17B.6 LONG TERM OBSERVATIONS OF LONG WAVE RADIATIVE FLUX DIVERGENCE IN THE STABLE BOUNDARY LAYER OVER LAND

G.J. Steeneveld, M.J.J. Wokke, C.D. Groot-Zwaaftink, S. Pijlman, B.G. Heusinkveld, A.F.G. Jacobs, and A.A.M. Holtslag
Wageningen University, Wageningen, The Netherlands.

1. INTRODUCTION & BACKGROUND

After sunset, the Earth's surface cools due to long wave radiation emission to space, and a stable atmospheric boundary layer (SBL) develops. The SBL structure develops due to different physical processes: turbulent mixing, radiative cooling, the interaction with the land surface, gravity waves, katabatic flows, etc. Despite previous research efforts, these processes and their interactions are insufficiently understood. Consequently, the SBL is poorly represented in atmospheric models. Numerical weather forecast (NWP) and climate models experience serious errors for the SBL (e.g. Viterbo et al., 1999; Dethloff et al., 2001, Gerbig et al., 2008). Typically, surface temperatures are forecasted too high for calm conditions (Steeneveld et al., 2008). On the other hand, these models often show an unrealistic decoupling of the atmosphere from the surface, resulting in runaway surface cooling (e.g. Mahrt, 1998). The poor model representation of the SBL results in evident problems for air quality prediction (Salmond and McKendry, 2005). Thus improved understanding and representation of the SBL is desirable.

This paper focuses on the role of long wave radiative cooling in the heat budget of the SBL close to the surface (lowest 20 m). Our aim is to analyze and quantify long wave radiation divergence (LWRD) by means of observations. Finally, we propose a practical and robust parameterization for LWRD for use in atmospheric models without the need for high computational capacity.

Despite its expected importance during calm conditions, LWRD in the SBL has not been studied very intensively, since most attention has been paid to the turbulent transport (e.g. Cuxart et al., 2006). LWRD occurs at (sudden) changes of the temperature or concentration of absorbing gases with height. Since this occurs close to the surface, we expect LWRD to be important for the near surface SBL heat budget. A second important term is the absorption of radiation that originates from the land surface.

Only limited amount of LWRD observations are available. Funk (1960, 1961) and Fuggle and Oke (1976) found typically 6.6 K h^{-1} LWRD (*cooling*) between 0.5-1.5 m AGL. On the contrary, Lieske and Stroschein (1967) found 5 Kh^{-1} *heating* layer between 1-5 m in the Arctic. Xing-Sheng et al. (1983) reported typical cooling of 2.5 Kh^{-1}, with the strongest cooling at the top of a shallow surface inversion.

Unfortunately the previous studies only cover a few nights, and determined the LWRD only over a single layer. Hoch et al. (2007) showed year-round observations of LWRD over Greenland below 50 m, and examined the dependence of long wave cooling the on temperature gradient, surface humidity and wind speed. They concluded that the divergence of the outgoing long wave flux is the dominant contributor to the total LWRD. Recently, Drüe and Heinemann (2007) reported LWRD over Greenland up to 800 m. They found that LWRD is important not only during calm conditions, but also under moderate wind speeds. However, Estournel et al. (1986) found LWRD of secondary impact during the ECATS campaign. for stable nights with moderate winds. Sun et al. (2003) estimated LWRD between 48 and 2 m during CASES-99, and reported a small impact of LWRD during the core of the night. Moores (1982) documented observations that indicated substantial long wave heating in the daytime boundary layer. Below 150 m he found 0.05-0.52 Kh^{-1} heating (30% of the turbulent heating), and 0.06 K/h cooling above 150 m. Over all, we conclude that the relative role of radiative cooling is under debate, as are the numerical values.

Several technical limitations and difficulties need to be overcome (e.g. dew formation, ventilation, bias correction, mast influence), which explains the limited amount of research. Typically measurement uncertainties are close to the recorded signal.

Amongst others, Ha and Mahrt (2003) modeled LWRD. They and Räisänen (1996) showed strong sensitivity to model resolution, and even that the forecasted sign of the radiative tendency can be wrong for coarse resolution. Also, running a full radiation scheme that accounts for all absorbing gases at very grid cell and every time step is computationally too expensive for NWP and climate models. Moreover, these schemes have typically been calibrated and validated against the observed cooling in the full atmospheric column. However, the SBL is a very shallow layer with strong temperature and humidity gradients, which can differ substantially from free

[1] Corresponding author address: G.J. Steeneveld, Wageningen Univ., Meteorology and Air Quality Group, P.O.Box 47, 6700 AA Wageningen, The Netherlands.
E-mail:Gert-Jan.Steeneveld@wur.nl

atmospheric gradients. Therefore, it is likely that radiation transfer models as used in NWP models cannot correctly account for LWRD in the SBL. Also, different parameterizations can result in different nighttime cooling (Steeneveld et al., 2008), especially for calm conditions. At the same time, it is realized that a correct representation of LWRD might help to prevent models to enter a nonphysical decoupling. Thus, we seek to obtain a simple and robust parameterization for near surface LWRD, based on profile information that is present in a model.

2. Material and Methods

Wageningen University operates a meteorological observatory, in the centre of Netherlands (51.58ºN, 5.38ºW, 7 m a.s.l., Jacobs et al., 2007). During May-Nov, the grass is kept at a mean height of 0.1m. An aspirated psychrometer measures the air temperature, T_a, and wet-bulb temperature, T_w, at 1.5m. At 0.10 m the air temperature T_a(0.10m) is measured with a shielded Pt-100 thermometer. The incoming ($S^{\downarrow}$) and outgoing ($S^{\uparrow}$) shortwave radiation fluxes are measured with an aspirated pyranometer (Kipp&Zonen, model CM11) at a height of 1.4 m. At the same height, the incoming ($L^{\downarrow}$) and outgoing ($L^{\uparrow}$) long wave radiation fluxes are measured with a pyrgeometer (Kipp&Zonen, CG1).

In addition, we mounted 2 net long wave radiometers (Kipp&Zonen CG2) on a tower at 10 and 20 m, during 1 Feb-30 June 2006. After the experiment, the long wave radiation sensors have been calibrated relative to each other. This was done by mounting the sensors at the same height (1.4 m) for a two month period (July and August 2006) at a distance of 25 m from the sensor already mounted at 1.4 m. Since a CG2 is a net LW sensor with two CG1 sensors mounted in the same casing, three sensors measured $L^{\downarrow}$ and three sensors measured $L^{\uparrow}$.

The recorded tolerance for $L^{\uparrow}$ is larger than for $L^{\downarrow}$ (0.3 Wm^{-2}). This is most likely caused by the fact that the sensors that measured $L^{\uparrow}$ did not sense the same grass surface. Differences in the length of the grass, or wetness etc. can be a cause. The corresponding tolerance in net radiation ($L^{\downarrow}$-$L^{\uparrow}$) thus becomes 2.5 Wm^{-2}. Alternatively, Drüe and Heinemann (2007) estimate the tolerance as the standard deviation of the recorded long wave flux for stationary conditions. In our case the standard deviation of $L^{\downarrow}$ is relatively small, ~0.4 Wm^{-2}, especially at night. Contrary, the standard deviation for $L^{\uparrow}$ is larger, but at night still limited to 0.7 Wm^{-2}. The total uncertainty of the nighttime LWRD amounts 0.7 Kh^{-1}. As such, we can be confident in the nighttime observations. During daytime, the uncertainty is typically a factor 2 larger.

Next to instrumental uncertainties, also specific weather conditions can hamper reliability. Data (both for experiment and calibration period) were selected for wind speed more than 1.5 m s^{-1} to ensure sufficient ventilation of the radiometers at 10 and 20 m. Observations with rain in 2 previous hours were discarded to ensure the radiometers to be dry, as were periods with fog.

Hoch et al. (2007) correct long wave fluxes for emission by the tower. We performed the same correction method on our dataset, and the corrections were found to be relatively small, because we used an open tower of ~30 cm side length, so the azimuth over which the tower was seen was small. Secondly, the field of view of the radiometers was limited to 150°, so a relatively large part of the tower was not seen by the radiometers. Finally, we employed only a 20 m tower so the vertical angle that is seen by the radiometers is relatively small compared to taller towers.

3. RESULTS

a) clear days

For simplicity we start analyzing three diurnal cycles with clear skies and weak winds. Fig. 1 shows the median of the radiative heating between 1.3-10 m, 10-20 m, and 1.3-20 m. At night we a find a cooling that peaks just after sunset, and amounts 3 Kh^{-1} or even more for the layer between 1.3 and 10 m. Between 10-20 m the LWRD is limited to 1.5 Kh^{-1} after sunset and its magnitude gradually decreases with time. Contrary to model results by Ha and Mahrt (2003) and observations by Sun et al. (2003) that show that LWRD is a minor contributor in the remainder of the night, we find a substantial cooling for our vegetation type. As in previous studies the total atmospheric cooling is less than the radiative cooling. Note that for these typical clear days, MM5 forecasts not more than 0.1 Kh^{-1} radiative cooling after sunset (not shown).

Although radiative transport in the convective ABL is often assumed to be small, we find 1 Kh^{-1} heating close to the surface. Observations by Moores (1 Kh^{-1},1982) and simulations by Savijärvi (2006) 40 $Kday^{-1}$ supports these findings.

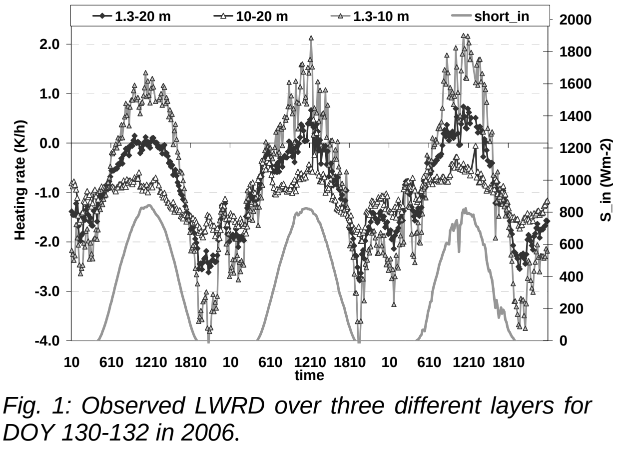

Fig. 1: Observed LWRD over three different layers for DOY 130-132 in 2006.

b) climatology

Fig.2 shows a 'climatology' of the diurnal cycle of radiative cooling. The median of LWRD amounts 1.8 K/h after sunset, and gradually reduces during the night. Radiative heating at noon is absent in this long term record. Fig. 2 also shows that estimating LWRD over deep layers substantially reduces the cooling.

Fig.3 shows the same graph as Fig.2, but for the individual flux components. We find that d$L^{\uparrow}$/dz dominates the total cooling at night (as in Hoch et al., 2007). During the day a slight heating by d $L^{\downarrow}$/dz is counteracted by cooling.

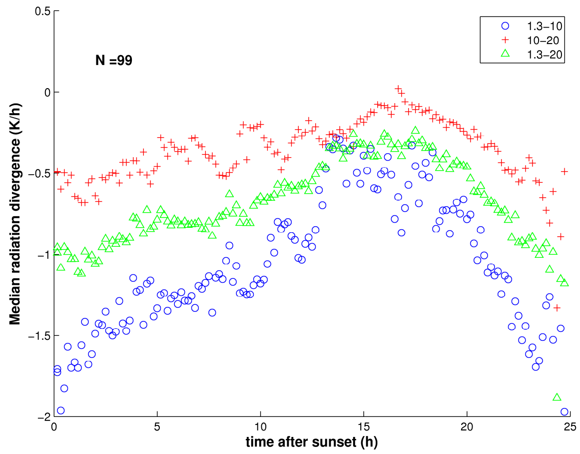

Fig. 2: Observed median of the LWRD for the diurnal cycle over three different layers.

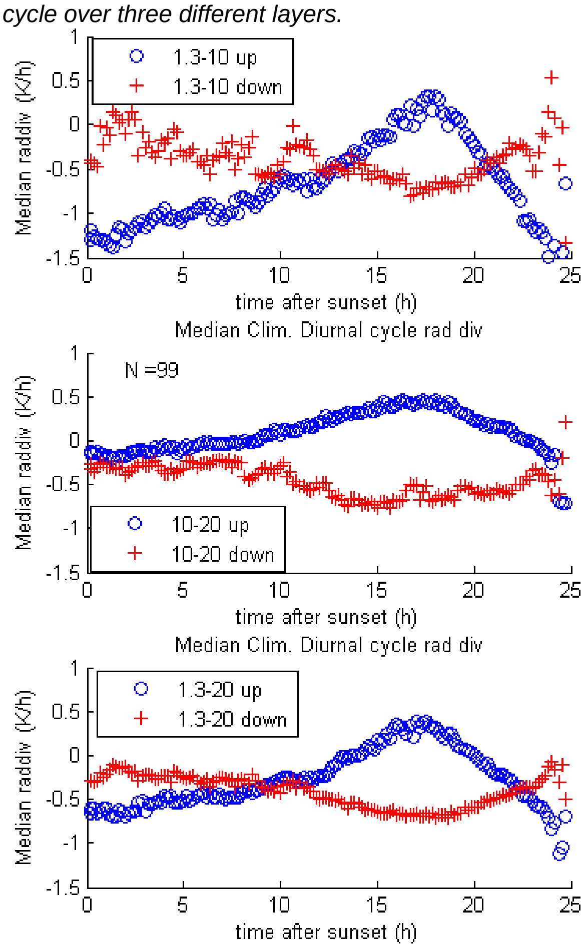

Fig. 3: Observed median of the LWRD for the diurnal cycle over three different layers, per component.

c) statistical model

Large-scale models could benefit from a cheap scheme that accounts for LWRD. We propose a statistical model with the relevant parameters that account for changes in temperature and humidity: temperature curvature, temperature slip (ΔT) and humidity gradient (dq/dz) (Eq. 1). Fig. 4 shows that such a regression approach is only limited successful.

$$-LWRD = 6.47(\pm 0.67)\frac{\partial^2 T}{\partial z^2} + 1.161(\pm 0.141)\frac{\partial q}{\partial z} + 0.134(\pm 0.003)\Delta T \qquad (1)$$

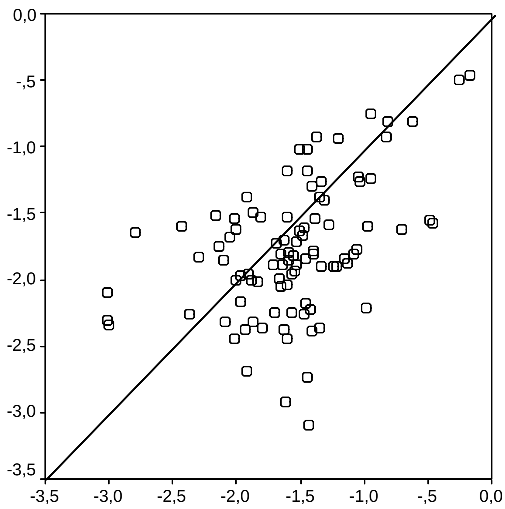

Fig. 4: Modeled (Eq. 1) and observed LWRD for clear nights.

d) physical model

Coantic and Seguin (1971) proposed a simplified scheme for the radiation difference ΔR between 2 levels, based on radiative transport equations, and of the temperature and humidity profile:

$$\Delta R = 4\sigma T_0^3 \left\{ \varepsilon(w)\left[(T_0 - T_G) + \theta_* \ln\frac{w}{w_0}\right] + \theta_*\left(R_2(w) - R_2(w_0)\right)\right\}$$

Herein T_0 is the surface air temperature, T_G is the surface ground temperature and ε is the emissivity for water vapor path w. R_2 is an empirical function that accounts for absorption with height The scheme only requires temperature and humidity profiles, or θ_* and q_*. This method is computationally inexpensive, and might be suitable to update the radiative tendency for the SBL at higher frequency in models. Fig. 5 shows the forecasted and measured radiative tendencies. The performance of the scheme seems reasonable, especially considering the large measurement uncertainties. The large scatter for the night might be the result of the difficulty in measuring θ_* and q_*. Otherwise the profile functions that enters Eq. (2) are poorly known for very stable conditions. Unfortunately the branch of overestimated model cooling in the third quarter could not be explained yet.

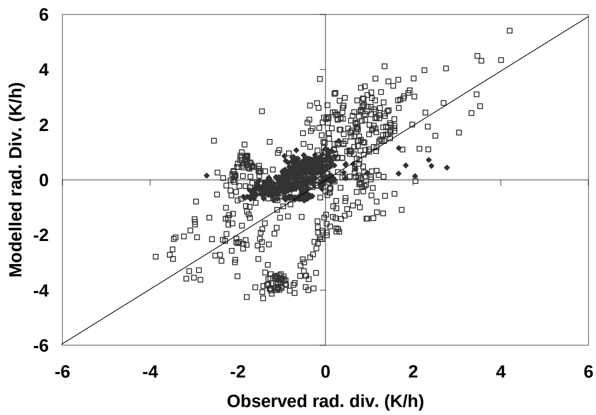

Fig. 5: Modeled Eq.(2) and observed LWRD (:1.3-10 m, diamond: 10-20m).

4. CONCLUSIONS

We measured long wave radiation divergence over 2 different layers in the lowest 20 m of the boundary layer, over a grass surface, We examined its role in the temperature budget of the stable boundary layer. We found typical radiative cooling of 1.8 Kh^{-1} after sunset which gradually decreases at night. For clear days, also substantial radiative heating is found at noon. A statistical and a physical model for radiation divergence at night were tested. For now the physical modelled should be preferred.

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