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MEAN DAILY VALUES FOR BARE-SOIL TEMPERATURE MEASURED AND CALCULATED USING STANDARD AND AUTOMATIC METHODS

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Abstract

This study presents the results of an analysis of mean daily values for soil temperature measured using mercury thermometers and electronic sensors during the period 2000-2009 at the Wrocław-Swojec Observatory. Daily averages were calculated on the basis of three measurements a day made using standard devices, as well as in two ways from automatic data: from the same terms and from all 24 hours. Linear regression, frequency and significance of differences, time series analysis (i.e. autocorrelation analysis and seasonal decomposition using the additive model) were performed to determine whether a change in the method of calculating mean daily values might reduce the differences between the two methods.

Key words

automatic method • daily averages • seasonal decomposition • soil temperature • standard station • time series

Introduction

One of the priorities of modern meteorology is to provide measurements of meteorological elements that are newer and of higher quality (Tam et al. 2005). This is widely manifested by the implementation of automatic meteorological stations (AWS) within the framework of the meteorological network. In comparison with standard manual methods this facilitates the collection and processing of different kinds of data. The AWS approach also allows for permanent measurement 24 hours a day with any time step and data obtained in this manner being of much greater accuracy and reliability (Mete 2008).

Automatic meteorological stations are not only used for narrow meteorological research. Data collected by electronic sensors are applied in the estimation of values for parameters that are needed to calculate evaporation (Kiedrowicz et al. 2012), or to describe the condition of the atmosphere as measurements of the concentrations of various gases are made (Tarkowski et al. 2012).

Notwithstanding the many advantages of automatic stations, the resignation from standard devices and their replacement by modern instruments leads to a number of methodological problems (Łomotowski & Rojek 2001). In line with the methodologies proposed by the Polish Institute of Meteorology and Water Management, a mean daily value obtained by standard measurement is calculated – depending on the meteorological element analyzed – using three or four terminal observations during the day, as opposed to data from all 24 hours in the case of an automatic station. Comparative studies of daily values calculated in both ways indicate that differences result from methods of calculation (Łabędzki et al. 2001). However, this hypothesis has never been confirmed in the case of long-term observation series. Thus, with a view to this hypothesis being verified, analyses were carried out in regard to mean daily values for soil temperature measured at depths of 5 and 10 cm beneath bare soil (t_{g5}, t_{g10}). Daily averages were calculated on the basis of three measurements a day made using standard devices, as well as in two ways from automatic data: from the same terms and from all 24 hours.

On the basis of the results obtained, the authors will seek to answer a question regarding the reason for differences between values obtained using the two methods of meteorological measurement, and specifically to determine whether differences are caused by the methods in which mean daily values are calculated, or else are a reflection of the differing construction and precision of devices used (Szwejkowski 1999).

Research methods

The research material used in the study consisted of soil-temperature values measured under bare soil using standard or automatic instruments. Meteorological observations of these parameters were conducted over the 10-year period 2000-2009 at the Wrocław-Swojec Observatory belonging to Wrocław University of the Environmental and Life Sciences. It is located about 4 km from the city center (ϕ=51°07'N; λ=17°10'E), and so is not encompassed by the Urban Heat Island.

In previous publications, the authors of this study developed research results for air temperature, relative air humidity and saturation deficit mean daily values, as recorded two meters above the ground. It emerged that the calculation of daily averages by reference to the automatic station and its terminal measurement, as opposed to 24-hourly values, did not bring a result of the expected kind, such as a significant reduction in differences between the two methods.

In the case of saturation deficit, the skipping of values from the night hours as the daily average formula from a standard station is applied which results in the obtainment of quantities overestimated in comparison with the data calculated from automatic observations over 24 hours. Therefore, only for saturation deficit were mean daily values counted on the basis of three daily term measurement by electronic sensors much more similar to standard daily values than averages from all 24 hours (Kajewska-Szkudlarek & Rojek 2013). The aim of this study is to perform analogical analysis for soil temperature measured under bare soil in a case in which daily average values are calculated in the same way as for saturation deficit.

Soil temperature obtained by the manual (standard) method was measured using mercury thermometers at depths of 5 and 10 cm. Daily averages were calculated from values for three times during the day: 7, 13 and 19 CET, while – in line with Institute of Meteorology and Water Management methodology – values from the night hours were neglected.

To ensure the principle of comparability of measurements, the electronic sensors used to measure soil temperature (thermistor 107s) were placed approximately 30 cm from the positions of mercury thermometers. These sensors were part of a Campbell automatic meteorological station (type CR23X). Mean daily values from automatic data were counted on the basis of all 24 hours or, on the other hand, from terms corresponding to the time slots used to calculate these values via the standard method.

Mean daily values received not only from standard, but also from automatic terminal observations were compared with automatic averages generated over 24 hours. For this purpose, use was made of analysis of regression, correlation coefficients, and the frequency and significance of differences between the standard and automatic methods and time series. Daily differences between soil temperature measured using the two methods in the period from the 1 January 2000 to 31 December 2009 were recognized as time series. Each analyzed depth (5 and 10 cm) yielded two time series: mean daily values according to the standard station minus automatic averages from term measurement and from all 24 hours.

Time series analysis included autocorrelation analysis and a seasonal breakdown of differences between soil temperature mean daily values from manual or automatic meteorological observations. The result of the breakdown was the isolation of individual time series components, be these seasonal, random, trend or long-term.

All statistical analysis were performed using Statistica 10.0.

Research results and discussion

At the outset, a comparison was made of regression-analysis results for mean daily values of soil temperature calculated using different methods. It emerged that the change in averaging daily values by the automatic station did not affect the outcome. There was hardly any difference at all between correlation coefficients calculated on the basis of three measurements per day (both standard and by the automatic station) or from all 24 hours (via the automatic method). The value of the correlation coefficient for t_{g5} increased to 0.986, while earlier (for standard and automatic continuous measurement) it had amounted to 0.984. In the case of $t_{g10,}$ the value for the correlation coefficient was 0.997 in both cases.

To assess the homogeneity of the measurement series, Lorenc (2006) proposed the use of frequency of the differences between daily values for meteorological parameters. The series was considered homogeneous where 90% of all values fell within the middle frequency class. In the present study, an analogous methodology was used to analyse differences between the daily values for bare soil temperature calculated in different ways. Particular attention was paid to the number of cases in the median class of frequency [-1.0, 1.0). The following figures illustrate the results for differences between the values derived from the standard terminal measurements and automatic ones from all 24 hours, and on the other hand between values measured with standard instruments or with electronic sensors in the course of three terminal observations during a day.

Change in the method of calculating the average daily values for soil temperature at both depths did alter the frequency of differences distribution significantly (Figs. 1, 2). The median classes [-1.0, 1.0) remained the best-represented intervals, though the 90% frequency threshold necessary if a measurement series is to be considered homogeneous was not achieved, no matter what formula for calculating mean daily values was applied.

For soil temperature measured under bare soil at a depth of 5 cm, the size of the median class increased from 64 to 70%, whereas the interval [-3.0, -1.0) included more than twice as many differences as earlier. These changes resulted from a reduction in the frequency of occurrence within the class [1.0, 3.0), from 25 to 5% (Fig. 1).

At a depth of 10 cm, the frequency in the median class increased from 84 to 87% and in terms of the interval [-3.0, -1.0) from 2 to 8%, In contrast, in the range [1.0; 3.0) there was an 11% decline in the differences' percentage (Fig. 2).

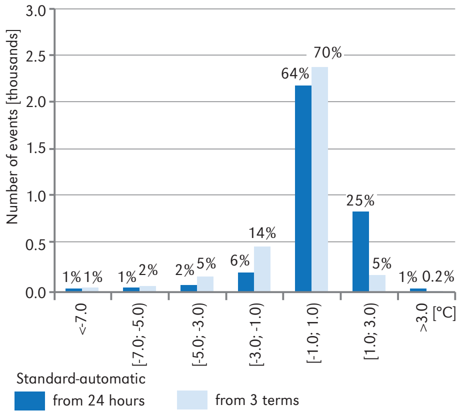

Figure 1. Frequency of occurrence of differences between daily values for soil temperature under bare soil (°C) at a depth of 5 cm, as measured using a standard or automatic station in the period 2000-2009

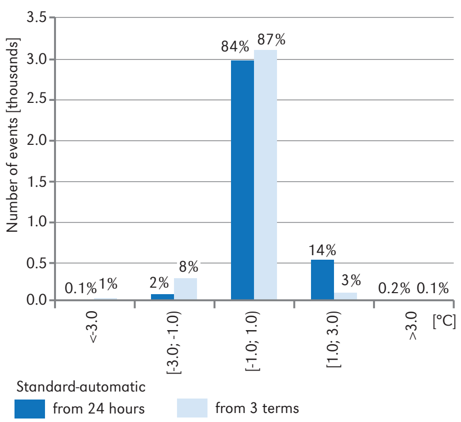

Figure 2. Frequency of occurrence of differences between daily values for soil temperature under bare soil (°C) at a depth of 10 cm, as measured using a standard or automatic station in the period 2000-2009

On the basis of the results obtained, it was concluded that the classification by Lorenc (2006) is too restrictive for a long comparative period. The author created it on the basis of the frequency of differences between the two methods for several stations in the short term, including through research conducted in one year only. For a long measurement series it would be more appropriate to lower the threshold of critical frequency of differences in the intervals given by Lorenc.

Subsequent figures present courses for the differences between t_{g5} or t_{g10} (means from three daily values), as measured using the two methods, as well as between the averages calculated from standard or automatic continuous measurements. With a view to their being rendered more comprehensible, the place of the original data is taken by averages for the 10-year study period, smoothed using a locally weighted linear regression smoothing procedure (Figs. 3, 4).

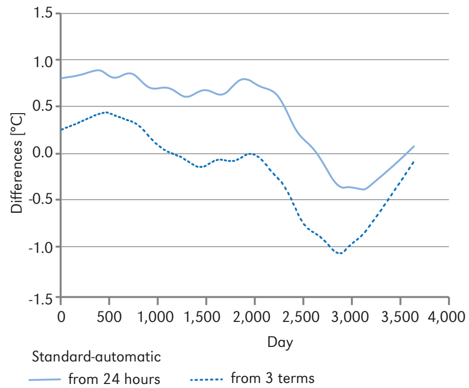

Figure 3. Daily differences between average values for t_{g5} (°C) measured using standard or automatic station in consecutive days of the period 2000-2009

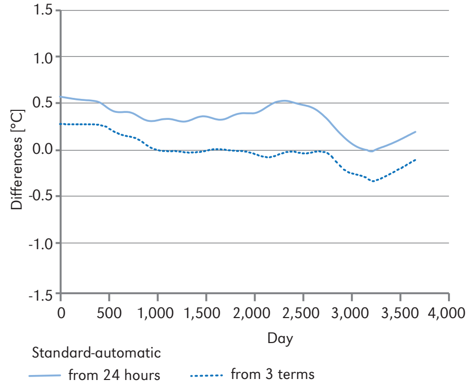

Figure 4. Daily differences between average values for t_{g10} (°C) measured using a standard or automatic station in consecutive days of the period 2000-2009

At both depths, the average difference between results from the standard and automatic methods of soil-temperature measurement decreased after the change in the method of calculating mean daily values (from the automatic station). The decline was of about 0.5°C for t_{g5}, while for t_{g10} it was about 0.3°C. For terminal average values, the seasonality to differences in the first six years of research (2000-2005) was not as noticeable as earlier. Seasonality was expressed in terms of the increase in the value of differences in the summer months. Quite a large range of variability still characterized differences in t_{g5}, which previously ranged from -7.9°C (2008, 2009) to 7.4°C (2008). After the change in the formula for the calculation of daily averages it ranged from -8.2°C (2006, 2007) to 6.4°C (2008). Extreme values in case of t_{g10} were firstly equal -4.3°C (2007) and 4.6°C (2000), as well as subsequently -4.6°C (2007) and 3.7°C (2005).

In particular months of the analyzed decade 2000-2009, the significance of differences between the standard and automatic methods of soil-temperature measurement was assessed (Tabs. 1, 2). The aim of this analysis was to determine whether the observed differences are significant.

Subsequent tables indicate significant differences between: mean daily values calculated on the basis of standard measurements or automatic observations over 24 hours; daily averages counted from standard and automatic terminal values (7, 13, 19 CET); significant differences in both cases.

Far more months with significant differences were noted for soil temperature measured at a depth of 5 cm as opposed to 10 cm (Tab. 1). The change in the method of calculating daily averages did not result in a decrease in their number.

In the case of t_{g5}, 20 months with significant differences between daily values counted on the basis of standard or automatic terminal observations were noted (in 2003, 2006-2009) while earlier values for standard and continuous automatic measurements in 21 months attained significance (i.e. in all years except 2006 and 2007). In both cases only in 8 months to 120 (in 2003, 2008 and 2009) were significant differences noted.

A quite different situation applied to t_{g10}. In 2000, 2001, 2004 and 2006, 8 months with significant differences between the mean daily values from standard or automatic continuous measurements were observed; while there were 5 (in 2006-2008) for terminal

Table 1. Significance of differences between mean values of t_{g5} measured with a standard or automatic station in the period 2000-2009

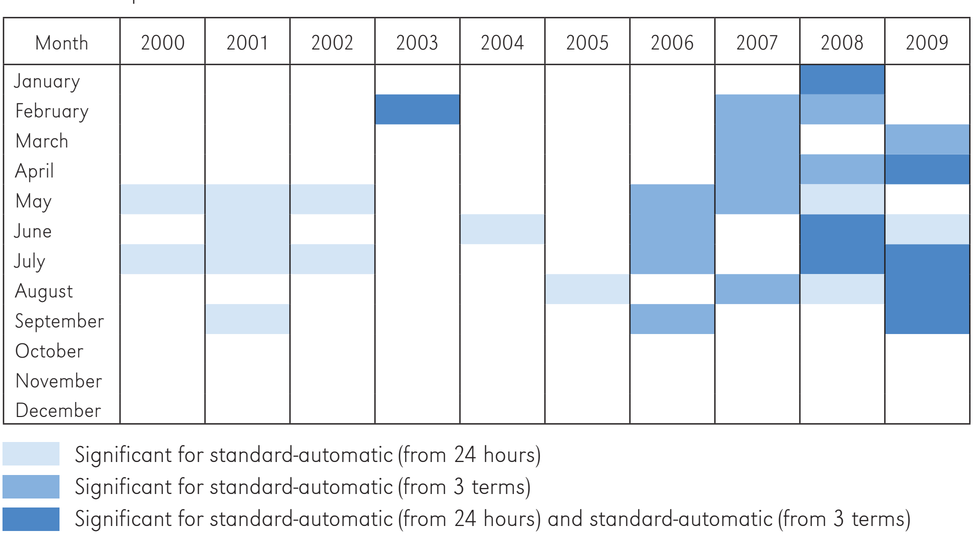

Table 2. Significance of differences between mean values of t_{g10} measured with a standard or automatic station in the period 2000-2009

Month	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009
January										
February										
March										
April										
May										
June										
July										
August										
September										
October										
November										
December										

Significant for standard-automatic (from 24 hours)

Significant for standard-automatic (from 3 terms)

Significant for standard-automatic (from 24 hours) and standard-automatic (from 3 terms)

observations (both standard and automatic). What is more, results obtained previously were not confirmed. Differences between soil temperature measured by two methods at a depth of 10 cm (regardless of the method of calculating the mean daily values) were not significant in the months of March, April and August–December (Tab. 2).

In earlier research, the authors analyzed the autocorrelation of time series for differences between the mean daily values calculated on the basis of standard or automatic measurements from 24 hours. The aim was to find seasonal fluctuations (Kajewska & Rojek 2011). A similar analysis was performed on the basis of daily averages from terminal observations using both methods (Fig. 5).

Charts presenting the autocorrelation show the dependence in the function of delay for 365 days (a year). On the figure, subsequent columns from the left represent delay, the autocorrelation coefficient for a current delay, standard error, Box and the Ljung Q factor, and the significance level of the result. The horizontal axis contains the confidence interval (0.05).

Out of the four graphs for autocorrelation obtained for t_{g5} and t_{g10}, the reader will find only one in the paper (Fig. 5), since the modification in the method of calculating mean daily values did not bring significant changes. The figure is the result of autocorrelation analysis conducted for the time series for differences between daily values of t_{g5} calculated on the basis of three terminal measurements during the day, or performed by standard and automatic methods. The received time series was characterized by annual seasonality. Regardless of the method by which daily averages are calculated, the autocorrelation coefficients noticeably exceeded the limit of two standard deviations, while the values for the 1st delay were high and amounted to 0.851 (t_{g5}) and 0.696 (t_{g10}). For delay 16th (first described in the chart) they were respectively equal to 0.476 and 0.405.

Subsequently, a seasonal breakdown for each time series was obtained, in order that individual components might be identified as seasonal, trend and random indicators. Figures obtained for the differences between the daily averages calculated on the basis of standard or automatic measurements over 24 hours (Figs. 6A-11A) were compared with the results received for the time series for differences between standard and automatic terminal observations (Figs. 6B-11B).

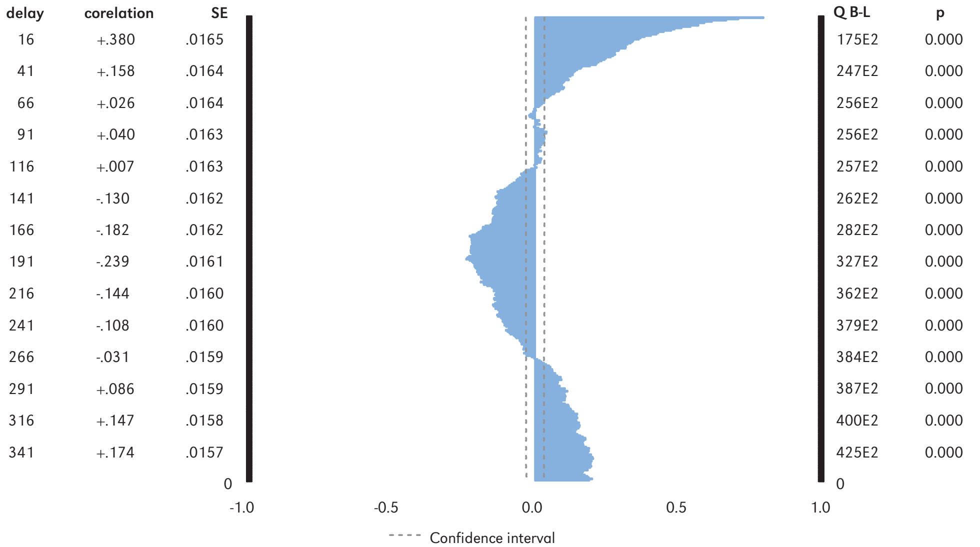

Figure 5. Diagram showing autocorrelation for differences between daily values for soil temperature under bare soil at a depth of 5 cm (°C), as measured with a standard or automatic station

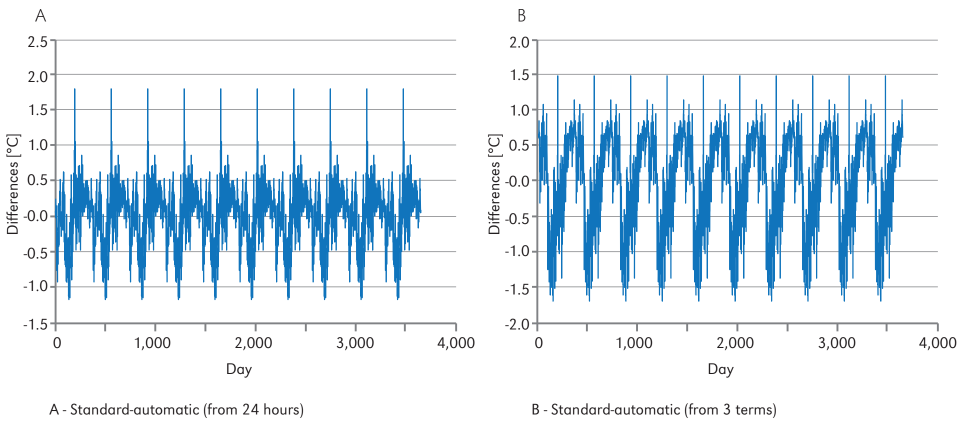

Figure 6. Seasonal component to time series for differences between daily values for soil temperature under bare soil at a depth of 5 cm, as measured with a standard or automatic station

In the first case, the seasonal component for t_{g5} ranged from -1.2°C in winter to 1.8°C in summer. This means that in summer the soil temperature was higher by 1.8°C, and in winter lower by 1.2°C, than values resulting from the trend (Fig. 6A). The change in daily average calculation on the basis of terminal automatic measurements resulted in a seasonal component ranging from -1.7 to 1.5°C (Fig. 6B). For t_{g10}, differences between manual measurements and automatic continuous observations as regards the seasonal component fluctuated between -0.8°C and 0.8°C (Fig. 7A), while in the case of differences between daily averages calculated from terminal values it ranged from -0.8°C in winter to 0.6°C in summer (Fig. 7B).

The line illustrating the trend for differences between mean daily values of t_{g5} counted by standard or automatic measurements over 24 hours was characterised by a slight downward trend over the entire 10-year

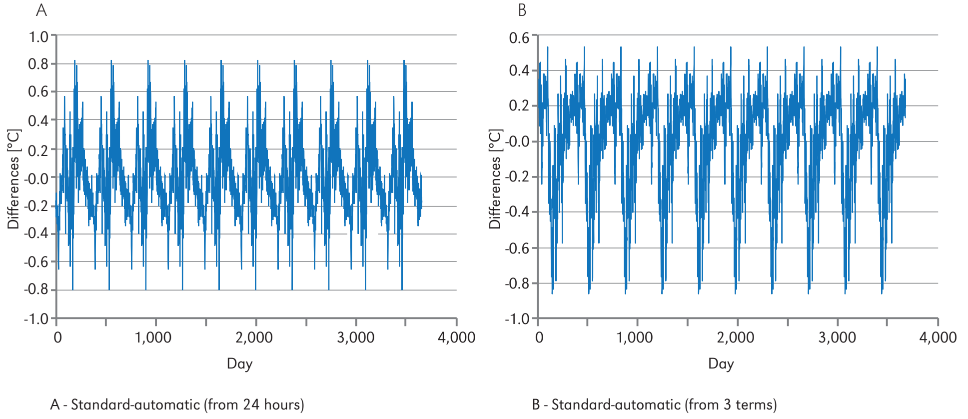

Figure 7. Seasonal component to time series for differences between daily values for soil temperature under bare soil at a depth of 10 cm, as measured with a standard or automatic station

period of research, with noticeable differences also present between values obtained in summer and winter. The values ranged from -8.0 to 4.0°C, but the extreme differences only occurred after 2007 (Fig. 8A). In Fig. 8B, the overall downward trend has been maintained, while the range of fluctuation was lower by 2.0°C and ranged from -7.0 to 3.0°C.

The trend line isolated from t_{g10} differences, regardless of the method of calculating daily averages, showed a downward trend. Indications of electronic sensors were maximum 4.0°C higher than values read off from mercury soil thermometers (Fig. 9A, B).

The random component was the last element isolated from time series through decomposition. It supplies information about all random incidents capable of affecting the magnitude of differences between values for meteorological parameters obtained through standard or automatic methods of measurement. For t_{g5} differences (standard–automatic averages over 24 hours), the value fluctuated between -4.0 and 7.0°C, while in the second case (standard–automatic from averages based on 3 terms), it ranged from -3.5 to 5.0°C, if with most values amounting to between -2.0 and 3.0°C (Figs. 10A, B). The random component for t_{g10} daily differences

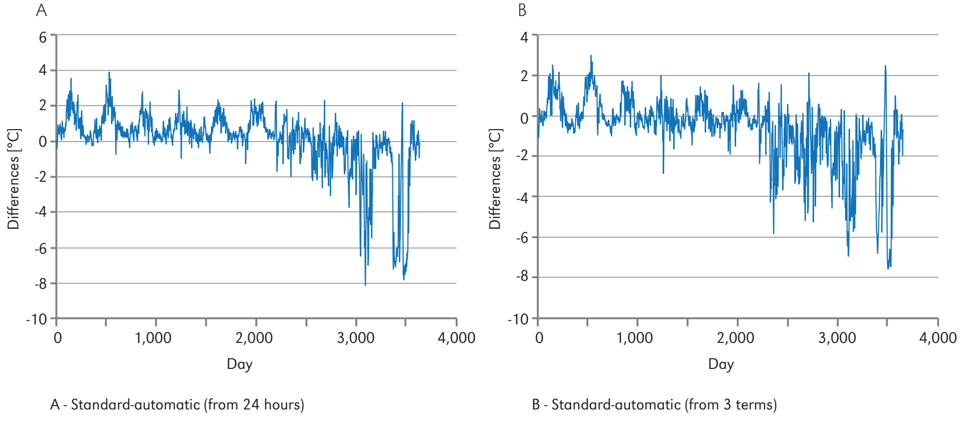

Figure 8. Trend for time series of differences between daily values for soil temperature under bare soil at a depth of 5 cm, as measured with a standard or automatic station

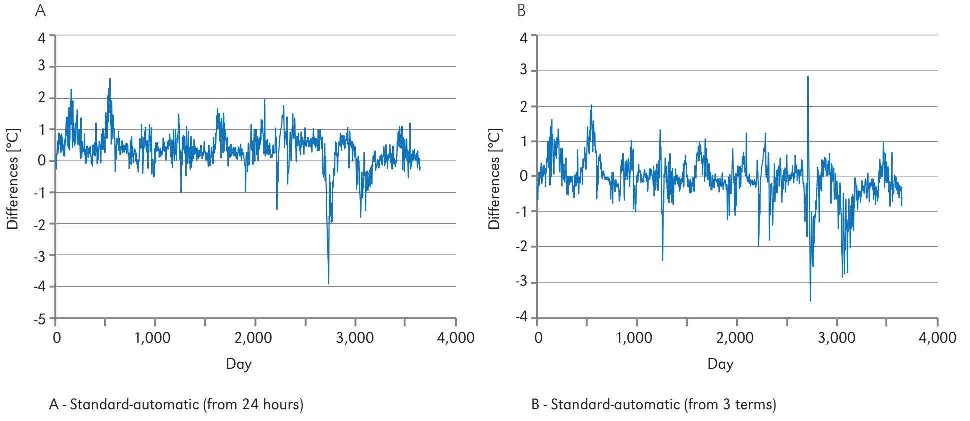

Figure 9. Trend for time series of differences between daily values for soil temperature under bare soil at a depth of 10 cm, as measured with a standard or automatic station

between mean daily values calculated on the basis of standard and automatic measurements (both formulae) ranged from -2.5 to 3.0°C (Fig. 11A, B).

Regardless of the method of calculating soil-temperature daily averages, all the analyses show a significant increase in differences between the two methods after 2006. A comparison of deviation statistics for the first five years (2000-2005) and for the entire study period (2000-2009) was done to confirm this observation (Tab. 3).

Analysis of means and medians indicates that higher values were recorded in the subperiod 2000-2005. Higher minimum values were obtained for 2000-2009. Maximum values were also higher for t_{g5} (A and B) during this period, whereas t_{g10} (A and B) showed the same values in both periods.

Other statistics (the range, variance and standard deviation) assumed significantly higher values when a 10-year study period was taken for analysis. The results indicate that extension of the time series caused a significant increase in values for the differences between the two methods of soil-temperature measurement. In spite of the regular calibration of sensors after 2006, a systematic error which was of an instrumental nature made its appearance. Following analysis of the results

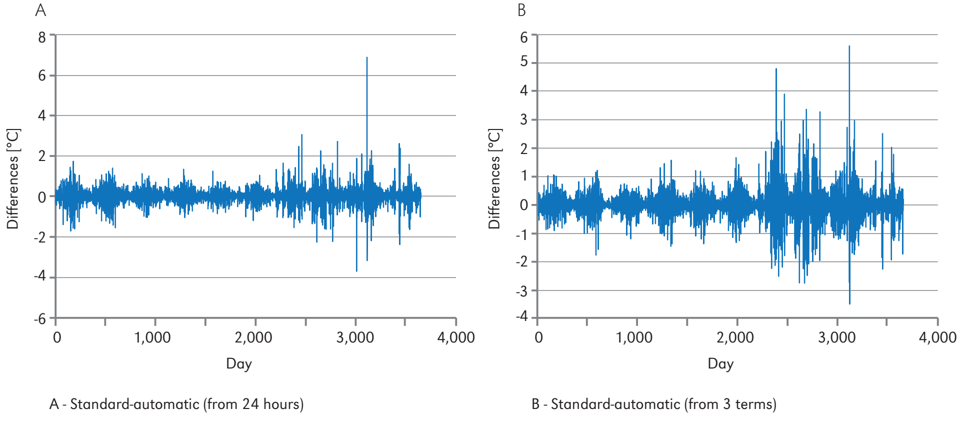

Figure 10. Random component to time series for differences between daily values for soil temperature under bare soil at a depth of 5 cm, measured with a standard or automatic station

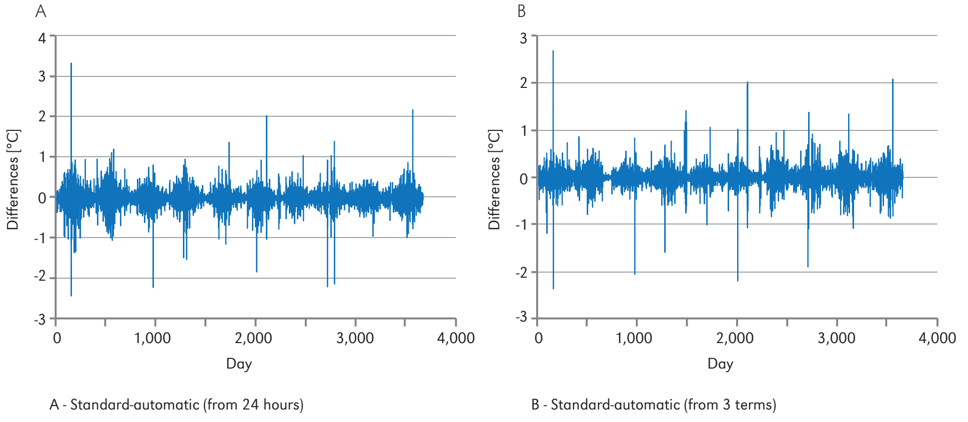

Figure 11. Random component of time series for differences between daily values of soil temperature under the bare soil at a depth of 10 cm, measured with a standard or automatic station

(for t_{g5} in particular), a decision as regards the purchase of new sensors and replacement of the old ones was taken.

Conclusions

A change in the method of calculating soil-temperature mean daily values on the basis of automatic measurements from 24-hourly to three terminal observations with values for the night hours skipped did not cause an observable reduction in the sizes of differences between the two methods. The use of such an approach would mean unnecessary resignation from the much more accurate data furnished by continuous observations with any time step.

Following the complete automation of meteorological measurements, the creation of a homogeneous time series would best make use of methods of correcting data generated on the basis of parallel measurements with both stations.

Regardless of the method of calculation, the mean daily values on the basis of automatic observations, the 90% of threshold frequency of differences in the centre interval [-1.0; 1.0) has not been reached.

The time series of differences obtained for soil temperature measured under the bare

Table 3. Statistics for differences between soil temperature measured using a standard or automatic station under bare soil in the periods 2000-2005 and 2000-2009

Element	Mean	Median	Minimum	Maximum	Range	Variance	St. Dev.
2000-2005							
t_{g5} (A)	0.850	0.700	-2.500	4.700	7.200	0.572	0.756
t_{g10} (A)	0.487	0.367	-2.700	4.600	7.300	0.395	0.629
t_{g5} (B)	0.110	0.213	-3.733	3.133	6.867	0.529	0.728
t_{g10} (B)	0.090	0.087	-3.800	3.663	7.463	0.291	0.540
2000-2009							
t_{g5} (A)	0.275	0.467	-7.934	7.418	15.352	2.433	1.560
t_{g10} (A)	0.367	0.303	-4.257	4.600	8.857	0.434	0.659
t_{g5} (B)	-0.467	0.022	-8.210	6.419	14.629	2.597	1.612
t_{g10} (B)	-0.088	0.020	-4.582	3.663	8.245	0.490	0.700

A standard–automatic (from 24 hours); B standard–automatic (from 3 terms) soil at depths of 5 and 10 cm were characterized by annual seasonality. This is manifested through an increase in the size of differences in summer and a decrease in winter.

Editors' note:
Unless otherwise stated, the sources of tables and figures are the authors', on the basis of their own research.

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