SPORADIC BREAKDOWNS OF STABILITY IN THE PBL OVER SIMPLE AND COMPLEX TERRAIN

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Abstract. Breakdowns of stability in the PBL are examined using one-minute average horizontal wind speeds and temperatures observed over many nights at stations located in simple and complex terrain. The analysis is based on the temporal behavior of the wind speed-temperature covariance, which is obtained by digital bandpass filtering. It is shown that breakdowns are a common feature of the stable PBL over both simple and complex environments. Vertical fluxes of heat during breakdowns are estimated to be a significant fraction of the nighttime average heat flux. It is hypothesized that a major portion of the nighttime vertical transfer of heat, momentum, and atmospheric pollutants occurs during periods of stability breakdowns.

1. Introduction

It is commonly assumed that the levels of turbulence and diffusion in the stable planetary boundary layer (PBL) are low. This assumption strongly affects the modeling of the atmospheric surface layer. However, beginning with the early observations by Durst (1933), Gifford (1952), and Lyons *et al.* (1964) and later by, for example, Bean *et al.* (1973), Kondo *et al.* (1978), Mahrt (1985), and Gossard *et al.* (1985), it is now clear that sporadic outbreaks of turbulence and enhanced vertical diffusion are common in the stable PBL. These effects have not been accounted for in conventional PBL theory and because of this, model predictions of surface fluxes may be underestimated. For example, in a recent paper Tjemkes and Duynkerke (1989) compared model calculations of the evolution and structure of the nocturnal PBL with observations. The observed surface temperatures show fluctuations throughout each of the two nights studied, but these fluctuations are not simulated by the model. Also, the model consistently underestimates the fluxes of latent plus sensible heat, net radiation, and soil heat. It may be that these underpredictions are due to breakdowns of the stability which are not accounted for by the model.

For long-term air quality considerations, the assumption that vertical transfer is small in the stable PBL is generally acceptable; however, in treating the problem of short-term exposure to hazardous materials, consideration of the non-stationary aspects of the PBL is crucial. For example, during a breakdown event, pollutants in the upper levels of the PBL can be brought downward to the surface layer with relatively little dilution. Harrison *et al.* (1978) and Winkler (1980) show that sudden increases in ozone concentration at the ground surface are correlated with disturbances in the stable PBL as indicated by sodar traces. They relate these concentration increases to turbulent transport from higher levels, where ozone concentrations are higher than at the ground surface.

The cause-and-effect relationships associated with PBL breakdowns are not yet clear. Businger (1973) gives a qualitative description of the breakdown process. As the ground cools at night, the establishment of a stable thermal stratification near the ground causes the Richardson number, Ri, to approach and finally exceed its critical value, Ri_c, at some height above the ground. When this happens, turbulence is suppressed, a laminar layer develops, and the downward transfer of heat and momentum from higher layers is impeded. Hence, the wind near the ground surface diminishes and a near-surface calm develops. Above the laminar layer, momentum is still transferred downward, but little heat is transferred because the stratification at this level is nearly neutral. The winds aloft are essentially disconnected from the surface, and the air aloft is free to accelerate with little resistance from surface friction. A strong wind shear then builds up and because there is not a similar increase in the heat flux, Ri must decrease and eventually become less than Ri_c. When this happens, the laminar layer is destroyed from above by turbulence. The turbulence then diffuses downward, eventually reaching the ground as a "burst" of heat and momentum.

Kondo *et al.* (1978) suggest that under very stable conditions, there exists a distinguishable interface dividing the active turbulent ground-based layer from a quiet layer above. Undulations of this interface are produced by Kelvin–Helmholtz billows which develop in response to the speed and density differences across this interface. The movement of these undulations past an instrumented tower are marked by periods of enhanced turbulence and negative heat flux. Kondo's *et al.* (1978) data indicate a time scale of about ten minutes for these periods. However, they point out that it is not the propagation and undulations of these billows, but rather their breaking and consequent mixing processes that contribute to the long-term average heat flux.

It is commonly accepted that surface obstacles can cause streamline deformation sufficient to trigger bursts of turbulence in stable stratification, but turbulence episodes have been observed by, for example, Debaas and Driedonks (1984) in areas well away from and presumably unaffected by upwind mountain ranges, etc. Theoretical investigations of disturbed nocturnal inversions conducted by, for example, Chimonas (1980), Finnigan and Einaudi (1981), Fua *et al.* (1982), and Finnigan (1988) are based on the theory of gravity wave/turbulence coupling. The basic hypothesis of this theory is that intermittent episodes of turbulence are generated by gravity-wave modulated values of the local Richardson number. A dynamically stable layer of air ($Ri > Ri_c$) can be modified by a passing gravity wave so that Ri is lowered below Ri_c, and turbulence results. With the passage of the wave, the layer may return to a stable state. A train of such waves can result in several turbulence episodes throughout a night. Thus, through this mechanism, turbulence can occur even though the boundary layer is observed to be dynamically stable in the mean.

The rapid destruction of the stable PBL due to internal gravity waves generated by distant thunderstorms has been documented by Curry and Murty (1974), Uccellini (1975), Balachandran (1980), Shreffler and Binkowski (1981), and Doviak and Ge (1984). The observations generally show gravity waves with amplitudes of 1 to 2 mb, wavelengths of several hundred kilometers, and phase velocities between 25 and 50 m s^{-1}. These waves can propagate many hundreds of kilometers. In the stable PBL, their passages are usually marked by intense gusts and destruction of the stable inversion. These disturbances typically last from 2 to 3 h and extend vertically upward a few kilometers.

Regardless of the mechanisms leading to PBL breakdown events, and it is likely that several mechanisms can act simultaneously, it must be determined if these events are a significant feature of the stable PBL. If this is the case, then it will be necessary to modify conventional PBL theory to account for the effects of these breakdowns. In this paper, we shall show that breakdowns of the nighttime PBL are a regular feature over both simple and complex terrain.

2. The Data

Data which we consider representative of simple terrain environments were taken from the EPA Regional Air Monitoring System (RAMS) which is described in detail by Schiermeier (1978). These data were collected at 25 stations within and around St. Louis, MO from 1975 through 1977. Figure 1 shows the locations of these stations, which were arranged in approximate rings with average radii from the central station (station 1) of 5, 11, 20, and 44 km. One-minute averages of meteorological variables were formed at each station from half-second samples. In this study, we use horizontal wind speed and temperature measured at 30 m above the ground surface at stations 1 (urban) and 23 (rural). Station 1 was located north of the city center in an area of one- and two-story buildings; station 23 was located east of the city in open farmland.

Data over complex terrain were taken at the Walker Branch Watershed field station near Oak Ridge, TN from February, 1987 to June 1988. Figure 2 illustrates the terrain contours in the Oak Ridge region. In this part of the eastern Tennessee River Valley, the terrain consists mostly of parallel ridges aligned along the valley axis. The ridges are typically 50 m high, 1 km wide, and 1 to 2 km apart. The region is mostly forested except for towns and small farms in the valleys. The monitoring system at the Walker Branch site consisted of a three-component Gill anemometer,* an aspirated bead thermistor, and a Meloy continuous-measuring ozone monitor all mounted at the 40 m level of the Walker Branch tower. This

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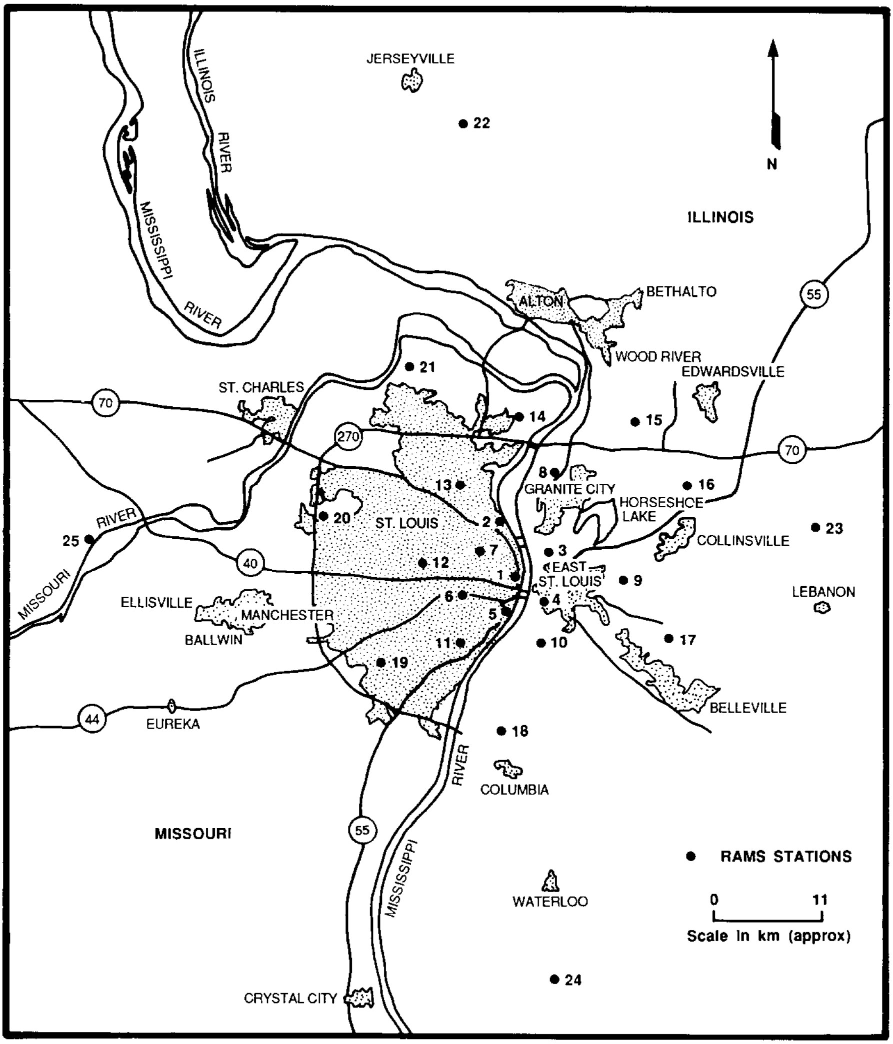

Fig. 1. Locations of the RAMS stations.

level is some 17 m above the forest canopy. The tower is on the crest of a ridge which has an average elevation of about 60 m above the floor of the Tennessee River Valley. From observations taken every half-second, one-minute averages of horizontal wind speed, temperature and ozone mixing ratio were formed. In addition to these measurements, a monostatic sodar was in operation in a clearing located about 400 m away from the tower.

All the data were screened for continuity, and only those nights with more than 80% data recovery were used. Missing data were filled in by assigning to these points the most recent valid value. The number of nights of useful data are 165 for the Walker Branch, 103 for RAMS station 1, and 76 for RAMS station 23.

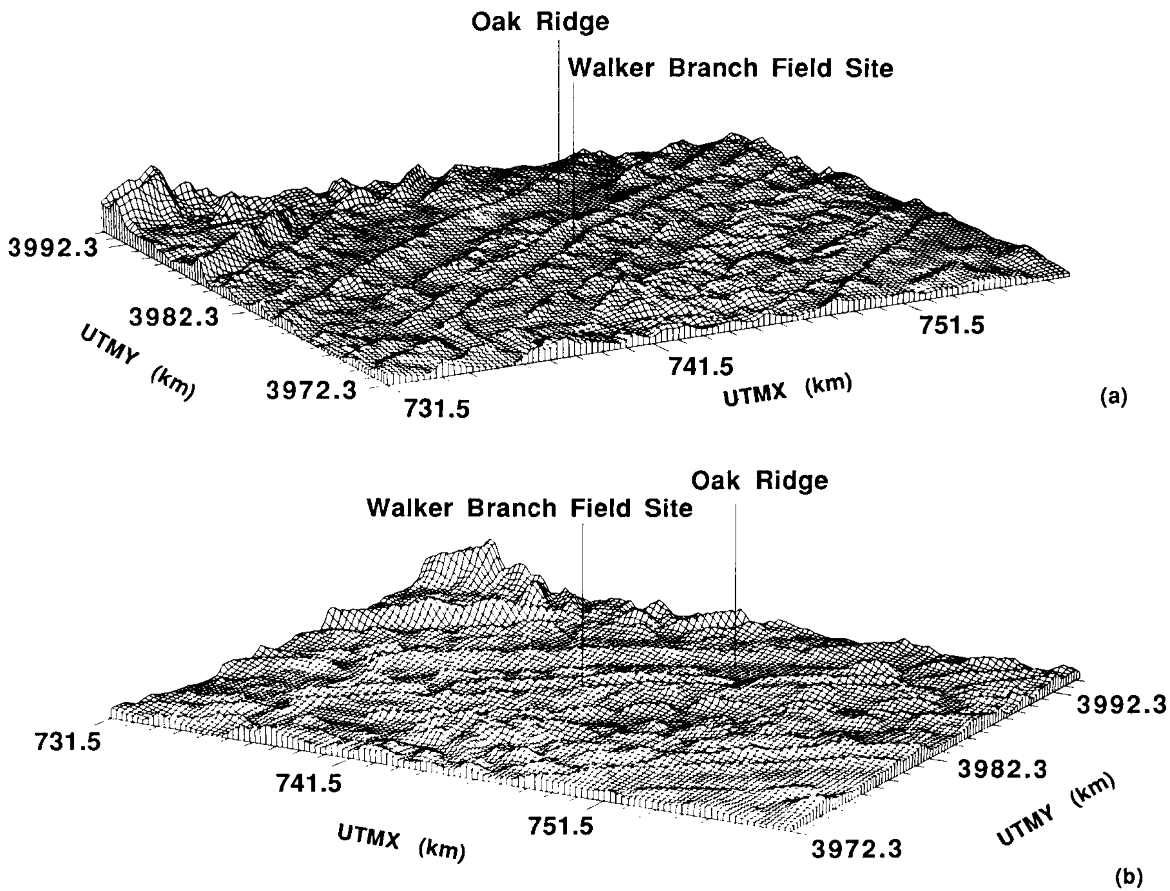

Fig. 2. Topography of the eastern Tennessee River Valley in the Oak Ridge area viewed from the southwest (a) and the southeast (b).

3. Method of Analysis

The crux of the analysis lies in the detection of a breakdown event from the time series of one-minute average horizontal wind speed and temperature. An alternative and perhaps more direct method would be to use turbulent heat flux data obtained using sonic anemometers and fast-response temperature sensors, but continuous records of such data over many nights are rare. The breakdown event is pictured as an overturning of the PBL air. In the presence of vertical wind shear and a stable thermal stratification, such an overturning transfers downward high-speed warm air toward the ground surface, and lifts low-speed cool air upward away from the ground. These events will appear in the individual time series as perturbations, which can be isolated through the use of a digital bandpass filter. The filtering is done using Gaussian-weighted running means of the general form

$$\langle q_i \rangle = \sum_{j=-N}^{N} q_{i+j} \exp\left[-\frac{(t_i - t_j)^2}{2\sigma^2} \right] \quad (1)$$

where $\langle q_i \rangle$ represents the running mean value of some variable q at time t_i, σ is the scale width of the filter window, and N is the number of samples used in the averaging. Typically, $N = 3\sigma$. The raw wind speed and temperature time series are first smoothed using Equation (1) with $\sigma = 5$ min. This reduces the amplitudes of the minute-to-minute fluctuations. We consider these fluctuations too short-lived to be breakdown events. The smoothed time series are represented by, for example, $\langle q \rangle_5$. Next, we apply Equation (1) to the series $\langle q \rangle_5$, but now $\sigma = 30$ min. This smoothing produces the long-term running mean of q. We represent this series by $\langle q \rangle_{30}$. Figure 3 shows the raw and smoothed wind speed and temperature time series for a typical night at RAMS station 23. The bandpass filtering is accomplished by subtracting $\langle q \rangle_{30}$ from $\langle q \rangle_5$, which results in the time series of the perturbations we associate with the breakdowns occurring throughout the night. Figure 4 shows an example of these windspeed and temperature perturbations plotted on the same graph where $U' = \langle U \rangle_5 - \langle U \rangle_{30}$ and $T' = \langle T \rangle_5 - \langle T \rangle_{30}$. The wind speed and temperature fluctuations tend to occur at about the same time, but there are also periods when they do not. A more certain way of detecting a breakdown event is given by examining the time series of the wind speed-temperature covariance, C_{UT}, which is obtained by forming the product of the two perturbation time series, i.e.,

$$C_{UT} = (\langle U \rangle_5 - \langle U \rangle_{30})(\langle T \rangle_5 - \langle T \rangle_{30}) \,. \quad (2)$$

Figure 5 shows the time series of the covariance for the case shown in Figures 3 and 4. We see that C_{UT} is mostly positive throughout the night, but periods of negative covariance also exist. Spikes of negative covariance occur at 2300, 0015, and 0100 h. Examination of Figure 4 shows that during those times, the temperature perturbation lags the speed perturbation by several minutes. We attribute

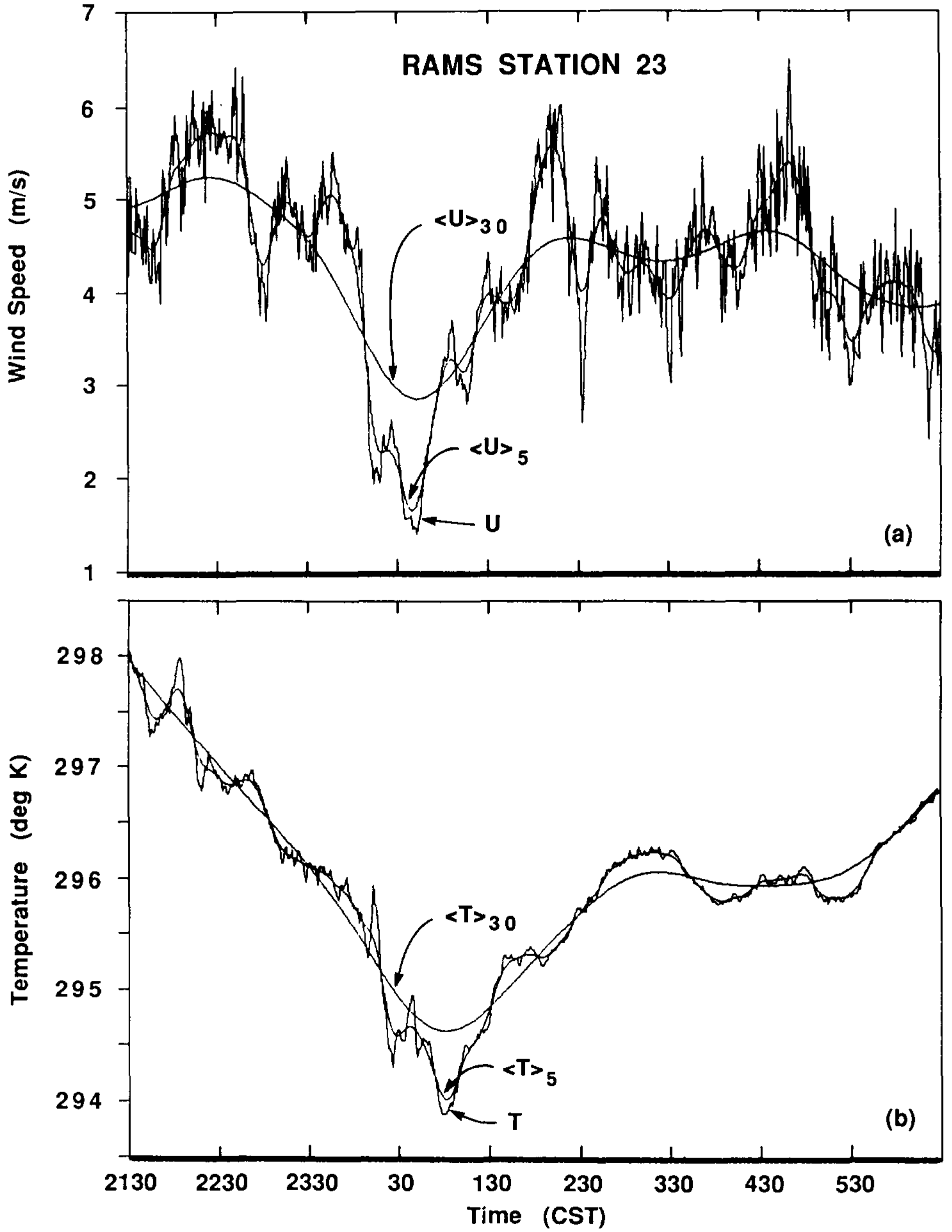

Fig. 3. Raw and smoothed time series of wind speed (a) and temperature (b) for a typical night at RAMS station 23.

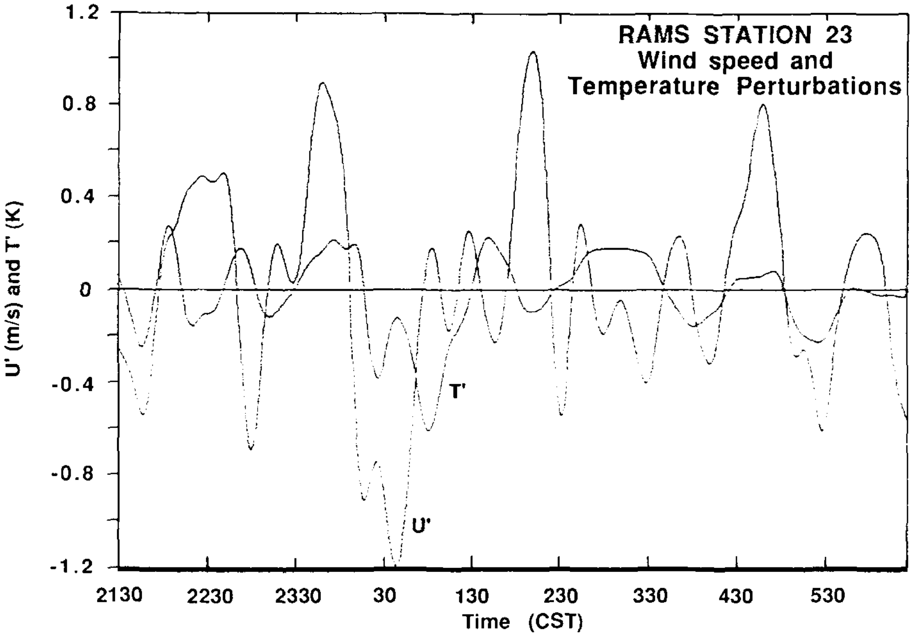

Fig. 4. Perturbation wind speed, U, and temperature, T, at RAMS station 23 for the same night as shown in Figure 3.

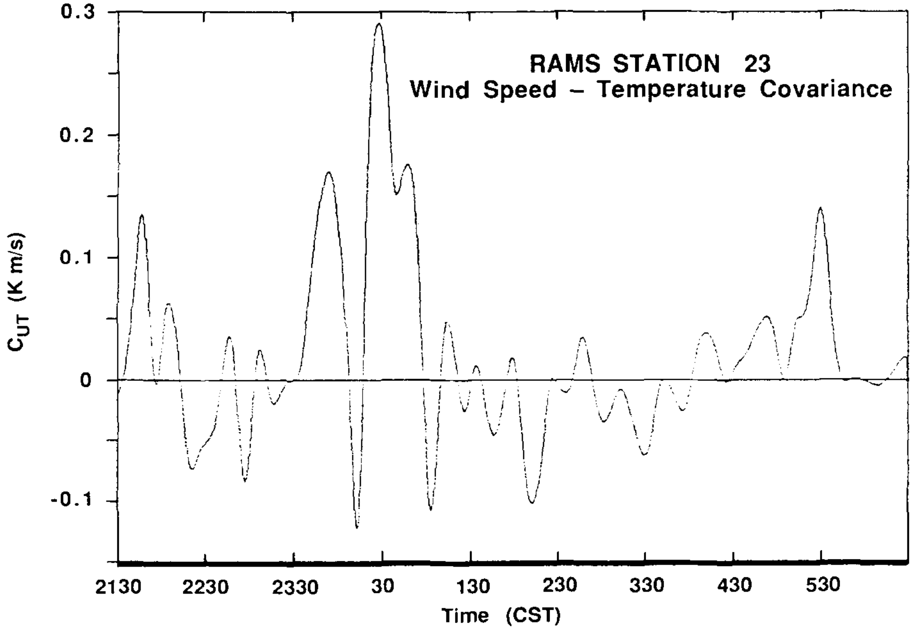

Fig. 5. Wind speed-temperature covariance for the case shown in Figure 3.

these short intervals of negative covariance to differences in response times of the temperature and wind speed sensors. Also, the relative sensitivities of the instruments will affect the covariances. We assume a breakdown begins when C_{UT} exceeds 10% of the average nighttime covariance, and ends when C_{UT} drops below this value. We take the nighttime period to run from 2000 to 0600 LST; however, the final results do not appear to be overly sensitive to these times. The statistics of interest are the number of breakdowns per night, the durations of the breakdowns, and the length of time between breakdowns. This latter quantity is significant because it relates to the relaxation time of the PBL.

The results presented in this paper are obtained by examining C_{UT}; however, because the ozone mixing ratio generally increases with height above the ground surface during stable conditions (Harrison *et al.*, 1978), an overturning of the PBL air will bring high-speed ozone-rich air down toward the ground surface, and lift low-speed ozone-depleted air up away from the ground surface. The result is a positive covariance of wind speed and ozone, C_{UO}. However, Nappo *et al.* (1988) show that the nighttime vertical distribution of ozone can have zones of significant depletion due to scavenging by nitrogen, sulfur or hydrocarbons. If air from these zones is brought downward to the ground, then a negative covariance of wind speed and ozone will result. Figure 6 shows an example of C_{UO} measured at the Walker Branch site. The sharp negative spikes are probably due to differences in instrument response times. However, the time series of C_{UO} is in general quite similar to that of C_{UT}.

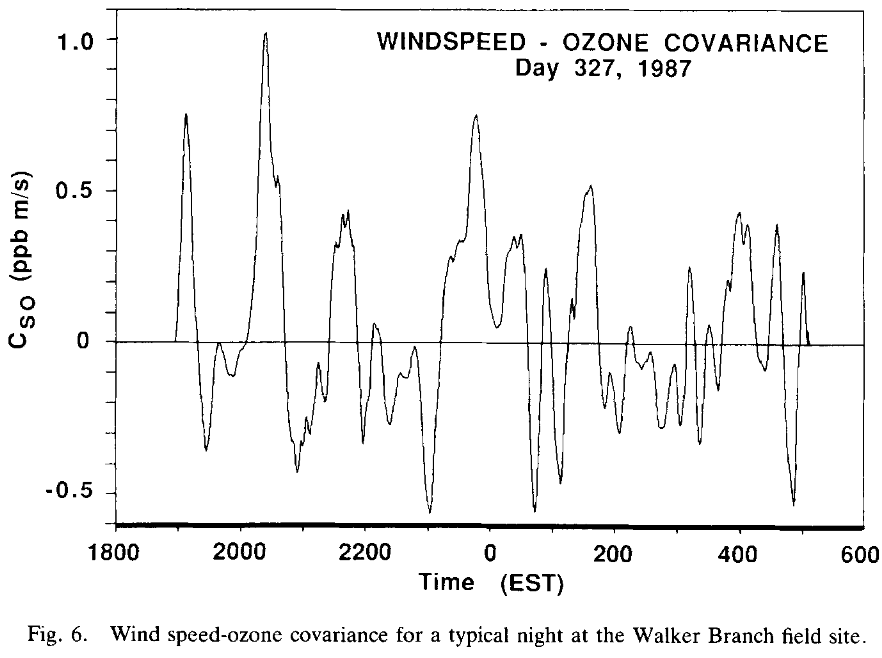

Fig. 6. Wind speed-ozone covariance for a typical night at the Walker Branch field site.

4. The Results

(A) Simple terrain

The relative frequencies of breakdowns per night for urban (RAMS station 1) and rural (RAMS station 23) locations are shown in Figure 7. The distributions appear somewhat Gaussian, with average values of 13 breakdowns per night for the urban station, and 15 for the rural one. For both locations, the distributions are slightly

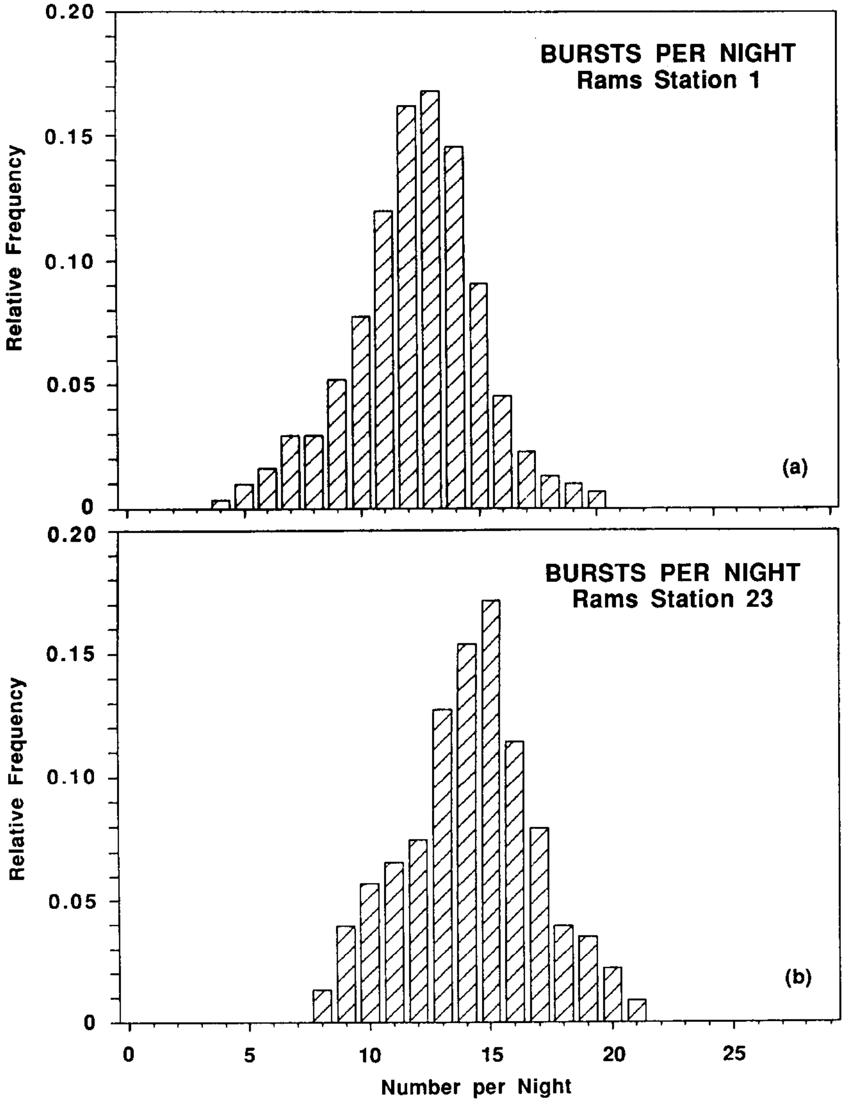

Fig. 7. Relative frequencies of breakdowns per night at the urban RAMS station 1 (a) and rural RAMS station 23 (b).

skewed toward lower values. The range of the number of breakdowns per night is greater for the urban station than for the rural one, but the number of breakdowns per night at the rural station is greater than at the urban one. The relative frequencies of the durations of breakdown events observed at the urban and rural stations are shown in Figure 8. The distributions appear somewhat lognormal. All breakdowns longer than 60 min are grouped into the 60-min cell. Note that because the resolution of the covariance time series is one minute, we cannot detect

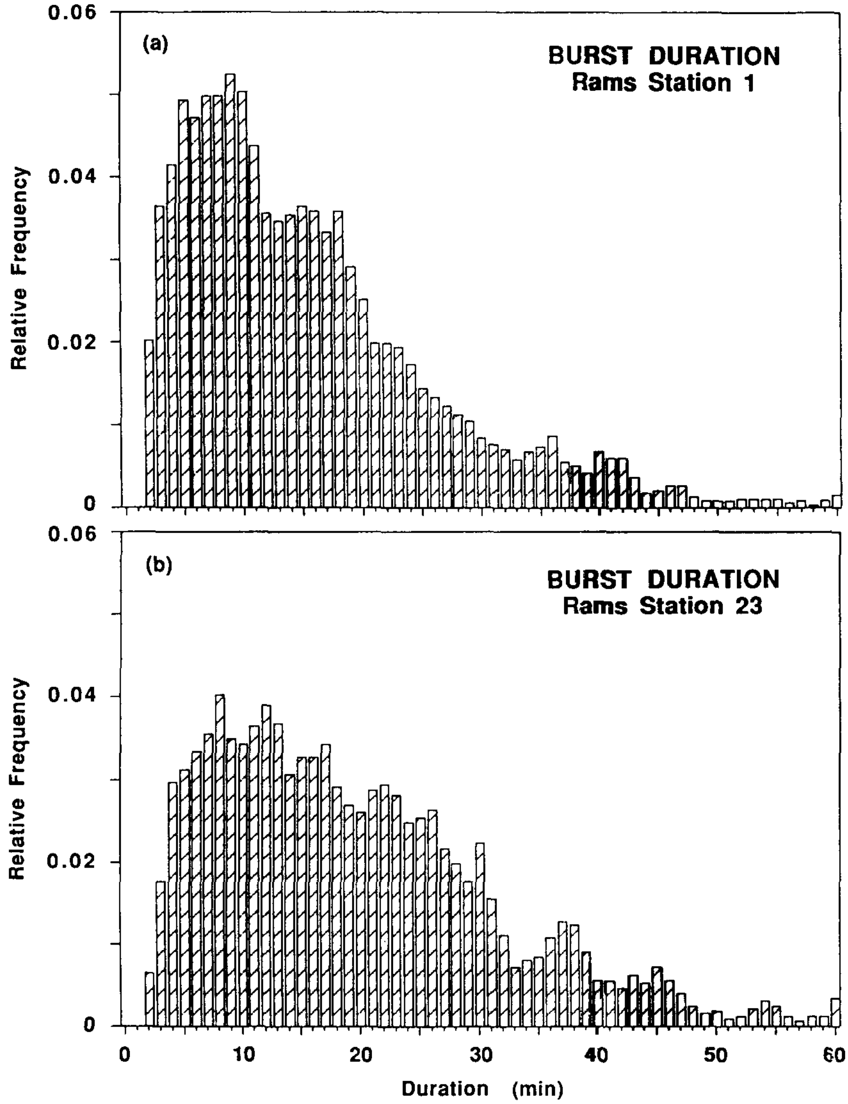

Fig. 8. Relative frequencies of the durations of breakdowns at the urban RAMS station 1 (a) and rural RAMS station 23 (b).

breakdowns which last less than 2 min. The average duration of breakdowns is 15 min for the urban station, and 19 min for the rural station. The mode of a probability distribution marks the most likely value of the variant, and for this reason is perhaps a more meaningful statistic than the average. The mode is estimated by inspection to be about 8 min for the urban station, and about 10 min for the rural station.

Figure 9 shows the relative frequencies of the intervals between breakdown events for the urban and rural stations. These quiescent periods are skewed more

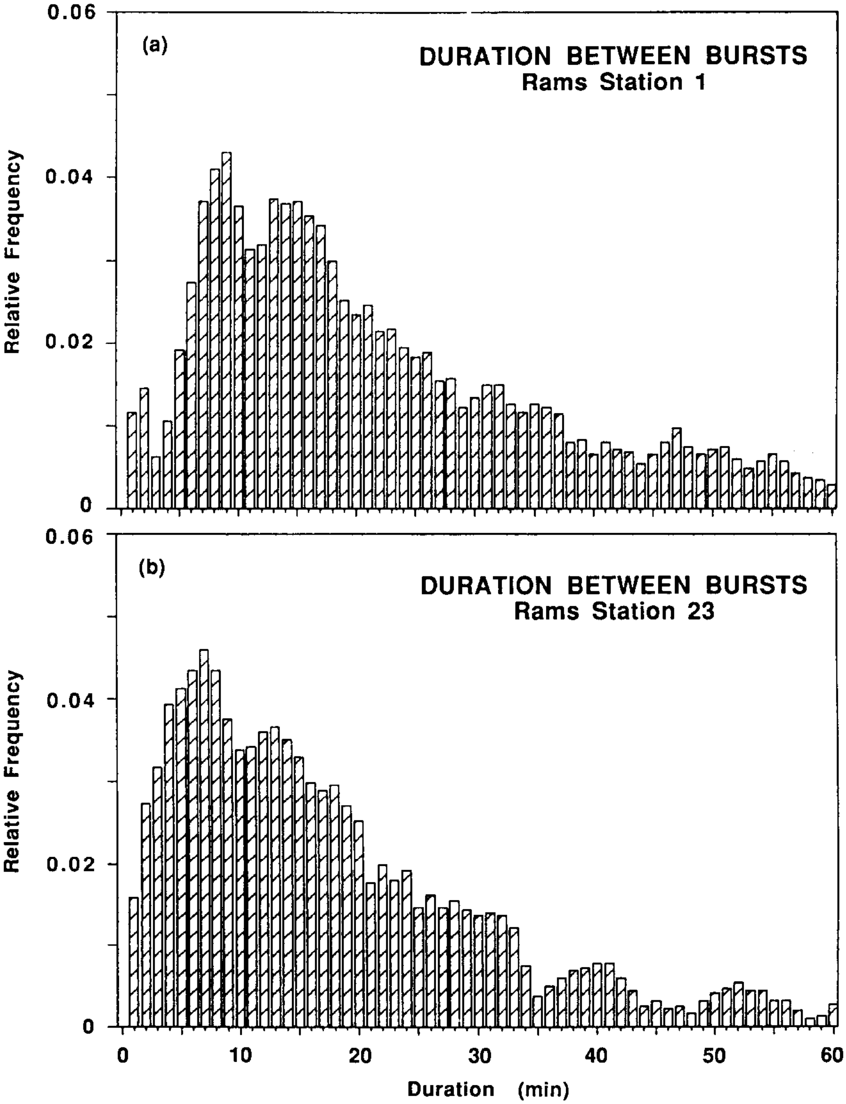

Fig. 9. Relative frequencies of the intervals between breakdowns at the urban RAMS station 1 (a) and rural RAMS station 23 (b).

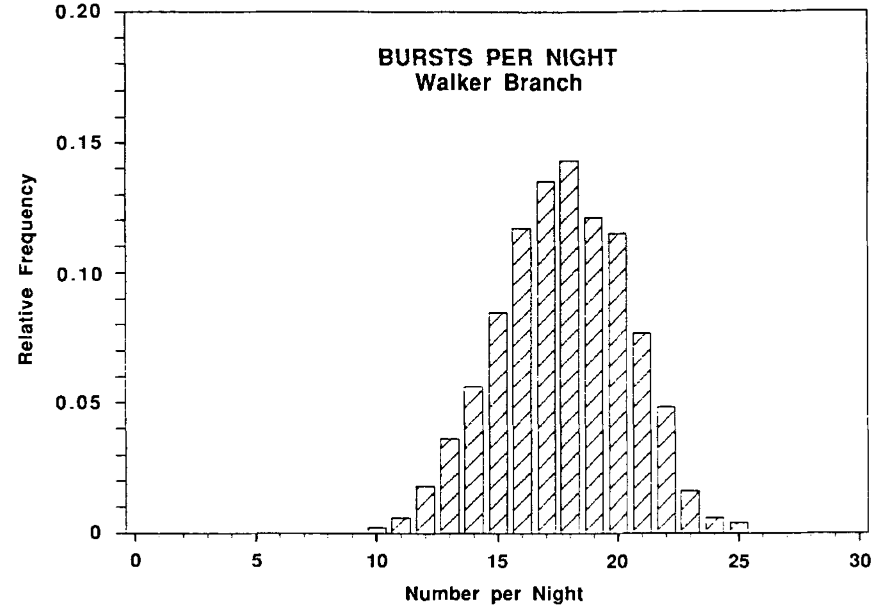

Fig. 10. Relative frequencies of breakdowns per night at the Walker Branch site.

toward higher values for the urban than for the rural station. The average interval between breakdowns is 21 min for the urban station, and 17 min for the rural one. The modes are estimated to be about 6 min for the rural station, and about 12 min for the urban station if we smooth over the peaks at about 8 and about 14 min.

(B) Complex terrain

The relative frequency distribution of breakdowns per night for the Walker Branch field station is shown in Figure 10. The distribution is Gaussian-shaped, and just as for the simple-terrain case, the distribution is slightly skewed toward lower values. The average number of breakdowns per night is 18. The relative frequency distributions of breakdown duration and intervals between breakdowns are shown in Figures 11 and 12, respectively. These distributions appear quite similar to the corresponding ones for the simple-terrain case. The average duration of a breakdown event is 16 min, and the average interval between breakdown events is 14 min. The distribution of breakdown durations, Figure 11, has two peaks at 4 and 10 min, but we do not consider this significant; thus we estimate the mode of the distribution to be about 6 min. The mode of the distribution of intervals between breakdowns is estimated from Figure 12 to be about 4 min.

5. Discussion

The average values of the breakdown characteristics are presented in Table I. The average value of the covariance per breakdown is obtained by dividing the sum

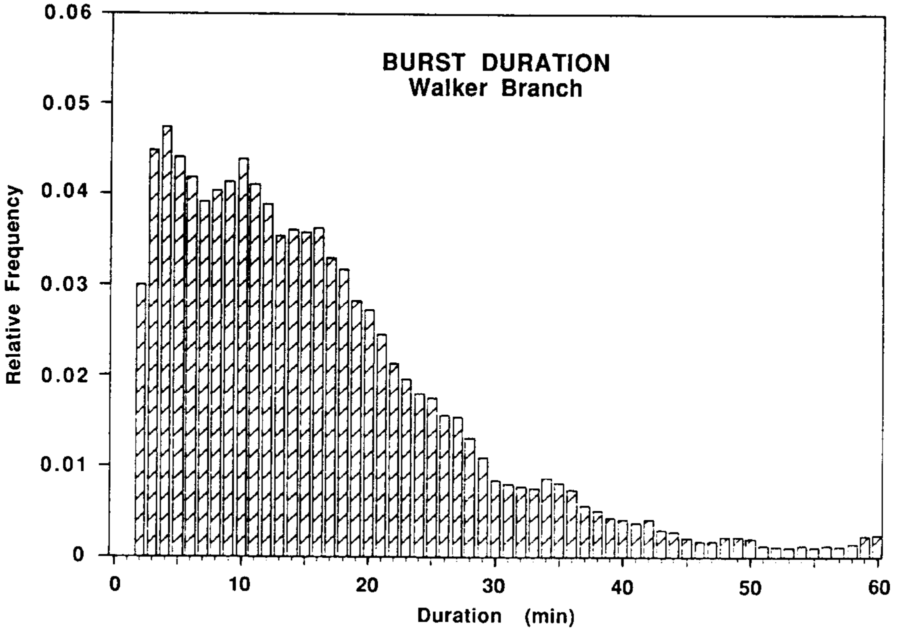

Fig. 11. Relative frequencies of the durations of breakdowns at the Walker Branch site.

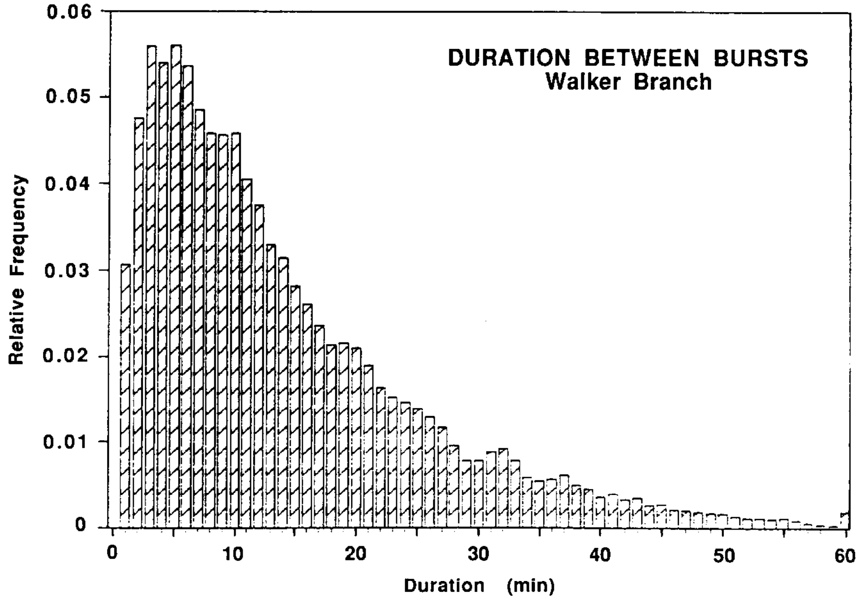

Fig. 12. Relative frequencies of the intervals between breakdowns at the Walker Branch site.

TABLE I

Average values of breakdown characteristics

	RAMS #1 (urban)	RAMS #23 (rural)	Walker Branch (complex terrain)
Breakdowns per night	13	15	18
Duration of breakdowns (min)	15(8)*	19(10)	16(6)
Interval between breakdowns (min)	21(12)	17(6)	14(4)
Covariance per breakdown (k-m s^{-1})	3.2×10^{-2}	5.5×10^{-2}	4.8×10^{-2}
Nighttime average covariance (k-m s^{-1})	0.6×10^{-3}	12×10^{-3}	-7.8×10^{-5}

* Numbers in parentheses are the modal values of the distributions.

of all the covariance values during breakdowns by the total number of minutes of breakdown. The nighttime average covariance is formed by first calculating the average C_{UT} for each night, and then forming the average of these values. The values of the individual characteristics are seen to be not very different over the three sites, even though these sites are located in quite contrasting environments. This is significant because it suggests that breakdowns are not exceptional events limited to a certain terrain type, but rather are a regular feature of the stable PBL. This hypothesis is supported by the fact that average values of C_{UT} during breakdowns at the three sites are about the same. Differences in these values can be explained qualitatively. At the urban station, both the heat island effect and the large surface roughness act to limit both the strength of the temperature inversion and the velocity shear near the ground surface (Arya, 1988). These effects will result in small values of the temperature and wind speed perturbations caused by the breakdowns. Thus covariances will be small as well as the number of breakdowns per night and the duration of the breakdowns. This effect also causes the large duration between breakdowns at the urban station. At the rural station, we can expect the nighttime PBL temperature and wind speed gradients to be larger than at the urban station; however, this does not automatically result in greater PBL stability. Thus we can expect that the number of breakdowns per night and their durations will be about the same as at the urban station. But because the gradients are larger, the perturbations near the ground surface will also be larger than at the urban site, and this will result in greater values of wind speed-temperature covariance. At the Walker Branch site, the nighttime PBL experiences frequent, short duration breakdowns. This is consistent with terrain-generated disturbances such as, for example, gravity waves, streamline deformation, and vortex shedding. However, the covariances associated with these breakdowns have about the same values as that for the RAMS 23 station.

The values of nighttime average covariance in Table I for the RAMS stations are in accord with the characteristics of the breakdowns. For example, the average covariance over a night can be given by

$$\overline{C_{UT}} = \frac{(Covariance/breakdown)(duration\ of\ breakdown)(breakdowns/night)}{duration\ of\ night}. \quad (3)$$

Using the average values in Table I in Equation (3) and assuming an 8 h night, we get $\overline{C_{UT}} = 0.13 \times 10^{-3}$ k m s^{-1} for station 1 and 33×10^{-3} k m s^{-1} for station 23. However, for the Walker Branch site, we get $\overline{C_{UT}} = 29 \times 10^{-3}$ k m s^{-1}, which is quite different from the measured value of -7.8×10^{-5}. We can account for this difference in the following way. Recall that the Walker Branch site is located atop a 60 m ridge. Air flow directed over the ridge will tend to speed up as the flow streamlines converge above the ridge, and this will create a positive wind speed perturbation. However, because this flow originates at lower elevations, it will be colder than the ambient air at the instrument height some 100 m above the valley floor, and this will create a negative temperature perturbation. The result is a negative covariance. These types of events occur throughout the night, and lead to the low values of nighttime average covariance.

The relationship between breakdown events and turbulence is illustrated in Figure 13, where the monostatic sodar trace and C_{UT} are plotted for one night at the Walker Branch site. The elevation of the tower instruments is about 40 m above the sodar. The covariance is essentially zero until just before 2200 h when a sharp rise occurs. This jump in C_{UT} corresponds with the sudden appearance of turbulence in the PBL as indicated by the sodar trace at the 40 m height. After this initial period, the covariance and the turbulence are seen to vary with time; however a correlation exists between these quantities if examined on the 40 m level sodar trace. At about 0400 h, the turbulence and C_{UT} both fall to zero and remain there. Large negative values of the covariance such as those seen at 0215 and 0330, are attributed to the effects of flow over the ridge as described above.

This analysis of breakdown events is based on fluctuations of 1 min averages of horizontal wind speeds and temperatures, which we assume to arise from overturnings of the PBL air. However, we have seen that horizontal advection can also lead to fluctuations, but this effect may be more pronounced over complex terrain. If we take the covariances to represent, in some sense, a vertical flux, then a heat flux can be defined as $-\rho c_p C_{UT}$, where ρ is the air density and c_p is the specific heat of air at constant pressure. Using the values from Table I, and the standard density of air, the average heat fluxes per breakdown are -40 Wm^{-2} for the urban station, -68 Wm^{-2} for the rural station, and -59 Wm^{-2} for the complex terrain station. These values are greater than the heat flux values normally observed in the stable PBL; however, these are intermittent values which must be averaged, according to (3), to get the appropriate nighttime value. For example, at RAMS station 23, the heat flux averaged over an 8-h night is about -21 Wm^{-2}, which is a reasonable value, and no longer larger than normally observed.

We have examined the wind speed-ozone covariances; however, these results are not easily interpreted. For example, if we associate the covariance with a

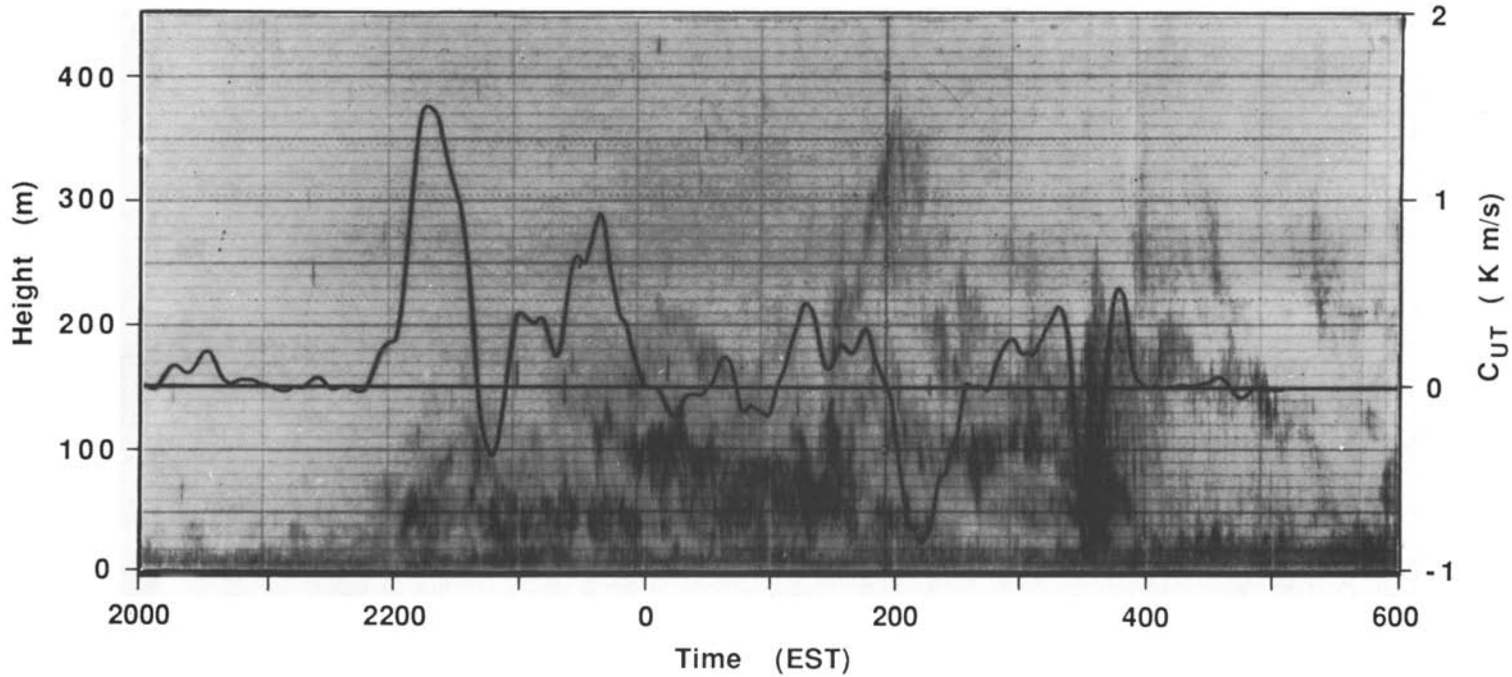

Fig. 13. Sodar trace and wind speed-temperature covariance for a typical night at the Walker Branch site. The covariance is measured at about the 40 m height of the sodar record.

vertical flux of ozone, then we can define a deposition velocity as the ratio of the covariance to the concentration. The deposition velocities for ozone during breakdowns are found to be 87 cm s^{-1} at RAMS station 1 and 83 cm s^{-1} at RAMS station 23. These values are about two orders of magnitude greater than what one would expect from eddy correlation measurements. These results suggest that we cannot simply relate the covariance of horizontal wind speed and ozone concentration to the vertical flux of ozone. Rather, we expect the true vertical flux to be some small fraction of the total flux.

6. Conclusion

The results of this study demonstrate that sporadic turbulent breakdowns are a consistent feature of the stable PBL over all types of terrain. We speculate that significant portions of the nocturnal exchanges of heat, momentum, and atmospheric pollutants between the atmosphere and the ground surface occur during these breakdown episodes. Conventional PBL diffusion theory does not account for these episodes, and because of this, model predictions of nighttime vertical fluxes may be inaccurate. This may not be a serious problem for long-term air quality considerations; however, for short-term predictions of ground surface concentrations of hazardous materials, failure to account for PBL breakdowns is potentially dangerous.

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References

Arya, S. P.: 1988, 'Introduction to Micrometeorology', *International Geophysics Series* **42**, Academic Press, New York, 307 pp.

Balachandran, N. K.: 1980, 'Gravity Waves from Thunderstorms', *Mon. Weath. Rev.* **108**, 804–816.

Bean, B. R., Frisch, A. S., McAllister, L. G. and J. R. Pollard: 1973, 'Planetary Boundary-Layer Turbulence Studies from Acoustic Echo Sounder and in situ Measurements', *Boundary-Layer Meteorol.* **4**, 449–474.

Businger, J. A.: 1973, 'Turbulent Transfer in the Atmospheric Surface Layer', in D. A. Haugen (ed.), *Workshop on Micrometeorology*, Amer. Meteor. Soc., Boston, Massachusetts, 392 pp.

Chimonas, G.: 1980, 'Waves, Stability, and Turbulence', in J. C. Wyngaard (ed.), *Workshop on the Planetary Boundary Layer*, Amer. Meteor. Soc., Boston, Massachusetts, 392 pp.

Curry, M. and Murty, R. C.: 1974, 'Thunderstorm-Generated Gravity Waves', *J. Atmos. Sci.* **31**, 1402–1408.

DeBaas, A. F. and Driedonks, A. G. M.: 1985, 'Internal Gravity Waves in a Stably Stratified Boundary Layer', *Boundary-Layer Meteorol.* **31**, 303–323.

Doviak, R. J. and Ge, R.: 1984, 'An Atmospheric Solitary Gust Observed with a Doppler Radar, a Tall Tower and a Surface Network', *J. Atmos. Sci.* **41**, 2559–2573.

Durst, C. S.: 1933, 'The Breakdown of Steep Wind Gradients in Inversions', *Quart. J. Roy. Meteorol. Soc.*, **54**, 131–136.

Finnigan, J. J.: 1988, 'Kinetic Energy Transfer Between Internal Gravity Waves and Turbulence', *J. Atmos. Sci.* **45**, 486–505.

Finnigan, J. J. and Einaudi, F.: 1981, 'The Interaction Between an Internal Gravity Wave and the Planetary Boundary Layer. Part II: The Effect of the Wave on the Turbulence Structure', *Quart. J. Meteorol. Soc.* **107**, 807–832.

Fua, P., Chimonas, G., Einaudi, F., and Zeman, O.: 1982, 'An Analysis of Wave Turbulence Interaction', *J. Atmos. Sci.* **39**, 2450–2463.

Gifford, F. A.: 1952, 'The Breakdown of a Low-Level Inversion Studied by Means of Detailed Soundings with a Modified Radiosonde', *Bull. AMS.* **33**, 373–379.

Gossard, E. E., Gayner, J. E., Zamora, R. J., and Neff, W. D.: 1985, 'Fine Structure of Elevated Stable Layers Observed by Sounder and in situ Tower Sensors', *J. Atmos. Sci.* **42**, 2156–2169.

Harrison, R. M., Holman, C. D., McCortney, H. A., and McIlvenn, J. F. R.: 1978, 'Nocturnal Depletion of Photochemical Ozone at a Rural Site', *Atmos. Environ.* **12**, 2021–2026.

Kondo, J., Kanechika, O., and Yosuda, N.: 1978, 'Heat and Momentum Transfers Under Strong Stability in the Atmospheric Surface Layer', *J. Atmos. Sci.* **35**, 1012–1021

Lyons, R., Panofsky, H. A., and Wallaston, S.: 1964, 'The Critical Richardson Number and its Implications for Forecast Problems', *J. Appl. Meteorol.* **3**, 136–142.

Mahrt, L.: 1985, 'Vertical Structure and Turbulence in the Very Stable Boundary Layer, *J. Atmos. Sci.* **42**, 2333–2349.

Nappo, C. J., Herewehe, J. A., and Thompson, A. M.: 1988, 'Observations of Ozone Profiles in a Developing Boundary Layer', *Proceedings of the Quadrennial Ozone Symposium*, 4–6 August 1988, Gottengen, FRG.

Schiermeier, F. A.: 1978, 'RAPS Field Measurements are in', *Environ. Sci. and Tech.* **12**, 644–651.

Shreffler, J. H. and Binkowski, F. S.: 1981, 'Observations of Pressure Jump Lines in the Midwest, 10–12 August 1976', *Mon. Weath. Rev.* **109**, 1713–1725.

Tjemkes, S. A. and Duynkerke, P. G.: 1989, 'The Nocturnal Boundary Layer: Model Calculations Compared with Observations', *J. Appl. Meteorol.* **28**, 161–175.

Uccellini, L. W.: 1975, 'A Case Study of Apparent Gravity Wave Initiation of Severe Convective Storms', *Mon. Weath. Rev.* **103**, 497–513.

Winkler, K.: 1980, 'Störungen der nachtlichen Grenzschicht', *Meteorol. Rdsch.* **33**, 90–94.