snow and it is measured as differences of air temperature readings t_{air} between couples of identical sensors in identical shields, positioned one in a point a, over snow, the other in a second point b, snow-free area: this difference is here indicated as

$$\Delta t_{air} = t_{air}(a) - t_{air}(b) \tag{1}$$

and it includes all the corrections evaluated for each pair of sensors during the described laboratory and field characterisations. These two measurement points are arranged in close vicinity and on a flat surface, free from obstacles, thus exposed to the same topoclimatic conditions, but far enough to accommodate a significant area covered by snow on one point and a sufficient area (some meters of radius) with natural ground left free from snow on the other point. Readings from each pair of sensors are recorded by means of a unique data logger. The investigated effect is therefore the result of a relative analysis, involving identical instruments and single reading unit: this allows minimizing influencing factors and uncertainties. In between the two measurement points, other instruments are deployed to measure the quantities of influence, which took part in the analysis as uncertainty components.

The site hosting the experiment requires a number of specific features. It must be a free, flat surface of at least 50 m of diameter with a minimum presence of obstacles - as trees, buildings or roads in the surrounding area - and spatially uniform solar exposure during the daytime central hours. Besides the presence of snow, the original ground must be covered with natural low vegetation. Other characteristics are related to logistic aspects such as: electric power available throughout the winter, easy vehicular access for maintenance, no agricultural or sport activities, strictly reduced access to public and no presence of vehicles. The experimental site scheme is reported in Figure 1.

2.2 Quantities of influence

The main quantities of influence on the temperature measurements for the evaluation of the albedo effect must be constantly monitored during the experiment. The theoretical work cited identified these quantities as wind speed, air relative humidity and solar radiation. Global solar radiation (downward) and reflected solar radiation (upward) were measured in the same position of each temperature sensor. Snow thickness and conditions have also been monitored (see section 3.2).

2.3 Sensor characterization

Before starting the experimental activities, temperature sensors must be characterized in order to understand their behaviour in different situations. The experimental protocol prescribes two different characterization phases: in laboratory and in field conditions.

The laboratory characterization is needed to evaluate possible systematic differences between couples of sensors exposed to the same temperature under controlled conditions. ~~Being the investigation based only on~~ relative temperature differences among pairs of identical instruments, the sensors calibration is not necessary as no traceable absolute temperature measurements are required for the evaluation of the albedo effect in field. This avoids the inclusion of the calibration uncertainty in the overall uncertainty budget and makes the adoption of this procedure easier, also for users willing to make similar analysis without the calibration costs and time required. Laboratory controlled conditions also allow the evaluation of the sensors' stability, sensitivity and resolution of the readout.

Different systematics can arise when the sensors are deployed in the field, due to environmental factors. For this reason, an in-field characterization of the sensors is also needed to evaluate their behaviour in such conditions. Performing an estimation of the uncertainty components of on-site measurements is necessary to quantify the accuracy reached in the experiment. For more details, Musacchio et al., (2019) gives an in-depth description of the whole method, as well as its assumptions and prescriptions.

3. Experimental set-up, preliminary characterizations of site and instruments, uncertainty components

The experimental activity reported in the present work was carried out in the framework of MeteoMet project. In 2016 a call was opened for MeteoMet collaborators manufacturers, to take part in the experimental activities by sending couples of identical thermometers, with identical solar shields. Data loggers were also requested, one for each couple of instruments, in order to make the data available as recorded by the users. Different shapes and dimensions, mechanically aspirated or naturally ventilated shields were collected to have a range of such commonly used devices as broad as possible.

Six different instruments from four different producers were selected for the experiment as described in Table 1.

Additional sensors for the measurement of the quantities of influence were installed, including a cup-and-vane anemometer, a thermo-hygrometer (both positioned in the central measurement point of the experimental area) and two albedometers, one for each measurement point (Table 2). The air temperature reference value was the one measured in the central point, but it is not included in the evaluation of the differences among the pairs of sensors under test, nor it contributes to the uncertainty budget. This further air temperature value is recorded as another potential quantity of influence, in terms of further possible dependence of the temperature differences also on the temperature itself, in addition to the one investigated in laboratory and was evaluated to be a negligible effect.

3.1 Laboratory activities

Preliminary tests on the selected sensors were performed in laboratory for the characterization of the sensors and the complete system. (Figure 2).

This part of the work was performed in the new "Climate Data Quality Laboratory" of the Istituto di Ricerca per la Protezione Idrogeologica - Consiglio Nazionale delle Ricerche (IRPI-CNR). During this phase, a study of the different data loggers working principles was also made, together with the evaluation of best mounting solutions.

The activities started with a preliminary evaluation of the differences between couples of sensors readings, without the shields, in stable temperature conditions, to check for systematic values to be corrected. The sensors were then assembled in the shields, taking notes of both sensors and shield serial numbers, in order to keep the same sensor-shield group in the field experiment,

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and all the relative differences of temperature measurements of each pair of instruments, Δt_{instr}, were measured. The characterization was then performed in a controlled environment with slow temperature change, to keep into account possible effects, without being affected too much by the sensors' dynamics. Too rapid air temperature transients will in fact not be included in the final data analysis, since sensors dynamics can predominantly influence the trueness of the analysis (Burt and de Podesta, 2020). All sensors underwent the laboratory characterisation in order to obtain the information reported in table 3. Stability of the instruments was also tested in laboratory during a one-month continuous acquisition, to check for longer term drifts and potential maintenance required in field. No failures or significant effects were observed.

3.1.1 Laboratory

The laboratory controlled experimental conditions have been evaluated in the testing zone, using traceable reference sensors. Room temperature drift was found to be < 0.02 °C for one day and < 0.05 °C over one week. For time interval corresponding to data loggers' acquisition and recording times, the laboratory air temperature stability was evaluated as $u_{stab} = 1$ mK. The temperature homogeneity was measured and found to be < 0.05 °C $\cdot$ m^{-1} in the laboratory measuring volume. The sensor pairs were positioned at a distance of about 20 cm, as a compromise between minimizing the gradient and avoiding mutual influences such as heating from the electronics or fan motors. The uncertainty due to the laboratory temperature homogeneity was therefore evaluated as $u_{hom} = 0.01$ °C.

The total uncertainty contribution due to laboratory conditions was evaluated as $u_{lab} = \sqrt{u_{stab}^2 + u_{hom}^2} = 0.01$ °C for all the sensors.

3.1.2 Instruments

The evaluation of possible systematic differences Δt_{instr}, among pairs of identical sensors kept at the same temperature (within the laboratory homogeneity uncertainty) was performed by repeated readings over several intervals of about one hour. As shown in Figure 3, all sensor pairs were found to have systematic differences Δt_{instr}, which have to be taken into account for the correction of field data. Associated uncertainty values are reported in Table 3. The repeatability of temperature differences Δt_{instr} contribute to the uncertainty budget with a component reported as $u_{\Delta t_{instr}}$.

These contributions u_{lab} and $u_{\Delta t_{instr}}$ are reported in the overall uncertainty Table 5.

Finally, a check to verify the drift of the sensors was performed at the end of the experiment, after the field campaign and exposure to meteorological conditions. In particular, the drift of Δt_{instr} was evaluated again in stable laboratory condition, by measuring the systematic differences among the pairs of thermometers when kept at the same controlled temperature. The drift was then evaluated as differences in the systematic differences measured before and after the field campaign: values were found to be of the same order of magnitude of the instruments noise. This is an expected result, since only high-performance temperature sensors have been selected, normally produced to guarantee top level stability in time and low drifts, to reduce

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maintenance and recalibrations by the users. The drift in the relative difference becomes therefore negligible for the duration of the experiment and no correction or uncertainty components have been included.

3.2 Measurement site and experiment set-up

Being the experiment performed in a mid-latitude region, a mountain site in the Alps was chosen, to assure the presence of snow cover throughout the winter, for collecting enough records for a statistically significant analysis of the investigated effect. The measurement site, selected to meet logistics and experimental requirements, was found in the municipality of Balme at 1410 m of elevation (45°18'9.31" N, 7°13'19.18" E), in the Ala Valley, northwest of Turin (Italy). (Figure 4, 5)
Only a 3-m wide local road with almost no traffic and a small unmanned building were present in the area, at more than 50 m from the measuring point. Coppa et al., (2021) performed a metrological quantification of the influences on air temperature measurements introduced by the proximity of roads, that revealed a significant effect only at closer distances (less than 50 m) and mainly at very low or even null values of incident radiation. Since for this experiment only records associated to sun radiation are relevant and the road is at more than 50 m, its presence was considered negligible. According to a similar experiment for the evaluation of the effect of buildings, (Garcia Izquierdo et al., in prep) a building of the size of the hut ~~there present~~ and at that distance causes no influence in air temperature records. Moreover, during the experiment set-up, great care has been put in order to place both measurement points at similar distances from each possible source of heat and disturbance: their potential influences, as evaluated by the mentioned works, affect both measurement points in the same way, thus cancelling out during relative differential evaluations.
The chosen area turned out to be a reasonable compromise between the necessity of an alpine location in terms of snow cover presence and duration, and the logistics of a heavily-instrumented research site.
The equipment was installed following the prescription of the protocol. The experimental scheme of Figure 1, based on the three described measurement points, was followed: the two external poles hosting the couples of identical shielded thermometers and the albedometers, the central one with the data loggers, the electric power connection and the auxiliary measurements of humidity, wind speed, wind direction and central air temperature (Figure 6). The two instruments of each couple were positioned in the same orientation and in case of asymmetric shapes, following manufacturers specifications (i.e., ventilation aperture facing North).
~~At~~ significant precipitation events, the snow was removed from a 5 m radius area centred in point *b* (Figure 7 and Figure 8 respectively show the site before and after the removal of snow); the site and instrument were constantly supervised and the meteorological conditions recorded. The weather conditions are fundamental to select, in terms of day and time, periods when the albedo effect, as defined in the model, can be better detected in its maximum values. The 5 m radius was decided as a compromise between maximising the snow-free area under the sensor and having the measurement points close enough to keep the assumption of homogeneity of local weather conditions. This radius could not be expanded because the third measurement point, i.e., the one carrying control and ancillary measurements, would fall in the snow-free area, while it was important that these measurements were representative of the natural state of the site.

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As mentioned in section 2.2, the experimental protocol mandates an evaluation of snowpack thickness and snow conditions for a full understanding of the quantities of influence. Instruments have been positioned at 2 m from the ground and during the whole measurement campaign the snow thickness never surpassed 40 cm, thus keeping sensors ~~never less than~~ 1.5 m from the surface below (both above natural soil and snow-covered area). The measurement protocol included a recommendation to remove data in case of snow thickness surpassing 1 m, to avoid other effects (extra cooling, turbulences) to introduce errors or uncertainties and the measurement be made not according to prescribed height. As for snow conditions, they were also neglected because snow removal was performed immediately after a snowfall, thus all the differential measurements have been recorded in conditions of fresh snow.

3.3 Characterization of sensors on-site

The theoretical method assumption is that, under the same conditions of snow cover, the difference of air temperature measurements between the two sensors at position a and position b (Δt_{site}) is zero. In real conditions, to achieve this hypothetical assumption, environmental factors must be evaluated and corrections must be adopted. Non-symmetries can occur, for instance, in cases of variable wind direction and speed, asymmetric shadows or other non-homogeneous atmospheric or surface conditions, causing a non-null temperature difference among the same sensors over the same snow-covered surface. A specific preliminary measurement campaign was made on site, at first snow event, to evaluate such possible systematic temperature differences Δt_{site} among the couples of instruments the following considerations were taken in to account:

- data was recorded when snow was present below both the measurements points;
- data was selected during day time with incident radiation greater than zero;
- data was selected when the reflected radiation difference was zero.

Values of Δt_{site} were then used to correct the raw data recorded on site.

The repeatability of the difference Δt_{site} itself can change significantly during the experiment, due to seasonal changes in the site conditions, such as vegetation on trees, water level in rivers etc. All those contributions have been taken into account when evaluating the uncertainty, $u_{\Delta t_{site}}$ on Δt_{site}. Results of this characterization are presented in Table 4.

Events of asymmetric shadows, cast only over one of the two measurement points, were also identified as due to a mountain peak occasionally projecting its shadow during the period of shortest daytime (December to January): records associated to this shadowing effect were neglected form the data analysis, thus also from the evaluation of $u_{\Delta t_{site}}$.

3.4 Uncertainty budget

The overall uncertainty budget $u_{\Delta t_{air}}$ for the temperature differences Δt_{air} have been derived according to the Guide to the expression of Uncertainty in Measurement (GUM) (JCGM, 2008), from the instruments characteristics and experimental conditions. As reported above, no calibration uncertainty components are here introduced, since the measurand is a relative difference, which does not require absolute accuracy.

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The expression for the evaluation of overall uncertainty is defined as:

$$u_{\Delta t_{air}} = \sqrt{u_{res}^2 + u_{lab}^2 + u_{\Delta t_{instr}}^2 + u_{\Delta t_{site}}^2} \tag{2}$$

where:

- u_{res} is due to the resolution of instruments and data loggers as provided by manufacturers;
- u_{lab} is the component of uncertainty due to laboratory conditions and is composed by temperature uniformity and stability of the laboratory itself;
- $u_{\Delta t_{instr}}$ was evaluated during the laboratory testing of thermometers and is mainly ascribed to sensors short term stability and statistical contributions;
- $u_{\Delta t_{site}}$ is related to the non-ideal characteristic of the on-site conditions.

Table 5 summarizes the components of uncertainty with the expanded uncertainty $U_{\Delta t_{air}}$ reported with coverage factor $k = 2$ and confidence level of 95 %.

4. Data analysis

4.1 Data selection

The measurement campaign was performed between 8 September 2016 and 24 March 2017.
The acquisition frequency for every sensor was set to 10 min. The parameters recorded in both points *a* and *b* were: air temperature, incident and reflected radiation. During the campaign, an operator constantly accessed the experimental site and marked the best days for the analysis, in terms of sunny days (maximum radiation conditions) after a snowfall (maximum heat backward reflection) when the snow below instruments at point *b* was recently removed (maximum expected differences).
Snow was dug away on 4 days: 30 November ~~and~~ 22 December 2016, 20 January and 23 February 2017. Each time, snow was completely removed within the radius of 5 m, leaving the natural soil exposed. Salt was used each time to prevent the formation of ice, which would have changed the natural soil reflectivity, and to make snow removal easier and more complete. The preliminary data analysis was addressed to measurements ~~values~~ recorded in the days immediately after ~~the intervention of~~ snow removal from point *b*.
Preliminary results show~~n~~ that the albedo effect leads to larger Δt_{air} values during the central hours of those days with higher value of solar radiation and no wind. The effect was negligible or hidden under the general thermal noise and uncertainties in those days characterised by fog, clouds cover or wind. When the weather conditions are such to make the effect evident, one day records present a similar trend as the one showed in the example in Figure 9, with night-time differences close to zero and a noise coherent with the instrumental relative uncertainty. In daytime the effect becomes evident and different in its magnitude among the different typologies of sensors (A to F).

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Differences of incident radiation in the two measurement points have also been evaluated and taken into account, in order to exclude the cases when incident radiation differences in point *a* and *b* was significant and due for example to asymmetric shadow from clouds or from the occurrence of the mountain peak shadow as mentioned in section 3.3. Having already excluded those values, the incident radiation differences were mostly consistent within the instrument uncertainty. This uncertainty was evaluated to be 35 W·m^{-2} on the basis of sensors characteristics such as sensitivity, repeatability, resolution. Records of temperature differences have been included in the data analysis only when the associated radiation difference was within this uncertainty value. As expected, due to the vicinity of the two measurement points, only few records were excluded due to larger incident radiation differences.

On the other hand, reflected radiation in the two measurement points show very large differences due to the difference in reflectivity between snow-covered area and the natural ground on point *a* (Figure 10).

Since the study intends to evaluate the largest values of the investigated effect, a threshold on the difference of reflected radiation, $\Delta Rad_{\mathrm{ref}}$, equal to 200 W·m^{-2} was chosen to better select significant temperature differences ~~records~~. The threshold was chosen by observing that below this value the temperature differences between the two measuring points were distributed in a non-deterministic way, close to the combined measurement uncertainty, site effects and data noise.

In Figure 10, plots (a) and (b) show the reflected radiation recorded in position *a* and *b* during the entire period. Plot (c) shows the differences of the reflected radiation recorded in position with and without snow. The threshold value on the reflected radiation is applied.

On this subset, a further data selection is applied, by excluding the values of temperature differences among pairs of sensors that fall below the Δt_{site}. This is the reason why the total number of significant records are not the same for all pairs of instruments. The number of available data for each pair of instruments was found to be proportional to the amplitude of the albedo effect. This result is not surprising, since when the differences distribution is skewed towards larger values, it follows that more temperature differences are found above the Δt_{site} limit. This is clearly evidenced in the following Figure 12.

4.2 Albedo effect evidence from recorded data

As a preliminary analysis, records from the deployed instruments were initially considered all together, as a single set, to understand an overall meaningful effect. The plot in Figure 11 shows the distribution of Δt_{air} amplitude grouped in bins of 0.2 °C regardless the sensors typologies.

The most frequent values of Δt_{air} are found between 0 °C and 0.4 °C, with a significant number of records between 0.4 °C and 1.6 °C. The less populated classes are from 2 °C to 4 °C. Maximum Δt_{air} values ranged up to 3.8 °C while 95 % of the values were found to be within 2.4 °C, which can be considered the highest significant value for this specific experiment.

The analysis shows that no instrument is immune from the effect, resulting in different values of Δt_{air} depending on the different technical features. Records where then segregated according to the manufacturers and typologies as reported in the following plots (Figure 12).

As in the previous histogram (Figure 11), most records are concentrated between 0 °C and 2 °C.

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Looking at each pair of sensors, it became clearer that Type B and Type F show a wider range of Δt_{air}. The temperature differences for Type A, Type C and Type D sensors were always under 1.5 °C, and almost all records were concentrated between 0 °C and 1 °C, while Δt_{air} for Type E stays under 2 °C. In some cases, Δt_{air} reached 3.1 °C for Type B and 3.8 °C for Type F. Table 6 summarises the maximum difference Δt_{air} ~~measured,~~ for each instrument type with the associated uncertainty. The expanded uncertainty $U_{\Delta t_{air}}$ is reported with coverage factor $k = 2$ and confidence level of 95%.

4.3 Wind speed and radiation effects

Further data analysis was addressed to evidence the relations between temperature differences and the main quantities of influence such as wind speed and radiation.

Figure 13 shows Δt_{air} values, as calculated in previous section, as a function of wind speed.

Values between 0 m s^{-1} and 5 m s^{-1} were observed. As expected, increasing wind significantly reduce the albedo effect due to air mixing in the sensor area and to the increase in heat dissipation by convection. For wind speed greater than 3 m s^{-1} the effect was clearly reduced.

In the same plot for each measurement value, grey scale is used to evidence the difference of reflected radiation, $\Delta Rad_{\mathrm{ref}}$, associated to each temperature difference calculated.

To better evidence the behaviour of albedo effect, Figure 14 shows values of Δt_{air} as a function of $\Delta Rad_{\mathrm{ref}}$. In the plots, a positive trend of Δt_{air} is apparent for type B and type F instruments, but the spread in values does not allow for a definition of a relation by fitting, nor it was possible to calculate a function between Δt_{air} and $\Delta Rad_{\mathrm{ref}}$.

4.4 Night-time reversed effect

Differences of air temperature Δt_{air} during the night were also recorded to evaluate possible reversed differences: air temperature in the snow-covered area could result colder than in the ground area without snow, in some nights. This effect was observed in almost absence of wind, in the early spring time, when the day temperature rises above 0 °C. In this case, the ground covered by snow keeps its temperature around 0 °C, due to the energy absorbed in the snow phase transition to liquid, while the land portion without snow can become warmer and emit some heat at night. This effect falls out of the scope of this investigation, since it was not related to the instruments, but is a thermodynamic phenomenon here reported for completeness. The maximum observed meaningful difference was of 0.6 °C with opposite sign to the one recorded in daytime.

5. Discussion

The analysis here presented shows that the backward reflected radiation from a snow-covered surface affects the reliability of meteorological thermometers by transferring extra heat. This effect results in a temperature increase here evaluated with respect to identical sensors positioned in the same site, at the same time, but placed over natural ground not covered by snow. Air

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temperature records are therefore higher than the expected true value, being the latter the actual temperature of the atmospheric air in the site, which also takes into account the warming of the air due to snow presence.

The main considerations are here summarised:

- Some typologies of instruments resulted more influenced than others, with significant differences observed even over 3 °C;
- Out of the whole group of instruments, 95 % of the differences were found within 2.4 °C;
- Highest temperature differences between couples of identical instruments were found to significantly vary among the different types of shields;
- Forced ventilated shields differences were found falling in the lower mean values recorded, with naturally ventilated shields with helical shapes scoring the lowest difference values;
- The highest temperature differences between couples of identical instruments were found in conjunction with the maximum reflected radiation differences between the two positions, as expected;
- The wind has the effect of reducing the highest temperature differences between couples of identical instruments;
- The overall uncertainty on temperature differences in field conditions ranged between 0.1 °C and 0.4 °C in $k = 2$;
- The distribution of differences as a function of the reflected radiation was found, at first approximation, to be uniform.

This experiment also evaluated a minor reversed effect at night of maximum 0.6 °C where the sensors over the snow-removed area warmed more than those with the snow below. This effect and value are not within the scope of this investigation and is here reported just as an occurrence due to the artificial removal of the snow.

Three limitations are identified in this work: (a) a limited number of instruments available (b) short period of field measurement (c) non-perfect site. Some considerations are reported on how those limitations do not affect the overall value of the study:

(a) As reported, this work involved six couples of identical thermometers and shields, plus a complete set of instruments to measure ~~all~~ other quantities of influence. Although limited in number, the instruments selected covered ~~all the instrumental commercial solutions~~ of modern meteorological sensors with a reasonable balance of aspirated, naturally ventilated and new designs included. It is not expected that other studies involving this kind of instrumentation, could show very different values of the effect.

(b) Due to the costs of installation, maintenance, site activities, work in remote location, this study required a funded project. Project rules are such that results must be delivered during the three years of the project lifetime. For this reason, after the selection process, laboratory characterisation and field installation activities, only one winter season was left before the project conclusion. Nevertheless, the number of days with snow cover lasted from November to March, allowing to meet almost all meteorological conditions in the site, including radiation and wind variability. Repeating the experiment is surely beneficiary to apply more statistical analysis, although it is not expected that the

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differences among the instruments vary significantly. A valuable representativeness of the obtained results, with respect to atmospheric ranges and measurement conditions is here considered achieved.

(c) An appropriate site with easy access for maintenance, long lasting presence of snow but not excessive thickness, electric current to feed all instrumentation and ventilated screens (solar panels cannot supply enough power), maintenance and surveillance, closeness to have staff removing the snow at early occurrence is not an easy find. Moreover, the site needs to be flat, covered by natural soil, without significant shadows and slopes. Alpine valleys rarely allow such multitude of conditions. Thanks to an intensive site selection and the support of local Communities, a site was identified showing reasonable compromises among the required characteristics. Field measurements on possible effects of the site features (trees, small building, shadow) were in any case made, to select data and correct ~~from~~ systematic effects. Such effects resulted to be of the order of magnitude of the uncertainty and only for one couple of sensors they were taken into account in data analysis.

From the considerations above, the results here delivered are considered valid to understand the order of magnitude of the effect. This work also gives an example on how to evaluate this phenomenon and take it into account in terms of correction and associated uncertainty. A complete correction curve in function of reflected radiation, wind speed for a specific instrument can be generated by users, having available at least a couple of identical instruments and the auxiliary equipment here described.

In scientific literature or documented procedures, very few - close to none, are the examples of similar evaluations, methods or prescriptions to quantify the studied effect on near surface thermometers. The work mentioned in the introduction by Huwald et al., (2009), reaches the same conclusions that “Temperature errors decrease with decreasing solar radiation and increasing wind speed” and that this effect ranges in the order of degrees Celsius. With respect to the aforementioned study, the key difference of the work here presented, which we consider as an improvement for the analysis, is that here the effect is evaluated in a relative way, instead than assuming the readings of a sonic anemometer as reference. It is agreed that non-contact thermometry is immune from a number of quantities of effect, but the accuracy achieved by using anemometers as thermometers is not sufficient to let this instrument be a reference. The method here proposed can be adopted just by buying a second identical thermometer and shield, significantly reducing costs. The resulting uncertainties in detecting the effect are reduced with respect to comparing different systems and even different physical principles in measuring air temperature. Finally, in this analysis the investigation was extended to more different kind of sensors and shields, thus making the results representative of a wider typology of solutions adopted in meteorology.

Beside delivering the numerical results, the key output of this work is a methodology for evaluating a factor affecting temperature data in climatology (and meteorology) and give an example on how this can be implemented and adopted when selecting instruments as in the case of surface stations of climatological networks.

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6. Recommendations to users and manufacturers

One of the main tasks of the MeteoMet project was to give metrological support to the meteo-climatology community, including data users, station staff and manufacturers. A ~~synthetic indication~~ that summarise the outcomes of the work here ~~presented~~ has been presented at the WMO CIMO TECO 2018 (Musacchio et al., 2018) and sent to the WMO CIMO expert team on Observation In-Situ technologies.

Following the publication of the experimental method (Musacchio et al., 2019) indications on how to design and implement a field experiment, to evaluate the errors in temperature readings in thermometers positioned above snow-covered land have been prepared and sent to WMO CIMO task and expert teams on “Metrology”, “Surface Measurements” and “Overall Uncertainties”. The indication is summarised as it follows.

When instruments are positioned in sites where snow can occur, it is recommended that a specific analysis is performed to evaluate the bias in data records, due to extra heating from reflected radiation, causing errors in thermometers readings. To perform the study, two identical systems (thermometers and shield) must be installed in the vicinity, one positioned above a snow-covered area and one above an area where snow is removed. The procedure here reported and the cited protocol must be followed, involving the required auxiliary instrumentation to constantly record and monitor the environmental factors of influence. The differences between the temperature readings of the sensors should be recorded for at least one full snow season, to meet most of the meteorological conditions of the sites and evaluating the associated effects and factors of influence. A correction can then be generated in terms of a relationship between temperature corrections with respect to the reflected radiation, wind speed and air temperature. The associated uncertainty budget is then evaluated through the Gaussian propagation: components of uncertainty are calculated by field analysis of systematic differences in temperature and by knowledge of each involved instrument performance, including radiometers and anemometers.

The objective of the recommendation is to report and inform users and manufacturers of instruments to consider and possibly minimize the effect of reflected radiation from a snow-covered surface on near surface temperature data. The content is also relevant for the definition of data quality and instrument features by the GCOS and the WMO in promoting climatological reference stations. For high quality installations and climate reference stations, the analysis here presented can lead to improving the data quality by adding an evaluated correction and associated uncertainty. Manufacturers should also evaluate and declare this effect on their product datasheets and where possible adopt solutions to minimize it.

7. Conclusions

The study here presented was performed to evaluate the accuracy of near-surface air temperature data series, recorded by thermometers in solar shields positioned above snow. The work investigated this phenomenon in terms of extra heating transferred to sensors, causing a temperature difference in their measurements. The well-known effect of air temperature increase due to the snow albedo effect is not here considered, since this is a meteorological phenomenon: only the extra heating induced to the sensors and shields is here considered as a bias in ~~record series~~. The study strictly followed an already published method and its associated experimental protocol. The method designs the experimental site in terms of two measuring points, equipped with the same kind of identical sensors and shields or groups of different couples of sensors and shields as in this case, mounted 2 m above the ground level. At snow occurrence, snow is removed from one measurement point, leaving natural ground exposed, thus thermometers measuring actual air temperature; snow is left on the second point and the sensors are thus exposed to the backward reflected radiation that, especially during sunny days, warms the sensors introducing a temperature difference Δt_{air}. Preparing a theoretical method and coherent experimental protocol, based on deeply discussed aspects, made the installation and the data analysis a more robust process, with less adjustments due in course of the work. The study involved a representative number and different typologies of modern sensors and solar shields, including naturally ventilated, aspirated and helical shields. The instruments were provided as commercially offered by manufacturers, equipped with dedicated data loggers and measurements have been taken in the same conditions of use. The effect was evident for all the typologies of sensors with maximum values observed in absence of wind and at high reflected radiation conditions such as in sunny days with clean fresh snow. The amplitude of the maximum effect ranged from 1.2 °C up to 3.8 °C.

The method was validated by the experimental results and can be considered a procedure for further similar investigations involving other typologies of sensors. This process can be adopted by manufacturers to test and characterise their product as well as by station staff and data users to include this effect, correction and associated uncertainty to the records. A similar analysis should be performed when selecting instruments to take part in a climate reference network, such as the planned GCOS Surface Reference Network GSRN, for those stations positioned on sites with snow presence.

Finally, further work can be addressed to evaluating correction curves in the form of temperature difference relationship with reflected radiation and wind conditions. The calculation of a correction function requires longer time of field activities, to meet the wider range of atmospheric conditions as well as having more data available for statistical analysis by filtering significant data. The uncertainty budget associated to the curve will then be completed by including the statistical analysis and all components from the instruments involved: thermometers, anemometers, radiometers.

In a site where a high-quality installation is planned to be permanent, a study like this is recommended among the overall efforts to increase data quality and understand uncertainties in meteorological observations for climate.

Author contributions

Andrea Merlone, Chiara Musacchio and Graziano Coppa designed and run the experiment, with contributions by all co-authors. Laura Massano performed the data analysis with contributions by Chiara Musacchio. Chiara Musacchio prepared the manuscript with contributions from all co-authors.

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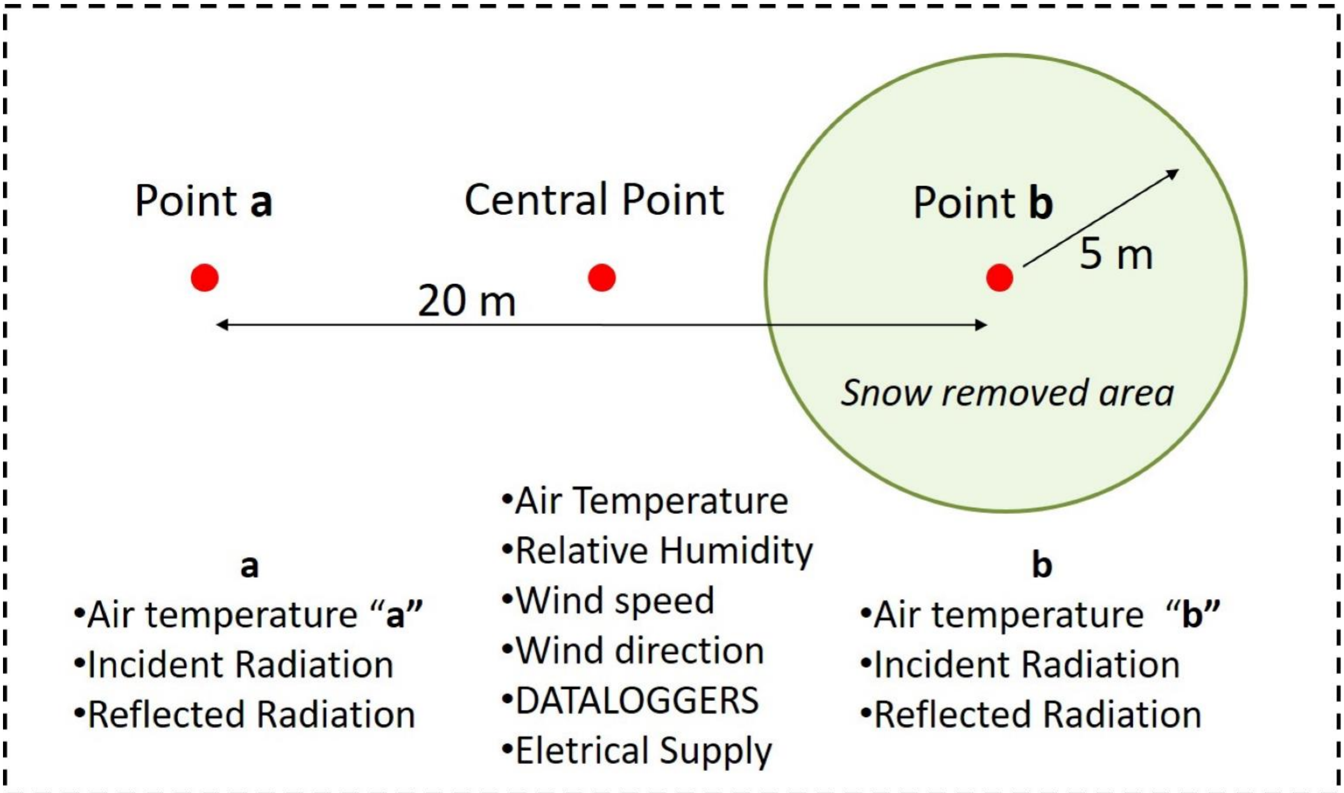
525 

Figure 1: Scheme of the installation area. Points “*a*” and “*b*” host the identical thermometers and shields of each couple. The central point hosts auxiliary equipment, data loggers and sensors for measuring quantities of influence.

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530 **Figure 2: Part of the collected couples of instruments ready for the preliminary laboratory characterisation.**

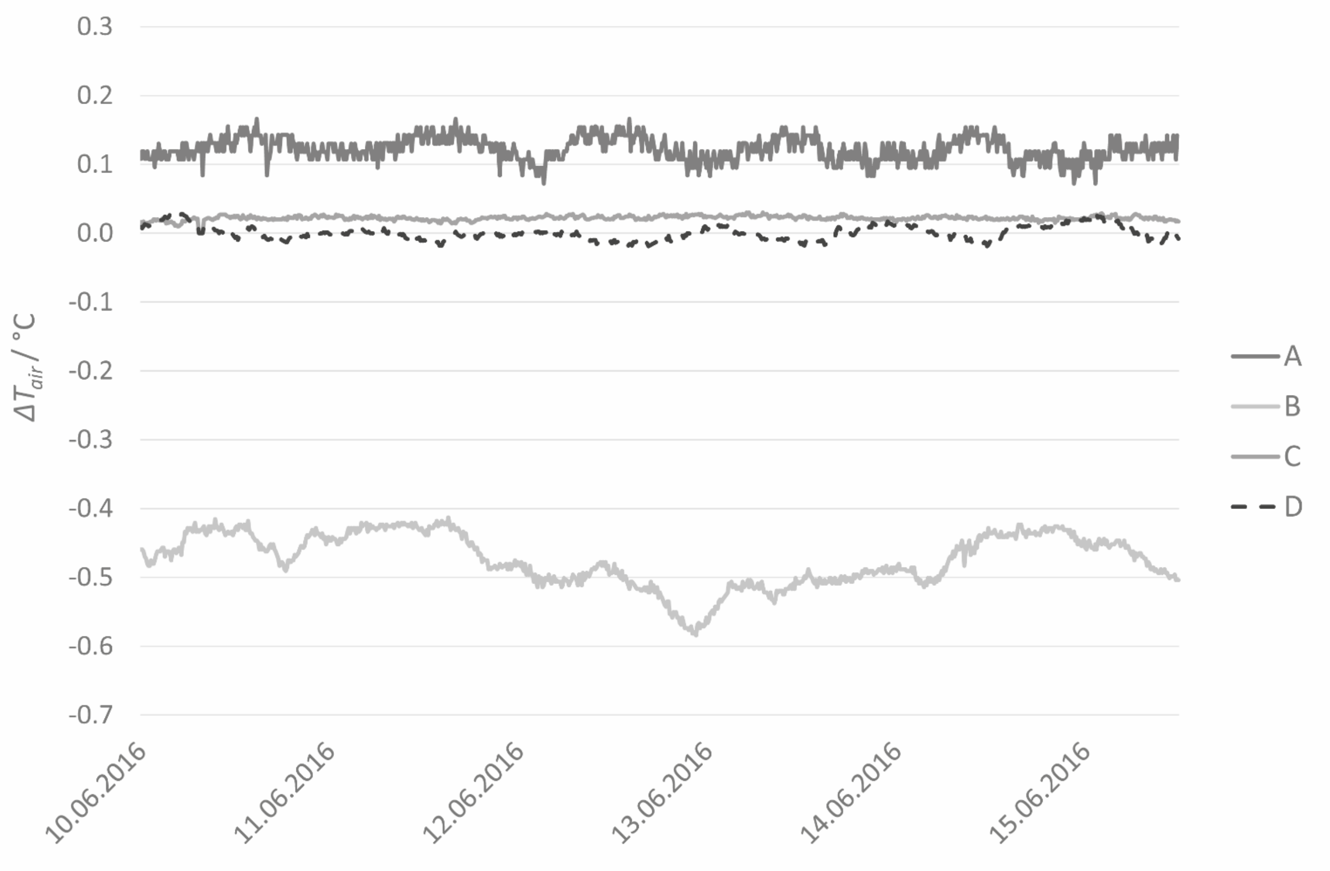

Figure 3: Example of laboratory characterisation for four couples of sensors. One-week acquisition of differences between the readings of the two sensors of the pair.

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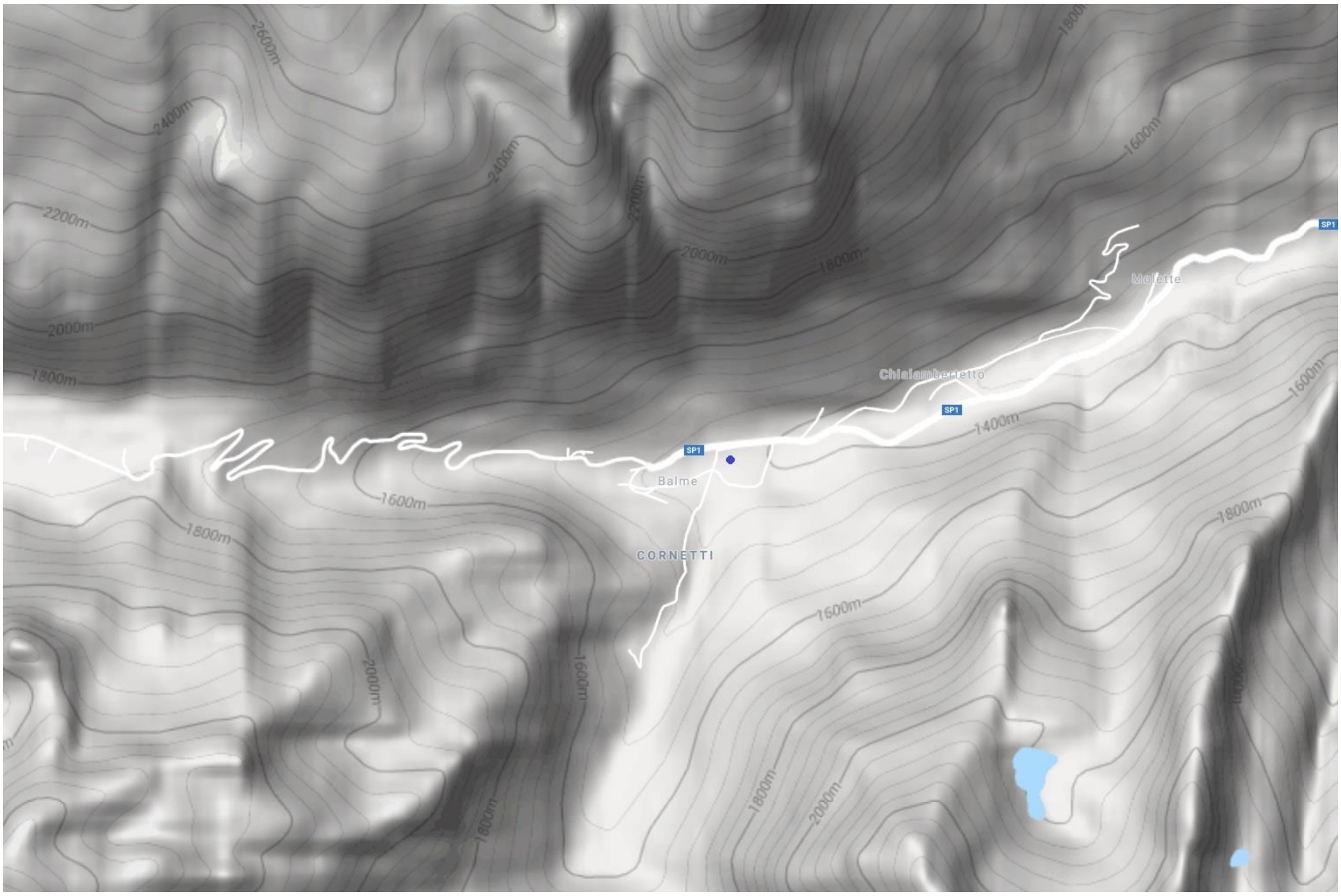

Figure 4: **Google Relief map (©Google, 2017) of the area (approximately 2.5x1.5 km) surrounding the measurement site and its topography. The Ala valley is aligned in an East-West way: mountains close the valley from the North, while on the South a small lateral valley opens up the horizon to other high mountains. The measurement site is marked with a blue dot.**

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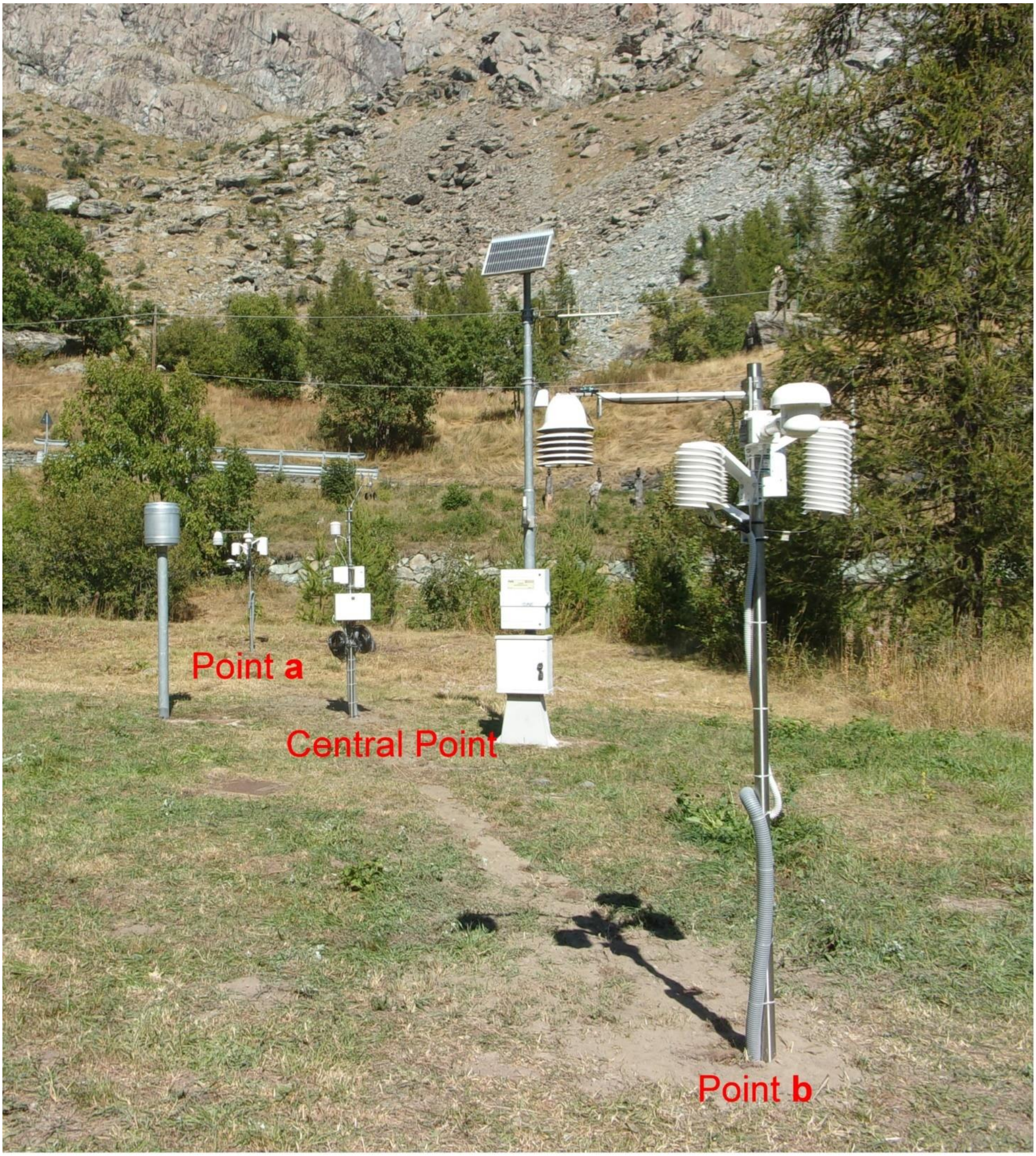
Figure 5: Zoomed in (200x100 m) Google Earth (©Google 2017) picture of the experimental site. The approximate positions of the two measurement stations are marked by the yellow spots.



545 **Figure 6: The experimental site in summer, after the installation of the instruments.**

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Figure 7: The measurement site in its original, un-shovelled configuration. In the background position *a*, where snow will be left. In the foreground position *b*, with snow still to be removed.

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Figure 8: Point *b* in snow-removed condition, after a snowfall.

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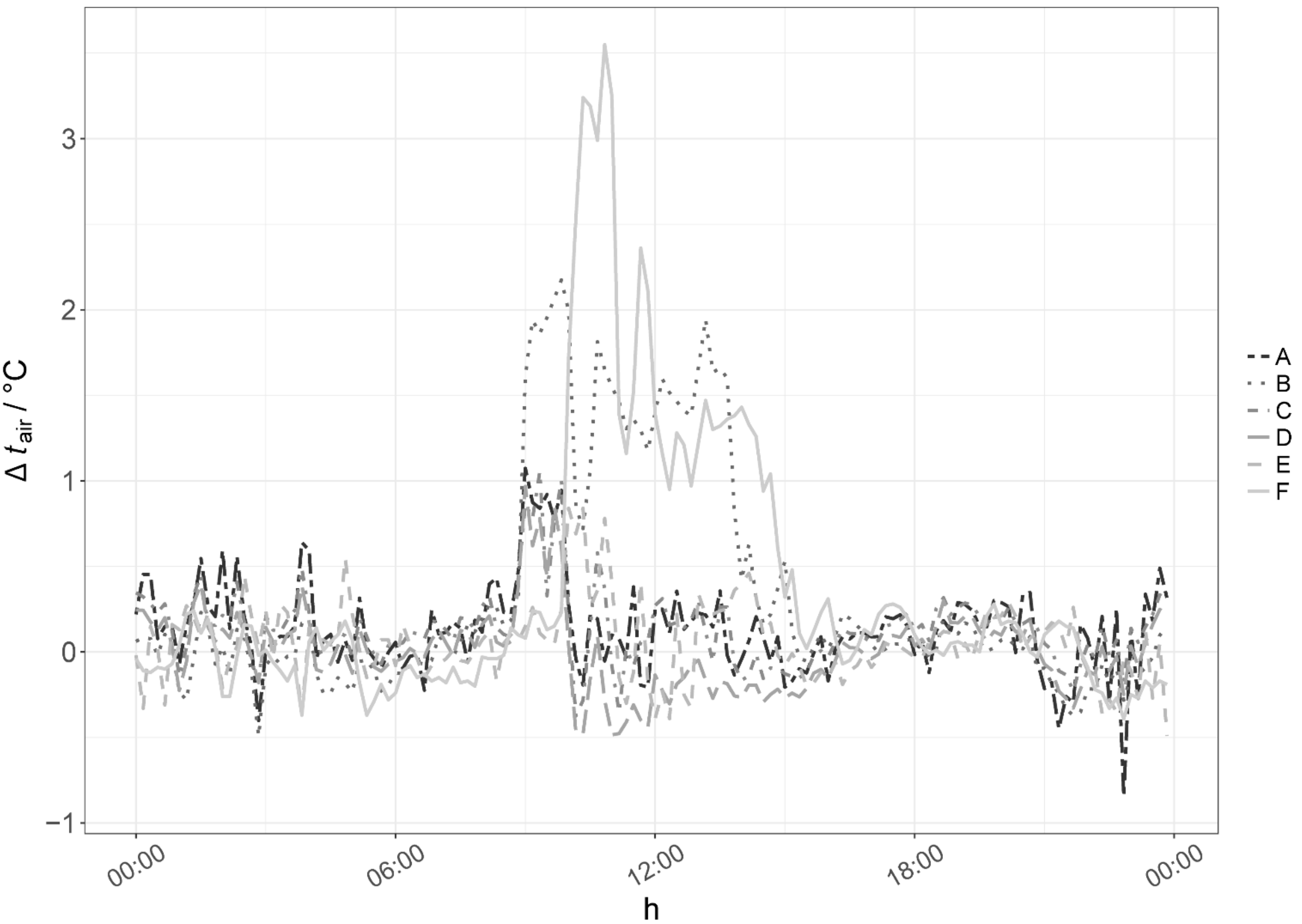

555 **Figure 9: A typical plot of a one-day-long acquisition, demonstrating the studied effect in terms of temperature differences Δt_{air} between each of the couples of identical sensors (25 February 2017). The day has been selected as a representative example, with snow removed some days before. Weather was mainly sunny, with maximum incident radiation of 700 W·m^{-2}, maximum reflected radiation of 500 W·m^{-2} in snow condition and less than 100 W·m^{-2} in the area where snow was removed. Hours are reported in local time (Central European Time - CET).**

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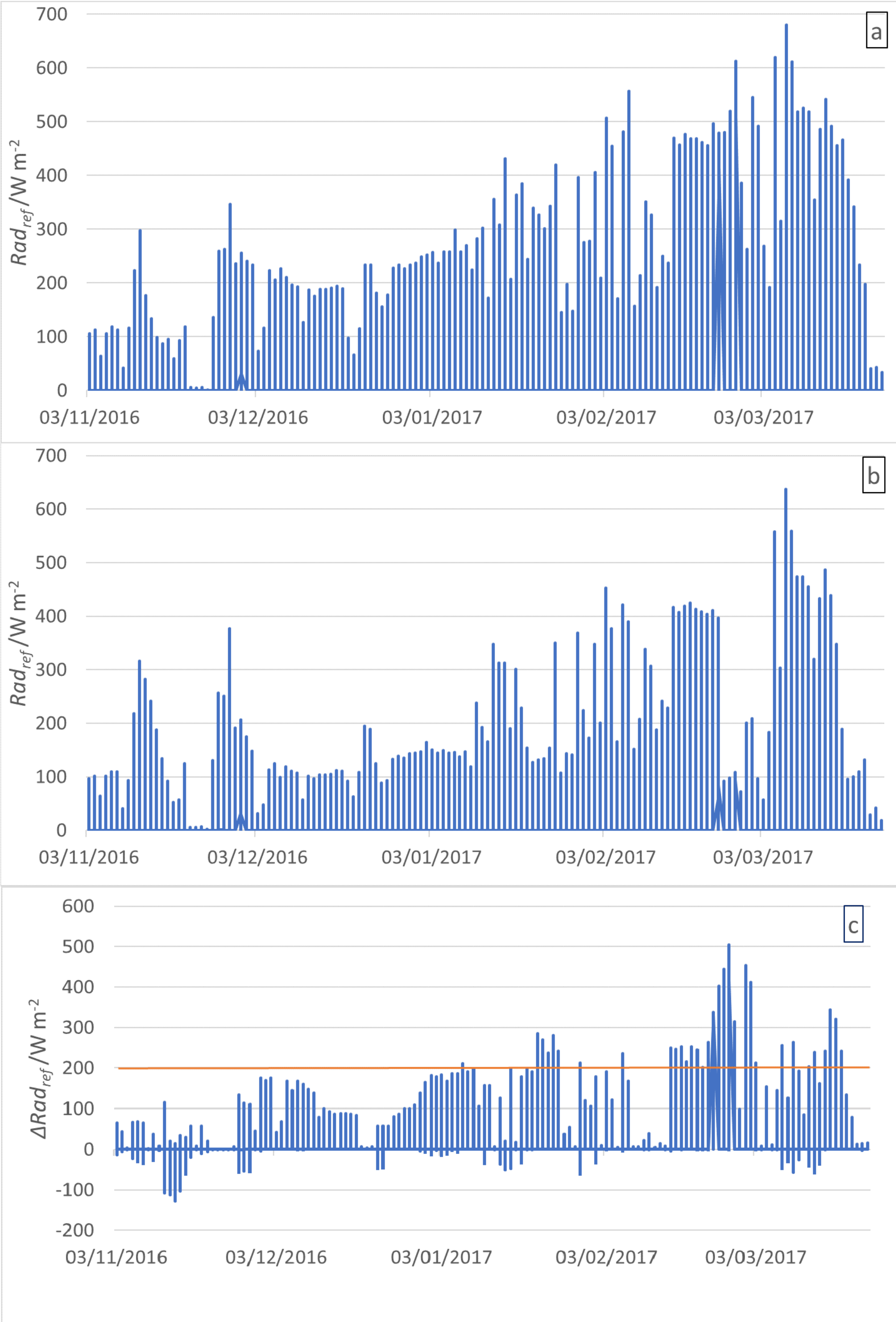

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Figure 10: Results of measured reflected radiation recorded in position *a* - sensor above snow (a), and *b* – sensor above natural ground (b) during the entire period of the experiment. Differences of reflect radiation recorded in position "*a*" and "*b*", $\Delta Rad_{\mathrm{ref}}$, are shown in (c). The threshold chosen to better select the associated temperature differences are indicated by horizontal lines.

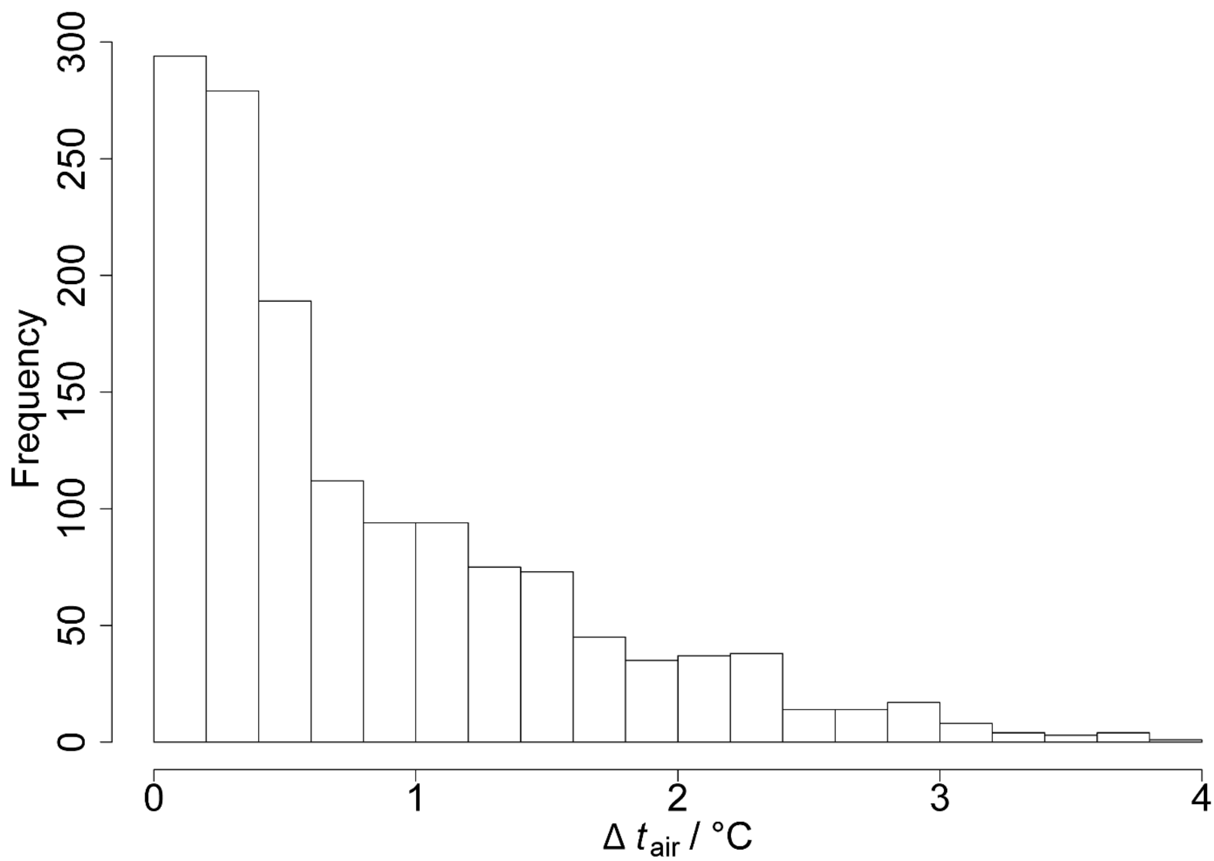

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Figure 11: Frequency of temperature difference, Δt_{air}, considering all pairs of instruments, and the records that exceed the radiation difference threshold.

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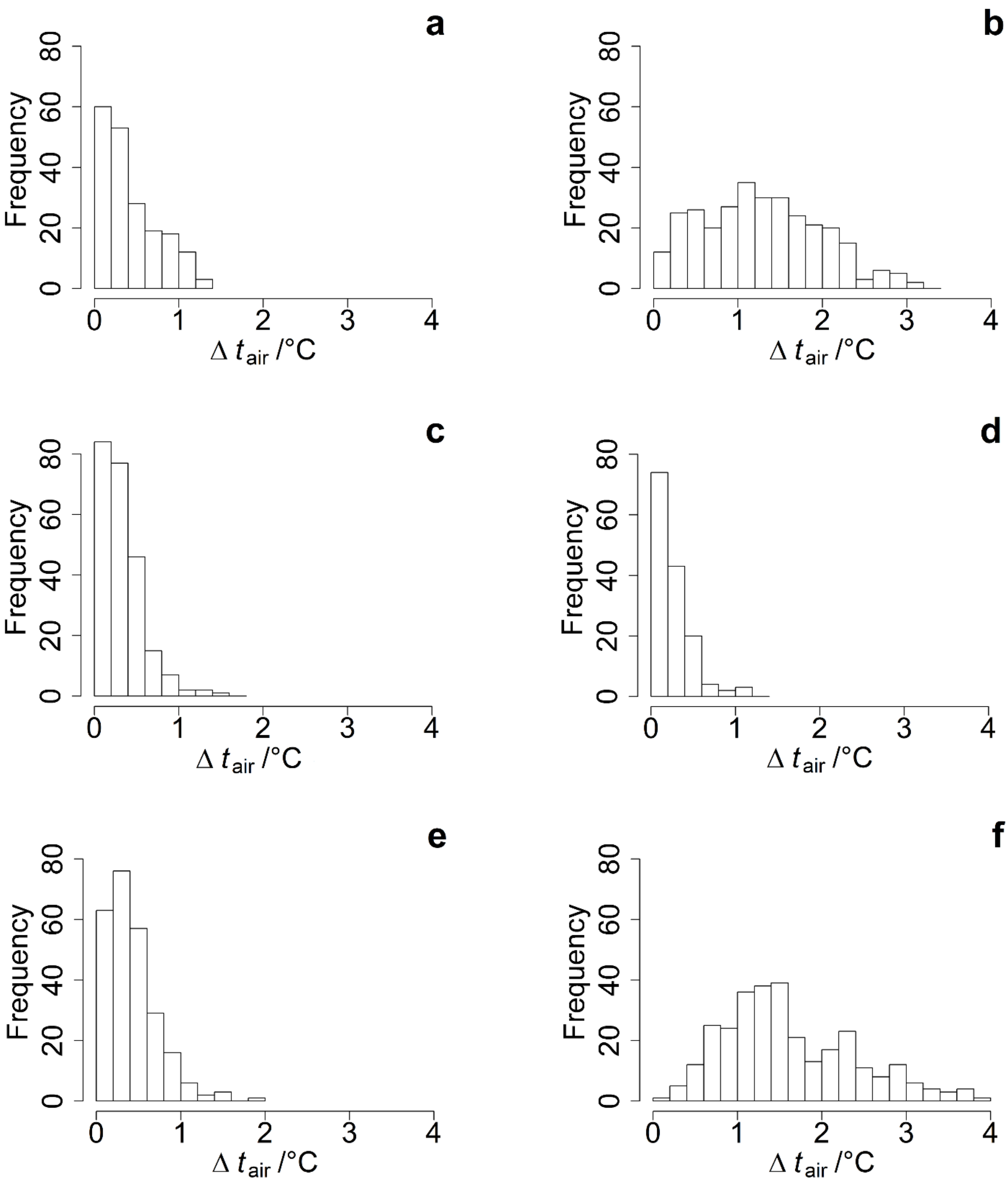

570 **Figure 12: Results of evaluation of Δt_{air} for each pair of sensors from different manufacturers. Instrument types are identified with letters from a to f. The histogram is divided in bins of 0.2 °C and the number of occurrences of Δt_{air} is shown for each instrument.**

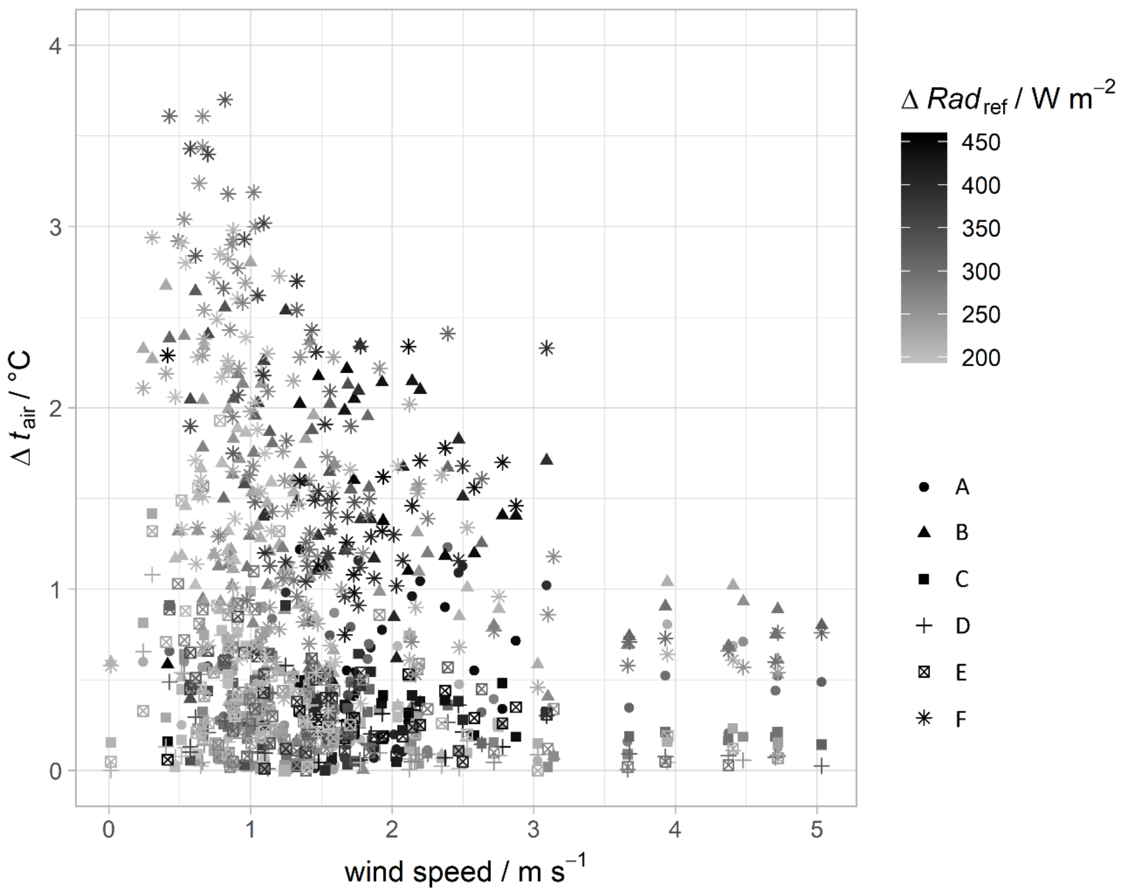

Figure 13: Temperature difference Δt_{air} measured as a function of wind speed for all the instrument type A-F. Grey scale is used to
575 **evidence the value of the difference of reflected radiation, $\Delta Rad_{\mathrm{ref}}$, related to each value of Δt_{air} reported.**

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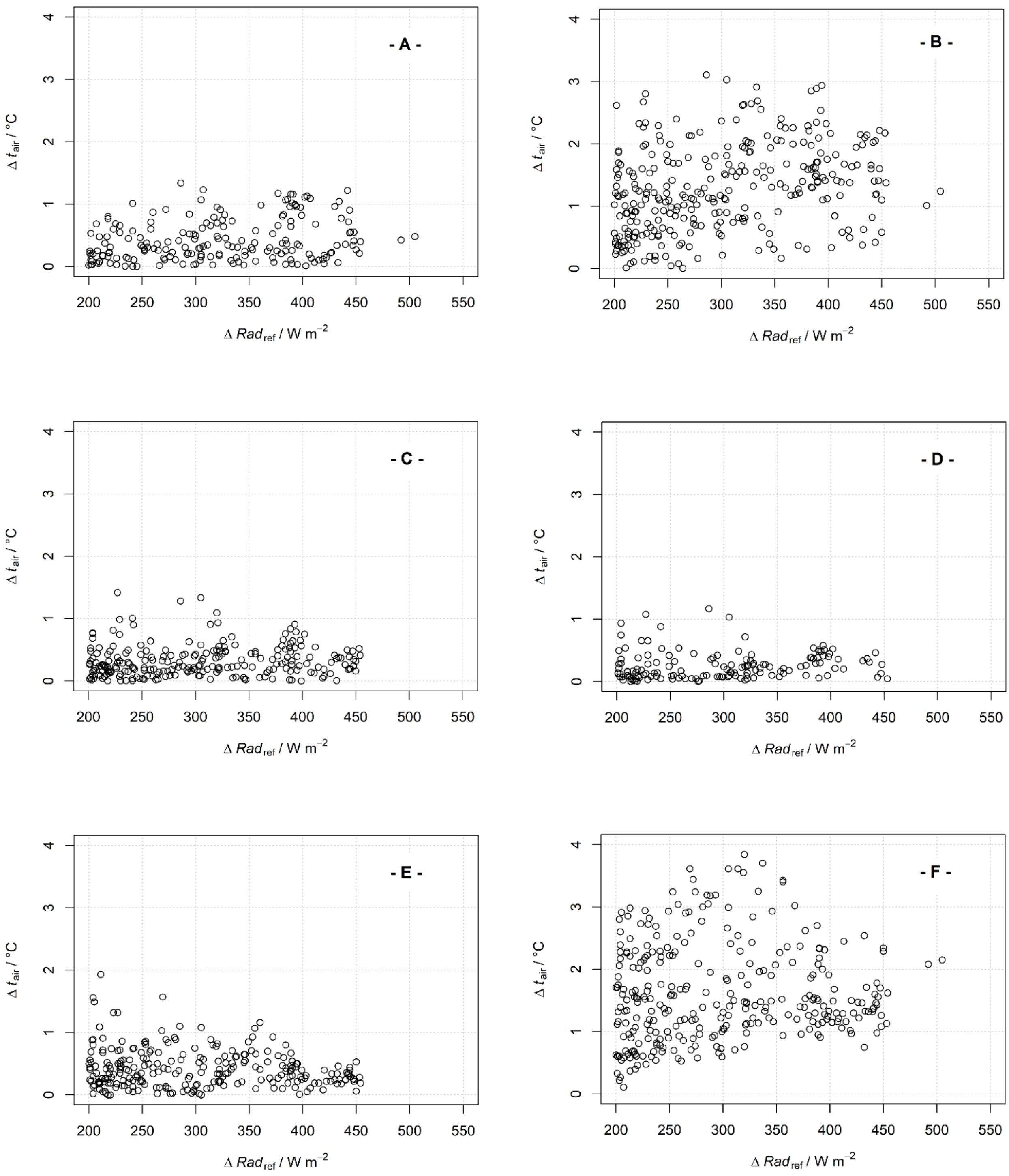

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Figure 14: Temperature differences Δt_{air} evaluated in the data analysis plotted as a function of reflected radiation difference between point *a* and *b*. Labels from A to F identify the instrument type.

Table 1. Selected air temperature measurement instruments and their main characteristics.

Instrument ID	**Sensor type**	**Shield type**
Type A	Pt100	Fan aspirated
Type B	Pt100	Passive
Type C	Thermo hygrometer	Passive helicoidal
Type D	Thermo hygrometer	Passive helicoidal
Type E	Pt100	Passive
Type F	Pt100	Passive

Table 2. Sensors used for measuring the quantities of influence and their positioning referred to the scheme of Figure 1.

Quantity	**Sensor type**	**positioning (see Fig. 1)**
Temperature and Relative Humidity	Pt100 class A and capacitor (thermo-hygrometer)	Central point
Wind	Cups and vane	Central point
Global incident Radiation	Thermopile (pyranometer)	Point *a*, facing up
Global reflected Radiation	Thermopile (pyranometer)	Point *a*, facing down

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Global incident Radiation	Thermopile (pyranometer)	Point *b*, facing up
Global reflected Radiation	Thermopile (pyranometer)	Point *b*, facing down

Table 3. Results of the evaluation of Δt_{instr} and the associated uncertainties for each instrument type.

Sensor type	**Type A (°C)**	**Type B (°C)**	**Type C (°C)**	**Type D (°C)**	**Type E (°C)**	**Type F (°C)**
Δt_{instr}	0.12	-0.47	0.022	0.002	0.043	0.063
$u_{\Delta t_{instr}}$	0.05	0.09	0.015	0.026	0.035	0.067

Table 4. Results of the evaluation of Δt_{site} and the associated uncertainties for each instrument type.

Sensor type	**Type A (°C)**	**Type B (°C)**	**Type C (°C)**	**Type D (°C)**	**Type E (°C)**	**Type F (°C)**
Δt_{site}	0.02	0.17	0.12	0.10	0.08	0.11
$u_{\Delta t_{site}}$	0.02	0.17	0.11	0.11	0.09	0.09

Table 5. Contributions to the uncertainty budget evaluated in the laboratory and on-field characterization.

	Type A (°C)	**Type B (°C)**	**Type C (°C)**	**Type D (°C)**	**Type E (°C)**	**Type F (°C)**
u_{res}	0.012	0.003	0.001	0.001	0.01	0.01
u_{lab}	0.01	0.01	0.01	0.01	0.01	0.01

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$u_{\Delta t_{instr}}$	0.05	0.09	0.015	0.026	0.035	0.067
$u_{\Delta t_{site}}$	0.02	0.17	0.11	0.11	0.09	0.09
$u_{\Delta t_{air}}$	0.05	0.19	0.11	0.11	0.10	0.11
$\boldsymbol{U}_{\Delta t_{air}}$ (k = 2)	**0.11**	**0.38**	**0.22**	**0.23**	**0.20**	**0.23**

Table 6. Maximum difference - Δt_{air} - measured, for each manufacturer on a significant number of events and with the associated uncertainty from Table 5. Values are rounded at first decimal and $U_{\Delta t_{air}}$ rounded up according to normative (EA-4/02).

Instrument Type	**Max diff. Δt_{air} (°C)**	**$U_{\Delta t_{air}}$ (°C) (*k* = 2)**
A	1.4	0.1
B	3.1	0.4
C	1.4	0.3
D	1.2	0.3
E	1.9	0.2
F	3.8	0.3