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ACOUSTIC DETECTION OF MOMENTUM TRANSFER DURING THE
ABRUPT TRANSITION FROM A LAMINAR TO A TURBULENT
ATMOSPHERIC BOUNDARY LAYER

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ABSTRACT

Acoustic sounder measurements of a vertical profile of the abrupt transition from a laminar to a turbulent atmospheric boundary layer were compared with meteorological measurements made at 10 m and 137 m on an instrumented tower. Sounder data show that conditions necessary for onset of the momentum burst phenomenon exist sometime during a clear afternoon when heat flux changes sign and the planetary surface cools. Under these conditions, the lowest part of the atmospheric boundary layer becomes stable. Prior to this situation, the entire boundary layer is in turbulent motion from surface heating. The boundary layer is then an effective barrier for all fluxes, and as the maximum flux Richardson number is reached at some height close to but above the surface, turbulence is dampened and a laminar layer forms. The profile of this layer is recorded by the sounder. Surface temperature drops, a strong wind shear develops, and the Richardson number decreases below its critical value ($Ri_{CR} < 0.25$). Subsequently, the laminar layer is eroded by turbulence from above, and with a burst of momentum and heat, it eventually reaches the ground.

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1. Introduction

Remote sensing of the atmospheric boundary layer using acoustic methods has become an increasingly fertile area of applied meteorological research (Beran et al., 1971; Emanuel et al., 1972; Hall et al., 1974, 1975; Hooke et al., 1972; and Schubert, 1975). Our understanding of the dynamics of the atmospheric mixed layer is enhanced by graphically recording in real time the temperature-turbulence microstructure of the mixed layer. The data from an acoustic sounder are displayed on a facsimile recorder depicting the vertical profile with time of the passage of the boundary layer over the sounder site. These data are then catalogued as to category and height of the mixed layer, prior to further processing.

2. Location and Characteristics of the Observation Site

Observations of the atmospheric boundary layer were made on the Savannah River Plant (SRP) site. SRP occupies a circular area in South Carolina of about 777 km², 40 km southeast of Augusta, Georgia (Fig. 1). The acoustic sounder was located in a cleared area adjacent to a 4-meter-tall Quonset hut in an area of rolling hills covered with tall (10 to 15 meters high) pine trees (*P. taeda*, *P. palustris*, and *P. elliottii*). The sounder's minimum "fetch" (radius of response) over the forest is 6 km.

Wind speed and temperature data were obtained from instruments mounted on the WJBF-TV tower, described by Pendergast (1974), located 16 km northwest of the sounder site.

3. Evolution of the Momentum Burst

The transition from laminar to turbulent flow can be defined by use of the gradient Richardson number

$$Ri \equiv \omega_{BV}^2 / (\partial U / \partial z)^2 \quad (1)$$

with the criterion that

$$Ri \leq 0.25 \quad (2)$$

where ω_{BV}^2 is the Brunt-Väisälä frequency

$$\omega_{BV}^2 = (g/\theta)(\partial\theta/\partial z)$$

and g is the gravitational acceleration, θ is the potential temperature, z is the vertical distance, and U is the horizontal wind velocity. The numerator of Ri is a measure of the buoyancy or static stability of the atmosphere, and the denominator is a measure of the wind shear or destabilization effect. Any condition that causes Ri to be small (≤ 0.25) implies a small stabilizing influence in relation to the destabilizing influence, and is therefore a necessary condition for the onset of turbulence in a previously laminar flow. However, $Ri \leq 0.25$ is a necessary but not the only required condition for the onset of turbulence.

During the afternoon of a clear day, the typical sounder record shows thermal plume activity produced by solar heating of the planetary surface (Fig. 2). Shortly before sundown, the

heat flux changes sign from upward to downward, the air becomes stably stratified (Fig. 3), the wind near the surface diminishes (Turner, 1973), and a laminar layer forms. This layer is an effective barrier for all fluxes, and the transfer of momentum and heat from the higher layers will be blocked (Businger, 1972). The result is that the wind dies and a period of calm sets in. This is a well known and frequently observed phenomenon that takes place during fair weather conditions. During this period the net radiation is outgoing because of the clear sky and the lack of downward heat flux from the higher levels; therefore a dramatic drop in the temperature occurs near the surface (Fig. 4). Because there is no downward momentum transfer (it cannot pass through the laminar layer), the momentum increases in the upper layer. A strong wind shear develops (Fig. 5), and because there is no increase in the heat flux in this layer, the Richardson number must decrease (Fig. 6). The Richardson number eventually decreases below the critical value ($Ri_{CR} < 0.25$), and the layer becomes conditionally unstable. Subsequently the laminar structure of the boundary layer abruptly becomes turbulent and, with a burst of heat and momentum, the mixed layer reaches the ground (Fig. 7). This sequence of events could repeat itself. But at this site, the atmospheric boundary layer usually remains in a well-mixed or turbulent state for the rest of the nighttime period.

4. Conclusions

The acoustic sounder provides a graphic means of monitoring in real time the transition of the atmospheric boundary layer from one state or condition to another state or condition. Until recently, these transition periods were inferred from data obtained using meteorological towers with the usual restrictions of height and widely separated measurements (spatial). The acoustic sounder presents the investigator with a continuous profile of the boundary layer between ground level and heights well above most towers. The abrupt transition from the laminar flow to a turbulent flow as observed on 9 June 1975 does not appear to be a unique case; the records shown in Fig. 8, 9, 10, 11, and 12 indicate that it is probably a common phenomenon. The essential characteristics are 1) clear sky in the preceding afternoon and evening, 2) little or no surface mixing prior to the transition, 3) rapid surface cooling after sundown, and 4) moderate wind shear with height.

Turbulent mixing is the mechanism for the breakdown of the laminar flow, but the triggering mechanism is not clearly evident from the sounder records. The triggering could possibly be brought about by Kelvin-Helmholtz instabilities between the layers. These instabilities create regions of intense shear in the inner layer (Scotti et al., 1972; Rao et al., 1971) or a liftup or up-welling from an adverse pressure gradient caused by horizontal roll vortices (Offen et al., 1975; Le Mone, 1973).

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Fig. 1. Map of parts of South Carolina and Georgia showing the location of the Savannah River Plant sounder and WJBF-TV tower.

Fig. 2. Sounder record of typical thermal plumes produced by solar heating of the planetary surface.

Fig. 3. Sounder record of typical stratified stable laminar layers.

Fig. 4. Potential temperatures as a function of time at the 137-meter and 10-meter levels, 9 June 1975.

Fig. 5. Wind speed as a function of time at the 137-meter and 10-meter levels, 9 June 1975.

Fig. 6. Richardson number as a function of time for 9 June 1975 computed from winds and temperatures from the 137-meter and 10-meter level on the WJBF-TV tower.

Fig. 7. Transition from a laminar to a turbulent atmospheric boundary layer at 2210 hours, local standard time, 9 June 1975.

Fig. 8. Transition from a laminar to a turbulent boundary layer, 15 June 1975.

Fig. 9. Transition from a laminar to a turbulent boundary layer, 29 June 1975.

Fig. 10. Transition from a laminar to a turbulent boundary layer, 3 July 1975.

Fig. 11. Transition from a laminar to a turbulent boundary layer, 9 July 1975.

Fig. 12. Transition from a laminar to a turbulent boundary layer, 4 August 1975.