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STURCTURE OF THE NOCTURNAL BOUNDARY LAYER OVER A COMPLEX TERRAIN (U)

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Structure of the Nocturnal Boundary Layer Over a Complex Terrain

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Introduction

The complex nature of the nocturnal boundary layer (NBL) has been shown extensively in the literature (eg. Businger et. al., 1971, Mahrt et. al., 1979, Andre and Mahrt, 1982, Caughey, 1984, Nieuwstadt, 1984). Project STABLE (Weber and Kurzeja, 1991 hereafter W&K) was conducted in 1988 to study NBL turbulence and diffusion over the complex terrain of the Savannah River Site (SRS) near Augusta, Georgia. The third night of the study was particularly interesting because of the unusual phenomena observed in the structure of the NBL. Further analyses of microscale and mesoscale data (see Figure 1) from this night are presented using data from SRS' network of eight 61 m towers (A, C, D, F, H, K, L, P) over 900 km^2, from six launches of an instrumented tethersonde, from permanent SRL meteorological instrumentation at seven levels of the 304 m (1,000 ft) WJBF-TV tower near SRS, and additional data collected at 36 m (CC) by North Carolina State University (NCSU) including a one dimensional sonic anemometer, fine wire thermocouple, and a three dimensional propeller anemometer. Also, data from the nearby Plant Vogtle nuclear power plant observation tower and the National Weather Service at Augusta's Bush Field (AGS) are presented. The passage of a mesoscale phenomenon, defined as a microfront (with an explanation of the nomenclature used), and a vertical composite schematic of the NBL which shows dual low level wind maxima, dual inversions, and a persistent, elevated turbulent layer over a complex terrain are described.

Locations of Instrumentation of Project STABLE

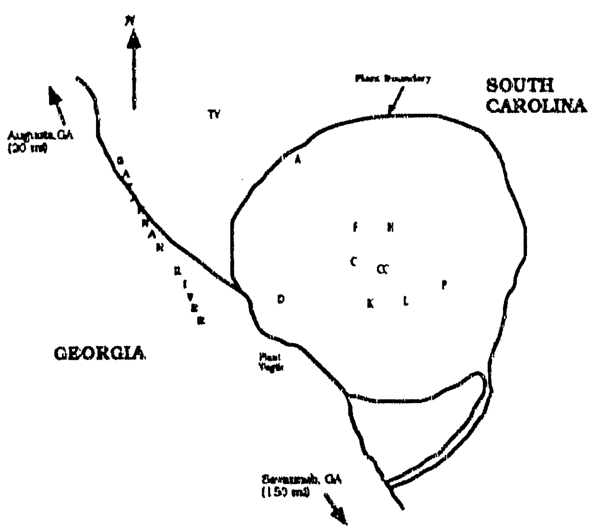

Figure 1. Outline of the Savannah River Site.

Local Terrain and Synoptic Conditions

The highest terrain at SRS is located to the east of the Savannah River valley. Tower D is located in the flood plain. The foliage of the site varies from thickly forested 15 to 18 m deciduous trees in the flood plain to a more broken forest composed of 8 to 10 m pine and deciduous trees over the higher terrain above the flood plain. Areas not covered by forest consist of a much smaller percentage of fields, buildings, parking lots and roads, and two cooling lakes.

The synoptic condition at 0200 Eastern Daylight Time (EDT) was governed by a large high pressure system centered over central Tennessee with a stationary front located in the vicinity of northern Florida. This high pressure cell moved to North Carolina by 0800 EDT. A pressure trace from a microbarograph showed variations of less than one millibar throughout the night. Surface observations indicated clear skies with little or no wind at ground level.

Spatial Wind Variations

Wind speed measured at a height of 61 m at each of the network towers at the SRS were comparatively light before 0000 EDT, but a sharp increase was observed roughly between 0000 and 0100. A closer examination of the period when the wind speed increased is shown in Figure 2 where data are plotted from towers along a north-south line extending from the TV tower south to the nearby Plant Vogtle nuclear power plant just to the west of the Savannah River. A peak in the Vogtle wind speed (15 minute averages centered on the hour) was detected at 2300, a peak at D occurred at 0100, after 0100 at A, and between 0030-0130 at the 91 m level of the TV tower. This implies a north-south spatial extent of at least 50 km in the observed sharp wind speed increases. Data from the SRS towers which extend roughly east-west from D to P indicated that wind speed maxima were observed near 0030 with values from 5.5 to 7.3 m s^{-1} and that the east-west spatial extent was at least 30 km. The relative strength of the maxima decreased from south to north as shown by the maximum of about 8 m s^{-1} at Plant Vogtle to the minima of about 4.5 m s^{-1} at A and the TV towers, and this is consistent with sodar echoes

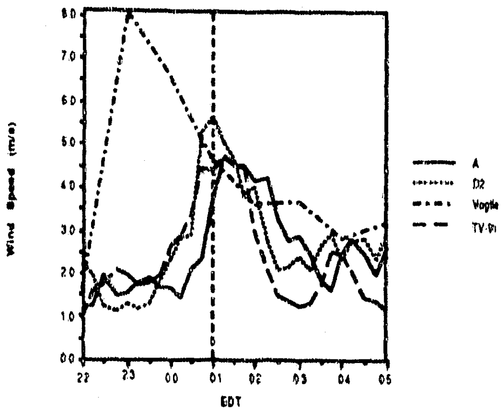

Figure 2. **Microfrontal passage as shown by wind speed.**

which indicated that strong turbulence at this time was more prevalent at CC than at the TV tower site. Observations at AGS did not clearly indicate a peak in wind speed values during the night.

The cause of the sharp increase in wind speed is not known. As stated above, there was no synoptic scale frontal activity present within several hundred kilometers, and skies were clear with very little barometric pressure change throughout the night. The NBL characteristics during this night correspond well with a Type IV night as described by Kurzeja et. al. (1991) in a SRS climatological study of TV tower data. These nights are characterized as unsteady; that is they begin with the normal formation of a surface inversion and then suddenly transform into a much more turbulent boundary layer. This transformation is associated with the passage of a "microfront," which can occur during weak prevailing pressure gradients. The term "microfront" is used very loosely since the accepted definition of a microfront (Mahrt, 1989, Stull, 1988) is associated with the passage of the backside of a large thermal in a convective boundary layer. The spatial extent of the wind speed increase is at least 30-50 km or the approximate length scales of the meso-α and meso-β scales, however, the term "mesofront" is clearly associated with mesoscale activity such as the outflow from large complexes of thunderstorms (Schaefer, et al, 1986). For the purposes of this study, the term microfront will be used to describe the phenomenon identified in the wind field at SRS.

The dynamics of the microfront are not well understood. The wind direction backed only 20-30° after the microfront passed. Normally, cold fronts pass from the northwest to southeast in the Southeastern United States, but not from south to north as the microfront moved. Also, the local topography suggests that drainage flows associated with terrain of the Savannah River valley would pass from northwest to southeast not from south to north. Microfrontal passage at the TV tower were shown by Kurzeja, et al (1991) to occur during 15% or more of a year. The thickness of the microfront was at least 300 m as was (see following sections) shown in the TV tower data, but the microfront probably did not extend to above normal NBL heights since the there was a strong high pressure cell dominating the local weather conditions.

Vertical Structure of the NBL

As indicated by the SRS tower data discussed in the previous section, the spatial structure of the NBL varied considerably throughout the night. To observe the vertical structure of the NBL, six launches of an instrumented tethersonde were made between 0200 and 0530 EDT at roughly half hour intervals. Data from these runs consisted of wind speed and direction, air temperature, and specific humidity. All of the tethersonde launches occurred after the passage of the microfront, and the launches were made in A area.

Figure 3 shows the profiles of the wind speed

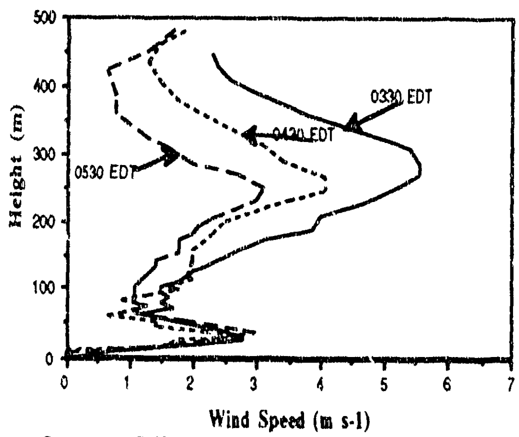

Figure 3. **Wind speed from tethersonde launches.**

obtained at 0330, 0430, and 0530 EDT. Two wind speed maxima were observed; one just below 50 m and the other near 250 m. The lower maximum remained near 3 m s^{-1} except for slightly higher values at 0200 EDT which was just after the passage of the microfront. The upper level maximum dropped from a maximum of 6 m s^{-1} to 3 m s^{-1} as the night progressed. This decrease may have been due to the large wind shear between the upper and lower maxima which developed by 0530 EDT. W&K also identified two similar low level wind maxima at the TV tower after the microfront had passed. The heights of the two wind speed maxima observed at the TV tower and in the tethersonde data were nearly the same. Statistically, based on the climatological study by Kurzeja, et al. (1991), nights with dual low level wind maxima may occur 10-30% of the year at SRS. The existence of two low level wind maxima in the NBL in this study differs from the expected wind speed profile over a nearly homogeneous terrain which will usually exhibit only one wind speed maximum.

Potential temperature profiles (see Figure 4) also

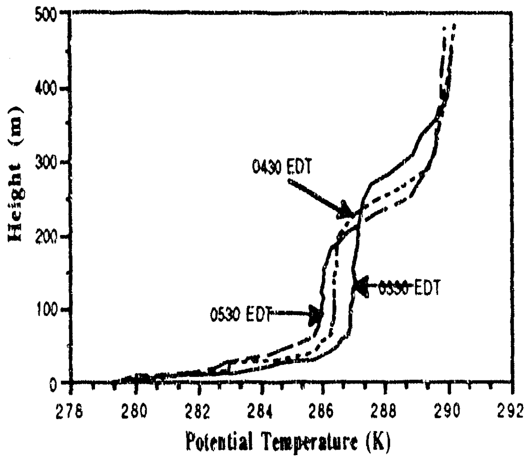

Figure 4. Potential temperature from tethersonde.

were significantly different from the generally observed NBL structure. Two inversions and associated stable layers were observed near 250 m and below 50 m during the night. An adiabatic layer existed between these two layers. Considerable mixing may have produced adiabatic conditions, but the thickness of this layer decreased as the night progressed. The upper level (250 m) wind maximum generally was located just above the upper level inversion even as the height decreased. The height of the lower level wind maximum was slightly below the height of the lower inversion and remained in this relative position throughout the remainder of the night. A general cooling trend was also observed. The turbulent layer "sandwiched" between the two stable layers may have been created by the persistent breaking of gravity waves. Typical NBL profiles show the existence of a ground based inversion as opposed to a ground based and an elevated inversion with an active turbulent layer observed in this study.

Time Histories of Air Temperature

The TV tower is instrumented with slow response temperature probes (with a time constant of about 5 s) at seven different levels (18, 36, 91, 137, 182, 243, and 304 m), and these were used to create 5 second averages. The time series of the upper levels are shown in Figure 5. Two general features are apparent from this figure. A general cooling trend is evident as the night progressed. The second feature is a sharp discontinuity just after 0030 EDT. This discontinuity involved a significant (2-4°C) drop in temperature associated with the passage of the microfront. This feature was described by W&K as a turbulent "burst", however, the spatial wind field data suggest that the microfront may have been the cause of this drop in temperature.

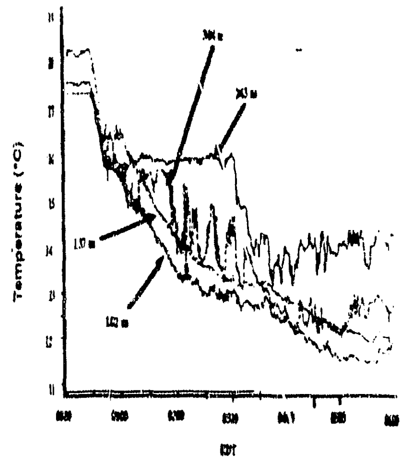

Figure 5. TV tower temperature time histories.

Some other relevant information on the turbulence characteristics of the NBL can also be deduced from the time histories of the air temperature. Often, during strongly stable conditions, temperature time series show the existence of internal gravity waves (SethuRaman, 1977, and 1980) as seen at the 304, 243, 36, and 18 m levels. However, the 91, 137, and 182 m levels exhibited the presence of few or no gravity waves. These three traces indicated the presence of an elevated adiabatic layer with active turbulence throughout the night. The layer between 200 and 300 m and that below 100 m were stable and much less turbulent. The elevated adiabatic layer was also indicated by the tethersonde data presented in later sections.

Richardson Number Contours

Contours of the gradient Richardson number, Ri, obtained from tethersonde data for the period 0230 to 0530 EDT are shown in Figure 6. Flow was generally nearly laminar (Ri > 0.5) above 250 m. Similar values were also observed below 50 m. A more turbulent layer is indicated by values of Ri < 0.25 between the upper and lower stable layers. "Pockets" of stronger turbulence (Ri < 0) were observed at varying heights before 0430 EDT, and these may have indicated breaking gravity waves caused by shear instability (SethuRaman, 1977, and 1980). The thickness of the turbulent layer between the upper and lower inversions showed a decreasing trend from about 150 m to only 50 m by 0600 EDT. This could be due to the increasing stability of the NBL as the surface continued to cool.

Despite differences in temporal and spatial resolutions, the tethersonde Ri contours correspond well with Ri obtained after 0000 EDT

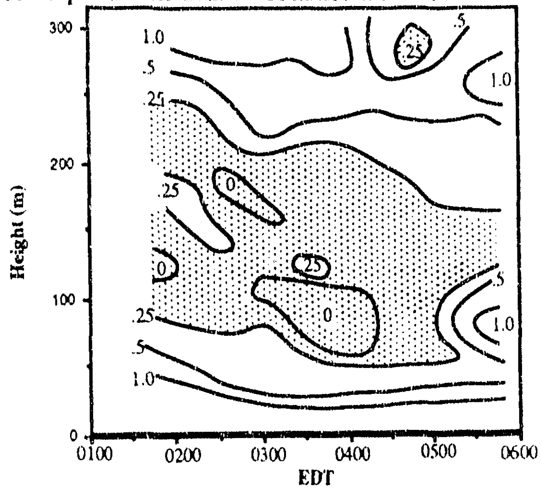

Figure 6. Tethersonde Ri contours.

from one minute averages of the observations made at the TV tower as presented by W&K. The persistent turbulent layer sandwiched between the stable layers was shown to exist at the TV tower and the tethersonde launch sites after the passage of the microfront which implies a spatial extent of at least 30 km. Turbulent episodes extending to the surface were observed at the TV tower at 0150 and 0345 EDT but were not detected by the tethersonde data which may have been due to the relatively coarse time resolution of the tethersonde data compared to the TV tower data (30 min to 1 min) and to the different measuring sites which were 30 km apart.

In order to create a composite structure of the NBL, Ri contours (Figure 7) were calculated

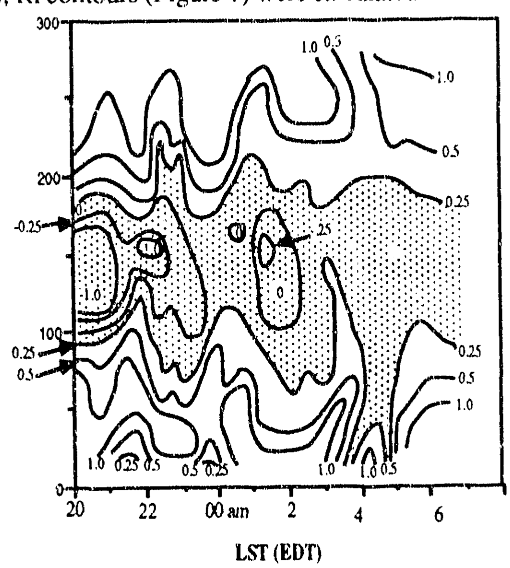

Figure 7. TV tower Ri contours.

from 15 minute averages of TV tower data for the entire night. Shaded areas indicate values below 0.25 which are presumed to be turbulent. Residual daytime turbulence existed between 100-180 m well after sunset until about 2200 EDT. The persistent adiabatic layer between 75-200 m which was identified by the tethersonde and TV tower data existed throughout the entire night. The microfront which passed the TV tower near 0030 had little effect on the values of Ri although a turbulent period was noted from 0100 to 0200 between about 100-180 m. Two turbulent periods which may have reached the surface were observed at 0330 and 0450.

Composite Structure of the NBL

Figure 8 shows a composite of the NBL structure for the entire night. The composite is based on the discussion of the previous sections, turbulence data gathered by NCSU, and the results of W&K. Residual daytime turbulence (1) was observed until about 2100 EDT. A ground-based inversion (2) developed soon after sunset and rose to 50 m by 2300 EDT, and a weak inversion (3) formed near 250 m by 1930 EDT. A stable layer existed above the upper and below the lower inversions. An elevated turbulent layer (4) existed between the two stable

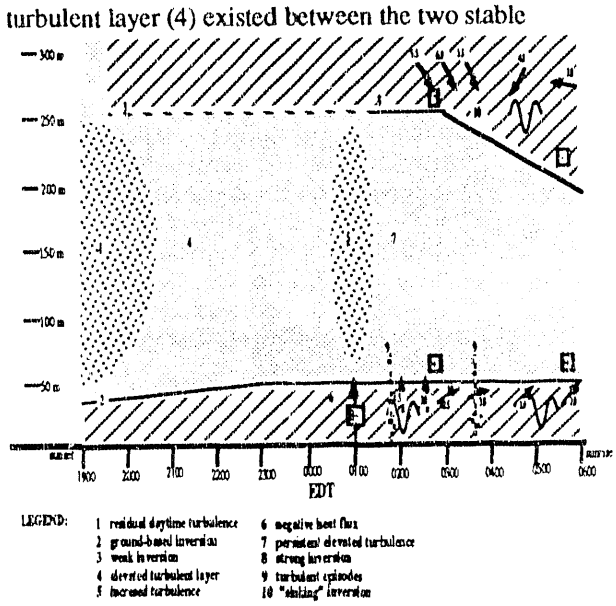

Figure 8. Composite NBL structure.

layers through the entire night. Near 0100 EDT, increased turbulence was observed (5) during the passage of a microfront with considerable cooling at the lower levels as evidenced by negative heat flux (6). Turbulence decreases in intensity between stable layers (7) but remains in place-possibly due to persistent breaking of internal gravity waves. The upper inversion (8) strengthens and remains near 250 m, and internal gravity waves (∿) become evident above 250 m and below 50 m. A low level jet forms just below 50 m at 0200 EDT, and an upper jet formed near 270 m by 0230 EDT. Turbulent episodes which reached the surface (9) were observed at 0150 and 0345 EDT. Specific humidity maxima (q+) were observed just above the lower inversion, and minima (q-) just above the upper inversion during each of six tethersonde runs. The upper level inversion (10) began sinking at 0300 EDT as the elevated turbulent layer decreased in thickness to about 150 m by sunrise.

Conclusions

A mesoscale feature which exhibited frontal characteristics, defined as a microfront, and a complex vertical structure of the NBL were observed on the night of this study. The spatial extent of the microfront was at least 30-50 km, but the forcing is not well understood since the microfront occurred without the presence of a synoptic scale cold front, under clear conditions, and with no discernable discontinuity in a microbarograph pressure trace. The the existence of dual low level wind maxima and dual inversions, rarely mentioned in the literature, differed considerably from the expected homogeneous terrain NBL structure. The persistent elevated turbulent layer was shown to have had a spatial extent of at least 30 km and to have existed from sunset to sunrise. Internal gravity waves were observed in the stable layers above and below the persistent elevated turbulent layer, and the persistent adiabatic layer may have resulted from internal gravity waves which were breaking due to shear instability.

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