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Shallow Boundary Layers and Suppressed Vertical Mixing in the Very Stable Boundary Layer with a Weak LLJ

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1. INTRODUCTION

Under weak-wind, very-stable conditions previous studies have found that the depth of the very stable boundary layer (vSBL) is often only 10-30 meters (Smedman 1988; Mahrt And Vickers 2006). In this study we use data from the 60-m tower, the Tethered Lifting System (TLS), and the High-Resolution Doppler Lidar (HRDL), deployed during the September 1999 campaign of the Cooperative Atmospheric-Surface Exchange Study (CASES-99), for two purposes: (1) to investigate the depth of the SBL under very stable conditions using data available from CASES-99, and (2) to show that the turbulent mixing in a layer immediately above this shallow boundary layer (BL) was so strongly suppressed as to be negligible.

The depth of the boundary layer is generally taken to be the depth of the atmosphere that interacts with the surface of the Earth through turbulent mixing processes. The 'traditional' BL has a maximum of turbulence and fluxes at the surface decreasing monotonically to 0 at the top of the BL (Fig. 1). Under stable conditions the role of purely turbulent mixing processes is often masked by lower-frequency mesoscale and terrain-forced processes. Vickers and Mahrt (2003, 2005), however, have shown that by using a two-step averaging procedure, the contributions due to purely turbulent fluxes can be isolated. Here we use this averaging procedure to determine the profiles of turbulent variance and fluxes using data from the 60-m CASES-99 tower (Poulos et al. 2002).

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2. CASES-99 MEASUREMENTS

Data from three of the weakest-wind nights during CASES-99 were selected for analysis, including 26, 20, and 18

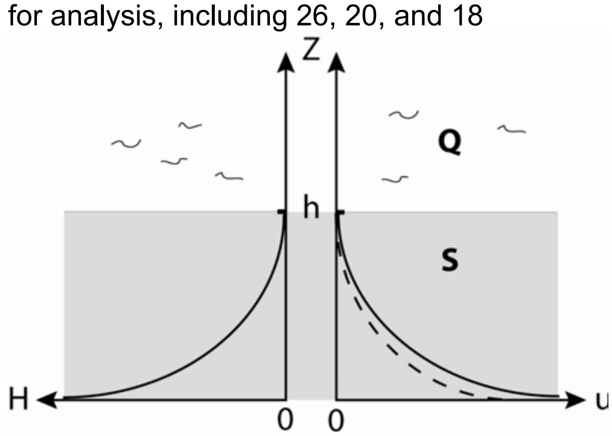


Figure 1: Schematic profiles of heat flux *H*, vertical velocity variance σ_w^2, and friction velocity u_* showing "traditional BL" structure. Shaded portion marked S represents the shallow BL, and the region above marked Q represents the quiescent layer aloft.

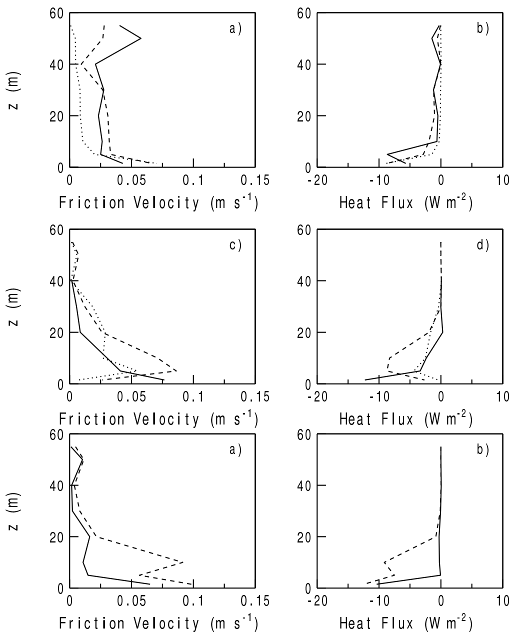


Figure 2. Profiles of 60-min averaged u_* and H, showing traditional BL structure beneath quiescent layer for hours beginning 04, 06, and 08 UTC (22, 00 and 02 CST) (solid, dashed, dotted) on 26 October (panels a and b), for hours beginning 04, 05, and 06 UTC (22, 23 and 00 CST) on 20 October (panels c and d), and for hours beginning 04 and 07 UTC (22 and 01 CST) (solid, dashed) on 18 October (lower panels).

October (Banta et al. 2002). Weak LLJs, which were < 5 m/s^{-1} on two of the nights and 6-8 m/s^{-1} on the third, have been associated with large values of the Richardson number Ri and very stable conditions with low turbulence levels (Banta et al. 2003). Profiles of friction velocity u_* and heat flux H confirm the existence of very shallow BLs having traditional structure, with depths of the turbulent-flux layer ranging mostly from 5 to 20 m (Fig. 2).

Just above this shallow BL, the profiles consistently show a layer of negligible turbulence, with magnitudes often so weak as to be barely measurable (Fig. 2). Another indicator of layers of very weak turbulence above the shallow BL is seen in the profiles of TKE dissipation ε measured by the TLS (Fig. 3). Values of ε, which were already weak at 10^{-4} m^2 s^{-3} in the shallow SBL, drop by two factors of 10, to 10^{-6} or less, in the layer above the shallow BL. Profile data in the vSBL thus show two strata, a surface-based traditional BL with weak, intermittent turbulent mixing, lying beneath a quiescent layer of negligible turbulence and turbulent transport.

Time series of thermocouple data taken at 20 Hz on the CASES-99 tower can also be used to characterize these turbulent layers. Fig. 4 shows that the amplitudes of the fine-scale-fluctuations were considerably suppressed at the upper tower levels as compared with the lower levels. But perhaps even more significantly, Fig.4 also shows the temperature T becoming nearly constant at the 40-55 m levels AGL for several hours in the middle of each night considered. The constancy of T

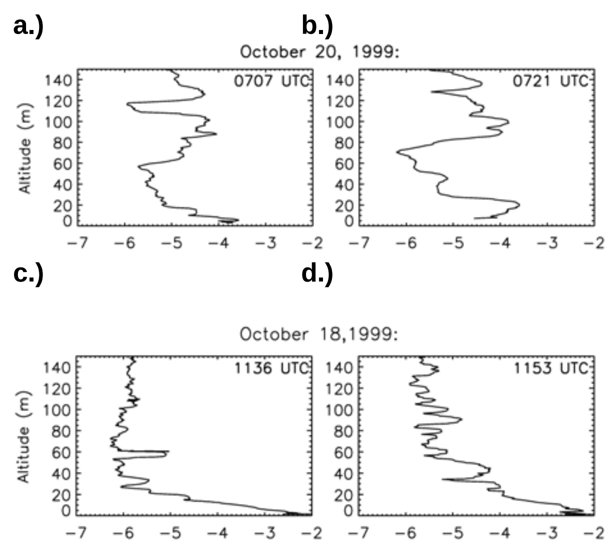
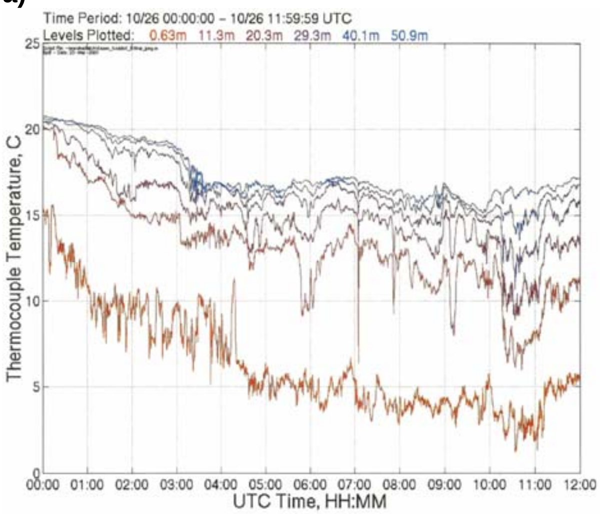


Figure 3. Vertical profiles of TKE dissipation log ε (m^2 s^{-3}) calculated from high-frequency (200 Hz) TLS data from 20 October 1999 (panels a and b) and from 18 October 1999 (panels c and d).

a)



b)

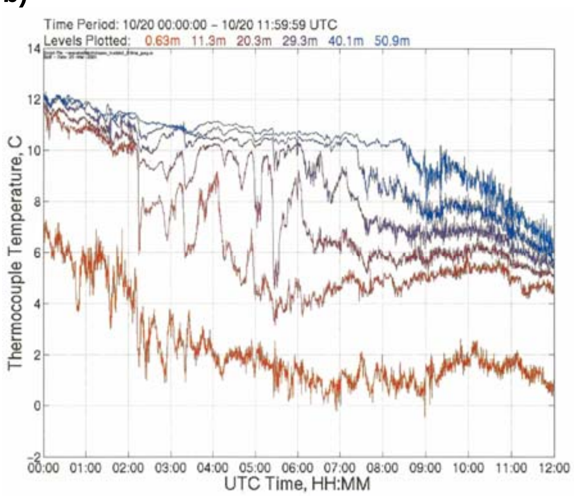


Figure 4. Thermocouple time series (*T* in °C) at 6 levels for a) 26 October and b) 20 October.

indicates that the very cold air at the surface was not being mixed upward to levels above the ~25 m depth of the shallow BL, considering that Sun et al. (2003) have shown the radiative flux divergence to be an insignificant contribution to the SBL heat budget after the first 3 hours of the night during CASES-99.

3. OZONE BEHAVIOR

The significance of this quiescent layer above the shallow BL is that the atmosphere above the shallow BL was essentially detached from surface processes. Further indication of this kind of behavior was also found in time series of ground-level ozone (O_3) concentrations from a July 1999 field-measurement program in Nashville, Tennessee (Fig. 5). On nights with stronger winds, O_3 concentrations remained above 20 ppb due to downward mixing of O_3 from aloft, but on light-wind, very stable nights, concentrations became zero, as a result of the lack of vertical mixing combined with near-surface sink activity (deposition and chemical reaction).

The O_3 behavior shown in Fig. 5 can be related to the contrasting structures of weak vs. stronger-wind SBLs. Doppler lidar profile data were available for some nights during SOS-99 (e.g., Darby et al. 2002). On nights when the ground-level O_3 vanished, the lidar data indicated weak LLJ speeds (peaks of 3-4 m s^{-1} or less below 200 m AGL), but when higher concentrations lasted throughout the night, the lidar measured stronger speeds (7-8 m s^{-1} or more). In other words, nights when O_3 concentrations remained high were stronger-LLJ (stronger-wind) nights, when enhanced vertical mixing brought fresh O_3 down from above to replenish that being lost near the ground (cf. Nappo 1991; Corsmeier et al.1997; Reitebuch et al. 2000; Darby et al. 2002). On the other hand, O_3 concentrations became zero at the surface on very stable nights, when exchange between surface and the ozone-rich layer aloft would be almost completely shut down.

This behavior can be explained as follows. Nighttime ozone removal can occur by two distinct processes. The first is via dry deposition, a permanent, irreversible loss to vegetation and other surfaces. The second is via rapid chemical reaction or titration, involving nitrogen-oxide (NO, NO_2) emissions (if no local emissions were present,

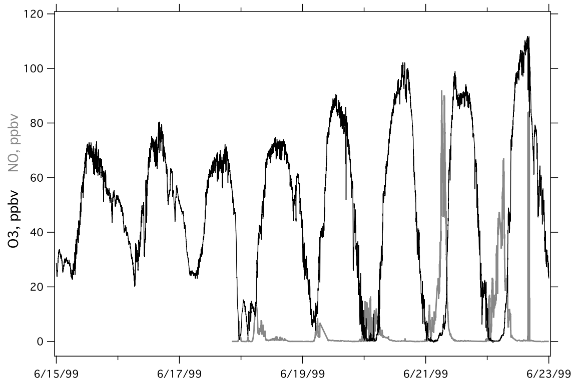


Figure 5. Time series of ground-level ozone (black line, 1-min values in ppb) at Cornelia Fort Airpark, Nashville, Tennessee for 15-22 July 1999 (times UTC). Daytime hours are marked by the maxima in O_3 concentrations, and nights are the periods of minimum concentrations. NO measurements (gray line, ppb) available after 17 June document local-source activity at this site at night. Late-night increases in NO concentrations on nights when the O_3 vanished indicate that the local emissions of NO were more than enough to titrate all the O_3.

removal could also be effected by other, slower chemical reactions). Emissions of NO, which can come from traffic or other local near-surface combustion activities at night, converts O_3 to NO_2 plus oxygen molecules on a time scale of seconds. But the next morning photochemical processes convert the enhanced NO_2 concentrations back to elevated O_3 concentrations, so this process does not represent a permanent loss of O_3 to the atmosphere.

On the nights when winds and vertical mixing were weak, the local emissions would be trapped within the shallow BL, where they would remain at high concentrations and could titrate all the O_3, driving O_3 concentrations in the shallow BL to 0 (given sufficient NO). On the other hand, when the winds and vertical mixing were strong, the emissions would be diluted over a much deeper layer, reducing titration effects on O_3 concentrations, and fresh O_3 would also continually be brought down to the surface. The effect would be to keep ground-level O_3 concentrations higher.

The complete loss of O_3 near the surface on weak LLJ nights can therefore be explained by the trapping of a limited amount of O_3 along with the local emissions within the shallow BL. It is also of interest to consider the effects on the column O_3 budget. In the light-wind, very stable case, the total amount of O_3 exposed to surface removal processes would be confined to the shallow BL, because of the lack of vertical mixing out of the shallow BL and into the quiescent layer, as described. In other words, the shallow BL would be the only portion of the atmosphere interacting with the ground, as far as O_3 was concerned (Fig. 6, left). Thus, considering a vertical column of O_3 a kilometer or so deep (i.e., deep enough to include the previous afternoon mixed-layer depth), the total amount of O_3 lost via surface deposition would be insignificant. This would be true even if all the O_3 in the shallow BL were lost to the surface, but, of course, a significant fraction of it would have been titrated and therefore not irreversibly lost. In the strong-wind case the continual replenishment of O_3 at the surface

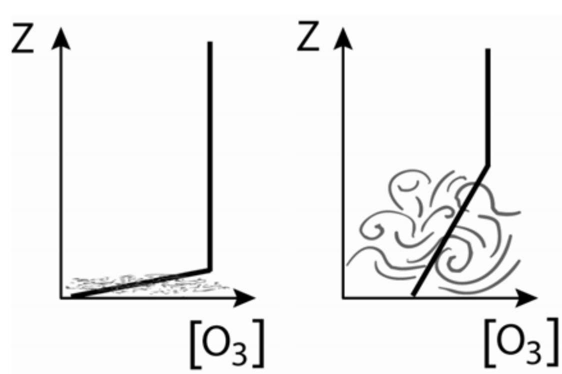


Figure 6. Schematic representation of ozone distribution with height for the vSBL (left) and the stronger-wind SBL (right).

would mean greater exposure of O_3 to the surface from a deeper layer and thus greater removal rates via deposition, representing a permanent loss of O_3 to the atmosphere (Fig. 6, right). Interestingly, effects similar to these have been noted in mountainous terrain flows by Broder and Gygax (1985) and Banta et al. (1997). Thus, it is perhaps ironic that on the nights when surface O_3 remained high, total O_3 losses through a vertical column would be greater, whereas on nights when surface O_3 concentrations became zero, losses through the column would be minimal, because dry-deposition losses would occur only from a very thin layer. Viewed in this way, the O_3 time series data indicate a nearly complete disconnect between the shallow, surface-based BL and the atmosphere higher up on the weak LLJ nights when the O_3 vanished.

4. CONCLUSION

Implications of the complete decoupling of the atmosphere above the shallow BL from the surface are many. For example, the appropriate way to parameterize the surface layer in numerical models under very stable conditions would be to shut off vertical mixing processes between the surface and the atmosphere. Practically, this would mean modeling this lower boundary as a free-slip, thermally insulated layer, in which source or sink activity between the surface and the atmosphere was set to 0.

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