11.2 HEAT BALANCE IN NOCTURNAL BOUNDARY LAYERS

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1. INTRODUCTION

Early measurements indicated that radiative flux divergence at night contributed to clear air cooling and was always larger than the observed cooling in the lowest few meters (Funk, 1960; Fuggle and Oke, 1976; Roach et al. 1976; Nkemdirim, 1978; Zhou and Chang, 1982; Moncrieff, 1983; and Nkemdirim, 1988). Based on sensible heat flux divergence observations, Kondo et al. (1978) and Howell and Sun (1999) found that the sensible heat flux was divergent in the lowest 10 m in the nocturnal boundary layer, and contributed significantly to cooling, instead of warming as predicted by the previous studies.

Radiative flux divergence has also been studied using numerical models (Garratt and Brost,1981; André and Mahrt, 1982; Li et al. 1983; Tjemkes and Nieuwstadt, 1990; and Räisänen, 1996). Numerical studies found that the radiative flux divergence and sensible heat flux divergence dominated the cooling in the lower (surface layer) and upper part of the NBL, respectively (Garratt and Brost, 1981; and Li et al. 1983).

During the Cooperative Atmosphere-Surface Exchange Study (CASES-99) (Poulos et al. 2002), vertical variations of radiative and sensible heat fluxes were carefully measured (section 2). In section 3, we focus on the relative roles of radiative and sensible heat flux divergences in the heat balance at night. The results are summarized in section 4.

2. OBSERVATIONS

CASES-99 was conducted about 5 km southeast of Leon, Kansas, USA, during October, 1999. A 60-m tower at the main site was surrounded by 6 Integrated Surface Flux Facility (ISFF) 10 m towers (Sun et al. 2002a). Ten Eppley Precision Infrared Radiometers (Model PIR) were deployed to measure the longwave radiative flux divergence: four of the pyrgeometers were installed on a 5 m boom at 48 m on the 60-m main tower, two to measure the downward longwave radiative flux and two the upward longwave radiative flux (Burns et al. 2000; and Burns et al. 2002). Among the remaining six pyrgeometers, two were installed at stations 1 and 2 to monitor the downward longwave radiation at 2 m height, and the other four pyrgeometers were installed at stations 3 and 5 to monitor the upward longwave radiation at 2 m height for the four dominant surface types surrounding the 60-m tower.

The outgoing longwave radiation measured by the downward-looking pyrgeometer is formulated as the integral of the longwave radiation intensity normal to the flat ground surface over a hemisphere (Liou, 1980). Assuming the surface area that the downward pyrgeometer at 48 m sees consists of 4 simplified surface types, where the downward longwave radiation measurements were available, the upward longwave radiation at 48 m can be simplified as

$$I^{\uparrow}_{48m} = 0.94\ I^{\uparrow}_1 + 0.03\ I^{\uparrow}_2 + 0.02\ I^{\uparrow}_3 + 0.01\ I^{\uparrow}_w. \quad (1)$$

Here the subscripts 1, 2, 3 and w represent the upward longwave radiation from the surface-types near stations 1, 2, and 3, and from a pond close by (Sun et al. 2002b). The weights in Eq.1 are derived using dimensions of the simplified surface types. Eq.1 indicates that contributions other than from surface type 1 to the longwave radiation measured at 48 m are small. In order to keep the same surface contribution to the upward longwave radiation measured at both 48 m and 2 m, the weights from each surface type in Eq.1 are also used in calculating the upward longwave radiation at 2 m. Using the standard deviations of each pyrgeometer calibrated during the bench period, the measurement error for radiative flux differences between 2 m and 48 m is estimated as 1.2 W m^{-2}.

3. NOCTURNAL HEAT BALANCE

The heat balance within a layer can be expressed approximately as (Stull, 1988),

$$\frac{\partial\overline{\theta}}{\partial t} + \frac{\partial\overline{u}\overline{\theta}}{\partial x} + \frac{\partial\overline{w'\theta'}}{\partial z} = \frac{\overline{T}}{\overline{\theta}c_p}\frac{\partial\Delta I}{\partial z}, \quad (2)$$

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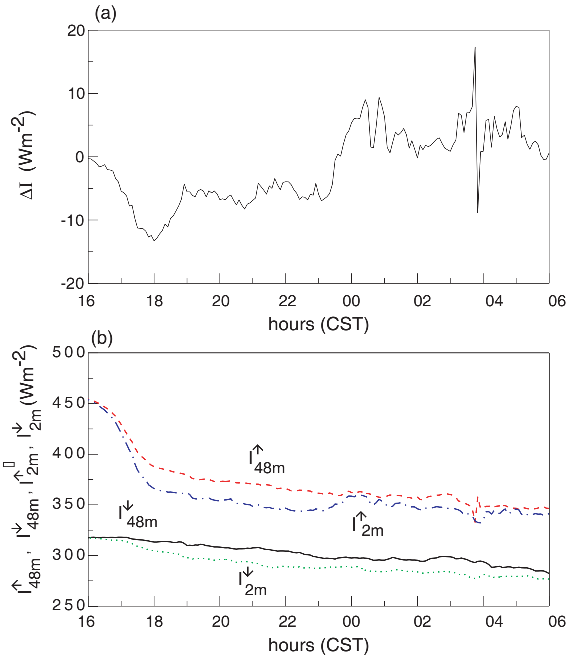

Figure 1: (a) Net radiative flux difference between 2 m and 48 m and (b) the measured incoming and outgoing longwave radiation components at 2 m and 48 m for the night of October 21, CST.

where $\overline{\theta}$, and $\overline{T}$ are the mean potential temperature and temperature, c_p is the specific heat at constant pressure, $\overline{u}$ is the mean wind speed, $\overline{w'\theta'}$ is the sensible heat flux, and x and z are the along-wind and vertical coordinates, respectively. In Eq.2, we assume that the horizontal turbulent heat flux divergence $(\partial(\overline{u'\theta'})/\partial x)$ and the mean vertical advection of heat $(\partial(\overline{w}\overline{\theta})/\partial z)$ are negligible compared to the other terms.

On the night of October 21 in CST (October 22 in UTC), the outgoing longwave radiation started to decrease sharply around 1700 CST (Fig. 1). As a result, the radiative flux divergence increased to about 13 W m^{-2} (i.e. about 1 C h^{-1}). The sensible heat flux started to become downward close to the ground as the ground cooled, while the residual heat flux above was still slightly positive or zero, leading to the vertical divergence of the sensible heat flux between 1.5 m and 50 m of about 5 W m^{-2} (i.e. about 0.4 C h^{-1}). The sum of the radiative and sensible heat flux divergences is about 1.4 C h^{-1}, which accounts for most of the local temperature decrease of 2 C h^{-1} between 2 m and 48 m (Fig. 2). Fig. 3 indicates that the spatial variation of the temperature at 2 m above the ground varied with the surface elevation and the wind was relatively weak, about 0.66 ms^{-1} at 2 m. The largest elevation difference between the six ISFF stations is

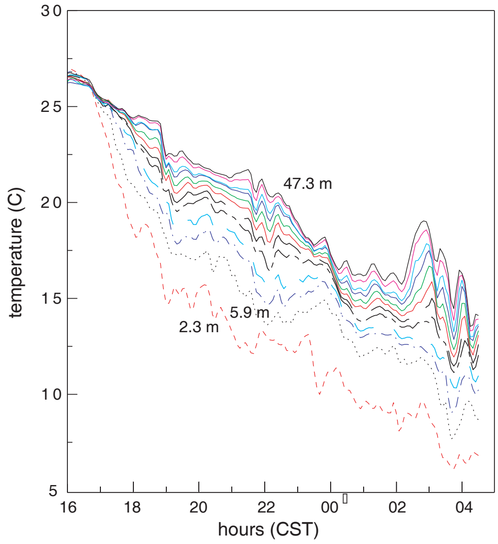

Figure 2: Time series of the thermocouple temperature between 2 m and 48 m for the night of October 21. The height increment between adjacent levels is 1.8 m.

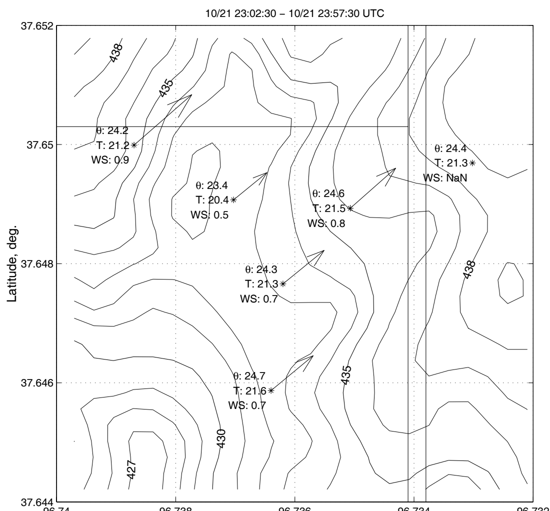

Figure 3: Temperature and wind speed and direction at 2 m between 1700-1800 CST at the six stations. The contour lines are the surface elevation at 1 m intervals.

about 6 m, which leads to a negligible potential temperature correction of about 0.06 C. In order to obtain the heat advection of 0.6 C h^{-1} based on the residual calculation above, the estimated horizontal temperature gradient has to be about 0.05 C km^{-1}, considering the approximate wind speed of 3 m s^{-1} within the layer at the time. This small temperature advection is not measurable with towers separated by 100 m or even one km in view of the accuracy of current temperature measurements.

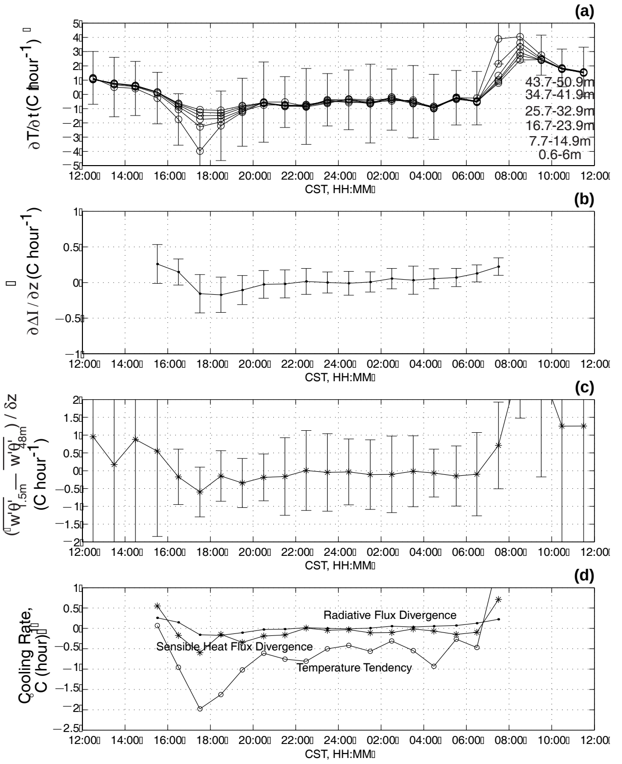

Figure 4: Hourly bin-averaged measurements for the 20-day deployment period of: (a) Thermocouple temperature tendency (different from the potential temperature by less than 1%) within various layers between 2 m and 51 m; (b) radiative flux divergence (negative); (c) sensible heat flux divergence between 2 m and 48 m. The error bars indicate plus-and-minus one standard deviation of the 5-minute averaged data within that hourly bin. Here both the temperature tendency and the sensible heat flux divergence are calculated using 5 min averaged data. The cooling rates based on the above composite components are plotted together in (d).

The radiative flux divergence composited over the entire field campaign shows that on average the radiative flux divergence is close to zero except in the early evening (Fig. 4). The relatively small composite radiative flux divergence is partly due to the fluctuation of the ground longwave radiation emission with wind speed. The fluctuation of the surface radiation temperature is not captured in all the numerical studies on the heat balance. The sensible heat flux divergence is about 30% of the cooling between 2 m and 48 m. Therefore, temperature advection is important in the heat balance at night.

4. SUMMARY

In contrast to previous radiation divergence measurements obtained within 10 m above the ground, we measured radiative flux divergence within a deeper layer between 2 m and 48 m. Combining our observations with the earlier studies implies that the radiative cooling at night is typically stronger than the temperature decrease close to the ground, but the opposite occurs in an overlaying layer. This result indirectly confirmed previous numerical calculations that the relative contribution of the radiative flux divergence to the local cooling at night decreases with height. As a result, the relative contribution of the sensible heat flux transport and temperature advection to the local cooling increases with height, although the absolute values of the sensible heat divergence and temperature advection decrease with height following the local cooling. Within our observation layer the radiative flux divergence is, on average, comparable to or smaller than the sensible heat flux divergence. Our unique observations of both radiative flux and sensible heat flux divergence indicate the importance of the temperature advection over even a reasonably flat surface.

Our observations also indicate that the measured radiative flux divergence between 2 m and 48 m was typically largest at the beginning of night and may fluctuate around zero throughout the night due to variations of wind speed. However, close to the ground it can be significant based on the radiative flux divergence below 10 m in the earlier studies. The wind speed variation can change not only the sensible heat transfer, but also the surface longwave radiation due to variations of the area-exposure of warmer grass stems and soil surfaces. The magnitude of the radiative flux divergence in the early evening depends on how fast the ground cools and on the vertical temperature gradient within the measured layer. The large radiative flux divergence in the early evening, more than 10 W m^{-2}, was dominated by the large outgoing longwave radiation under conditions of weak wind and clear sky after a hot day. The air temperature at 2 m generally depends on the measurement height at night when the wind speed is weak.

5. ACKNOWLEDGEMENTS

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