What determines the nocturnal cooling timescale at 2 m?

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[1] An evaluation of high-frequency temperature observations revealed, that annually there exist 80–100 calm weather days, when a significant part of the nocturnal cooling period can be well fitted with a simple exponential function. Statistics of characteristic time constants indicates a wide, skewed distribution and the lack of an annual cycle. A search for basic meteorological variables determining the magnitude of the cooling rate remained inconclusive. No correlation was found with daily average temperature anomaly, soil moisture, absolute air humidity, wind speed, pressure, nighttime outgoing and daytime incoming radiation. The air temperature is more strongly coupled to the soil temperature, but surprisingly, the cooling rate in the soil seems to be very weakly correlated with the cooling rate of air at 2 m. INDEX TERMS: 3307 Meteorology and Atmospheric Dynamics: Boundary layer processes; 3322 Meteorology and Atmospheric Dynamics: Land/atmosphere interactions; 3359 Meteorology and Atmospheric Dynamics: Radiative processes. Citation: Pattantyús-Ábrahám, M., and I. M. Jánosi (2004), What determines the nocturnal cooling timescale at 2 m?, Geophys. Res. Lett., 31, L05109, doi:10.1029/2003GL019137.

1. Introduction

[2] Probably the most fundamental aspect of boundary layer meteorology is an understanding of the diurnal temperature cycle. Irrespective of the geographic location, the near surface temperature is controlled by three factors: (i) heat flux (net short and long wave radiation + sensible and latent heat + conductive and turbulent heat transport through ground and water mass + horizontal advection); (ii) heat storage or heat capacity; and (iii) water phase changes (switching between sensible and latent forms of heat) [e.g., Garratt, 1992; Holton, 1992; Hartmann, 1994; Thomas and Stammes, 1999]. Any model attempting to simulate or predict surface temperature needs some representation of the above constituents to provide a quantitative measure of their effects [Watterson, 1997; Meyer and Rao, 1999; Jacobson, 1999; Melas et al., 2001].

[3] Interest in effective physical modeling and forecasting nocturnal temperature fall and ground frost dates back to Brunt [1932]. His equation predicts the heat diffusion controlled evolution for the surface temperature $T_s$:

$$T_s(t) = T_0 - C_B \sqrt{t},$$

where the prefactor $C_B$ involves material parameters such as mean density, specific heat, thermal diffusivity, and effective radiation. Groen [1947] expanded the theory by considering variable effective radiation, and obtained

$$T_s(t) = T_0 + C_G \left[ \exp \left( \frac{t}{\tau} \right) \operatorname{erfc} \left( \sqrt{\frac{t}{\tau}} \right) - 1 \right],$$

where $C_G$ and $\tau$ are empirical constants related to net radiation and material properties, and ‘erfc’ denotes the complementary error function. The first term of the Taylor series for equation (2) agrees with Brunt’s formula (1), but it predicts much slower cooling rates at later times. [4] If the atmosphere is assumed to be an isothermal transparent layer cooling by pure radiation, temperature perturbations decay exponentially to an equilibrium value $T_E$ with an $\epsilon$-fold effective time constant

$$\tau_E = \frac{\rho_0 c_p}{4 g \sigma T_E^4},$$

where $\rho_0$ is the base pressure, $c_p$ is the specific heat, $g$ is the gravitational acceleration, and $\sigma$ denotes the Stefan-Boltzmann constant [see, e.g., James, 1994]. Terrestrial numerical values yield an estimate $\tau_E \approx 20$ days, which clearly indicates that the crude approximation (3) is unsuitable to describe temperature changes close to the surface. More complex models including air-soil interactions, absorption by humidity and CO$_2$, stratification, and backward radiation etc., yield to more realistic values for cooling characteristic times [Kuo, 1979; Tsuang, 2003]. [5] The evaluation of high temporal resolution air temperature data for the standard height of 2 m reveal that the effective cooling function in calm days is not like equation (1) or (2), but rather has a pure exponential form. Here we present a detailed statistical analysis of the time constants, based on two years of observations at two distant stations. Surprisingly, the time constants are not correlated with any simple meteorological parameters determined routinely, possible reasons are discussed.

2. Data Analysis

[6] Two records with a temporal resolution of 10 minutes were evaluated in detail. One is from the meteorological station of the Eötvös University, Budapest, Hungary, at the campus of the Faculty of Sciences (47.47°N, 19.07°E), standard surface temperature (2 m) and radiation data for the period 2001–2002. The other is the “Nerrigundah Catchment” located 11 km north-west of Dungog, NSW, Australia (32.19°S, 151.43°E). Besides standard air temperature and net radiation, many other meteorological and hydrological parameters were simultaneously obtained and recorded forming an extremely rich dataset [Walker et al., 2001] (see also http://www.civag.unimelb.edu.au/~jwalker/...
data/nerrigundah/). In our analysis, we considered the following characteristics: wind speed (3 m), relative humidity, atmospheric pressure, soil heat flux at two depths (−2 and −12 cm), soil temperature at −2 cm, soil moisture at −5 cm, and gross evapotranspiration.

Visual evaluation of the records revealed that approximately 30% of the days show a very regular temperature cycle (Figure 1). The weather is calm on these days, and radiation data indicate the lack of strong fluctuations in cloudiness (fully clear sky is not a prerequisite). Also, the average temperature can differ considerably from long term mean values (see Figure 1a). On such days, a significant part of the cooling periods can be fitted well with a simple exponential function (Newton’s law of cooling)

$$T(t) = [T_{0,d} - T_c(d)] \exp \left( \frac{t - t_{0,d}}{\tau_c(d)} \right) + T_c(d),$$

where the physically interesting parameters are the asymptotic cooling temperature $T_c(d)$, and the time constant $\tau_c(d)$ for the given day $d$. (The reciprocal value $k = 1/\tau_c$ is often referred to as “exponential cooling rate” or simply “cooling rate”.) Note that the parameter pair $T_{0,d}$ at $t_{0,d}$ can be directly read from the cooling curve, an optimal choice is a temperature value close after sunset. An exponential approximation works well in many cases for warming too, however, here we concentrate on cooling only, since it is associated with a simpler physics. The asymptotic temperature $T_c$ can be considered as an attribute of a thermodynamic equilibrium of the lower atmosphere, where the bottom layer relaxes to with unchanging boundary conditions. Of course, here we refer to a local dynamical equilibrium which can be far (as it is) from a static equilibrium state.

The general statistics of the time constant $\tau_c$ is shown in Figure 2. The numerical values were obtained by fits over the night hours (negative net radiation), but the actual range was flexibly adjusted to cut out short disturbances. When the error of $\tau_c$ exceeded 3–4%, the day was omitted from the statistics. Two important aspects of the results are that the values and the distributions (which are wide and skewed) are essentially the same for both stations, and there is no visible sign of an annual cycle.

3. Atmosphere-Soil Coupling

Since we intend to find a connection between cooling rates and other atmospheric or soil state variables, our following analysis is restricted to the Nerrigundah data set. The careful choice of the location (undisturbed land used for grazing, 11 km away from settlements, etc.) ensures that the boundary conditions were as intact as possible: no urban heat effects or drastically changing albedo as a consequence of intensive cultivation [Walker et al., 2001].

The strong coupling between soil, soil moisture, and air is well known [Hartmann, 1994], and many aspects have been experimentally studied in detail. For example, soil moisture reduces the diurnal cycle of air temperature [Betts and Ball, 1995], a number of land-surface characteristics influence the continental and global climate; these include albedo [Charney et al., 1977], soil moisture [Shukla and Mintz, 1982], roughness [Sud et al., 1988], and land-cover change [Nobre et al., 1991].

Figure 3 illustrates the coupling between air temperature at 2 m and soil temperature at −2 cm. The amplitude of the temperature cycle in the soil more strongly depends on the presence of moisture, as expected. The soil temperature has in general considerably smoother temporal vari-

![Figure 1](image1.png)  
**Figure 1.** Temperature records for consecutive days of calm weather for (a) Budapest and (b) Nerrigundah farm. Thin dashed lines indicate long term average temperatures, thick gray lines are exponential fits.

![Figure 2](image2.png)  
**Figure 2.** Values of time constant $\tau_c$, (solid circles) in units of minute as a function of time for (a) Budapest and (b) Nerrigundah. The appropriate histograms are plotted on the right (note the semilogarithmic scale).

![Figure 3](image3.png)  
**Figure 3.** Air (solid line) and soil (dashed line) temperature records for consecutive days (a) in the wet season, and (b) in a dry period. Gray lines indicate exponential fits.
ability, apparently 2 cm is enough for an effective insulation against short time irregularities induced by convection, surface wind, passing of clouds, etc. It is perhaps more interesting that the exponential function (4) provides the best fit for the cooling periods in the soil too. When the amplitudes are small (Figure 3a), power-law fits \( T(t) = T_0 / c t^\alpha \) also work; however, the exponent values cover a wide range, \( \alpha \in [0.4, 1.2] \) instead of being close to 1/2 (cf. equation (1)). At large amplitudes (Figure 3b), the exponential behavior is unambiguous. Furthermore, an exponential fit has the advantage that the cooling process can be easily characterized by a well defined timescale \( \tau_c \).

Usual correlation analysis [von Storch and Zwiers, 1999] revealed that the time evolution of temperature in the air and soil is strongly synchronized: the diurnal cycle in the soil at \(-2\) cm lags behind the air with a slight delay of \(~20\) minutes (see Figure 4a, inset). Note that this is a statistical statement for an average behavior, the variability can be large for particular cases (the lag is \(~2\) hours for the days shown in Figure 3a, but the soil temperature “overtakes” by a similar amount in Figure 3b). It is somewhat surprising that the cooling time constants for the air and soil show weak correlation, cf. Figure 4b. We emphasize that the scatter plot contains data for the days only when both cooling processes could be well fitted by exponential functions. On the other hand, the asymptotic temperatures show stronger correlation (Figure 4c), the temperature drop expected between the top layer of the soil and overlying air is statistically \(~6^\circ C\) for the given depth and location.

4. Cooling Time-Constant Analysis

[13] The exponential cooling on calm days (Figure 1), the “universality” and the wide distribution of the characteristic time \( \tau_c \) (Figure 2) need an explanation. When \( \tau_c \) is determined by a single meteorological parameter or by a combination of a few of them, exponential fitting could be even considered as a diagnostic tool. It could be used to improve the characterization of the state of the atmospheric boundary layer and/or the soil surface. Therefore, we analyzed correlations among high resolution meteorological and soil parameters, measured simultaneously at the Neriggundah catchment [Walker et al., 2001].

[14] Figure 5 shows representative results for six parameters. They are good candidates to determine the nocturnal cooling rate. For example, one could speculate that a large positive daily mean temperature anomaly would result in a faster nighttime cooling than an anomaly of the opposite sign. No such correlation was found, \( \tau_c \) is independent of

![Figure 4](image_url)

**Figure 4.** (a) Cross correlation function for the soil and air temperatures \( C_x(t) = \langle T_{soil}(t)T_{air}(t + \tau) \rangle \). The inset is zoomed to the origin, the local maximum is around 20 minutes. (b) Scatter plot for the cooling time constant of air and soil. Gray line indicates full correlation. (c) Scatter plot for the asymptotic temperature of air and soil. Dashed line is a fit of slope close to 1, which indicates a statistically most probable temperature difference of \( 6^\circ C \).

![Figure 5](image_url)

**Figure 5.** Scatter plot for the cooling time constant \( \tau_c \), and (a) temperature anomaly \( T_a \), (b) soil moisture \( SM \), (c) absolute air humidity \( AH \), (d) average wind speed \( v \), (e) nighttime outgoing radiation \( Rad_n \), and (f) daytime incoming radiation \( Rad_d \) on the same calendar days. Averages were obtained over the same interval as the exponential fits, except for (f) where integration was performed between sunrise and sunset.
the sign and magnitude of the anomaly (Figure 5a). Similarly, on the one hand, the amplitude of soil temperature variation is determined by the average soil moisture (integrated over the fitting period), on the other hand, we found that $\tau_c$ in the air is practically independent of it (Figure 5b). We emphasize that the same is valid for $\tau_c$ in the soil. Note, however, that the asymptotic cooling temperature $T_c$ is much more correlated with the soil humidity (not shown). Next we calculated the absolute air humidity (AH) in the usual way [e.g., Stull, 2000]. Though water vapor is the most important absorbing and back-radiating atmospheric component of infrared radiation, there is no correlation between $\tau_c$ and AH (Figure 5c). Wind enhances both evaporation and mixing, thus its effect on cooling time-constant can not be easily predicted. Figure 5d shows that weak average wind ($v < 2$ m/s) does not seem to be an important factor influencing $\tau_c$. Larger wind speeds are apparently connected with smaller time-constants (fast cooling). Nevertheless, statistics for $v > 2$ m/s is poor, because days of smooth exponential behavior (calm weather) are characterized by weak overall air flow. It is surprising that the cooling rate is independent of the average outgoing radiation, too (Figure 5e). Unfortunately, the distribution of cloud cover was not recorded during the Nerrigundah experiment. An indirect way of estimating cloudiness may be based on the average incoming radiation. Assuming that daytime cloud cover (indicated by low average insolation) may persist over the night, incoming radiation data might be used for correlation analysis, too. No correlation with cooling time-constant is observed (Figure 5f).

[15] Without showing additional figures, we emphasize that all scatter plots are similarly structureless also for the following parameters: atmospheric pressure, relative humidity, average temperature, heat fluxes at both depths, and Penman-Monteith evapotranspiration. We are fully aware of multivariate regression analysis. Nevertheless, the first step in order to observe any nontrivial correlation should be to find some promising variables by similar scatter plots.

5. Conclusions

[16] On calm weather days the nocturnal cooling can be described by an exponential function characterized by a timescale $\tau_c$. Statistical analysis shows no correlation among $\tau_c$ and several atmospheric and soil variables (see Figures 4b and 5a–5f). The simple exponential form suggests that an uncomplicated effective physical model is feasible. We think that the most important factor of nocturnal cooling rate is the total amount of water in the troposphere. This quantity is poorly represented by the boundary value of atmospheric vapor content. Condensed water in clouds has many orders of magnitude larger mass than that of in the gas phase [Houze, 1993]. Furthermore, the total water content can not be easily estimated by means of incoming short-wave radiation, since thin cloud layers reflect sunshine almost as efficiently as thick ones. Though the total atmospheric water content has a strong seasonality [Watterson, 1998], such tendencies are not visible in Figure 2. Detailed analysis of column-integrated precipitable and liquid water data, such as produced by the NASA Water Vapor Project [Simpson et al., 2001], and high resolution temperature time series might help for a better understanding of cooling processes.

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