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SEMI-COLLAPSED AND ADVECTIVE STABLE BOUNDARY LAYERS

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1. Introduction

Thermal internal boundary layers, responding to a sharp sign change of the surface heat flux, have been studied in some detail. However, most land surfaces induce a less dramatic advective boundary layer where the surface heat flux changes in the downwind direction but does not reverse sign. Although common, this class of surface heterogeneity is seldom studied from observations, probably because the response of the atmosphere is not as well defined compared to development of thermal internal boundary layers where the surface heat flux changes sign in the downwind direction. Mahrt (2000) referred to this flow situation as an "adjusting boundary layer", although his study did not contain enough data to establish characteristics of the adjusting flow. With this class of advective boundary layer, horizontal advection modifies the vertical divergence of the flux and therefore the structure and depth of the boundary layer but the surface heat flux does not reverse sign in the downwind direction. Advection associated with modest small-scale surface heterogeneity may influence only the lower part of the boundary layer (Schmid and Bünzli, 1995). Although the sign of the surface heat flux does not change in the downwind direction in the adjusting boundary layer, the vertical convergence of the heat flux may reverse sign in the downwind direction. de Bruin et al. (1991) observed large divergence of upward heat flux over irrigated grass downwind from strongly-heated, dry, bare ground. Daytime values of the heat flux divergence reached an equivalent cooling rate of 70 $^\circ$ C hr $^{-1}$, suggesting that the vertical divergence of the heat flux was balanced by strong advection of warmer air from the upwind unirrigated area.

2. Data

This study analyzes eddy correlation data from a 34-m tower in FLOSSII instrumented from 20 November 2002 to 2 April 2003, operated by the Atmospheric Science Technology Division of the National Center for Atmospheric Research. The tower site is located over grass south of Walden, Colorado, USA in the Arapaho National Wildlife Refuge. Mean temperature and relative humidity were measured at 8 levels using ventilated T/RH instruments built by the Atmospheric Technology Division of NCAR. Fast response data for eddy correlation fluxes and mean winds were collected at 1, 2, 5, 10, 15, 20 and 30 m with Campbell CSAT3 sonic anemometers. Campbell Krypton hygrometers were installed at four levels for computation of water vapour fluxes. The four components of the radiation budget were measured using up and down looking pyranometers for shortwave (Kipp and Zonen) and up and down looking pyrgeometers for longwave (Epply). The same eddy-correlation instrumentation was deployed at 2 m over a brush site with 0.2 - 0.5-m high bushes, about 1 km north of the main tower.

We analyze data from FLOSSII only for the wind direction sector 160 to 270 $^\circ$, which is the predominant wind direction interval. We include only daytime heated conditions where the net radiation exceeds 50 W m^{-2} for hours between 0900 and 1500 local time. We also require that the albedo exceeds 0.5 in order to limit the data sample to primarily snow-covered conditions, which includes some grass protruding above the snow and isolated snow-free patches. The tower is surrounded by short grass for a distance of 50-100 m upwind, which then yields to grasses of various heights, rushes and brush, depending on exact direction from the tower.

2.1 Flux profiles

This study focuses on the vertical structure of the fluxes in the lowest 30 m forced by the surface heterogeneity and advection of temperature. The vertical variation of the fluxes for one-hour records was remarkably systematic for heat fluxes but not as systematic for momentum fluxes. The heights where the heat flux or the heat flux divergence reversed sign with height, when such reversals occurred, were usually well defined, except for about 5% of the profiles where the heat fluxes were particularly small.

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3. Observed structure

We now examine the vertical structure of the heat flux at the grass site for snow-covered daytime conditions with surface net radiation exceeding 50 W m^{-2} and the restrictions on wind direction explained in Section 2. For above-freezing conditions, and expected snowmelt, the daytime 2-m heat flux at the grass site was downward for 35 out of the 38 cases. The 2-m heat flux was downward for 37 of the 80 below-freezing cases. The downward heat flux is associated with formation of stable stratification due to advection of warmer air from the taller heated vegetation and is encouraged by melting and evaporative cooling at the surface. In the remaining cases, the surface heat flux was weak upward due to solar heating of grass protruding from the snow surface.

Whether, the surface heat flux is downward or upward over the snow-covered grass, the vertical divergence of the heat flux near the surface is almost always positive, 103 out of the 118 cases. The flux divergence corresponds to increase of the downward heat flux toward the surface in the stable internal boundary layers, or increase of the upward heat flux with height in the adjusting boundary layers. The flux divergence near the surface extends to the top of the tower for 55 of the cases. For 15 of the 118 cases, the heat flux did not vary systematically with height in the tower layer.

Since the air is actually warming, the cooling due to the heat flux divergence is apparently offset by advection of warmer air from the upwind taller vegetation, which protrudes above the snow. The increase of upward heat flux or decrease of downward heat flux with height and implied warm air advection can also be qualitatively interpreted as increasing footprint with height (Figure 1). The footprint of the flux in the upper part of the tower layer extends upwind into the heated brush area while the footprint of the flux in the lower part of the tower layer is more confined to the grass surface.

The daytime heat flux at the brush tower site is almost always upward and almost always greater than the upward heat flux at the grass site, when it occurs. The dark brush ineffectively intercepts and retains snow with typical cold windy conditions in the North Park Basin and therefore effectively absorbs solar radiation, particularly at low winter sun angles. Although the brush upwind from the tower-site grass field is more patchy than that at the eddy-correlation brush site, we expect the heat flux upwind from the grass field to be also generally upward during sunny daytime conditions and greater than upward heat flux over the snow-covered grass field, when it occurs.

Several types of vertical structure over the snow-covered grass can be identified. To examine such vertical structure, we have composited all of the profiles where the heat flux is downward at 2 m (< -0.001 °C m s^{-1}) (Figure 2a, solid line) corresponding to a stable boundary layer and have composited all of the cases with upward heat flux at 2 m (> +0.001 °C m s^{-1}) (Figure 2a, dashed line) corresponding to an adjusting boundary layer. In both cases, the vertical divergence of the heat flux is large in roughly the lowest 15 m.

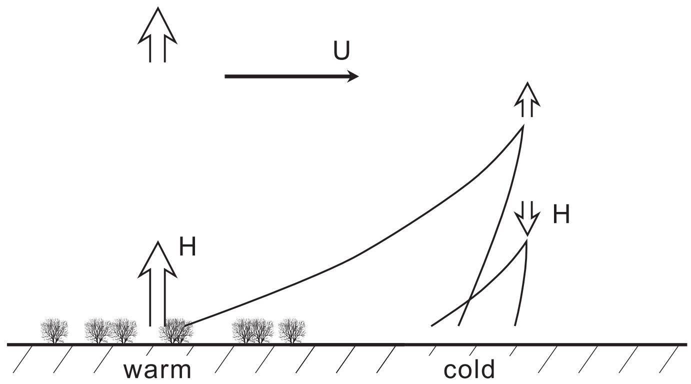

Figure 1: The change of the heat flux with height over the cool surface due to changing 'footprint' with height.

We have also composited profiles for cases where the 2-m heat flux is downward but reverses to upward at higher levels (Figure 3, solid line), allowing definition of a stable internal boundary layer. Finally, we composited profiles for a subset of cases where the 2-m surface heat flux is downward, reverses sign with height and reaches a maximum upward value within the tower layer (Figure 3, dashed line). The latter profile (dashed line) identifies a stable internal boundary layer where the heat flux is downward, an overlying transition layer where the heat flux is upward but still divergent and an advected convective boundary layer in the upper part of the tower layer where the upward heat flux decreases with height, corresponding to warming by heat flux convergence. The solid line in Figure 3 is dominated by cases where the advected convective boundary layer, when it exists, is above the tower layer. The solid line in Figure 2 is dominated by cases where both the convective boundary layer and transition layer, when they exist, are above the tower layer.

For the adjusting boundary layers (dashed line, Figure 2), the vertical transport of turbulence kinetic energy is generally upward in spite of the fact that the buoyancy-generation of the turbulence increases with height near the surface. This upward transport is due to dominance of shear-generation over the relatively weak buoyancy generation.

The large heat flux divergence near the surface implies that fluxes estimated at standard levels such as 5 or 10 m, will significantly underestimate the downward surface heat flux and overestimate the upward heat flux. For example, the averaged downward heat flux at 5 m is only about 65% of the downward surface heat flux (Figure 2a, solid line) where the latter is estimated by extrapolation to the surface.

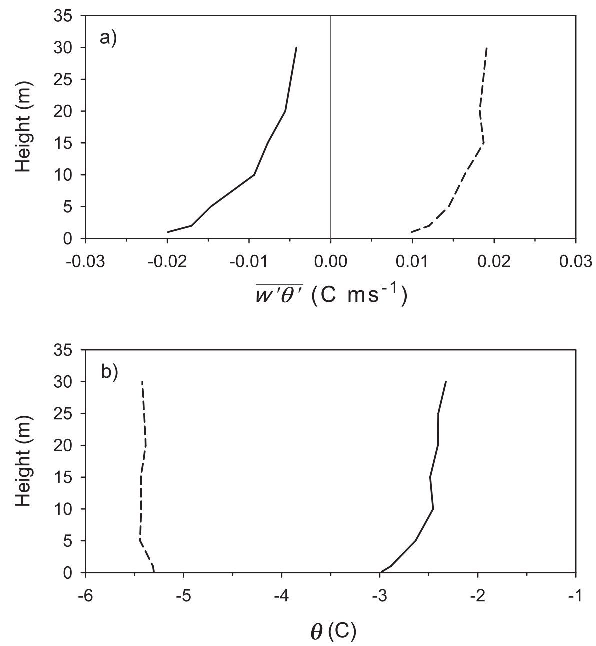

Figure 2: a) Composited profiles of the heat flux for upward 2-m heat flux (dashed line) and downward 2-m heat flux (solid line). b) Corresponding profiles of potential temperature.

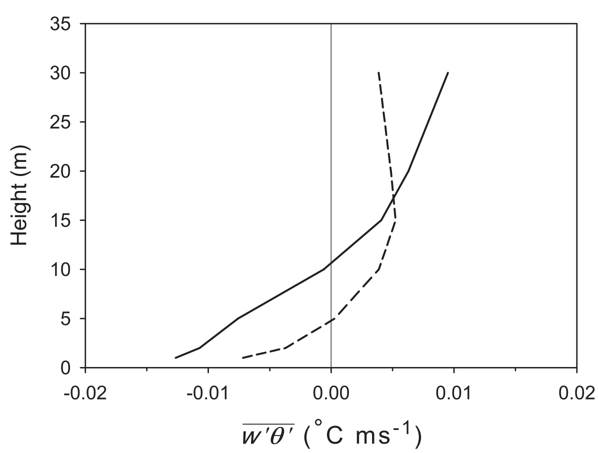

Figure 3: Composited profiles of the heat flux for downward heat flux at 2-m for 31 cases where the heat flux becomes positive at higher levels (solid line) and for a subset of 17 cases where the heat flux becomes positive at higher levels and then decreases with height at still higher levels (dashed line).

3.1 Vertical flux divergence

For the composited profiles corresponding to downward surface heat flux, the heat flux divergence in the lowest 10 m corresponds to a cooling rate of about 4.5 $^\circ$ C hr $^{-1}$. For the subset of cases where the downward heat flux reverses with height to upward heat flux higher in the tower layer, this cooling rate averages about 5.5 $^\circ$C hr^{-1}. This cooling rate averages about 2 $^\circ$C hr^{-1} for cases of upward surface heat flux. The heat flux divergence for the composited profiles decreases with height above 10 m.

The standard error for the composited heat flux for the class of downward heat flux (Figure 2, solid line) ranges from 6% of the flux magnitude near the surface to about 27% near the top of the tower where the magnitude of the heat flux is small. The standard error for the class of upward heat flux ranges from 15% near the surface to 11% at the top of the tower; recall that the upward heat flux increases with height. However, these estimates of the standard error cannot be used to estimate the uncertainty in the flux divergence of the composited profile because this standard error includes between-record shifts in the flux profile that does not affect the flux gradient. For example, the flux profile can be similar in shape but shift in magnitude between records at all levels. We therefore compute the standard error from the values of the heat flux divergence for individual profiles. The standard error for the vertical gradient of the heat flux between the 1-m and 30-m levels is 6.3% of the mean value for the class of downward heat flux and 13.1% for the class of upward heat flux. Computing the standard error of the vertical gradient of the heat flux for different combinations of levels indicates that the standard error increases slowly as the thickness between the levels decreases. Similar values of the standard errors are found for the profiles in Figure 3.

The observed warming rate at the tower averages less than 1.0 $^\circ$C hr^{-1}. Therefore, the warming of the air appears to be a small difference between the larger warm air advection and cooling due to vertical heat flux divergence. Even the large heat flux divergence of 5.5 $^\circ$C hr^{-1} could be offset by warm air advection associated with a small horizontal temperature difference. For a wind speed of 5 m s^{-1}, a temperature difference of only 0.03° C over the horizontal distance of 100 m between the tower and the edge of the brush would be required.

Much larger temperature differences were observed but estimation of these temperature differences are severely contaminated by ambiguity of choice of observational level over vegetation of varying height.

4. Semi-collapsed turbulence

With weak wind winds and warm air advection over a cooler surface, or strong radiative cooling, the turbulence becomes sufficiently weak that estimation of the fluxes becomes problematic. Such weak turbulent transport plays a crucial role in a number of applications including frost damage and dispersion. In these cases, very weak diffusion leads to quite different results compared to zero diffusion.

Since the fluxes are orders of magnitude weaker than with more typical stable boundary layers, and since the mesoscale activity does not systematically decrease as the turbulence becomes very weak, the problem becomes one of extracting a very weak turbulence signal from a much stronger mesoscale signal. The latter includes gravity waves, meandering motions and ubiquitous motions of unknown origin. Normal methods for computing turbulent quantities from a fixed averaging window, such as 5 minutes, leads to strong contamination of the perturbations by mesoscale motions (Vickers and Mahrt, 2003), which in turn leads to enormous random flux sampling errors associated with the inadvertently captured mesoscale motions. Since the miscalculated values of the friction velocity can be substantially more erratic than those of the heat flux, the large random sampling errors can lead to artificially improved performance of the ϕ_m- z/L relationship in Monin-Obukhov similarity theory through self correlation (Klipp and Mahrt, 2004).

5. Conclusions

The flow from the heated brush over the grass surface with partial snow cover leads to formation of either a stable internal boundary layer or formation of an adjusting boundary layer where the upward surface heat flux decreases in the downwind direction but does not reverse sign. In the adjusting boundary layer, the weak upward heat flux increases with height acting to cool the air. This vertical divergence of the heat flux appears to be approximately balanced by warm air advection from the upstream heated surface. We speculate that this adjusting boundary layer is more common than internal boundary layers over typical modest surface heterogeneity.

Acknowledgments

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