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An analysis of air-soil temperature differences at five locations: Application to passive standoff chemical detection

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Defence R&D Canada – Valcartier
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Abstract

For a passive spectral sensor such as CATSI (Compact ATmospheric Sounding Interferometer), the temperature difference (ΔT) that exists between a chemical cloud and the background scene is of prime importance because it is linked to the radiative contrast of the target. The larger ΔT, the better the radiative contrast and the more accurate is the detection and identification, of the cloud.

The purpose of this memorandum is to establish statistics on realistic air-soil temperature differences to be used to estimate the detection performance of CATSI-type sensors in a variety of scenarios and environments. To this end, an analysis of the air-soil temperature differences is presented for five locations around the world; namely, 1- Sanborn Field, Boone County, Missouri, USA, 2- Novelty, Knox County, Missouri, USA, 3- Macquarie University, Sydney, Australia, 4- Murdoch University, Perth, Australia, and 5- Bylot Island, Nunavut, Canada. The results of the analysis indicate that the statistics of the air-soil temperature differences are similar from one location to another. The average statistics over the five locations show a mean air-soil temperature difference of 3.5 °C and a median of 2.8 °C. An air-soil temperature difference of less than one degree Celsius occurs less than 14% of the time on the average. This suggests that, on average, air-soil temperature contrasts should yield good detection probabilities 86% of the time.

Résumé

Pour un capteur spectral passif comme CATSI (Compact ATmospheric Sounding Interferometer), la différence de température (ΔT) qui existe entre un nuage chimique et la scène d’arrière-plan est importante parce qu'elle est liée au contraste radiatif de la cible. Plus ΔT est grand, meilleur est le contraste radiatif et donc plus la détection et l'identification sont précises.

Le but de ce mémorandum est d`établir des statistiques sur les différences de température air-sol qui pourront être utilisées afin de déterminer la performance de détection des capteurs de type CATSI pour divers scénarios et environnements. À cette fin, on présente une analyse des différences de température air-sol pour cinq (5) emplacements autour du monde : 1- Banborn Field, Boone County, Missouri, USA, 2- Novelty, Knox County, Missouri, USA, 3- Macquarie University, Sydney, Australie, 4- Murdoch University, Perth, Australie et 5- île Bylot, Nunavut, Canada. Les résultats de l’analyse indiquent que les statistiques sur les différences de température air-sol sont similaires d’un emplacement à l’autre. La moyenne des statistiques sur les cinq emplacements montre une différence de température air-sol de 3,5 °C (valeur absolue) et une valeur médiane de 2,8 °C. L’occurrence à l’intérieur du premier degré Celsius est en moyenne inférieure à 14 % ce qui suggère que les contrastes de température air-

sol conduisant à de bonnes probabilités de détection se produisent en moyenne 86 % du temps.

Executive summary

Chemical warfare (CW) agents such as mustard and nerve agents present a very serious threat to military forces and civilian populations. Current reconnaissance systems depend on the use of point sensors to detect these types of agents. However, it would be especially advantageous if CW agents could be detected with the use of standoff sensors in order to rapidly monitor large surface areas from ground-based or airborne platforms.

Fourier-transform infrared (FTIR) spectrometers are used in a variety of applications for the passive remote sensing of atmospheric species and pollutants. Defence Research and Development Canada – Valcartier is currently developing a FTIR radiometric technique and a standoff sensor (CATSI) for the passive detection and identification of chemical agents at ranges up to 5 km. This type of sensor will assist the Canadian Forces (CF) in their surveillance operations, which should provide a significant force multiplier in the event of a chemical attack.

The Compact ATmospheric Sensing Interferometer (CATSI) is a Fourier-transform infrared spectrometer with two adjacent fields of view. The instrument uses a double-input beam FTIR interferometer where one input looks at the background scene and the other looks at the target scene. With this configuration, the two scenes can be optically subtracted in real time to yield a chemical cloud spectrum that is minimally perturbed by the background radiation.

In passive standoff detection, the temperature difference (ΔT) that exists between a chemical cloud and the background scene is important as it is linked to the radiative contrast of the target. The larger ΔT, the better the radiative contrast and the more accurate is the detection and identification of chemical agents or pollutants.

The purpose of this study is to establish statistics on realistic air-soil temperature differences that can be used to estimate the detection performances of CATSI-type sensors in a variety of scenarios and environments. To this end, an analysis of the air-soil temperature differences is presented for five locations around the world; namely, 1- Sanborn Field, Boone County, Missouri, USA, 2- Novelty, Knox County, Missouri, USA, 3- Macquarie University, Sydney, Australia, 4- Murdoch University, Perth, Australia, and 5- Bylot Island, Nunavut, Canada. These sites were selected because of the free and easy access to their data. The results of the analysis indicate that the statistics of the air-soil temperature differences are similar from one location to another. The average statistics over the five locations show a mean air-soil temperature difference of 3.5 °C and a median of 2.8 °C. An air-soil temperature difference of less than one degree Celsius occurs less than 14% of the time on the average. This suggests that on average, air-soil temperature contrasts should yield good detection probabilities 86% of the time.

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Sommaire

Les agents chimiques de combat (CW), tels le gaz moutarde et les agents neurotoxiques représentent une menace très sérieuse pour les forces militaires et les populations civiles. Les systèmes de reconnaissance actuels utilisent des capteurs ponctuels pour détecter le type de contamination sur les surfaces. Cependant, il serait particulièrement avantageux de pouvoir détecter les agents chimiques à l'aide de capteurs de télédétection afin de faire une surveillance rapide de surfaces étendues à partir d'une plate-forme au sol ou aéroportée.

Les spectromètres infrarouges à transformée de Fourier (FTIR) sont employés dans une variété d'applications pour la télédétection passive d'espèces atmosphériques et de polluants. Recherche et développement pour la défense Canada - Valcartier met présentement au point une technique radiométrique et un capteur FTIR (CATSI) pour la télédétection passive et l'identification d'agents chimiques pour des distances allant jusqu'à 5 kilomètres. Ce type de capteur sera utilisé par les Forces canadiennes (FC) dans leurs opérations de surveillance, ce qui devrait fournir un avantage considérable dans l'éventualité d'une attaque chimique.

CATSI (Compact ATmospheric Sensing Interferometer) est un spectromètre infrarouge à transformée de Fourier avec deux champs de vision adjacents. Cet instrument utilise un interféromètre FTIR à deux entrées dont l'une pointe sur la scène d'arrière-plan et l'autre sur la scène cible. Avec ce type d'instrument, les deux scènes mesurées sont soustraites optiquement en temps réel, produisant ainsi un spectre du nuage chimique minimalement perturbé par la radiation d'arrière-plan.

En télédétection passive, la différence de température (ΔT) entre un nuage chimique et la scène de fond est importante parce que liée au contraste radiatif. Plus ΔT est grand, meilleur est le contraste radiatif et donc plus la détection et l'identification sont précises.

Le but de cette étude est d`établir des statistiques sur les différences de température air-sol qui pourront être utilisées afin de déterminer la performance de détection des capteurs de type CATSI pour divers scénarios et environnements. À cette fin, on présente une analyse des différences de température air-sol pour cinq (5) emplacements autour du monde : 1- Banborn Field, Boone County, Missouri, USA, 2- Novelty, Knox County, Missouri, USA, 3- Macquarie University, Sydney, Australie, 4- Murdoch University, Perth, Australie et 5- île Bylot, Nunavut, Canada. Ces emplacements ont été sélectionnés en raison de l'accès facile et gratuit aux données. Les résultats de l'analyse indiquent que les statistiques des différences de température air-sol sont similaires d'un emplacement à l'autre. La moyenne des statistiques sur les cinq emplacements montre une différence de température air-sol de 3,5 °C (valeur absolue) et une valeur médiane de 2,8 °C. L'occurrence à l'intérieur du premier degré Celsius est inférieure à 14 % ce qui suggère que les contrastes de température air-sol conduisant à de bonnes probabilités de détection se produisent en moyenne 86 % du temps.

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These people and organizations contributed to this document by granting access to data taken by their weather stations. Moreover, they improved the document content with complementary information pertaining to the geographical situation of the weather station (latitude, longitude and elevation) and the types of probes.

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1. Introduction

A variety of electro-optical sensors are being developed to assist the Canadian Forces in their surveillance operations. Among them, passive IR spectral sensors are becoming a vital technology for the remote sensing of the battlefield environment that can provide unique information. One of the most promising military applications in passive spectral surveillance is the passive standoff detection of chemical warfare (CW) agents. The proliferation of chemical weapons continues to be a serious threat to world security and there is a growing need for rapidly deployable field surveillance systems to provide timely and accurate chemical threat assessments, thus ensuring prompt avoidance and the deployment of appropriate countermeasures.

Fourier-transform infrared (FTIR) spectrometers are used in a variety of applications for the passive remote sensing of atmospheric species and pollutants. Defence Research and Development Canada – Valcartier is currently developing CATSI (Compact ATmospheric Sensing Interferometer), a FTIR radiometer, for the passive standoff detection and identification of chemical agents at ranges up to 5 km. This type of sensor will assist the Canadian Forces (CF) in their continuous surveillance operations.

CATSI is a Fourier-transform infrared spectrometer with two adjacent fields of view [1] and a dual-beam interferometer that provides a differential detection capability. The differential detection method is based on the use of a double-input beam FTIR interferometer, where one input looks at the background scene and the other at the target scene. With this configuration, the two scenes can be optically combined into a single detector to give a real-time optical subtraction, and a cloud vapor spectrum that is minimally perturbed by the background radiation.

The purpose of this document is to build statistics on realistic air-soil temperature differences that can be used to estimate the detection performances of CATSI-type sensors in a variety of scenarios and environments. Chapter 2 discusses the detection principles and the importance of the temperature difference for an instrument such as CATSI. Chapters 3, 4, 5, 6 and 7 present temperature measurement results for five locations around the world: Sanborn Field, Boone County, Missouri, USA; Novelty, Knox County, Missouri, USA; Macquarie University, Sydney, Australia; Murdoch University, Perth, Australia; and Nunavut, Canada. Basic statistics, histogram, mean, median, and occurrence within the first degree are reported for the temperature difference at each location. A summary of the main findings of this work are given in Chapter 8 and conclusions are presented in Chapter 9.

This work was carried out at DRDC Valcartier from November 2003 to February 2004 as a Task under work unit 15ev13: “Alternate Sensing”.

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2. Background

A 3-layer atmospheric model is depicted in Figure 1[2]. The diagram shows the radiance components probed by the sensor (left side of Figure 1) for a clear atmosphere (L_{clear}), and for an atmosphere containing a gas (L_{gas}). The goal of this chapter is to link the differential radiance (L_{gas}-L_{clear}) to the temperature difference between the gas and the background clear atmosphere. Table 1 lists the parameters of the model.

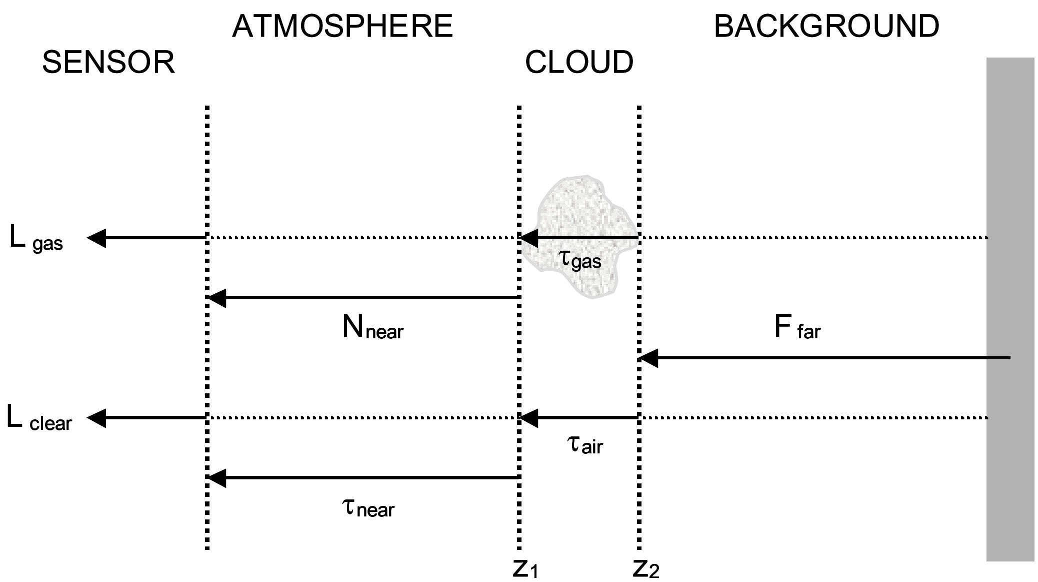

***Figure 1.** Diagram of the 3-layer model*

With reference to Figure 1, the radiance for the field of view associated with the clear atmosphere is given by

$$L_{clear} = \tau_{near}\tau_{air}F_{far} + (1-\tau_{air})\tau_{near}B_{air} + N_{near}\ , \tag{1}$$

and the radiance for the field of view associated with the atmosphere contaminated by the gas is given by

$$L_{gas} = \tau_{near}\tau_{gas}F_{far} + (1-\tau_{gas})\tau_{near}B_{gas} + N_{near}\ . \tag{2}$$

In the two previous equations, F_{far} corresponds to the far-field radiance evaluated at position z_2, τ_{near} is the transmittance for position z_2 to the sensor, B_{air} and τ_{air} are the Planck radiance and the transmittance associated with the air layer, B_{gas} and τ_{gas} are the Planck radiance and the transmittance associated with the gas layer, and N_{near} corresponds to the near-field path radiance of the atmosphere from position z_1 to the sensor. The CATSI instrument optically subtracts the radiance of the two fields of view, to yield the differential radiance:

$$\Delta L \equiv L_{gas} - L_{clear} = \tau_{near}\left(\tau_{air} - \tau_{gas}\right)\left[B_{gas} - F_{far}\right] + \left(1 - \tau_{air}\right)\tau_{near}\left[B_{gas} - B_{air}\right] \ . \tag{3}$$

Table 1. *Description of parameters used in the 3-layer model*

PARAMETER	DESCRIPTION
F_{far}	Far-field radiance evaluated at position z_2
τ_{near}	Transmittance from position z_1 to the sensor
B_{air}	Planck radiance associated with the air layer
τ_{air}	Transmittance associated with the air layer
B_{gas}	Planck radiance associated with the gas layer
τ_{gas}	Transmittance associated with the gas layer
N_{near}	Near-field path radiance of the atmosphere from position z_1 to the sensor
L_{clear}	Total radiance of a clear atmosphere (free of target gas)
L_{gas}	Total radiance of an atmosphere containing a target gas layer at position z_1

Equation (3) can be simplified using $\tau_{air} \approx 1$ to give

$$\Delta L \approx \tau_{near}\left(1 - \tau_{gas}\right)\left[B_{gas} - F_{far}\right] \ , \tag{4}$$

when B_{gas} is the Planck radiance associated with the temperature of the gas cloud (T_{gas}). Assuming that the distance between the background and z_2 is small and that the background emissivity is large for the wavenumber range of interest, F_{far} can be assumed to be the Planck radiance with the brightness temperature of the background (T_{bkg}).

The Plank radiance is a function of wavelength (λ) and temperature (T) of the blackbody such that

$$B(\lambda, T) = \frac{2hc^2}{\lambda^3}\frac{1}{e^{\frac{hc}{\lambda kT}} - 1} \ , \tag{5}$$

where λ is in m, T in K, h (J/K) is Planck's constant, c (m/s) is the speed of light in vacuum, and k (Js) is Boltzmann's constant. Equation (4) can now be rewritten as

$$\Delta L \approx \tau_{near}\left(1-\tau_{gas}\right)\left[B\left(\lambda,T_{gas}\right)-B\left(\lambda,T_{bkg}\right)\right] , \tag{6}$$

such that after performing a Taylor series expansion, the first-order approximation yields

$$\Delta L \approx \tau_{near}\left(1-\tau_{gas}\right)\frac{dB}{dT}\bigg|_{T=T_{gas}}\left(T_{gas}-T_{bkg}\right);\ T_{gas} \approx T_{bkg} \tag{7}$$

for the differential radiance.

Furthermore, assuming that soon after a cloud of gas is released, it will be in thermal equilibrium with the ambient air; the gas temperature can be estimated to be the same as the air temperature, and Eq. (7) becomes

$$\Delta L \approx \tau_{near}\left(1-\tau_{gas}\right)\frac{dB}{dT}\bigg|_{T=T_{air}}\left(T_{air}-T_{bkg}\right). \tag{8}$$

Equation (8) shows the importance of the temperature difference between the air and the background for the standoff detection of a gas cloud. The differential radiance is related to the temperature difference; the larger the temperature difference, the larger the corresponding differential radiance, and the detection probability is maximized.

In principle, the detection performance of CATSI-type sensors should be estimated using realistic background scene temperatures obtained from relevant environments. These background scenes can be a vegetal cover, a mountain, a concrete building, and many other types of natural objects. As a first attempt to evaluate the air-background temperature contrast at many locations around the world we have made the assumption that the soil temperature is a good first-order estimate of the actual background temperature at that location. This assumption is based on the fact that most natural backgrounds (excluding sky and metallic backgrounds) have an emissivity similar to that for soil (>0.9). The error resulting from this assumption is estimated to be less than 10%. For the remainder of this document, the temperature of the background is assumed to be equal to the soil temperature.

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3. Results from Sanborn Field, Boone County, Missouri, USA

This weather station is located in the city of Sanborn Field, Boone County, Missouri, USA [3]. Its latitude, longitude and elevation are 38 degrees 57 minutes north, 92 degrees 19 minutes west and 232 meters above mean sea level and the data were obtained on the Internet from the Missouri Historical Agricultural Weather Database [3].

3.1 Air and soil temperature variations in 2002

The air temperature is an hourly average obtained with a CS500 Vaisala Temperature and Relative Humidity Probe. The soil temperature probe is a Model 107 Temperature Probe from Campbell Scientific, Inc. Their precision is 1°C.

The top three graphs of Figure 2 show the recorded values of air and soil temperatures over the year. The soil temperature is taken in a bare soil; a fallow seedbed at depths of 5 and 10 cm. The bottom four graphs of Figure 2 present the air-soil temperature differences over the same time period. Figure 3 and Figure 4 are similar to Figure 2, except that they are taken only for a week during the winter and summer, respectively.

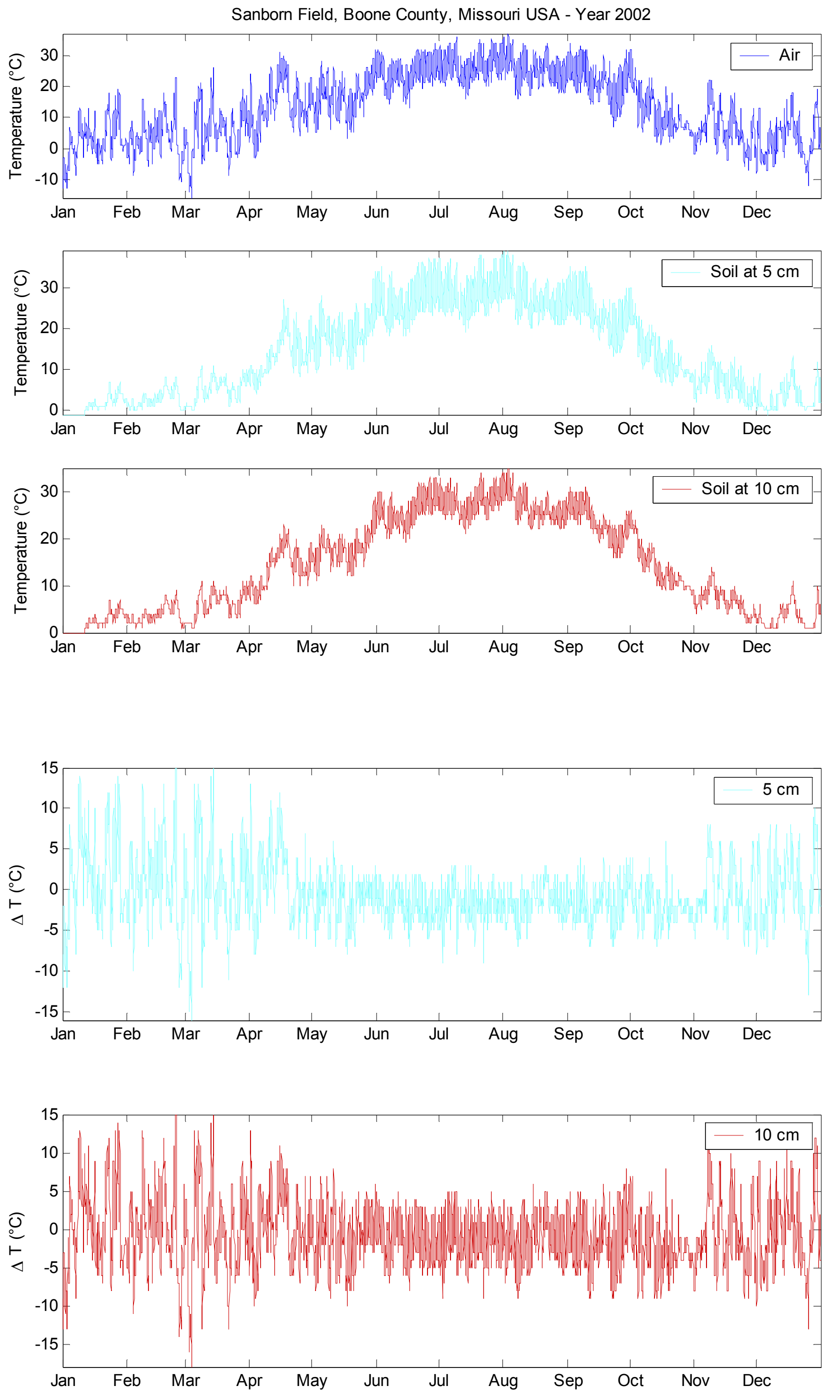

Figure 2. *Air and soil temperature measurements recorded in 2002 at Sanborn Field, Boone County, Missouri, USA. Top 3 graphs: temperature of air and bare soil at depths of 5 and 10 cm recorded every hour. Bottom 2 graphs: air-soil temperature differences.*

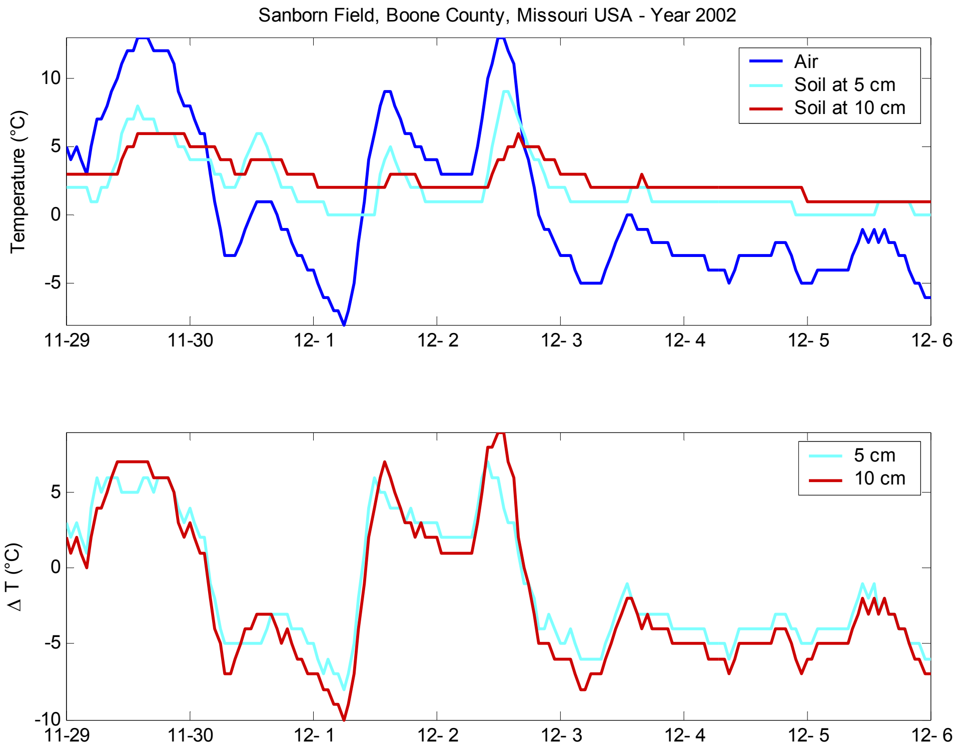

Figure 3. *Air and soil temperatures (top) and temperature differences (bottom) recorded over a week during the winter of 2002 at Sanborn Field, Boone County, Missouri, USA.*

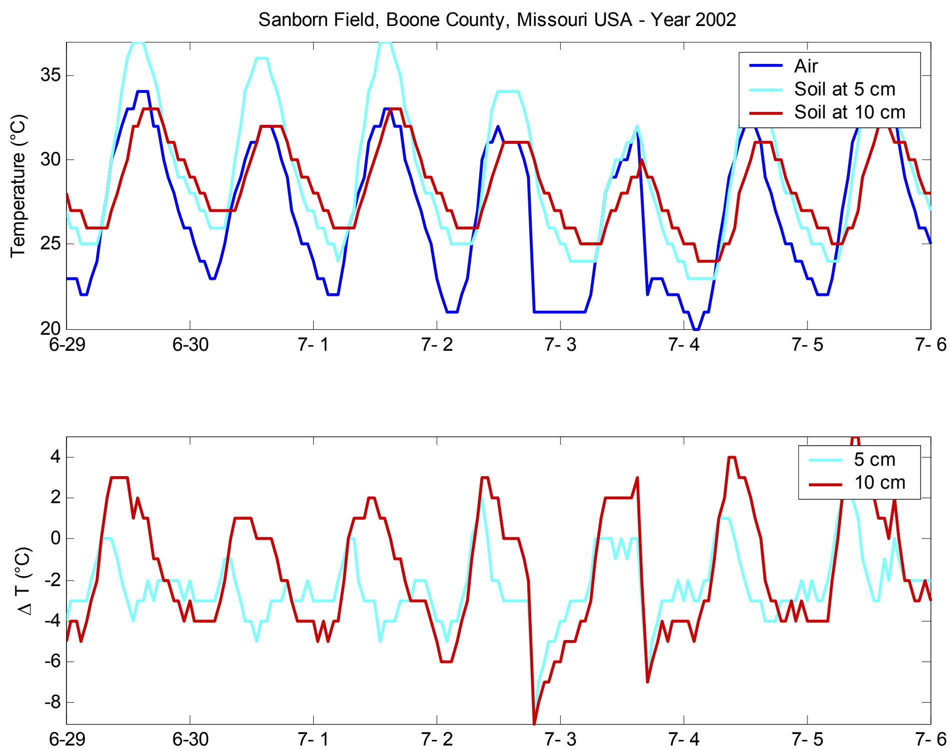

***Figure 4.** Air and soil temperatures (top) and temperature differences (bottom) recorded over a week during the summer of 2002 at Sanborn Field, Boone County, Missouri, USA.*

3.2 Histogram

As explained in Chapter 2, in passive standoff sensing, the detection efficiency of a sensor is proportional to the air-background temperature difference. Figure 5 presents the histogram of the absolute value of the temperature differences. The top graph is for a sensor depth of 5 cm, while the bottom graph is for a sensor depth of 10 cm. Each bin of the histograms counts the occurrence frequency of the absolute value of the temperature difference within an interval of 1°C. For example, every measurement result between 0 and 1°C is counted in the first bin. In the case of Figure 5, the temperature difference between 0 and 1°C occurs for 10.5% of the measured events for the sensor at a depth of 5 cm and for 8.3% of the events for the sensor at a depth of 10 cm. The mean temperature difference is 3 °C and the median is 2 °C for the sensor depth of 5 cm, and the mean is 4 °C and the median 3 °C for that at a depth of 10 cm. These values are calculated from the data not from the histogram.

For a sensor depth of 5 cm, 10% of the events occur for an absolute temperature difference below 0.95°C or above 6.64°C. At a depth of 10 cm, 10% of the events are below 1.09°C or above 7.57°C. These values are determined by assuming that the distribution is uniform between each degree. Table 2 contains the values of the mean, the median, the frequency occurrence and the upper limit of the temperature difference for the 10% and 90% percentile points for both sensor depths.

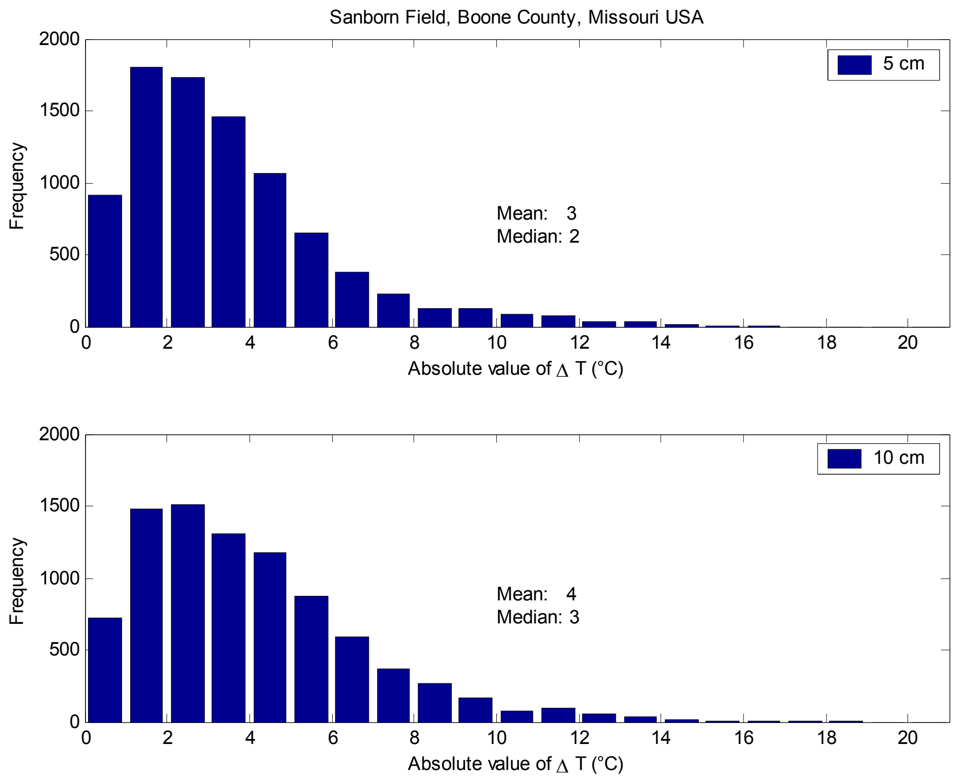

Figure 5. *Histogram of the absolute value of the air-soil temperature differences recorded in 2002 at Sanborn Field, Boone County, Missouri, USA. Top: the sensor depth of 5cm. Bottom: the sensor depth of 10 cm.*

Table 2. *Statistics for Sanborn Field, Missouri, USA*

LOCATION	*SENSOR DEPTH cm*	*MEAN °C*	*MEDIAN °C*	*TCO °C*		*OCCURRENCE %*		
				$T_{10\%}$	$T_{90\%}$	1°C	0.1°C	0.01°C
SANBORN FIELD, BOONE COUNTY, USA	5	3	2	0.95	6.64	10.5	NA	NA
SANBORN FIELD, BOONE COUNTY, USA	10	4	3	1.09	7.57	8.3	NA	NA

NA: Not available

TCO: Absolute temperature difference for a certain chance of occurrence.

$T_{10\%}$: Upper limit of the absolute temperature difference for 10% chance of occurrence.

$T_{90\%}$: Upper limit of the absolute temperature difference for 90% chance of occurrence.

4. Results from Novelty, Knox County, Missouri, USA

To investigate the impact of the type of soil on the air-soil temperature difference, a weather station located in Novelty, Knox County, Missouri, USA [3] was selected. Its latitude is 40 degrees 1 minutes 14 seconds north and its longitude is 92 degrees 11 minutes 24 seconds west. Its elevation is unknown. Again the data were obtained on the Internet from the Missouri Historical Agricultural Weather Database [3].

4.1 Effect of different soil types

The top four graphs of Figure 6 depict the temperature of the air and soil for the year 2002. Three types of soil are presented: bare soil, corn residue soil, and soybean residue soil. The bottom three graphs of Figure 6 present the air-soil temperature differences for the three types of soil. As seen, the temperature difference results are quite similar from one type of soil to another. Figure 7 and Figure 8 are similar to Figure 6, except that they are taken for a week during the winter and summer, respectively.

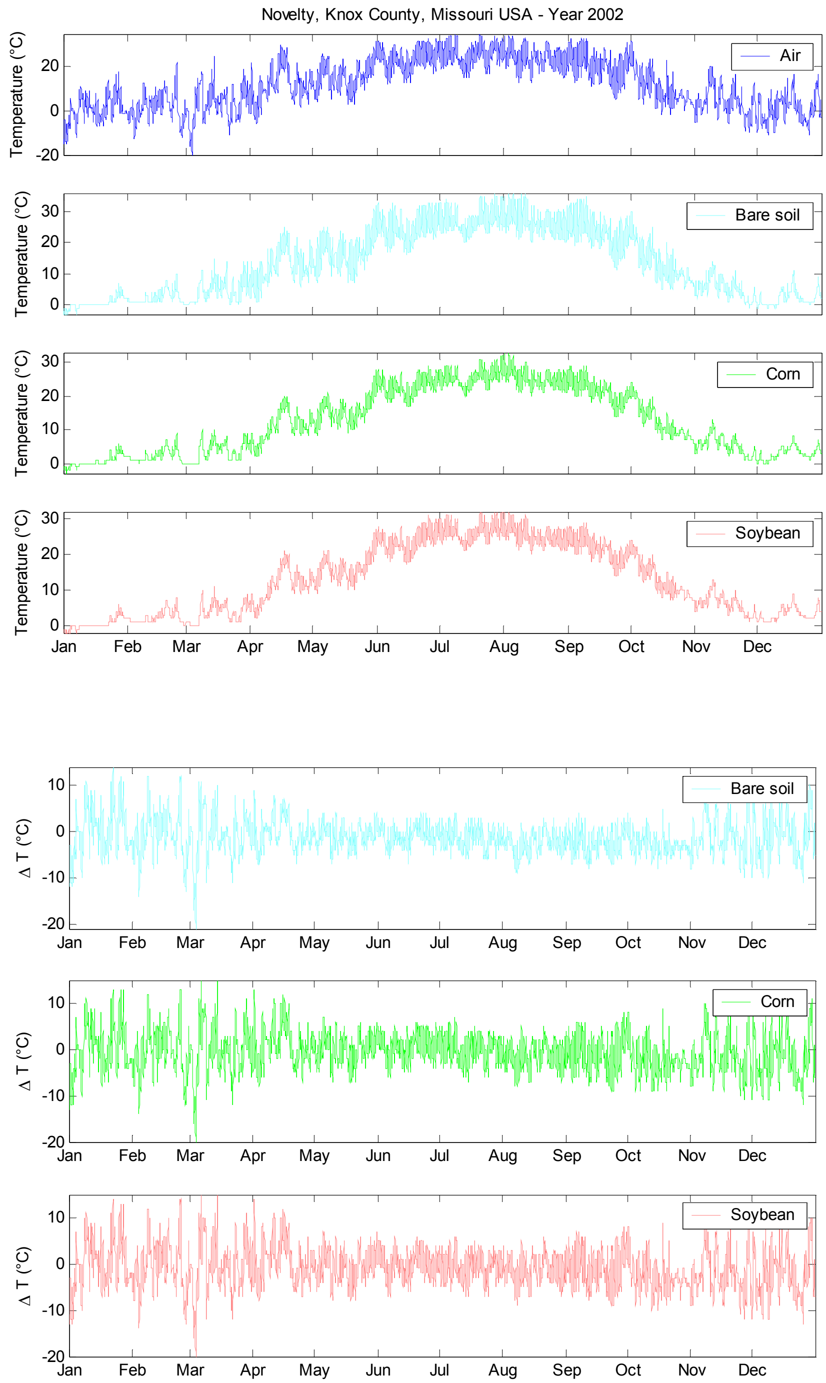

Figure 6. *Air and soil temperature measurements recorded in 2002 at Novelty, Knox County, Missouri, USA. Top 4 graphs: temperature of air, bare soil temperature, corn residue soil temperature and soybean residue soil temperature recorded every hour. Bottom 3 graphs: air-soil temperature differences.*

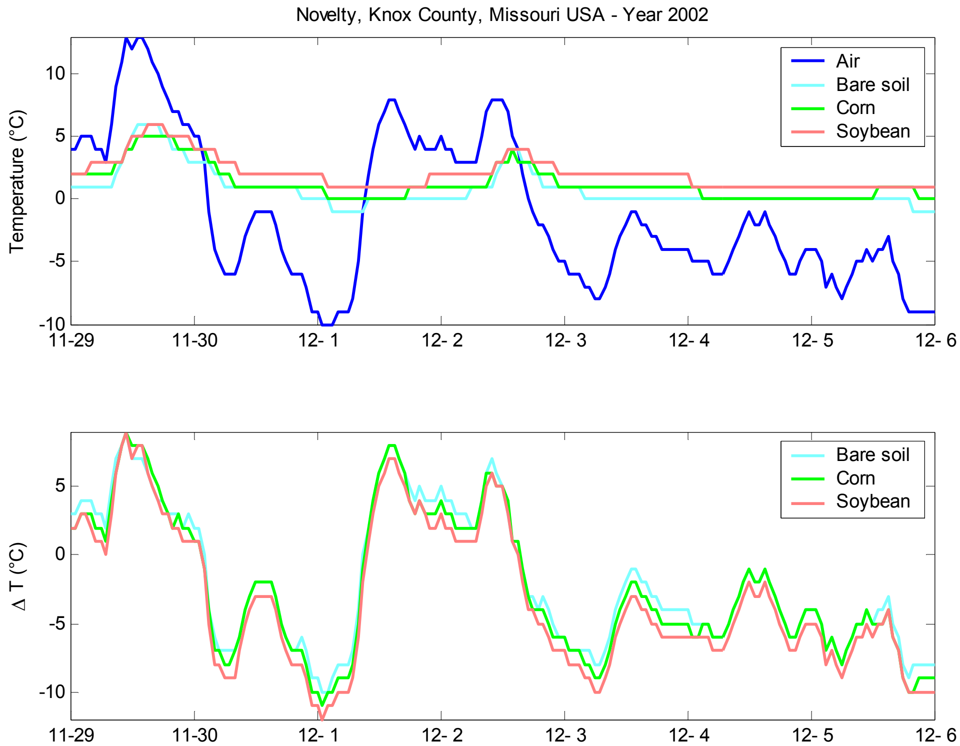

Figure 7. *Air and soil temperatures (top) and temperature differences (bottom) recorded over a week during the winter of 2002 at Novelty, Knox County, Missouri, USA.*

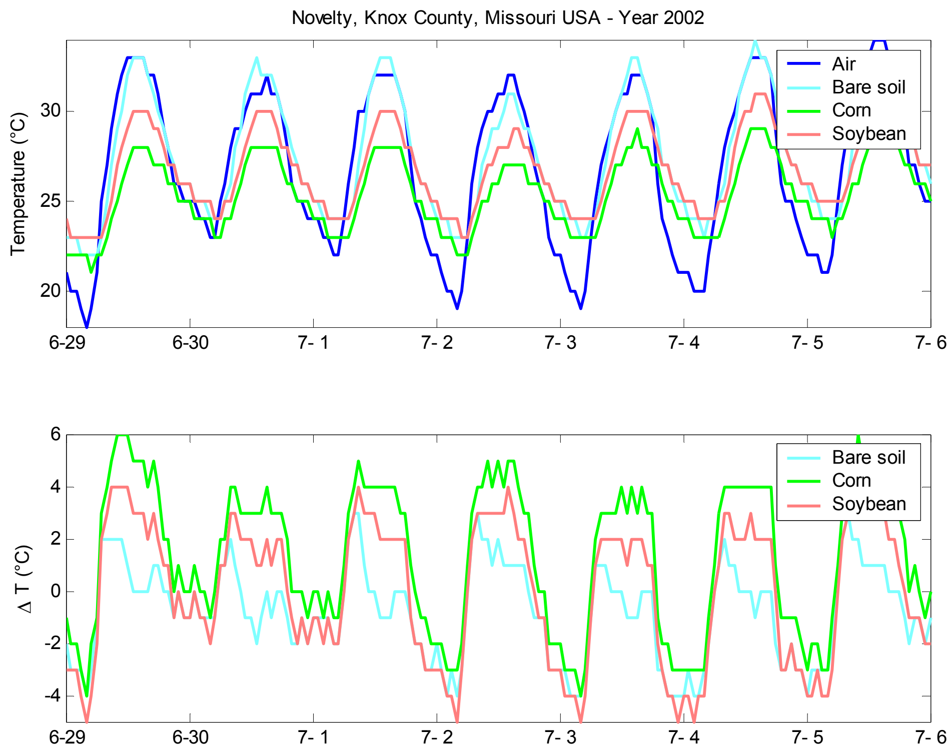

***Figure 8.** Air and soil temperatures (top) and temperature differences (bottom) recorded over a week during the summer of 2002 at Novelty, Knox County, Missouri, USA.*

4.2 Histogram

Figure 9 shows histograms for the three types of soils. The histograms of all three soils are very similar. The values of mean, median and frequency of occurrence within the first degree Celsius are summarized in Table 3. The means are 3°C, 3°C and 4°C for bare soil, corn soil and soybean soil, respectively, and; the medians are 3°C for all three soils.

For the bare soil, 10% of the events occur for an absolute temperature below 0.92°C or above 6.67°C; for corn residue, 10% of the events are below 1.05°C or above 7.43°C and for soybean residue, 10% of the events are below 1.10°C or above 7.67°C. Again for these calculations, the distribution is assumed to be uniform between each degree. These results are also summarized in Table 3.

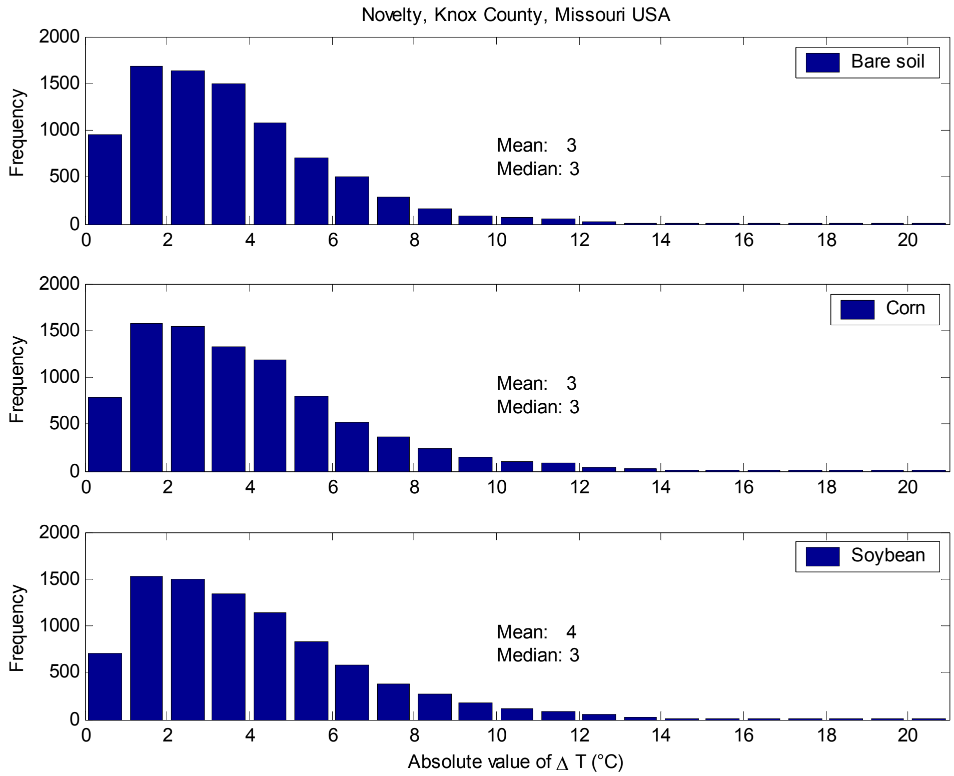

Figure 9. *Histogram of the absolute value of the air-soil temperature differences recorded in 2002 at Novelty, Knox County, Missouri, USA. Top: bare soil; middle: corn residue soil; and bottom: soybean residue soil.*

Table 3. *Statistics for Novelty, Missouri, USA*

LOCATION ***Novelty, Knox County, USA***	*SENSOR DEPTH* *cm*	*MEAN* *°C*	*MEDIAN* *°C*	*TCO* *°C*		*OCCURRENCE* *%*		
				$T_{10\%}$	$T_{90\%}$	1°C	0.1°C	0.01°C
Bare soil	5	3	3	0.92	6.67	10.8	NA	NA
Corn	5	3	3	1.05	7.43	8.9	NA	NA
Soybean	5	4	3	1.10	7.67	8.1	NA	NA

NA: Not available

TCO: Absolute temperature difference for a certain chance of occurrence.

$T_{10\%}$: Upper limit of the absolute temperature difference for 10% chance of occurrence.

$T_{90\%}$: Upper limit of the absolute temperature difference for 90% chance of occurrence.

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5. Results from Macquarie University, Sydney, Australia

The Automatic Weather Station is located within the sports grounds of Macquarie University at North Ryde, Sydney, Australia [4]. Its latitude, longitude and elevation are 33 degrees 46 minutes south, 151 degrees 7 minutes east and 55.0 meters above mean sea level. The data were obtained on the Internet from the database of the Atmospheric Science, Division of Environmental & Life Sciences, Macquarie University [4].

5.1 Air and soil temperature variations in 2002

The air temperature is recorded with a dry bulb sensor at a height of 1.2 m. It is a measurement of the kinetic energy of the molecules in the air and is taken inside a Stevenson screen using a PT100 Resistance Temperature Dependent (RTD) device.

The soil temperature is measured at the surface using a Campbell TCAV Soil Thermocouple Probe. This uses four probes connected in parallel to average the temperature at four locations. The temperatures are good to 0.01°C and are measured every 15 minutes.

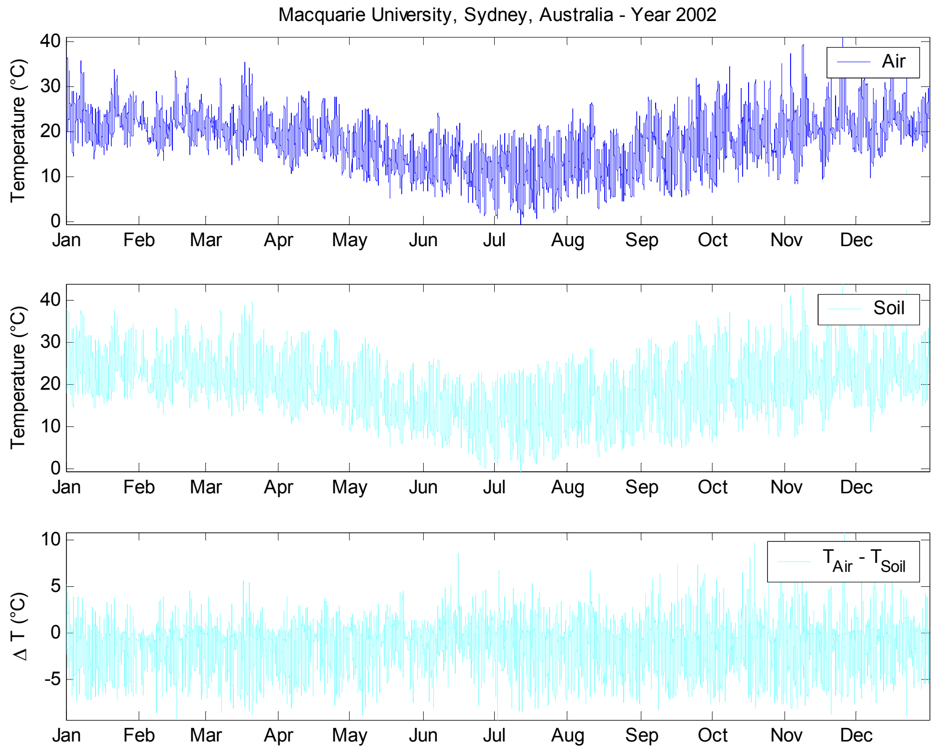

Figure 10. *Air and soil temperature measurements recorded in 2002 at Macquarie University, Sydney, Australia. Top 2 graphs: temperature of air and bare soil at the surface recorded every 15 minutes. Bottom: air-soil temperature differences.*

The top two graphs of Figure 10 show the recorded values for the air and soil temperatures in the year 2002. The bottom graph of Figure 10 presents the air-soil temperature difference over the same period of time. Figure 11 and Figure 12 are similar to Figure 10, except that they are for a week during the winter and summer, respectively.

From Figure 10, Figure 11 and Figure 12, it can be seen that the soil temperature has larger variations than the air through the day. The time delay between the air and soil temperature features are small, meaning that the extrema occur almost at the same time. The temperature differences are greatest when the temperature of the air (or soil) is at its maximum.

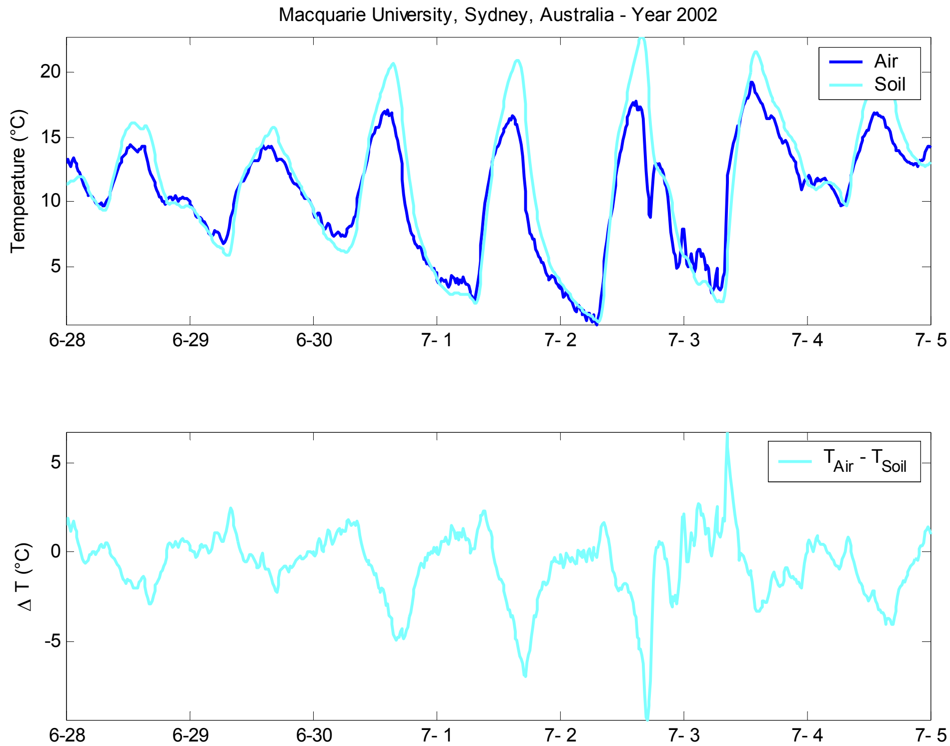

Figure 11. *Air and soil temperatures (top) and temperature differences (bottom) recorded over a week in July of 2002 (winter) at Macquarie University, Sydney, Australia.*

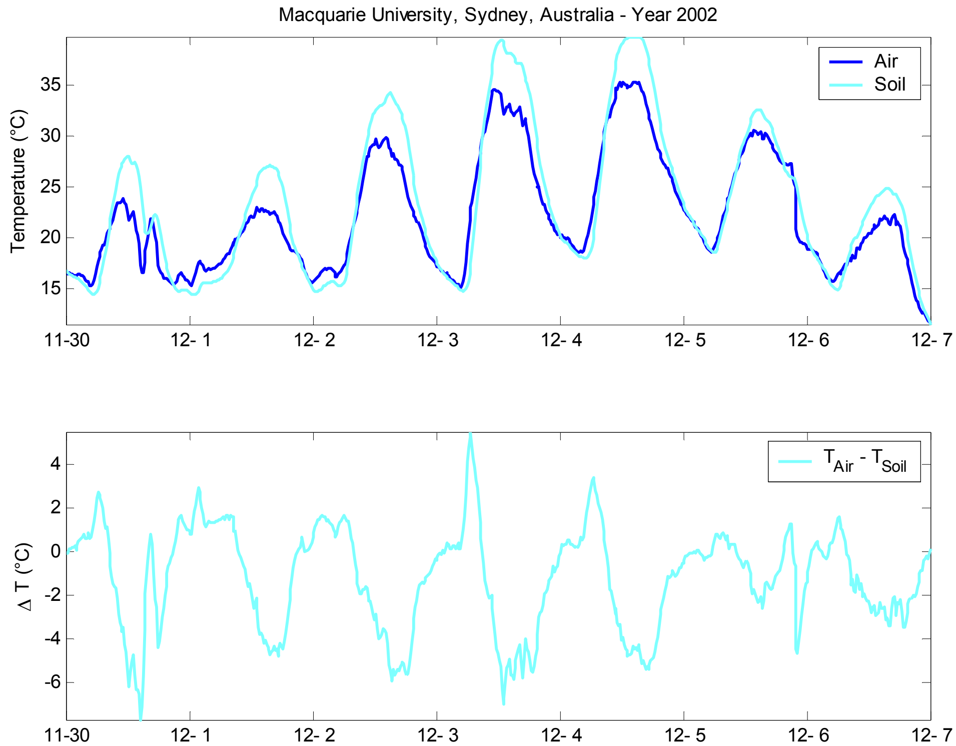

Figure 12. *Air and soil temperatures (top) and temperature differences (bottom) recorded over a week in December of 2002 (summer) at Macquarie University, Sydney, Australia*

5.2 Histogram

Figure 13 presents the histogram of the absolute value of the temperature differences for the year 2002. The y-axis is normalized as if the measurements were taken every hour instead of 4 times per hour, for this purpose the frequency of each bin has been divided by 4, so that the total number of events are equal for each weather stations. Each bin of the histogram counts the occurrence frequency of the absolute value of the temperature difference within an interval of 1°C.

A temperature difference between 0 and 1°C occurs for 43.81% of the measured events. The mean temperature difference over all measured events is 1.93 °C and the median is 1.25 °C.

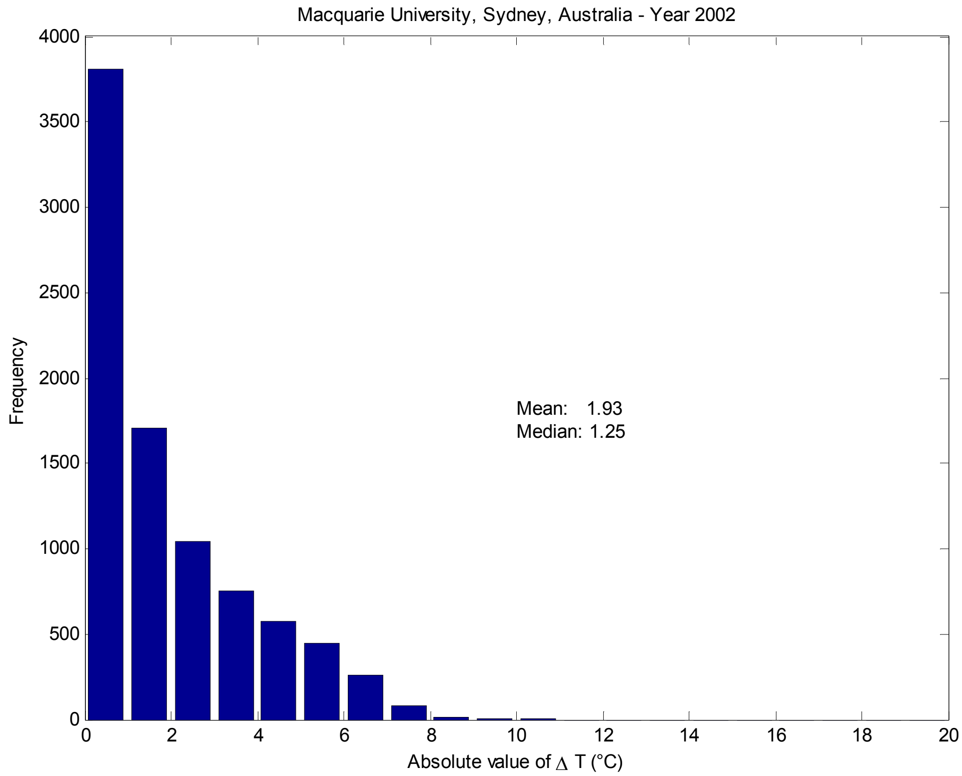

Figure 13. *Histogram of the absolute value of the air-soil temperature differences normalized to correspond to a measurement every hour recorded in 2002 at Macquarie University, Sydney, Australia*

Figure 14 and Figure 15 present a zoom of the histogram portion between 0 °C and 1 °C with a bin size of 0.1 °C and a zoom between 0 °C and 0.1° with a bin size of 0.01°C, respectively. For bin sizes of 0.1°C and 0.01°C in each histogram, the occurrences in the first bin are 4.90% and 0.56%, respectively. For this weather station, 10% of the events occur for an absolute temperature below 0.19°C or above 4.86°C. Table 4 summarizes the results.

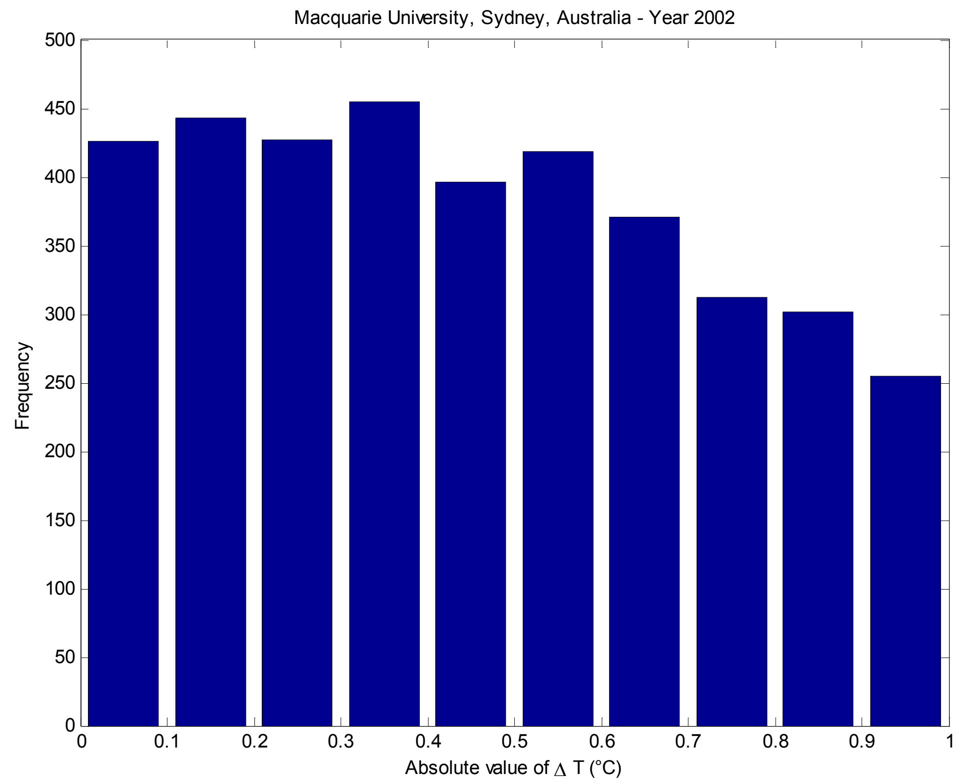

Figure 14. *Zoom between 0°C and 1°C in the histogram of the absolute value of the normalized air-soil temperature differences recorded in 2002 at Macquarie University, Sydney, Australia.*

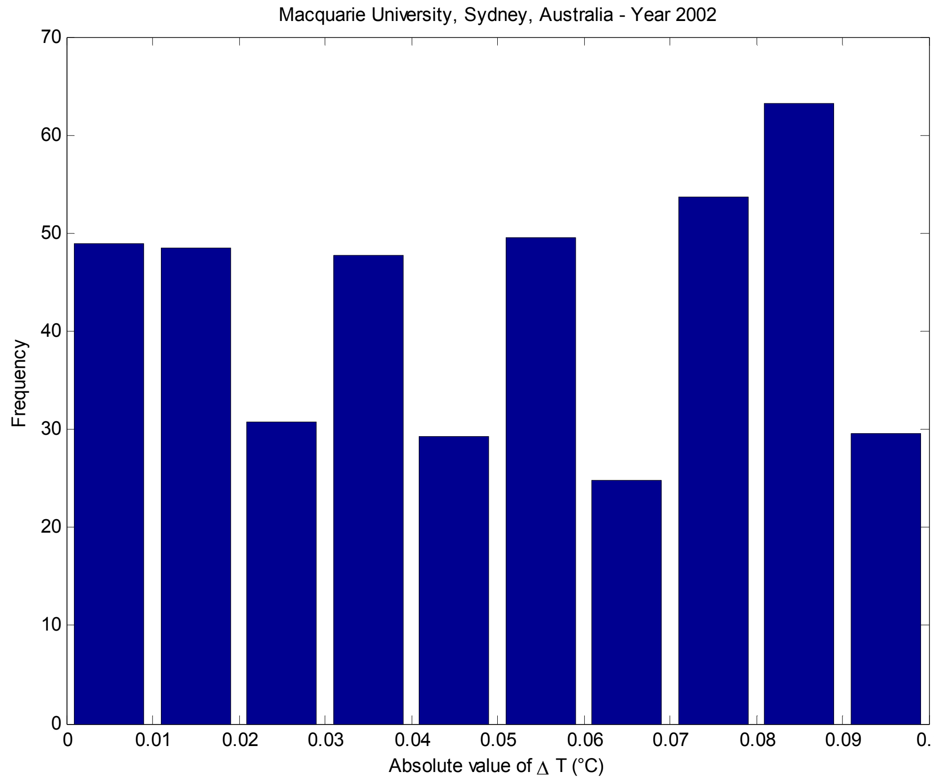

Figure 15. *Zoom between 0°C and 0.1°C in the histogram of the absolute value of the normalized air-soil temperature differences recorded in 2002 at Macquarie University, Sydney, Australia*

Table 4. *Statistics for Macquarie University, Sydney, Australia*

LOCATION	*SENSOR DEPTH* *cm*	*MEAN* *°C*	*MEDIAN* *°C*	*TCO* *°C*		*OCCURRENCE* *%*		
				$T_{10\%}$	$T_{90\%}$	1°C	0.1°C	0.01°C
MACQUARIE UNIVERSITY, SYDNEY, AUSTRALIA	5	1.933	1.25	0.19	4.86	43.81	4.9025	0.5639

NA: Not available

TCO: Absolute temperature difference for a certain chance of occurrence.

$T_{10\%}$: Upper limit of the absolute temperature difference for 10% chance of occurrence.

$T_{90\%}$: Upper limit of the absolute temperature difference for 90% chance of occurrence.

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6. Results from Murdoch University, Perth, Australia

The Murdoch University weather station is located in the city of Perth, Australia at a longitude of 115° 50 minutes 32.28 seconds east and the latitude of 32° 4 minutes 23.94 seconds [5]. The elevation is approximately 30 meters above the Australian Height Datum. The region is very sandy and covered with sparse grass. The weather station site is on a small hilltop and is quite exposed to the wind. The data were obtained on the Internet from the database of the Division of Science and Engineering, Murdoch University [5].

6.1 Air and soil temperature variations in 2002

Four temperature sensors are inserted in the ground at depths of 12.5, 25, 50 and 100 cm. Each soil temperature sensor is a Monitor TDC-02S mini transistor diode type. The air temperature sensor is a PT100 located within a meteorological screen. The temperature accuracies are 0.01°C for both sensors.

Both air and soil temperatures are measured every 10 minutes. The top graph of Figure 16 shows the recorded values of the air and soil temperature over the year. This graph shows that at a meter depth the ground acts as a filter by removing the high frequency fluctuations (daily fluctuations of temperature) to leave essentially only the seasonal fluctuations. In fact, the deeper the soil temperature sensor, the less the frequency content is and the greater the delay between the air and soil temperatures is. The bottom graph of Figure 16 presents the air-soil temperature differences for each sensor depth over the same period of time. Figure 17 and Figure 18 are similar to Figure 16, except that they are taken for a week during the winter and summer, respectively.

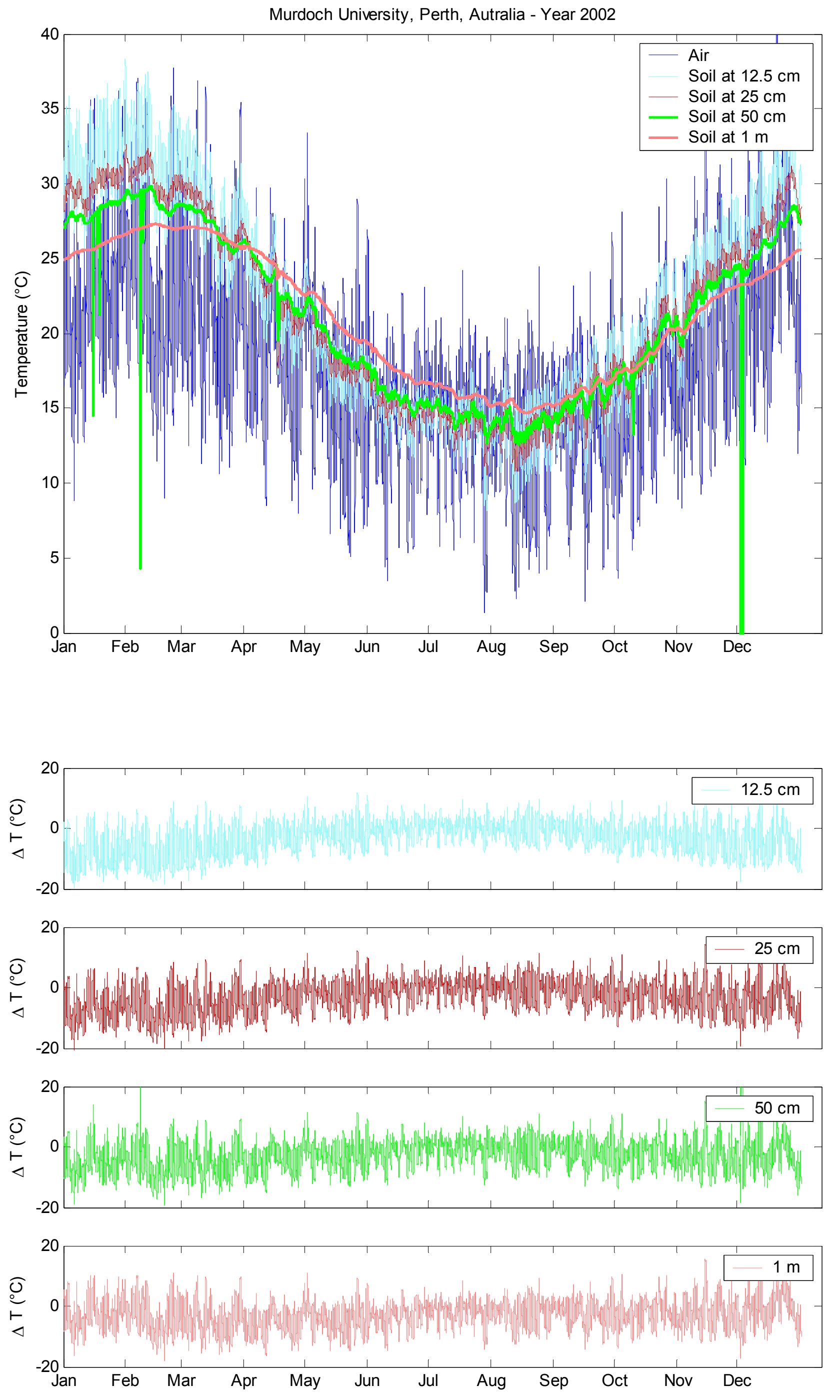

Figure 16. *Air and soil temperature measurements recorded in 2002 at Murdoch University, Perth, Australia. Top: temperature of air and bare soil temperatures at depths of 12.5, 25, 50 and 100 cm. The temperatures are recorded every 10 minutes. Bottom 4 graphs: air-soil temperature differences for all sensor depths.*

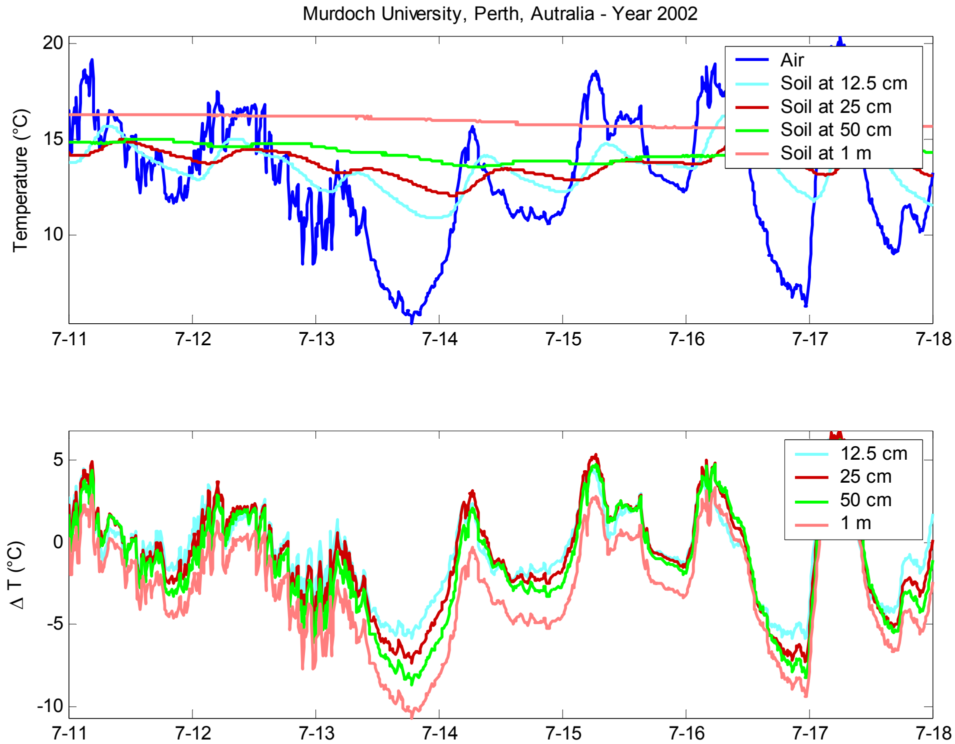

Figure 17. *Air and soil temperatures (top) and temperature differences (bottom) recorded over a week in July of 2002 (winter) at Murdoch University, Perth, Australia.*

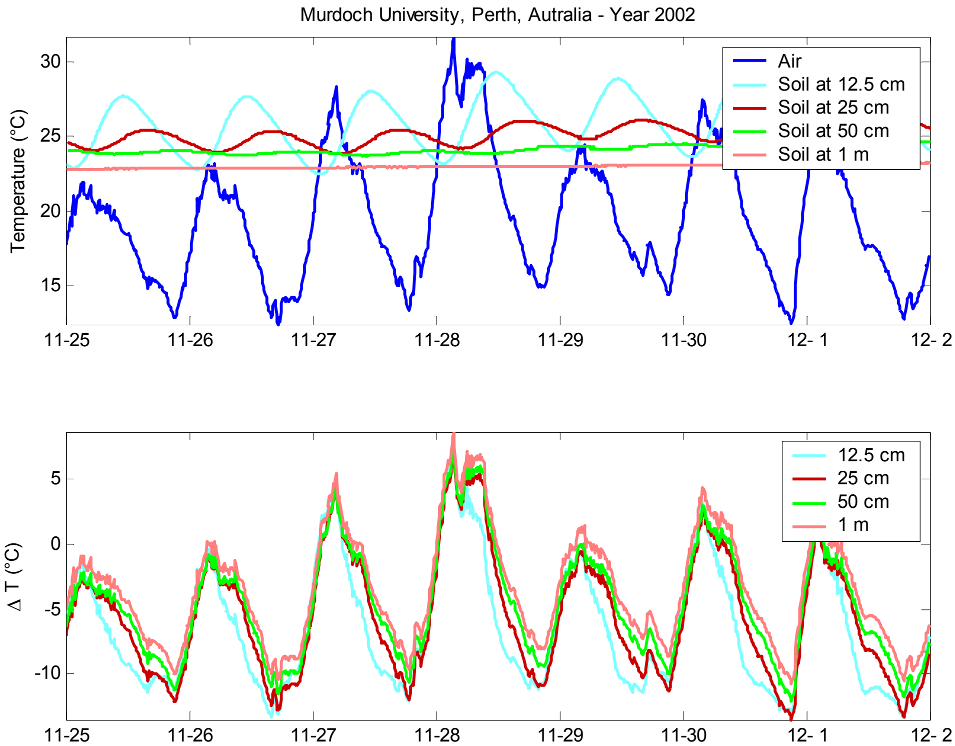

Figure 18. *Air and soil temperatures (top) and temperature differences (bottom) recorded over a week in December of 2002 (summer) at Murdoch University, Perth, Australia.*

6.2 Histogram

Figure 19 presents the histograms of the absolute value of the temperature difference for the four sensor depths in the ground. The y-axis is normalized as if the measurements were taken every hour instead of 6 times per hour; the occurrence frequency is divided by 6 to have the same frequency as if the measurements were taken every hour. Each bin of the histogram counts the occurrence frequency of the absolute value of the temperature difference within an interval of 1°C. For example, every measurement result between 0°C and 1°C is counted in the first bin. The occurrence frequency in the first degree, the mean and median temperatures are summarized in Table 5 for all four sensor soil depths.

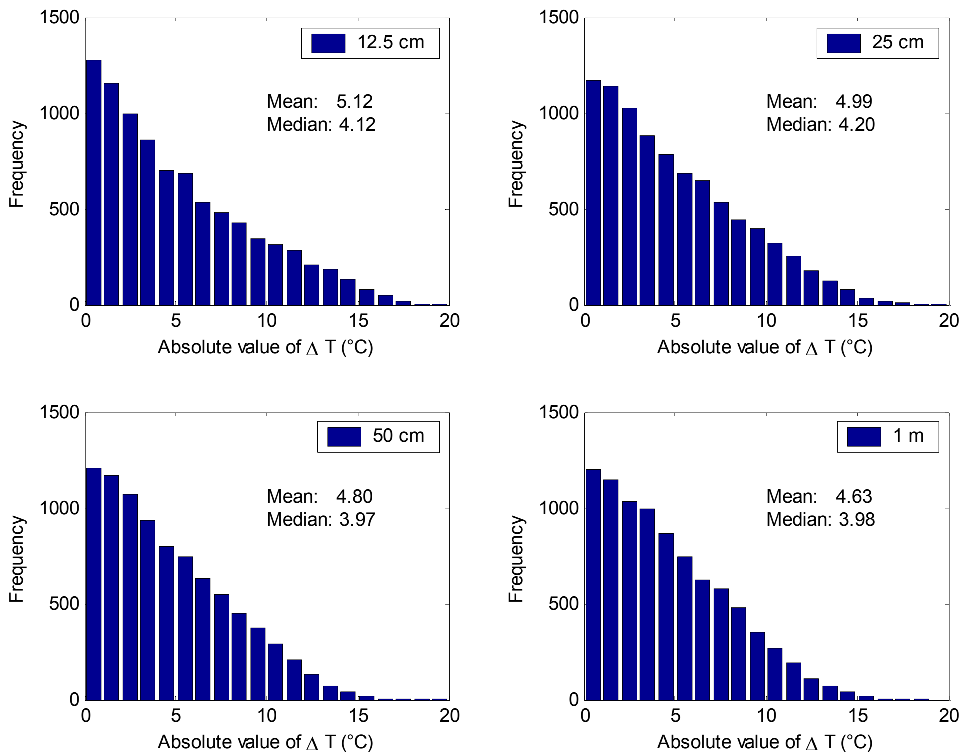

Figure 19. *Histogram of the absolute value of the air-soil temperature differences normalized to correspond to a measurement every hour recorded in 2002 at Murdoch University, Perth, Australia.*

Figure 20 and Figure 21 show a zoom on the histogram between 0 °C and 1 °C with a bin size of 0.1 °C and a zoom between 0 °C and 0.1 °C with a bin size of 0.01°C, respectively. For a depth of 12.5 cm, 10% of the events occur for an absolute temperature difference below 0.67°C or above 11.3°C; for 25 cm, it is 0.75°C and 10.47°C; for 50 cm, it is 0.71°C and 9.71; and for 100 cm, it is 0.71°C and 9.49°C. These results are summarized in Table 5.

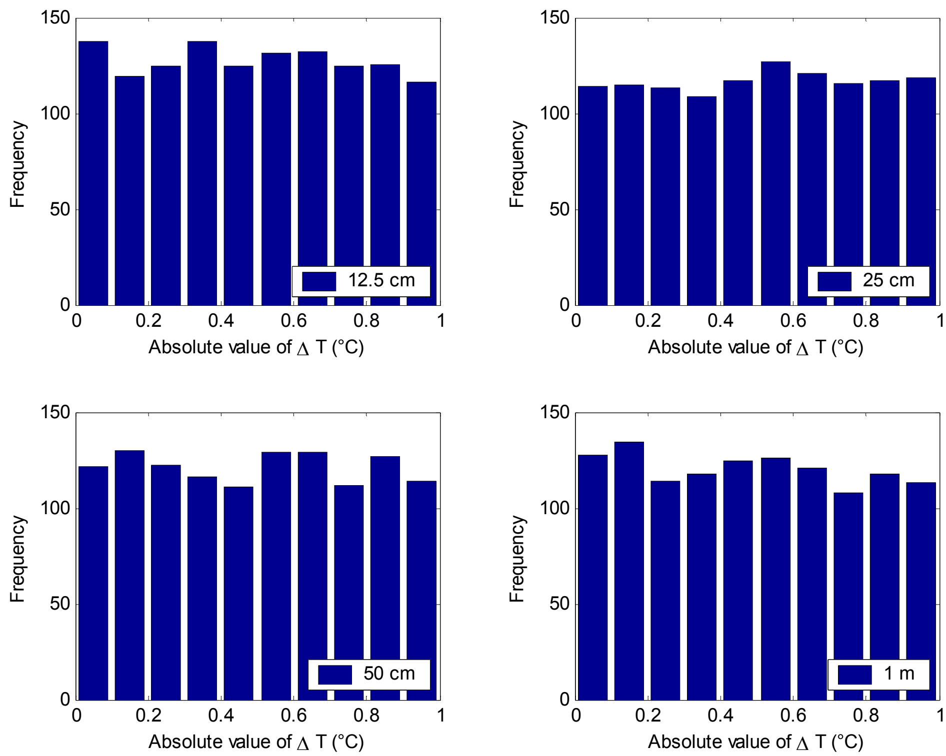

Figure 20. *Zoom between 0°C and 1°C for the histogram of the absolute value of the normalized air-soil temperature differences recorded in 2002 at Murdoch University, Perth, Australia.*

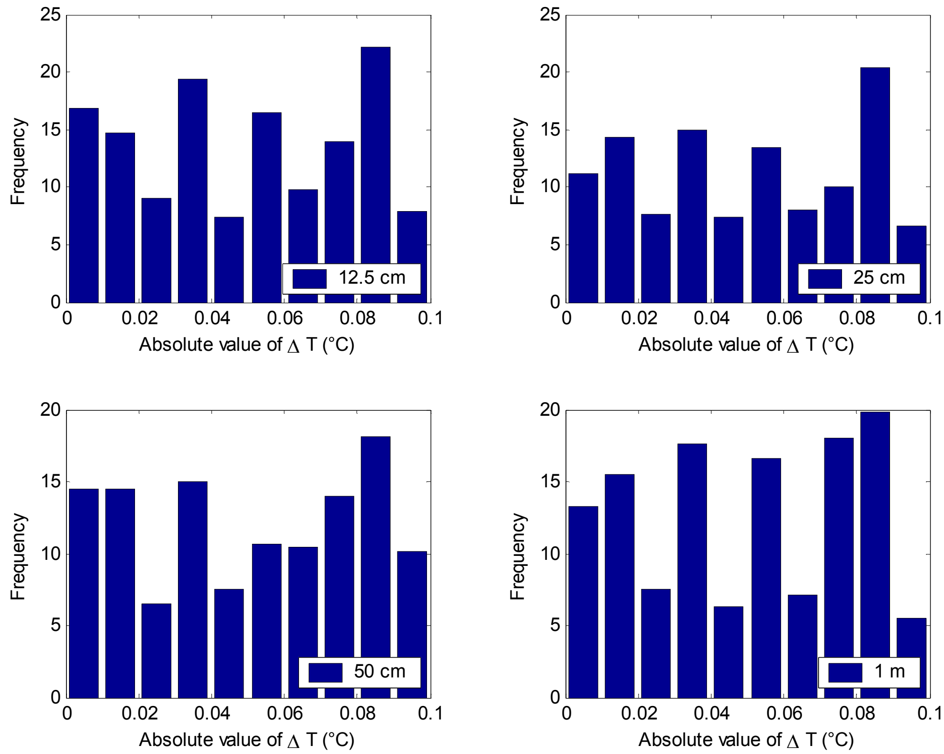

Figure 21. *Zoom between 0°C and 0.1°C for the histogram of the absolute value of the normalized air-soil temperature differences recorded in 2002 at Murdoch University, Perth, Australia.*

Table 5. *Statistics for Murdoch University, Perth, Australia*

LOCATION	*SENSOR DEPTH* *cm*	*MEAN* *°C*	*MEDIAN* *°C*	*TCO* *°C*		*OCCURRENCE* *%*		
				$T_{10\%}$	$T_{90\%}$	1°C	0.1°C	0.01°C
MURDOCH UNIVERSITY, PERTH, AUSTRALIA	12.5	5.12	4.12	0.67	11.30	14.57	1.57	0.19
	25	4.99	4.20	0.75	10.47	13.35	1.30	0.13
	50	4.80	3.97	0.71	9.71	13.88	1.39	0.16
	100	4.63	3.98	0.71	9.49	13.77	1.46	0.15

TCO: Absolute temperature difference for a certain chance of occurrence.

$T_{10\%}$: Upper limit of the absolute temperature difference for 10% chance of occurrence.

$T_{90\%}$: Upper limit of the absolute temperature difference for 90% chance of occurrence.

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7. Results from Nunavut, Canada

The Bylot-3 weather station is located on Bylot Island close to Pond Inlet in Nunavut, Canada approximately 650 km above the Arctic Circle at a longitude of 79° 55 minutes 12.24 seconds west and a latitude of 73° 8 minutes 23.82 seconds north [6]. The elevation is approximately 350 meters. The weather station site is on a snowless hill. The type of soil is permafrost with evidence of surficial periglacial processes (patterned ground) with the presence of hummocks and sparse arctic vegetation. The data were obtained from a private communication with the Centre d'études nordiques, Université Laval [6].

7.1 Air and soil temperature variations in 2002

The soil and air temperature sensors are model 107B thermistor cables from Campbell Scientific, Inc. The air temperature sensor is located 3 m above the ground. The temperature accuracies are 0.01°C and both air and soil temperatures are measured every hour.

The top graph of Figure 22 shows the recorded values of the air and soil temperatures over the year. The bottom graph of Figure 22 presents the air-soil temperature differences. Figure 23 and Figure 24 are similar to Figure 22, except that they are taken for a week during the summer and winter, respectively. Figure 23 (summer case) depicts significant daily fluctuations of air and soil temperatures, while Figure 24 (winter case) shows a smoother temperature evolution. This is due to the fact that there is no direct sunshine during the winter. At this latitude, depending on the cloud cover, the sun is last seen above the horizon on November 11 of each year. Around the 2nd of February, the sun reappears above the southern hills for a few minutes each day.

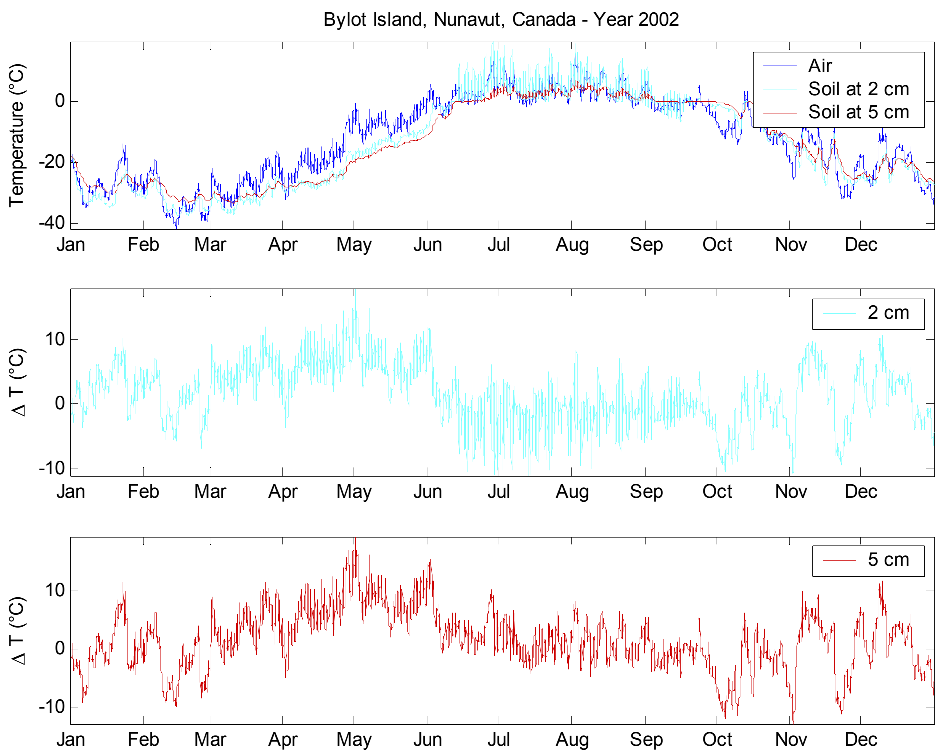

Figure 22. *Air and soil temperature measurements recorded in 2002 at Bylot Island, Nunavut, Canada. Top: temperature of air and bare soil temperatures at depths of 2 cm and 5 cm recorded every hour. Bottom 2 graphs: air-soil temperature differences.*

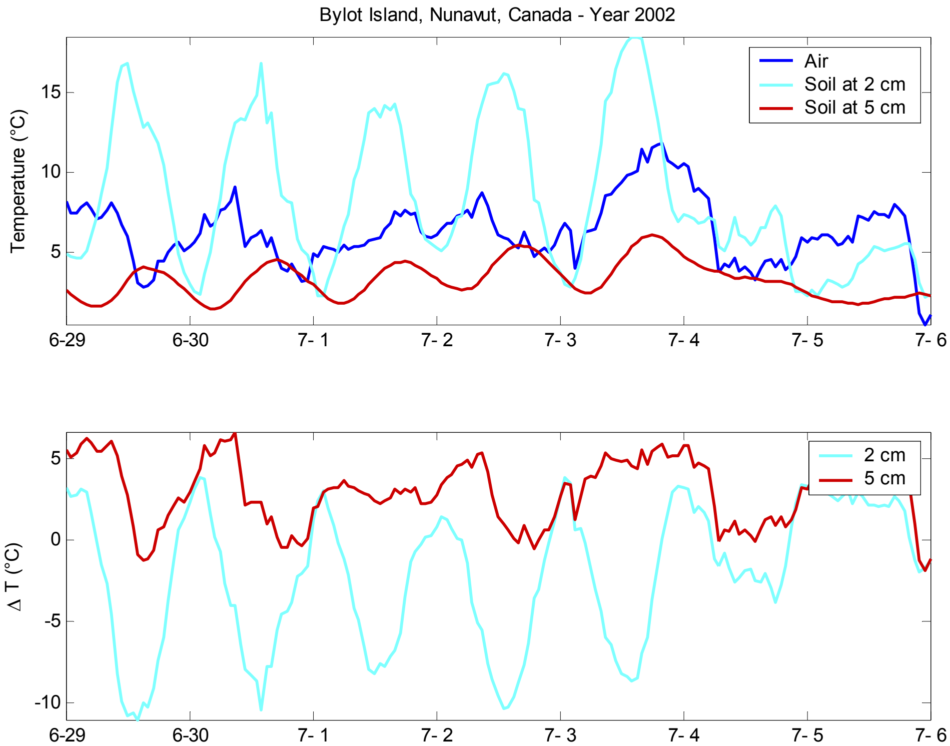

Figure 23. *Air and soil temperatures (top) and temperature differences (bottom) recorded over a week during the summer of 2002 at Bylot Island, Nunavut, Canada.*

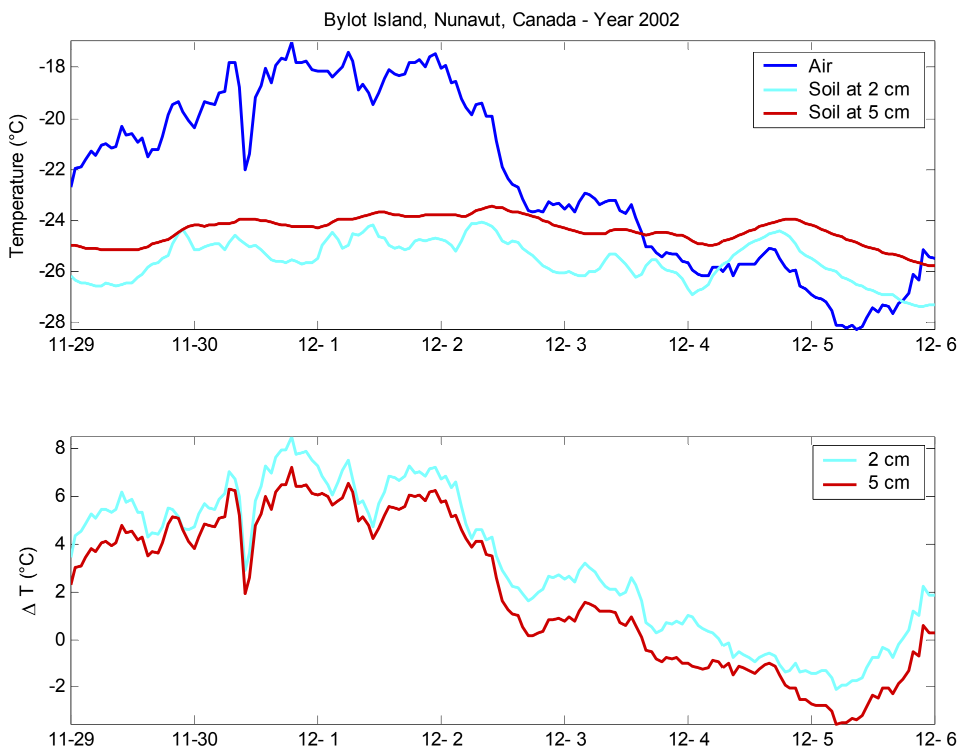

Figure 24. *Air and soil temperatures (top) and temperature differences (bottom) recorded over a week during the winter of 2002 at Bylot Island, Nunavut, Canada.*

7.2 Histogram

Figure 25 presents the histogram of the absolute value of the temperature differences. The top graph is for a soil temperature sensor depth of 2 cm, and the bottom graph for 5 cm. Each bin of this histogram counts the occurrence frequency of the absolute value of the temperature difference within 1°C. The mean temperature difference is 3.88 °C for the soil sensor at a depth of 2 cm and 4.15°C at a depth of 5 cm.

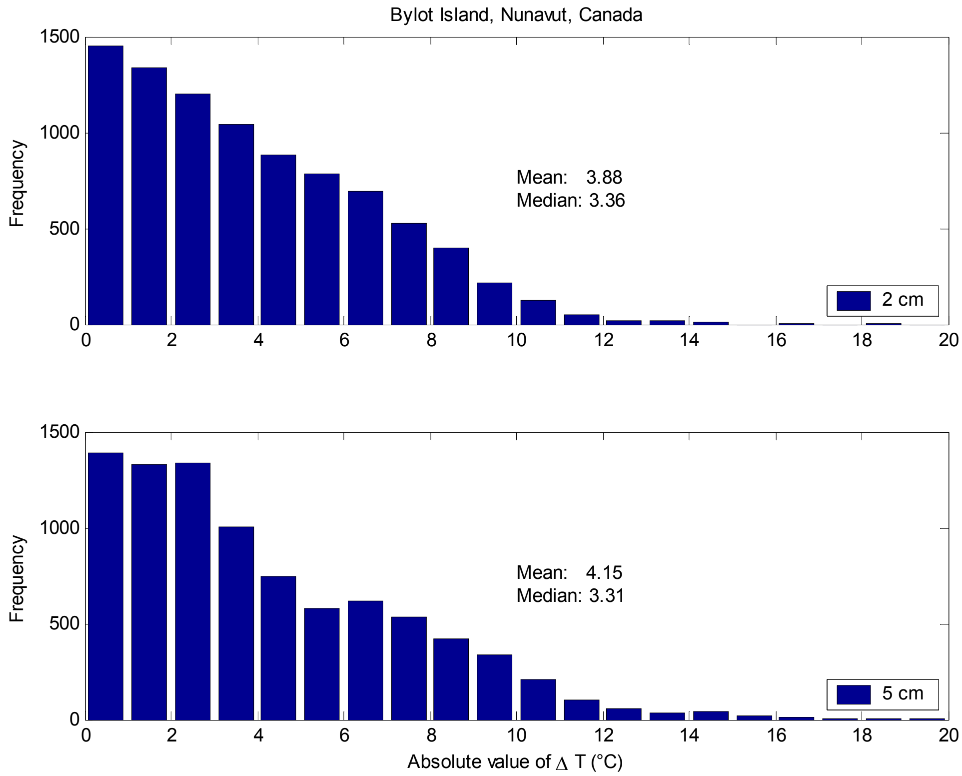

Figure 25. *Histogram of the absolute value of the air-soil temperature differences recorded in 2002 at Bylot Island, Nunavut, Canada.*

Figure 26 and Figure 27 show a zoom for the histogram portion between 0 °C and 1 °C with a bin size of 0.1 °C and a zoom between 0 °C and 0.1 °C with a bin size of 0.01°C, respectively. On both figures, the top graph is for a sensor depth of 2 cm and the bottom graph for a sensor depth of 5 cm. Table 6 shows the average value, the median and the occurrence frequency for 0.01°C, 0.1°C and 1°C for both sensor depths. For a depth of 2 cm, 10% of the events occur for an absolute temperature below 0.58°C or above 7.92°C; and for 5 cm, it is 0.62°C and 8.85°C. These results are summarized in Table 6.

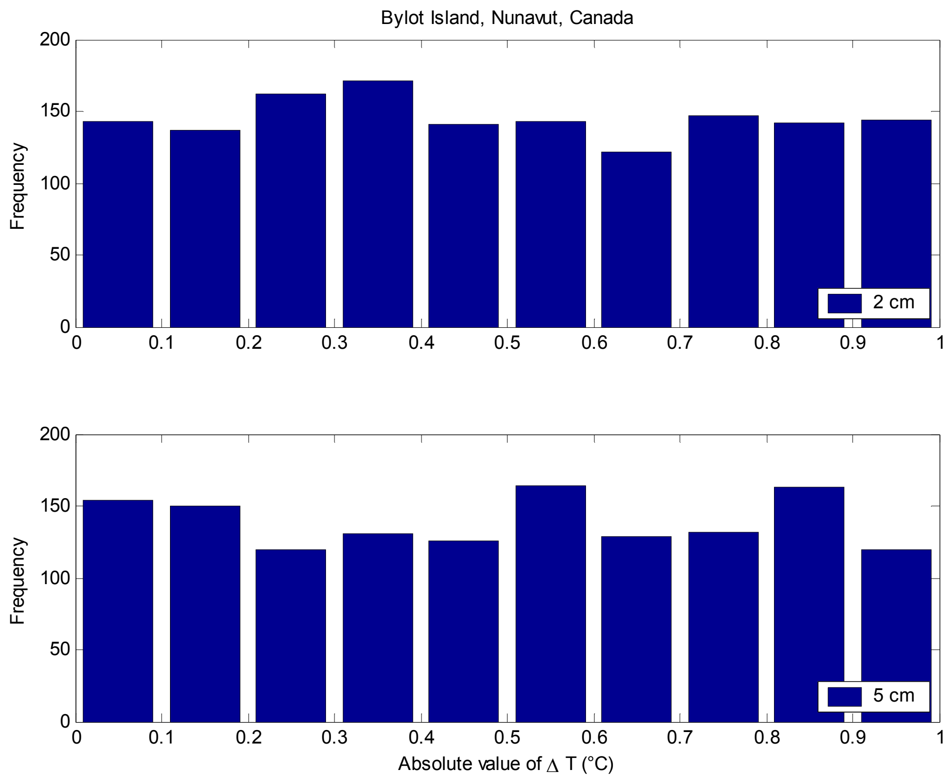

Figure 26. *Zoom between 0°C and 1°C for the histogram of the absolute value of the air-soil temperature differences recorded in 2002 at Bylot Island, Nunavut, Canada.*

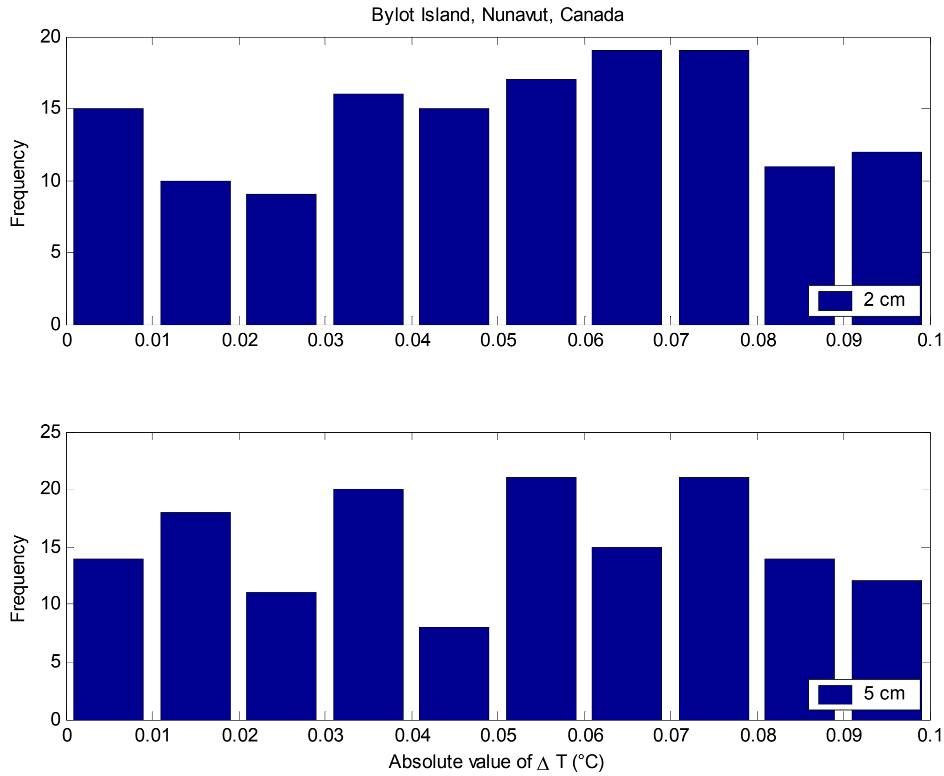

Figure 27. *Zoom between 0°C and 0.1°C for the histogram of the absolute value of the air-soil temperature differences recorded in 2002 at Bylot Island, Nunavut, Canada.*

Table 6. *Statistics for Bylot Island, Nunavut, Canada*

LOCATION	*SENSOR DEPTH* *cm*	*MEAN* *°C*	*MEDIAN* *°C*	*TCO* *°C*		*OCCURRENCE* *%*		
				$T_{10\%}$	$T_{90\%}$	1°C	0.1°C	0.01°C
Bylot, Nunavut, Canada	2	3.88	3.36	0.58	7.92	16.58	1.63	0.17
Bylot, Nunavut, Canada	5	4.15	3.31	0.62	8.85	15.86	1.76	0.16

TCO: Absolute temperature difference for a certain chance of occurrence.

$T_{10\%}$: Upper limit of the absolute temperature difference for 10% chance of occurrence.

$T_{90\%}$: Upper limit of the absolute temperature difference for 90% chance of occurrence.

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8. Results summary

Table 7 summarises the statistical results for the five locations, for all soil types and sensor depths.

Table 7. *Summary of statistics*

LOCATION	*SOIL TYPE*	*SENSOR DEPTH* *cm*	*MEAN* *°C*	*MEDIAN* *°C*	**TCO**		*OCCURRENCE* *%*		
					$T_{10\%}$	$T_{90\%}$	1°C	0.1°C	0.01°C
Sanborn Field, Boone County, Missouri, USA	Bare soil	5	3	2	0.95	6.64	10.5	NA	NA
Sanborn Field, Boone County, Missouri, USA	Bare soil	10	4	3	1.09	7.57	8.3	NA	NA
Novelty, Knox County, Missouri, USA	Bare soil	5	3	3	0.92	6.67	10.8	NA	NA
Novelty, Knox County, Missouri, USA	Corn residue	5	3	3	1.05	7.43	8.9	NA	NA
Novelty, Knox County, Missouri, USA	Soybean residue	5	4	3	1.10	7.67	8.1	NA	NA
Macquarie University, Sydney, Australia	Grass cover	~0	1.93	1.25	0.19	4.86	43.8	4.9	0.56
Murdoch University, Perth, Australia	Sand	12.5	5.12	4.12	0.67	11.30	14.6	1.6	0.19
Murdoch University, Perth, Australia	Sand	25	4.99	4.20	0.75	10.47	13.4	1.3	0.13
Murdoch University, Perth, Australia	Sand	50	4.80	3.97	0.71	9.71	13.9	1.4	0.16

Murdoch University, Perth, Australia	Sand	100	4.63	3.98	0.71	9.49	13.8	1.5	0.15
Bylot Island, Nunavut, Canada	Permafrost	2	3.88	3.36	0.58	7.92	16.58	1.63	0.17
Bylot Island, Nunavut, Canada	Permafrost	5	4.15	3.31	0.62	8.85	15.86	1.76	0.16
Average			3.58	2.94	0.72	7.58	13.81	1.76	0.19

NA: Not available

TCO: Absolute temperature difference for a certain chance of occurrence.

$T_{10\%}$: Upper limit of the absolute temperature difference for 10% chance of occurrence.

$T_{90\%}$: Upper limit of the absolute temperature difference for 90% chance of occurrence.

9. Discussion and conclusions

The first part of this document reviewed the basic concept of chemical vapour detection with a passive standoff sensor. It has been shown that in passive standoff sensing the detection of a chemical gas is a direct function of the temperature difference between the gas and the background. Higher temperature differences mean higher probabilities of detection. Air and background temperatures are highly variable in time and space and the sensor performance is affected accordingly. Our analysis provides a statistics on the air-soil temperature differences that can be used to estimate the detection performances of passive standoff sensors, such as CATSI, in different environments. In that, it has been assumed that the local soil temperature represents a good estimate of the background temperature at each location.

A statistical analysis of air and soil temperature data recorded at five locations around the World has been performed. These locations are Sanborn Field, Boone County, Missouri State, USA, Novelty, Knox County, Missouri State, USA, Macquarie University, Sydney, Australia, Murdoch University, Perth, Australia and Bylot Island, Nunavut, Canada. The measurements were obtained from the Internet for the first four locations and the data for Nunavut came from a private communication. The variations in air and soil temperatures over a period of one year have been analysed for all five locations. The results for the year 2002 are presented along with two one-week periods: one in summer and one in winter. The temperature differences between air and soil were reported for the same time periods. The document has presented histograms of the absolute value of the temperature differences, their averages and their medians. Frequency calculations of the difference of temperatures of less than one degree Celsius were retrieved. The absolute temperature differences for 10 % and 90 % chance of occurrence were calculated. The average of the absolute air-soil temperature differences for all five locations discussed in this document is 3.5°C and the average value of the median is 2.9°C.

The variation of ΔT for three different types of soil was studied using the results from the weather station in Novelty, Knox County, Missouri, USA. In this case, bare soil, corn residue soil and soybean residue soil were investigated. The average of the absolute value of ΔT for the three soils was between 3.0 and 3.5°C. The histograms obtained from these different types of soil were very similar. Three locations provided results at different sensor depths: Sanborn Field, Missouri, USA, Murdoch University, Perth, Australia and Bylot Island, Nunavut, Canada. The results from Murdoch University were particularly interesting because four probes located at different depths were utilized. The analysis has shown that the delay and frequency content of the soil temperature varies as a function of the soil depth. The deeper the sensor, the larger the delay and the more attenuated the high frequencies components. However, the results also emphasize that the mean of the absolute value of ΔT changes only by 0.5 °C for sensor depths varying from 12.5 cm to 100 cm. As a consequence, a large change in sensor depth has a relatively small effect on the mean value. The sensors located at Bylot Island and Sanborn Field showed similar results for sensor depths between 2 and 10 cm.

Of all the results analyzed in this study, those from Macquarie University appear to be significantly different from those of the other locations. For instance, a very large number of occurrences occur below 1°C, 43.8% of the occurrences for Macquarie University compared with 8 to 17% for all other locations, sensor depths and type of soils. This means that the soil surface temperature is very similar to the air temperature. As opposed to the types of soil of the four other locations, the Macquarie University soil has significant grass cover. This might explain the discrepancy. Future investigations will be oriented toward analyzing meteorological data from locations having soil types with grass and/or vegetal cover.

For an instrument such as CATSI, a large air-background temperature difference is desired in order to produce a radiative contrast that favors a greater probability of detection. Temperature differences of less than 1°C may impact the detection capability since they are transferred into a low differential radiance as explained in section 2. This happened 13.8% of the time on average for all five locations and corresponds to 3.3 hours per day with roughly half of this period (1 hour 40 minutes) occurring at sunrise and the other half at sunset. This is due to the heat capacity of the air compared with the soil.

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List of symbols/abbreviation/acronyms/initialisms

AHD	Australian Height Datum
CATSI	Compact ATmospheric Sensing Interferometer
CF	Canadian Forces
DND	Department of National Defence
FOV	Field of view
FTIR	Fourier-transform infrared spectrometer
RTD	Resistance Temperature Dependent
TCO	Temperature for a certain chance of occurrence

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An analysis of air-soil temperature differences at five locations: Application to passive standoff chemical detection

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For a passive spectral sensor such as CATSI (Compact ATmospheric Sounding Interferometer), the temperature difference (ΔT) that exists between a chemical cloud and the background scene is of prime importance because it is linked to the radiative contrast of the target. The larger ΔT, the better the radiative contrast and the more accurate is the detection and identification, of the cloud.

The purpose of this memorandum is to establish statistics on realistic air-soil temperature differences to be used to estimate the detection performance of CATSI-type sensors in a variety of scenarios and environments. To this end, an analysis of the air-soil temperature differences is presented for five locations around the world; namely, 1- Sanborn Field, Boone County, Missouri, USA, 2- Novelty, Knox County, Missouri, USA, 3- Macquarie University, Sydney, Australia, 4- Murdoch University, Perth, Australia, and 5- Bylot Island, Nunavut, Canada. The results of the analysis indicate that the statistics of the air-soil temperature differences are similar from one location to another. The average statistics over the five locations show a mean air-soil temperature difference of 3.5 °C and a median of 2.8 °C. An air-soil temperature difference of less than one degree Celsius occurs less than 14% of the time on the average. This suggests that, on average, air-soil temperature contrasts should yield good detection probabilities 86% of the time.

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Passive Standoff Detection, Air temperature, Soil temperature, Air-soil temperature difference, Distribution, Radiative contrast

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