Diurnal Variation of Air Temperature in the Atmospheric Surface Layer

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Summary

In order to illustrate the nature of the diurnal temperature variations in the atmospheric surface layer in all seasons a set of hourly observations at the Zagreb-Maksimir Observatory (Croatia), measured at three different levels (5 cm, 50 cm and 2 m above ground) during the year 2005, was used. An approximate method for calculating air temperature at 5 cm, using the air temperature at 2 m, is presented. For this purpose, hourly data (screen height temperature, cloudiness, air pressure at barometer level and wind speed at 2 m) collected at the Zagreb-Maksimir Observatory during the summer season of 2005 have been used. This method is based on the Monin-Obukhov similarity theory. Estimated values have been compared with observations. The results obtained are the most accurate for cloudy weather, and the least accurate in the case of clear sky. A systematic error of this approach was discovered using a clustering procedure and is briefly discussed.

Key words

air temperature; atmospheric surface layer; Monin-Obukhov similarity theory

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Introduction

Air temperature in the atmospheric surface layer (ASL) is a very important weather parameter because a great part of the biosphere is located within this layer. In weather observation networks, conventional observations include almost continuous observations of air temperature at 2 m above ground (also called screen height temperature). Hourly observations of air temperature at other heights are available only from special observations. Only the night-time minimum air temperature at 5 cm above ground surface is observed at weather stations. Hourly observations of this parameter are usually not made, although hourly data could be useful for many practical applications (e.g. in agriculture, surface transportation, etc.). Exceptionally, there are special observation periods like the ones at the Zagreb-Maksimir Observatory, during 1975 or 2005, when the hourly values of air temperature at 5 cm and wind speed at 2 m above ground (in 2005) were observed as well as other conventionally measured weather elements, like air temperature at 2 m and wind speed at 10 m, etc. Because of the lack of observed hourly air temperature data at 5 cm above ground, only a theoretical approach to their estimation is possible, using conventionally observed weather elements and a special set of measured data.

The intention of this paper is to examine the daily variations of air temperature at three levels above ground: 5 cm, 50 cm and 2 m (see e.g. Zaninović and Gajić-Čapka, 1998/99; Penzar and Penzar, 2000) including the testing of a method for the estimation of air temperature at 5 cm above ground covered with short grass (not higher than 5 cm) based on the Monin-Obukhov (M-O) similarity theory (Arya, 1988; Oke, 1987; Likso, 1997; 2005; 2006). In this approach, the basic term is *turbulent sensible heat flux*.

Material and methods

Data

Observations of air temperature at 5 cm above ground can be performed by electronic sensors in two different ways: with a small, non-conventional plastic shelter and without any shelter. In this case, air temperature at 50 cm and 2 m was measured by sheltered sensors (Figure 1). The instrument was installed at the Zagreb-Maksimir Observatory (Figure 2), inside the standard meteorological screen (the standard height of the screen is 2 m above ground). In addition to air temperature, other data like wind speed at 2 m and air pressure were used. The data used refer to the year 2005.

Figure 1.
Equipment for temperature measurements at 5 cm and 50 cm above ground.

Statistical approach used for the calculation of the average diurnal variation of air temperature

The average diurnal temperature variation can be calculated if hourly observations of air temperature are available for a longer time period. It is useful for carrying out a grouping procedure in order to obtain groups of data on a seasonal or monthly basis. A detailed typisation can be made using the clustering procedure, as it was done in Likso (2005 and 2006). In this case, diurnal temperature variation patterns can be classified within the groups in dependence of weather type (clear sky, cloudy, windy, etc.)

Deterministic approach used for the estimation of air temperature at 5 cm above ground level

In this paper, the estimation of air temperature at 5 cm above ground level is based on conventionally measured atmospheric parameters at weather stations (air temperature at 2 m, air pressure at barometer height), on a special set of observations (wind speed at 2 m), as well as on theoretical estimations of air temperature at 4 cm above ground level (obtained from the vertical temperature gradient above the ground surface). Upper-air data should also be available. The presence of a grass canopy (short grass) of an average height of about 5 cm was taken into account. A modified version of this method could be applied inside a high canopy (e.g. wheat, maize, vine),

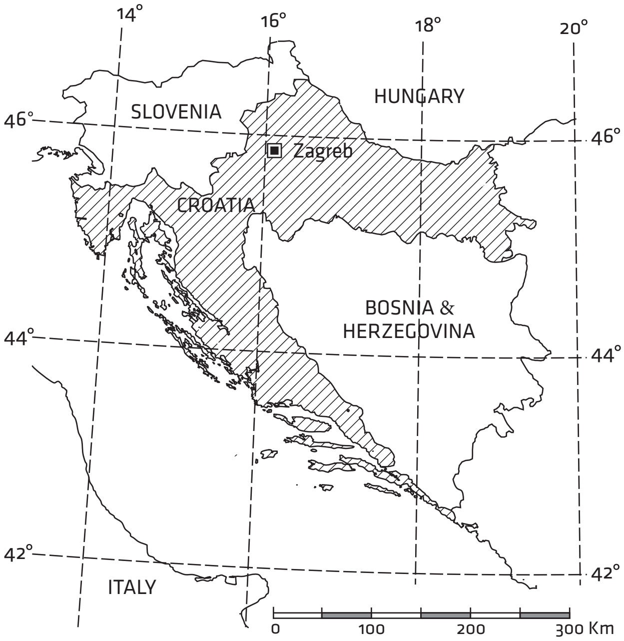

Figure 2.
Map of Croatia with the position of the Zagreb-Maksimir Observatory.

but this is not the objective of this paper (see e.g. Oke, 1987; page 138). As some readers of this paper may not be very familiar with the method presented, the authors think that a short presentation of the procedure could illustrate its applicability in practice.

1) Consider the roughness length for momentum, z_{0m}, which depends on surface characteristics. In all cases, z_{0m} is smaller than the physical height of the roughness element (Stull, 1988).

The definition taken to describe the dependence of z_{0m} upon the height of the canopy h_0 and the zero-plane displacement$^{(1)}$ d (according to Garratt, 1994) is:

$$z_{0m} = 0.2(h_0 - d). \tag{1}$$

With $d/h_0 = 2/3$ and taking $h_0 = 0.05$ m, this gives d = 0.033 m and $z_{0m} = 0.0034$ m. According to literature (e.g. Oke, 1987), these values are in good agreement with the aerodynamic properties of grass surfaces.

2) The roughness length for heat, z_{0h}, was obtained from the relationship by Garratt and Hicks (1973), valid for homogeneous surfaces:

$$\ln\left(\frac{z_{0m}}{z_{0h}}\right) \approx 2. \tag{2}$$

3) The bulk Richardson number was obtained according to:

$$R_{ib} = \frac{gz\Delta\theta}{\bar{\theta}u^2} \tag{3}$$

where $\Delta\theta$ is the difference of the potential temperature$^{(2)}$ at levels z (=2m) and z′(=0.04m), and $\bar{\theta}$ is the mean potential temperature of the layer. The potential temperature at z′=0.04 m was estimated from the vertical temperature gradient.

For stable atmospheric conditions$^{(3)}$ and when wind speed is $u \approx 0$, a critical bulk Richardson number, Ri_{b_crit}, is introduced into the calculation. For the Businger′s forms of stability functions, Ri_{b_crit} (when the M-O stability parameter $\varsigma \rightarrow \infty$) was obtained from (Carson and Richards, 1978):

$$Ri_{b\_crit} = [a(1-z_{0m}/z)]^{-1} \tag{4}$$

where a = 6.0. For z = 2 m and $z_{0m} = 0.0034$ m, $Ri_{b\_crit} = 0.17$.

4) Calculation of stability parameter ζ

In order to avoid an iterative procedure for calculating L, analytical solutions to the M-O stability parameter, $\varsigma = z/L$, in terms of (3), depending on atmospheric stability, were used (Launiainen, 1995). Hence:

a) Unstable conditions$^{(4)}$ ($\varsigma < 0$):

$$\varsigma = \left[\frac{(\ln z/z_{0m})^2}{\ln z/z_{0h}} - 0.55\right] Ri_b. \tag{5}$$

This relationship is valid for a limited range of z_{0m}/z_{0h} ($0.5 < z_{0m}/z_{0h} < 7.3$).

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(1) A height scale in turbulent flow over tall roughness elements (trees, buildings, etc.) associated with the average level of the action of momentum transfer between the flow and the roughness elements.

(2) The temperature that an unsaturated parcel of dry air would have if brought adiabatically and reversibly from its initial state to standard pressure, p_0, typically 100 kPa.

(3) These conditions are characterised by a positive change of potential temperature with height ($\partial\theta/\partial z > 0$) or when ζ is positive.

(4) This is the case with a negative change of potential temperature with height ($\partial\theta/\partial z < 0$) or when ζ is negative

b) Stable and neutral[(5)] conditions ($\varsigma \geq 0$):

$$\varsigma = \left[1.89\ln\left(\frac{z}{z_{0m}}\right) + 44.2\right] Ri_b^2 + \left[1.18\ln\left(\frac{z}{z_{0m}}\right) - 1.5\ln\left(\frac{z_{0m}}{z_{0h}}\right) - 1.37\right] Ri_b. \qquad (6)$$

5) Calculation of friction velocity

In order to estimate the kinematic sensible heat flux, the friction velocity, u_*, had to be calculated. For the stably and neutrally stratified ASL ($Ri_b \geq 0$), we used the results of the extended similarity theory (Zilitinkevich and Calanca, 2000). This layer was considered in the context of the planetary boundary layer (PBL) affected not only by the surface buoyancy flux, but also by the static stability beyond the turbulent boundary layer. They obtained:

$$u_* = \frac{uk - C_{u1}C_{u2}Nz}{\ln\frac{z}{z_{0m}} + C_{u1}\frac{z}{L}} \qquad (7)$$

where k = 0.40 is the von Karman constant, C_{u1} = 2.1, C_{u2} = 0.2 and N is the Brunt-Väisälä frequency of the free flow:

$$N = \sqrt{\beta\frac{\Delta\theta}{\Delta z}} \qquad (8)$$

where $\beta = g/T_0$, g=9.81 m s^2, Δz is the difference between the height of the standard isobaric surfaces 700 hPa and 850 hPa, and $\Delta\theta$ is the difference between the corresponding potential temperatures.

In unstable conditions ($Ri_b<0$), the following relationship for u_* was used (Wilson, 2001)

$$u_* = ku(z)\left[\ln\frac{z}{z_{0m}} - 3\ln\left(\frac{1+\sqrt{1+\gamma_m|z/L|^{2/3}}}{1+\sqrt{1+\gamma_m|z_{0m}/L|^{2/3}}}\right)\right]^{-1} \qquad (9)$$

where the suggested value for the constant is $\gamma_m = 3.6$ (Högström, 1996).

Using the expression for L, the temperature scale θ_* was obtained:

$$\theta_* = \frac{\overline{\theta}u_*^2}{kgL}. \qquad (10)$$

Then, the kinematic sensible heat flux[(6)] was calculated as:

$$\overline{w'\theta'} = -u_*\theta_*. \qquad (11)$$

6) The next step was the calculation of the potential temperature vertical gradient[(7)] according to:

$$\frac{\partial\theta}{\partial z} = -\frac{\overline{w'\theta'}}{K_h}. \qquad (12)$$

The exchange coefficient for heat was defined by the expression:

$$K_h = \frac{kzu_*}{\Phi_h(\varsigma)} \qquad (13)$$

where $\phi_h(\varsigma)$ is the approximate form of the similarity function for heat.

For calculating $\phi_h(\varsigma)$, modified Businger´s functions obtained for k = 0.40 were used, while the original formulae are given for k = 0.35 (Businger et al., 1971).

a) Unstable stratification:

$$\Phi_h(\varsigma) = 0.95(1\text{-}11.6\varsigma)^{-1/2} \qquad (14)$$

b) Stable and neutral stratification:

$$\Phi_h(\varsigma) = 0.95 + 7.8\varsigma \qquad (15)$$

Finally, the air temperature at 5 cm above ground level was obtained from (12), written in the form of finite differences.

Results

Average diurnal variations of air temperature

As a consequence of diurnal variations of net radiation and other energy fluxes, there are large diurnal variations in air temperature at all heights within the first hundred meters above ground, especially on clear summer days. The time of the maximum air temperature varies with height above ground: the higher the later and usually weaker (e.g. Sutton, 1953; Arya, 1988). In general, the amplitude of the diurnal air temperature variation is reduced by the presence of vegetation, cloud cover, smoke, haze, and strong winds. If the vegetation is dense or tall, it reduces the incoming radiation by absorption and reflection, and acts as the primary source of radiation during the night. The general effect is that the vegetative surface is subject to much less temperature variations than bare soil.

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(5) This is the case with $\partial\theta/\partial z=0$ or $\zeta=0$.

(6) In general, the kinematic flux is the transport of a variable per unit area per unit time (i.e. a dynamic flux), but in the case of heat flux, divided by the product of air density times specific heat of air at constant pressure. Statistically, kinematic fluxes are covariances.

(7) A change of potential temperature with height.

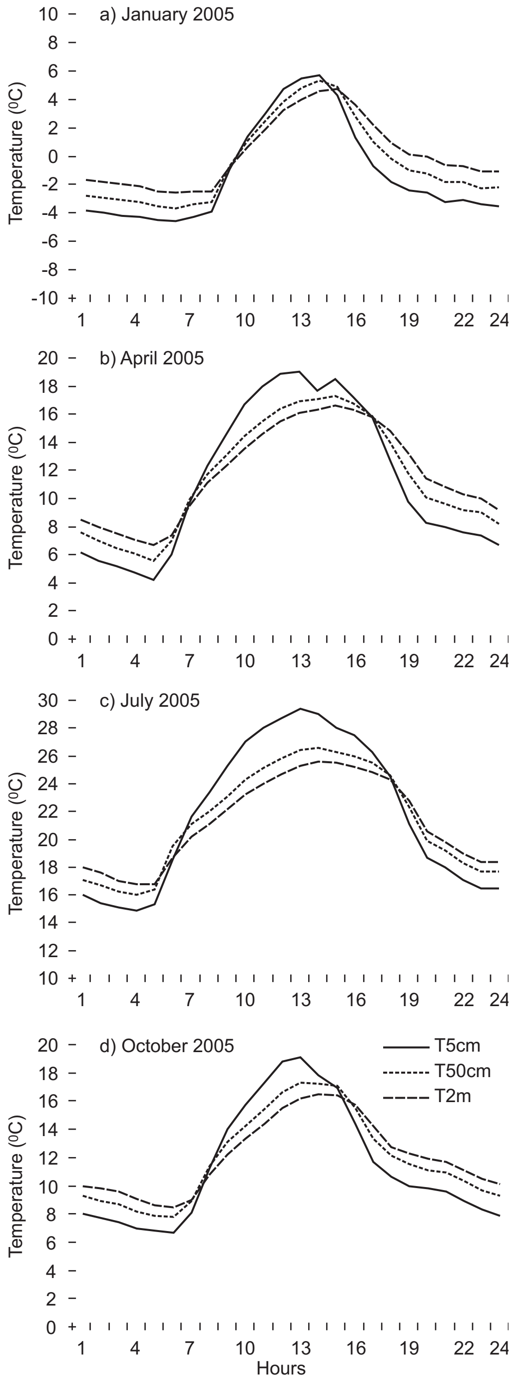

Figure 3.
Diurnal variations of air temperature at three heights (5 cm, 50 cm, 2 m) at the Zagreb-Maksimir Observatory for four months in 2005.

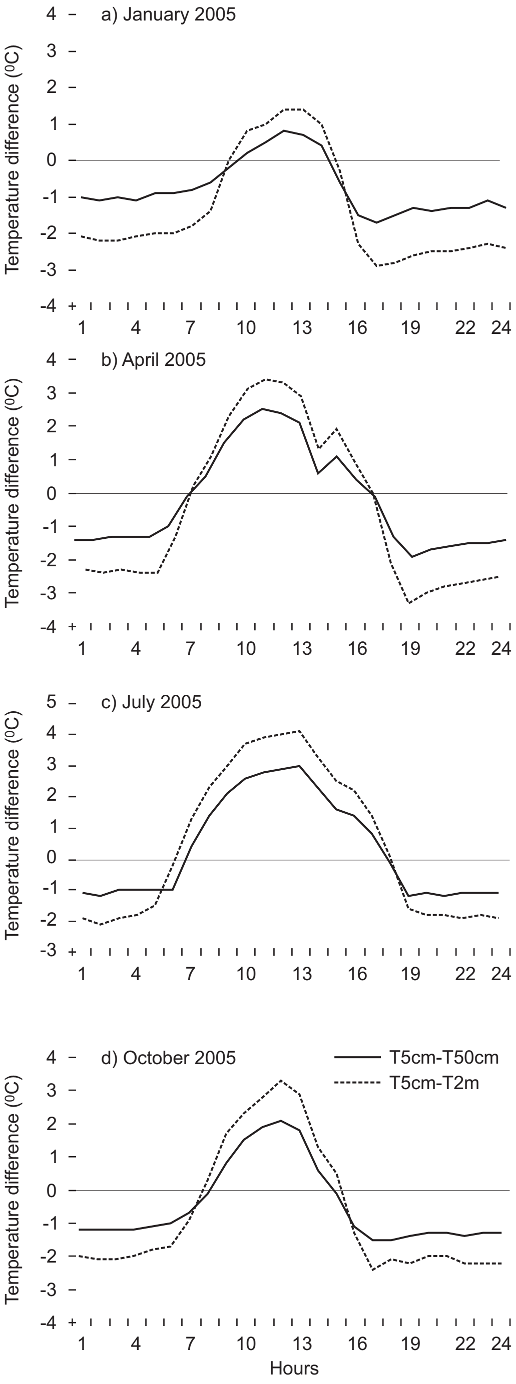

Figure 4.
Diurnal variations of air temperature differences within the ASL at the Zagreb-Maksimir Observatory for four months in 2005. The temperature differences refer to 5 cm and 50 cm as well as 5 cm and 2 m above ground level.

The average hourly values of air temperature at 5 cm, 50 cm and 2 m above ground were calculated for each month for 2005. The maximum number of data was 31. These average data are visualized in Figure 3 for January, April, July and October representing the winter, spring, summer and autumn season, respectively. It is obvious that the amplitude of daily variations of air temperature is the smallest in January and the largest in July. It is a consequence of the influence of solar radiation which is more intensive in summer than in winter. While the values in April and October are similar, the amplitude of daily variations in April is more similar to July than to October. The largest amplitude is for air temperature at 5 cm and the smallest for air temperature at 2 m. This also means that air temperature at lower heights is closely related to the diurnal variations of short-wave (solar) and long-wave (Earth-atmosphere) radiation.

Further analysis of the diurnal temperature variations can be performed taking into consideration the differences between the average hourly temperature values between two levels: t_{5cm}-t_{50cm} and t_{5cm}-t_{2m}. The results are presented in Figure 4. As can be seen from the figure, the night-time differences are almost the same for all seasons while the day-time differences are the lowest for winter (short-wave radiation is the weakest) and the highest for summer (short-wave radiation is the strongest). The differences in spring and autumn are very similar. The differences, in average, are higher between the temperatures at 5cm and 2m than between those at 50 cm and 2 m. Of course, this is not valid for all particular cases because diurnal temperature variations within the ASL strongly depend on cloudiness as well as on atmospheric stability and wind speed, as it was shown by Likso (2005 and 2006).

Discussion of the results obtained using the M-O similarity theory

The method described includes advection, so it can be used for estimating air temperature at 5 cm if measured hourly values of air temperature at 2 m above ground, wind speed at 2 m and upper-air data (heights of the standard isobaric surfaces 850 hPa and 700 hPa with the corresponding temperatures) are available.

The hourly values of air temperature at 5 cm at the Zagreb-Maksimir Observatory have been estimated using the M-O similarity theory for summer 2005. There are examples of good agreement between the observed and estimated data, as can be seen from Figure 5, which refers to 4 April 2005. The other results indicate that the method based on the M-O similarity theory underestimates the air temperature at 5 cm during daytime, especially when the sky is almost clear. Then, radiative effects dominate the near- ground temperature (see also Likso 2005 and 2006).

Using the clustering procedure, three groups (types) of days with similar diurnal variations of air temperature difference between 5 cm and 2 m, $\Delta T \equiv T_{0.05m}$-$T_{2m}$, have been found. Then, the average differences between estimated and observed values of air temperature at 5 cm above ground could be found for each type. The results indicate that the highest average differences are for clear days, somewhat lower for half-cloudy days and the lowest for cloudy days. These errors can be considered systematic errors of the method based on the M-O similarity theory. It is possible to eliminate these systematic errors from the estimated values - always the same value is subtracted for the same time of day and weather type (see Likso, 2006). In this case, the new estimation will not be perfect, but it is sure that the estimated values will be much better than before this operation.

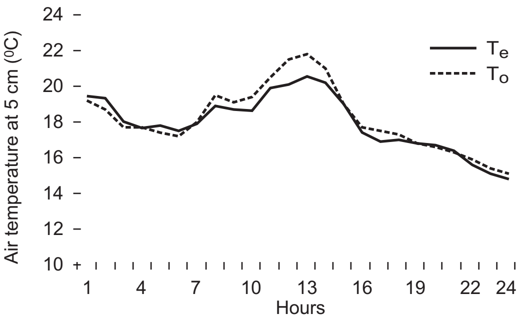

Figure 5.
Observed (T_o) and estimated (T_e) hourly values of air temperature at 5 cm above ground level. The method of estimating air temperature at this level is based on the M-O similarity theory. The results presented refer to the Zagreb-Maksimir Observatory for 4 August 2005.

To summarise, the method described, based on the M-O similarity theory, finds a reasonable fit to the observed values of air temperature at 5 cm above ground in the night-time for all cases and during the whole day for near-neutral conditions (overcast sky and strong wind). For clear weather, the largest deviations between the estimated and observed values appear in the warmest part of the day. This method is based on the assumption that the local temperature change in the daytime (summer period), at the level of 2 m, depends on the vertical change of the sensible heat flux, while the convergence and divergence of radiative fluxes are not taken into account. The consequence is a systematic deviation between the estimated and observed values in the daytime. The elimination of the systematic error for the warmest part of the day leads to acceptable results for all cases.

Conclusion

The one-year observations of air temperature at three levels above ground (5 cm, 50 cm and 2 m), during 2005, at the Zagreb-Maksimir Observatory, have provided useful results. They reveal that there is a seasonal dependence of the diurnal variation of the air temperature amplitude on season and height. These average temperature variations are mainly a consequence of the daily and seasonal change of short-wave radiation, while the diurnal variation for particular cases is also strongly influenced by cloudiness, wind speed, atmospheric stability, etc.

The deterministic estimation of air temperature at 5 cm is dependent on cloudiness and wind, i.e. atmospheric stability. Thus, for near-neutral conditions (cloudy and windy conditions) the estimations obtained are in good agreement with the measurements. On the other hand, for stable and unstable conditions there are systematic errors. In order to obtain better results for all weather conditions, further research is necessary. Moreover, a modification of this approach should be developed for different kinds of vegetative canopy (e.g. wheat, maize, vine etc.), which is a new task.

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