Acoustic Detection of Momentum Transfer during the Abrupt Transition from a Laminar to a Turbulent Atmospheric Boundary Layer[1]

J. F. SCHUBERT

Savannah River Laboratory, E. I. du Pont de Nemours & Co., Aiken, S. C. 29801

(Manuscript received 30 April 1976, in revised form 25 August 1977)

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 and 137 m on an instrumented tower. Sounder data show that conditions necessary for the 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.

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; Emanual *et al.*, 1972; Hall *et al.*, 1974, 1975; Hooke *et al.*, 1972; 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

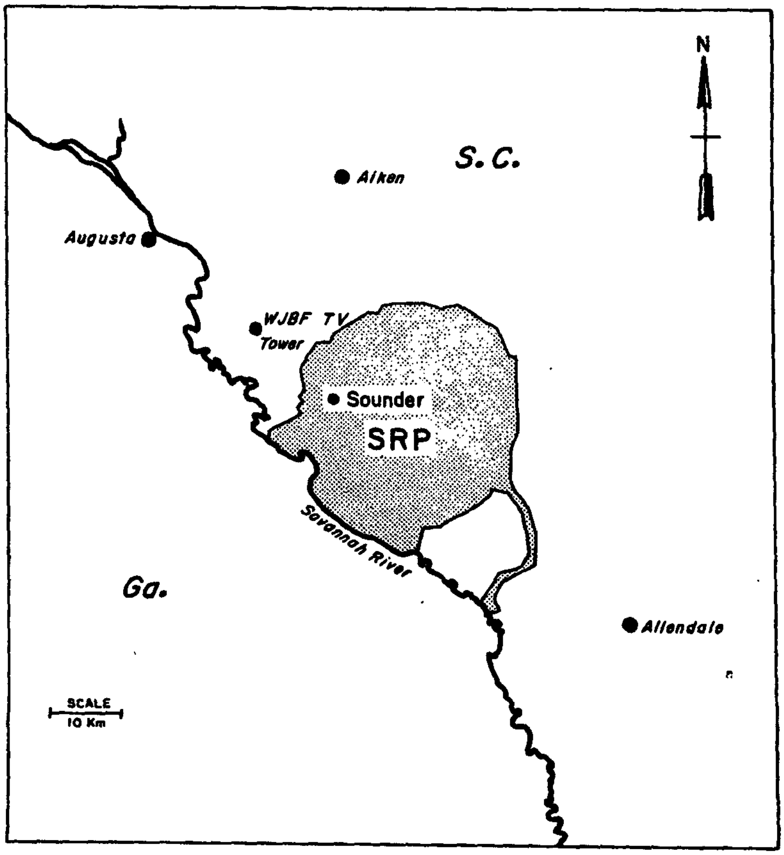

FIG. 1. Map of parts of South Carolina and Georgia showing the location of the

---

[1] This paper was prepared in connection with work under Contract No. AT(07-2)-1 with the U. S. Energy Research and Development Administration.

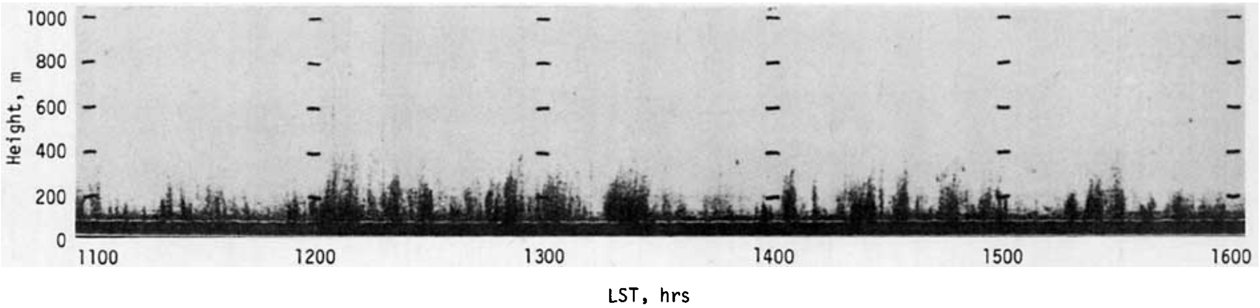

FIG. 2. Sounder record of typical thermal plumes produced by solar heating of the planetary surface.

on a facsimile recorder depicting the time variations of vertical profile of the passage of the boundary layer over the sounder site. These data are then cataloged 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 km^2, 40 km southeast of Augusta, Ga. (Fig. 1). The acoustic sounder was located in a cleared area of 37 ha (~610 m on a side) adjacent to a Quonset hut (4 m height) in an area of rolling hills covered with tall (10–15 m) pine trees (*P. taeda*, *P. palus 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 and Crawford (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 a quasi-local or finite-difference form of the Richardson number with the criterion that $Ri<0.25$. The Richardson number is defined as the ratio of the buoyancy force to a type of inertial force which is dependent on the shearing motion in the fluid. In the physics of the atmosphere it is customary to define the Richardson number by the equation (Lettau, 1953)

$$\mathrm{Ri}=g(\ln\theta)'/U'^2, \tag{1}$$

where g is the gravity acceleration (m s^{-2}), ln the natural logarithm, θ the absolute potential temperature (K), U the horizontal wind speed (m s^{-1}), and the primes denote partial differentiation with respect to height $z(m)$. Near the earth-air interface the absolute potential temperature is normally very close to the actual kelvin temperature T, so that (1) can be written

$$\mathrm{Ri}=g\theta'/T_mU'^2, \tag{2}$$

where T_m is the average Kelvin temperature of the air layer under consideration.

In micrometeorological studies the Richardson number is frequently approximated by the simplified form

$$\mathrm{Ri}_{2,1}=\mathrm{constant}\times(T_2-T_1)/U_2{}^2, \tag{3}$$

where T_2-T_1 is the temperature difference over the finite-height interval z_2-z_1, and U_2 is the wind speed at height z_2. Eq. (3) defines the "bulk" Richardson number of a finite air layer, while (1) and (2) define a "local" Richardson number which is valid at a reference level z.

Following Lettau (1953) we introduce the definitions

$$z\theta'\equiv\delta\theta/\delta\ln z,\quad zU'\equiv\delta U/\delta\ln z. \tag{4}$$

If z_1 and z_2 are common levels of simultaneous temperature and wind speed measurements the suitable reference level is the geometric mean height $z_{1,2}=(z_1z_2)^{\frac{1}{2}}$.

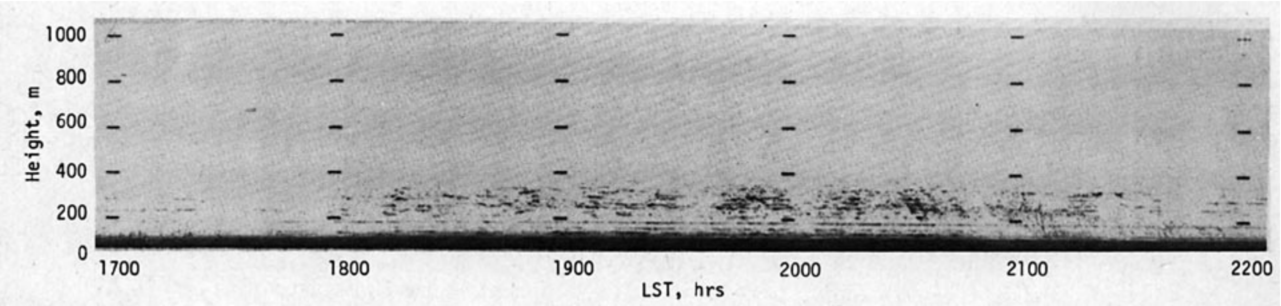

FIG. 3. Sounder record of typical stratified stable laminar layers.

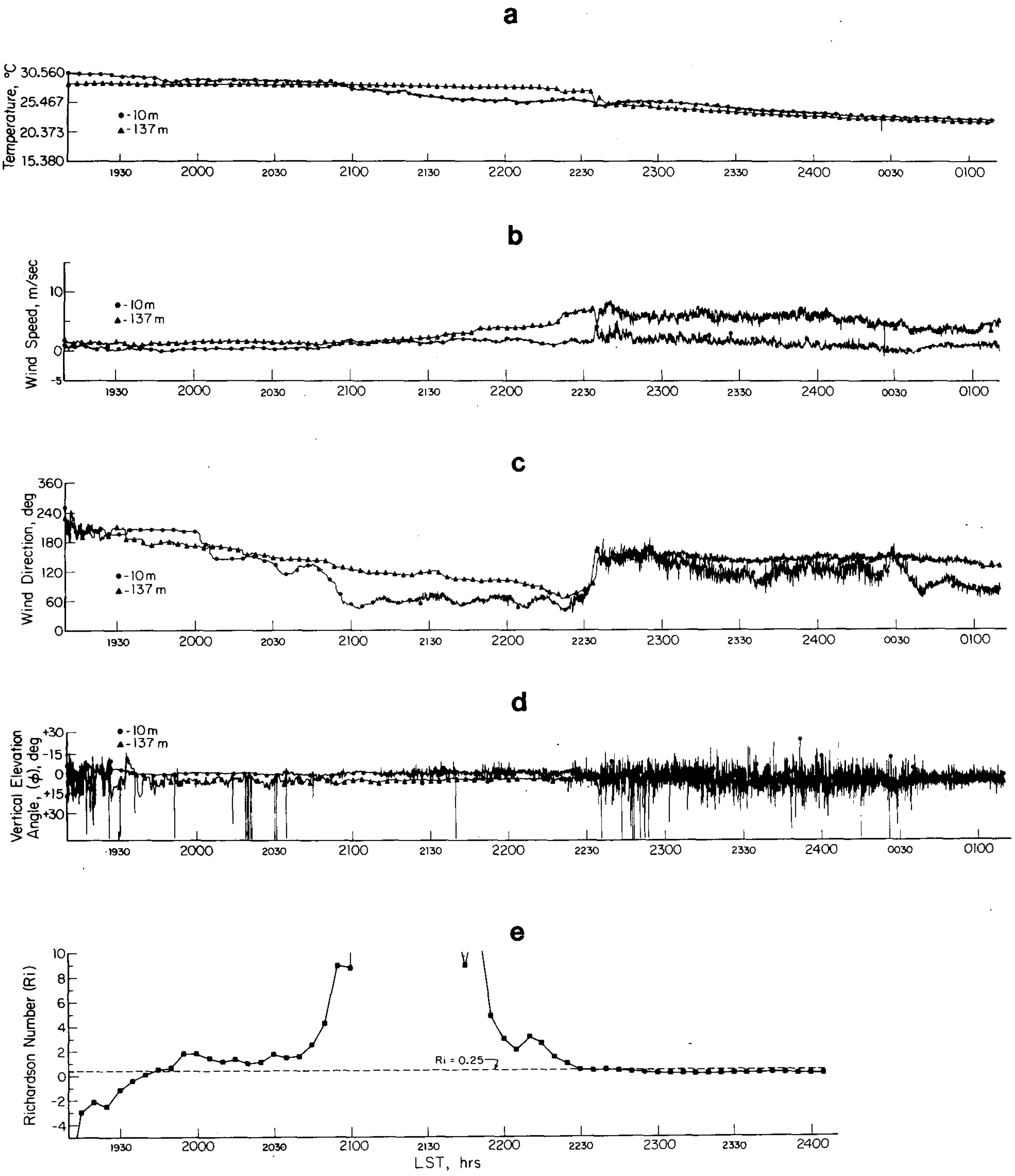

FIG. 4. WJBF-TV tower data for temperature (a), wind speed (b), wind direction (c), vertical elevation angle (d), and Richardson number at reference level of 37 m (e) for the period 1911–0211 LST 8–9 June 1975.

Let $n^2 = z_2/z_1$ so that $z_1 = z_{1,2}/n$, and $z_2 = nz_{1,2}$. When the height derivatives are approximated by difference quotients, the terms in (4) can be written

$$z_{1,2}\theta'(z_{1,2}) = (\theta_2 - \theta_1)/2 \ln n,$$
$$z_{1,2}U'(z_{1,2}) = (U_2 - U_1)/2 \ln n. \quad (5)$$

With the aid of (5) and (2) the quasi-local Richardson number at the reference level $z_{1,2}$ is

$$\mathrm{Ri} = 2gz_{1,2}(\theta_2 - \theta_1) \ln n / T_2(U_2 - U_1)^2. \quad (6)$$

It is sufficient to use T_2 in place of $(T_1 + T_2)/2$.

Ri is a measure of the convective stability; it is zero for the adiabatic or thermally neutral stratification of the atmosphere; negative for superadiabatic thermal stratification, i.e., in lapse conditions; and positive for inversional thermal stratification. The range of Ri in the atmosphere is typically from 10^{-4} to 10^{+2} (Wiin-Neilsen, 1973). 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, $\mathrm{Ri}<0.25$ 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 (this is shown starting at 2056 LST in Fig. 4). With relaminarization of the lower layer, its coupling to the ground is greatly reduced, and the effect of the shear stress on top of the lower layer together with the Coriolis force lead to an acceleration of the flow in the lower layer. But, since only molecular viscosity is acting near the top of the lower layer, the acceleration leads to a very slow increase of the velocity (Plate, 1971). Thus as the 10 m wind speed approaches that at 137 m (2056 LST in Fig. 4), the Richardson number becomes very large. 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. 4), and because there is no increase in the heat flux in this layer, the Richardson number must decrease (Fig. 4). The Richardson number eventually decreases below the critical value ($\mathrm{Ri}_{\mathrm{cr}}<0.25$), 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 (2236 LST in Fig. 4). The intensity of turbulence in the vertical direction is defined by Slade (1968) as

$$i_z=\left(\frac{\overline{w'^2}}{\bar{u}^2}\right)^{\frac{1}{2}}=\frac{\sigma_w}{\bar{u}},$$

where w' is the fluctuation of the vertical component of the wind and $\bar{u}$ the mean value of the horizontal component of the wind. Another statistic of the wind fluctuation is the standard deviation of the elevation angle ϕ measured between the wind vector and the horizontal. This angle (ϕ) can be measured by a vector vane. The standard deviation of the elevation angle σ_ϕ is related to the intensity of turbulence, i.e.,

$$\overline{\phi'^2}\approx\frac{\overline{w'^2}}{(\bar{u})^2} \quad \text{or} \quad \sigma_\phi=\frac{\sigma_v}{\bar{u}},$$

where ϕ' is the deviation of the elevation angle from the average.

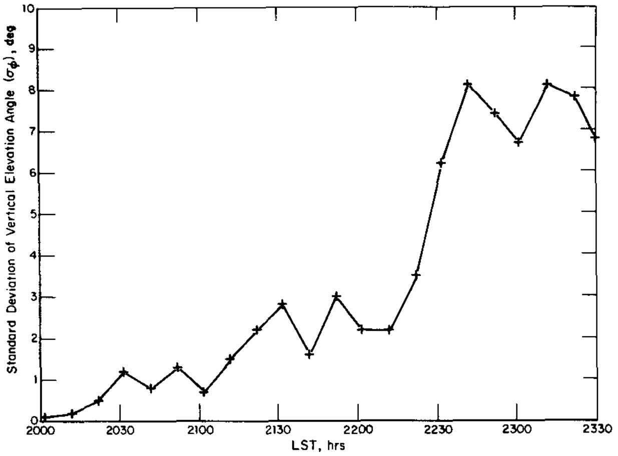

FIG. 5. Change in intensity of σ_ϕ with time at the 10 m level on the WJBF-TV tower, 8 June 1975.

The change of intensity of the turbulence at 2237 LST, shown in Fig. 5 is statistically significant at the 99% level. Fig. 6a is the sounder record for 8 June 1975, showing this abrupt change from a laminar to a turbulent atmospheric boundary layer. 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 8 June 1975 does not appear to be a unique case; the records shown in Figs. (6b–6d) indicate that it is probably a common phenomenon. The essential characteristics are 1) clear sky in the pre-

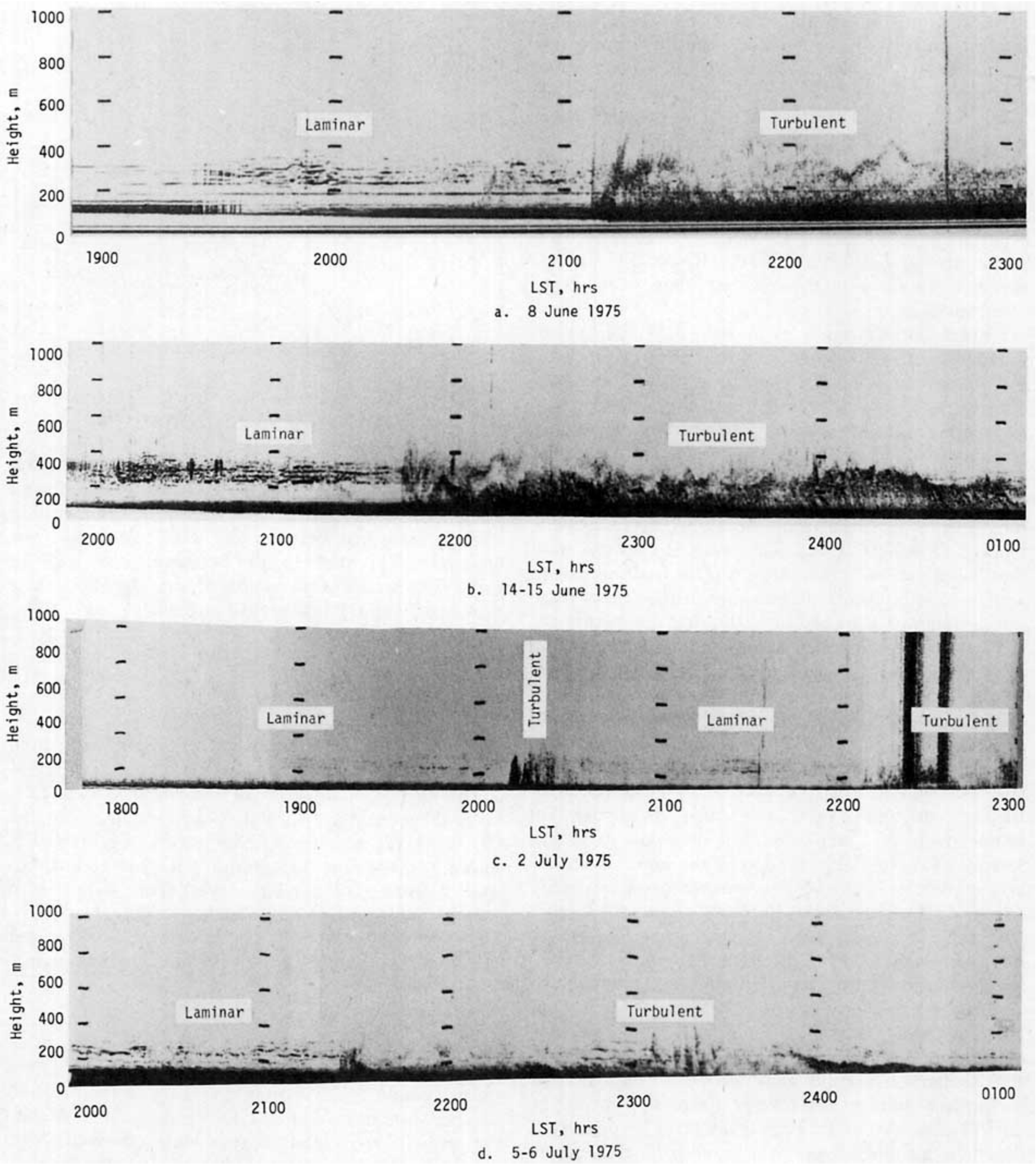

FIG. 6. Acoustic sounder records for several periods during June–July 1975 showing the transition from a laminar to a turbulent atmospheric boundary layer.

ceding 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 the Kelvin-Helmholtz instabilities between the layers. These instabilities create regions of intense shear in the inner layer (Scotti and Corocos, 1972; Rao *et al.*, 1971) or a liftup or upwelling from an adverse pressure gradient caused by horizontal roll vortices (Offen and Kline, 1975; Le Mone, 1973).

REFERENCES

Beran, D. W., C. G. Little and B. C. Wilmarth, 1971: Acoustic Doppler measurements of the vertical velocities in the atmosphere. *Nature*, **230**, 160–162.

Businger, J. A., 1972: Turbulent transfer in the atmospheric surface layer. *Workshop on Micrometeorology*, Amer. Meteor. Soc., 38–42.

Emmanuel, C. B., B. R. Bean, L. G. McAllister and J. R. Pollard, 1972: Observations of Hemholtz waves in the lower atmosphere with an acoustic sounder. *J. Atmos. Sci.*, **29**, 886–892.

Hall, Jr., F. F., and D. W. Beran, 1974: Real-time measurements of boundary layer winds and turbulence by acoustic echo sounding. *Preprints Symp. Atmospheric Diffusion and Air Pollution*, Santa Barbara, Amer. Meteor. Soc., 79–82.

Hall, F. F., J. G. Edinger and W. D. Neff, 1975: Convective plumes in the planetary boundary layer, investigated with an acoustic echo sounder. *J. Appl. Meteor.*, **14**, 513–523.

Hooke, W. H., J. M. Young and D. W. Beran, 1972: Atmospheric waves observed in the planetary boundary layer using an acoustic sounder and a microbarograph array. *Bound.-Layer Meteor.*, **2**, 371–380.

LeMone, M. A., 1973: The structure and dynamics of horizontal roll vortices in the planetary boundary layer. *J. Atmos. Sci.*, **30**, 1077–1091.

Lettau, H. H., 1953: *Exploring the Atmosphere's First Mile*, Vols. 1 and 2. Pergamon Press (see pp. 328–329).

Offen, G. R., and S. J. Kline, 1975: A proposed model of the bursting process in turbulent boundary layers. *J. Fluid. Mech.*, **70**, part 2, 209–228.

Pendergast, M. M., and T. V. Crawford, 1974: Actual standard deviations of vertical and horizontal wind directions compared to estimates from other measurements. *Preprints Symp. Atmospheric Diffusion and Air Pollution*, Santa Barbara, Amer. Meteor. Soc., 1–6.

Plate, E. J., 1971: Aerodynamic characteristics of atmospheric boundary layers. U. S. Atomic Energy Commission [NTIS Ref. No. TID-25465].

Rao, N. K., N. Narasimha and M. A. Badri Narayanan, 1971: The bursting phenomenon in a turbulent boundary layer. *J. Fluid. Mech.*, **48**, 339–352.

Schubert, J. F., 1975: A climatology of the mixed layer using acoustic methods. *Preprints Third Symp. Meteorological Observations and Instrumentation*, Washington, Amer. Meteor. Soc., 151–156.

Scotti, R. S., and G. M. Corcos, 1972: An experiment on the stability of small disturbances in a stratified free shear layer. *J. Fluid Mech.*, **52**, 499–528.

Slade, D. H., Ed., 1968: Meteorology and Atomic Energy 1968. U. S. Atomic Energy Commission, 45–55 [NTIS Ref. No. TIS-24190].

Turner, J. S., 1973: *Buoyancy Effects in Fluids*. Cambridge University Press, 367 pp.

Wiin-Neilson, Aksel, 1973: *Compendium of Meteorology*, Vol. 1, Part 1. *Dynamic Meteorology*. WMO, 240–241.