Monitoring of the Atmospheric Stability above an Urban and Suburban Site Using Sodar and Radon Measurements

DANIEL GUEDALIA, ANDRÉ NTSILA,[1] AIMÉ DRUILHET AND JACQUES FONTAN

Laboratoire de Physique des Aérosols et Echanges Atmosphériques, ERA No. 378, Université Paul Sabatier, 31077 Toulouse Cedex, France

(Manuscript received 20 March 1979, in final form 16 March 1980)

ABSTRACT

This study presents a method of obtaining the quantitative intensity of vertical diffusion during periods of atmospheric stability. This method associates the continuous measurement of radon concentration at ground level and the use of a monostatic sodar. The value of "equivalent mixing height" h_e is calculated using the radon variation which can be related to the global exchange coefficient of the inversion layer. The sodar detects the thickness of the nocturnal inversion layer.

Both systems operated simultaneously over several months at two sites (urban and suburban). In most cases the nocturnal layer was indicated both by sodar echoes and by a large decrease of the h_e value. In other cases the use of sodar alone can lead to a lack of detection of stable periods which, nevertheless, are shown clearly by radon. The comparison of measurement at two sites shows a modification of nocturnal stability above the urban site. The equivalent exchange coefficients are ~0.3 $m^2 s^{-1}$ (at the urban site) and 0.08 $m^2 s^{-1}$ (at the suburban site).

1. Introduction

The level of atmospheric pollution above an industrial or urban site depends both on the intensity of the pollution and on the rate of dispersion into the atmosphere (wind speed and vertical diffusion). Vertical diffusion depends mainly on the presence of an inversion layer during the night and the thickness of the mixing layer during the day.

In recent years developments have been made in the use of monostatic acoustic sounding—sodar—for monitoring the atmospheric stability above a site. As shown by numerous reports, in most cases the inversion layers correspond to zones where small-scale turbulence gives rise to sodar echoes; it is thus possible to follow the changes in time and space of the inversion layers.

A method has been developed in our laboratories which allows monitoring of the vertical stability of the atmosphere using continuous measurement of radon near the ground (Fontan *et al.*, 1976, 1979). A parameter called the equivalent mixing height (h_e) can be determined through this method during the period of nocturnal stability and at the beginning of instability.

The use of a sodar, along with the radon method, over several months has enabled us to compare the sodar echoes obtained during the stable periods to the stability parameter h_e calculated using radon. Therefore, it is possible to obtain a better interpretation of the sodar echoes in terms of vertical diffusion. The preliminary results of this study have already been presented by Guedalia *et al.* (1978). This paper deals with the overall results obtained—partly above an urban zone and partly above the suburbs.

2. Measurement techniques

a. Sodar

When sodar is used in the monostatic configuration, the intensity of the scattered wave depends solely on the thermal structure of the crossed layers. It can be shown that (Monin, 1962) the scattering cross section is

$$\sigma = 0.016k^{1/3}C_T^2/4T^2, \qquad (1)$$

where k is the wavenumber ($=2\pi/\lambda$), λ the emission wavelength, C_T the structure coefficient of the temperature and T the average temperature of the layer.

Generally, an inversion layer including wind shear gives a strong sodar echo; this often occurs in nocturnal inversions caused by radiative cooling of the ground (Beran *et al.*, 1973; Tombach *et al.*, 1973).

Several studies have been made to compare the sodar echo and the height of the inversion. There

[1] Present affiliation: École des Sciences Université de Brazzaville, R.P. Congo.

0021-8952/80/070839-10$06.50

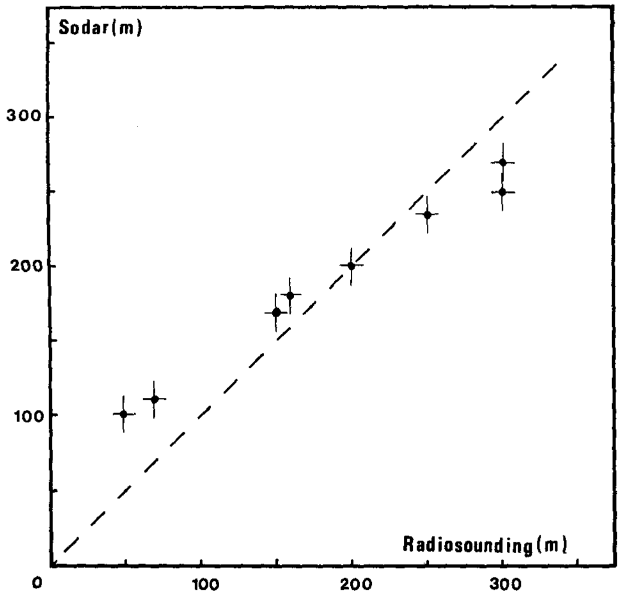

FIG. 1. Comparison of acoustic sounder and radiosounding temperature for the determination of the surface inversion layer thickness.

is usually a good agreement between both types of measurements (Parry *et al.*, 1975; Van Gogh and Zib, 1978). In this study a sodar loaned by the CNET (Centre National d'Etudes des Télécommunications) was used: power—120 W; emission frequency 2000 Hz; recorder—facsimile type allowing sodar echo display.

A preliminary study was made, during three weeks in November 1976, in order to compare the inversions detected by temperature radiosounding (carried out by the Météorologie Nationale) with the sodar echoes. All surface inversion layers gave sodar echoes. Fig. 1 shows the top of the sodar echoes versus the top of the inversion layer. Forty-three elevated inversions were detected with the radiosounding but only 31 correspond to sodar echoes.

All of the inversions not giving sodar echoes (probably due to the absence of wind shear) were found above 500 m and 75% of them had another inversion layer underneath which was detected by the sodar.

These results as well as those given by different authors, show that sodar is a simple and easy method for detection of nocturnal radiative inversions and most of the elevated inversions.

b. Determination of "equivalent mixing height" with radon measurements

Near the ground, the radon concentration usually undergoes a typical diurnal variation with a maximum at the end of the night (caused by accumulation during the nocturnal stability), and a minimum in the afternoon when the convection layer reaches its maximum development. Several authors have already used the vertical distribution of radon in the lower layers in order to study vertical diffusion (Hosler, 1968; Druilhet and Fontan, 1974; Cohen *et al.*, 1972).

1) THE METHOD

The method used in this study consists of determining the variation of h_e from the continuous

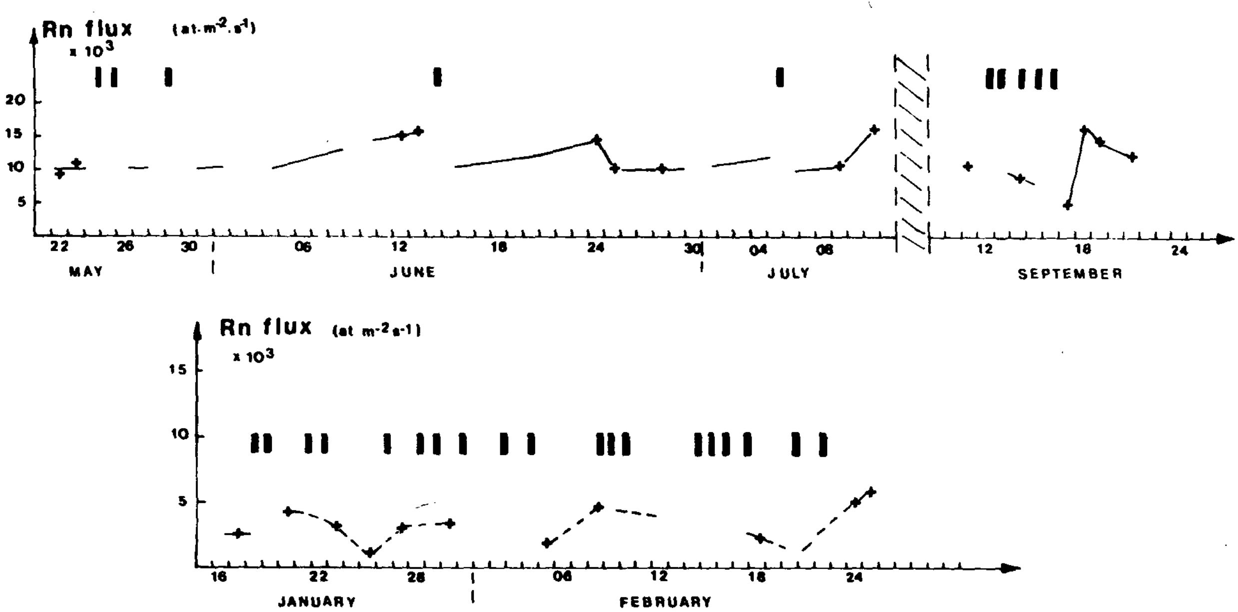

FIG. 2. Calculated values of surface radon flux. Vertical bars indicate rainfall periods.

measurement of the radon concentration near the ground. Two hypotheses are made in this calculation:

- The radon flux is constant during the whole stable period.
- The radon concentration variations are related solely to the vertical stability.

A discussion on the validity of these hypotheses and a complete description of the method can be found in Fontan *et al.* (1976, 1979). The present paper only gives the algorithm of the calculation.

The calculation of h_e is made during the period when radon accumulates near the ground, i.e., between the end of the afternoon and the morning of the next day. h_e is determined by the relation

$$h_e(t) = \phi_0 \Delta t / [C(t) - C_0], \tag{2}$$

where ϕ_0 is the radon flux at ground level; Δt is the time from the start of accumulation; $C(t)$ is the radon concentration; and C_0 is the radon concentration at the beginning of accumulation.

h_e can be considered as a quantitative feature of the diffusion properties of the atmosphere during the stable periods. This equivalent mixing height, determined from the radon concentration variation at ground level, has the same meaning as that proposed by Meetham (1950) and clarified by Fontan *et al.* (1979).

$$h_e = \frac{\int_0^\infty [c(t,z) - c(0,z)]dz}{c(t,0) - c(0,0)}, \tag{3}$$

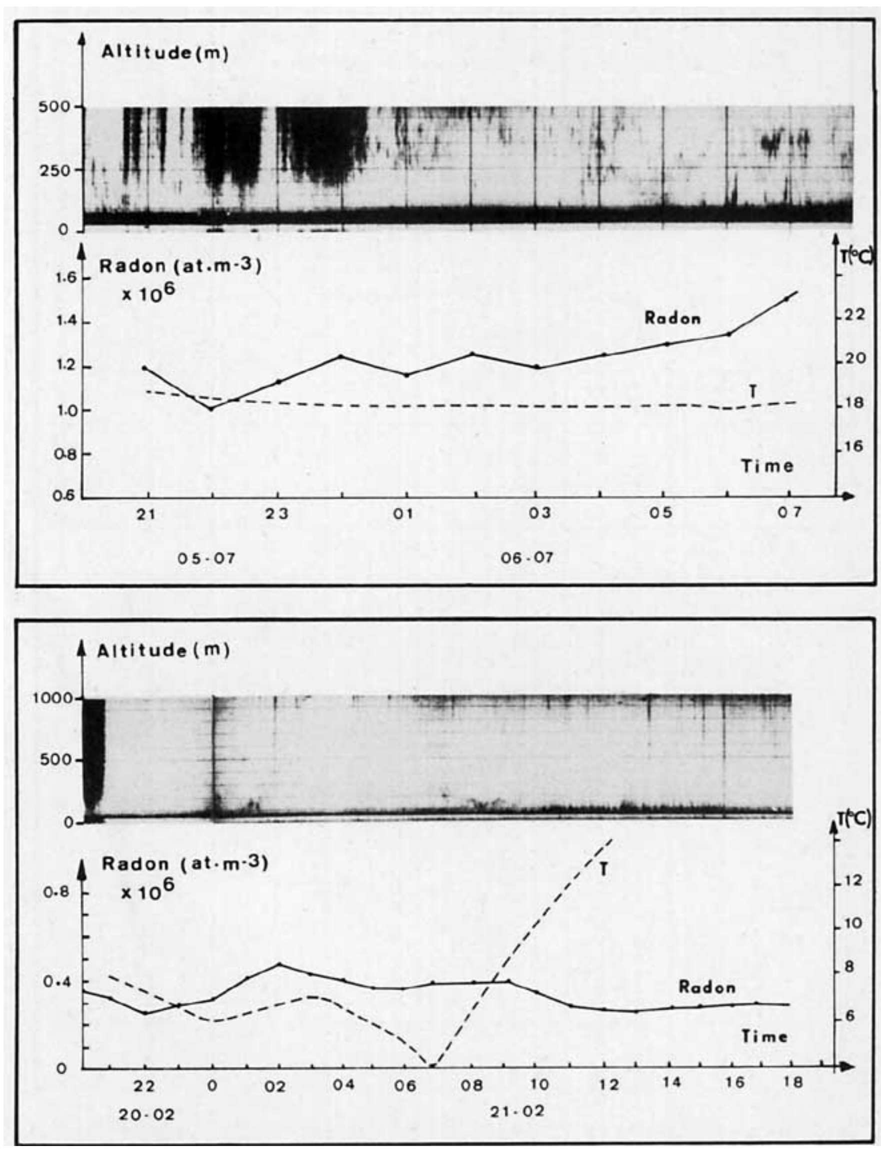

FIG. 3. Two examples of weak diurnal variation of atmospheric stability (no variation of radon and no sodar echoes).

where $C(t,z)$ is the concentration of an element at instant t and level z, when the source, situated at ground level, is homogeneous. The value of h_e can be related to that of an exchange coefficient K_e, which is constant with altitude throughout the stable layer (generally the inversion layer) (Fontan *et al.*, 1979):

$$h_e^2 \approx 0.8K_e t. \tag{4}$$

This relationship can be useful in some pollution problems when the stable layer can be characterized by such an exchange coefficient.

2) The radon flux

The determination of h_e using relation (2) requires the value of the source of radon ϕ_0. If ϕ_0 is not known, it is possible, using relation (2), to determine the relative variation of h_e over a fixed period, but not its absolute value. A method for direct measurement of the radon flux at ground level was proposed by Pearson (1965), but the experimental set-up is relatively complex and impractical on an unhomogeneous or urban site.

The large variations in the radon source, as in

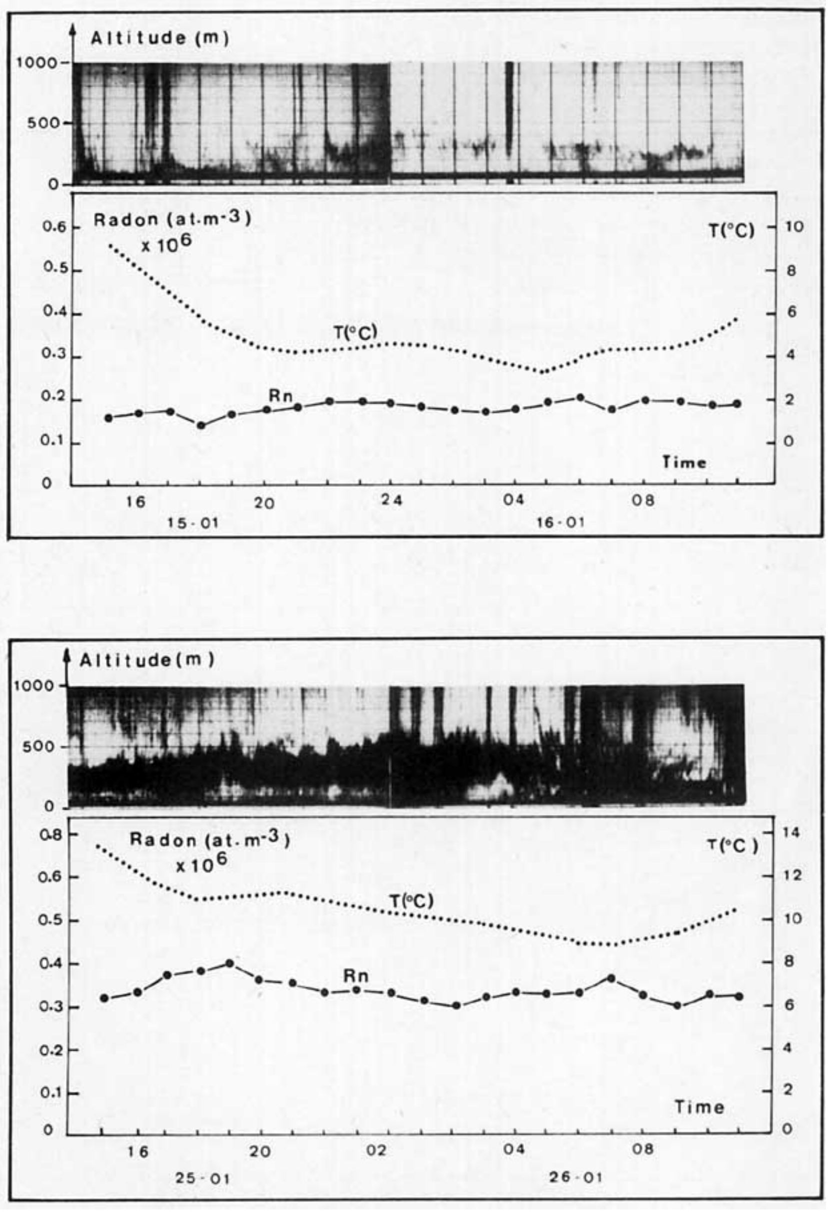

FIG. 4. Two examples in which the vertical stability does not change with time (see radon curve) and sodar echoes do not correspond to nocturnal inversion (see temperature curve).

the case of thoron (Guedalia *et al.*, 1970) depend on ground moisture; it is therefore to be expected that there are rapid source variations during rainfall and the following hours.

For this study, sodar was used to obtain an indirect estimation of the radon source over each experimental period (generally <24 h). The thickness of the mixing layer is determined by sodar at the beginning of the morning; substituting this value for h_e in Eq. (2) gives the radon flux ϕ_0. This method seems to be fairly convenient, considering the accuracy with which the average radon flux can be estimated.

For various reasons (absence of sodar echoes corresponding to the morning mixing layer, technical problems with the equipment etc.), radon flux determination was possible only on certain days; interpolation was used to estimate the flux values over the whole period. The variation of the radon flux at ground level throughout the experiment is shown in Fig. 2. During the months of May to July, the soil moisture is weak and the radon flux reaches high values (from 10 000 to 15 000 atoms m^{-2} s^{-1}).

These values must be compared to the average radon flux over the same area calculated from the vertical radon profile obtained by aircraft measurements (Guedalia, 1975) during the summer of 1973: between 9000 and 18 000 atoms m^{-2} s^{-1}. On the other hand, during the winter months the radon flux remains lower than 5000 atoms m^{-2} s^{-1}. This is due to the frequent rainfalls which make the soil extremely wet. This illustrates the large annual variation of the radon flux related to the wetness of the soil.

3) Radon measurement

The continuous measurement of radon was carried out using the disintegration chamber method. A detailed description of this method is given by Fontan *et al.* (1962).

3. Meaning of the parameter h_e

The continuous measurement of radon at ground level allows the calculation of the parameter h_e by means of Eq. (2), which can be used when the vertical stability starts to increase—as observed by the rise in concentration of radon. The calculation of h_e is performed during the whole period of noc-

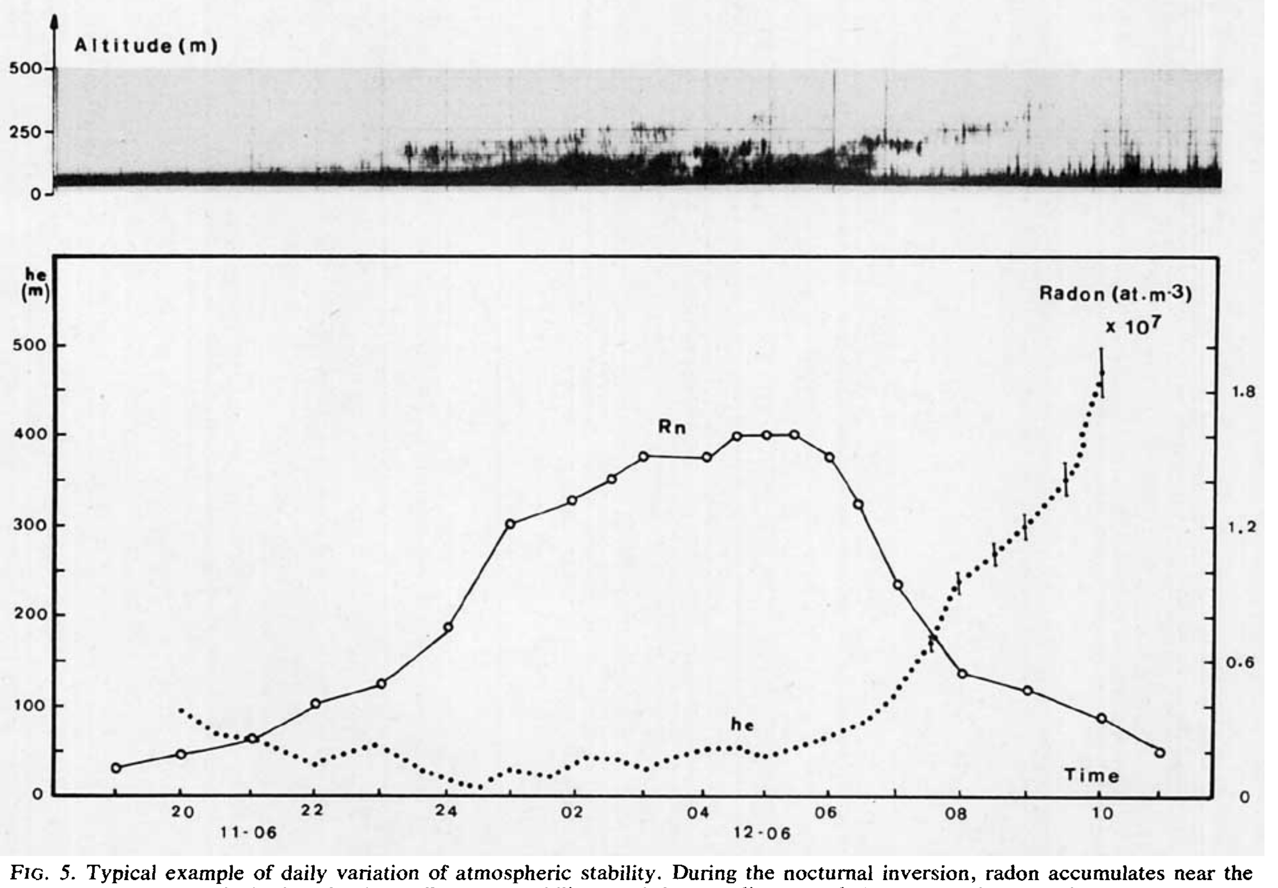

Fig. 5. Typical example of daily variation of atmospheric stability. During the nocturnal inversion, radon accumulates near the ground, the h_e value is small (strong stability), and the sounding record shows a continuous echo.

turnal stability and also during the first hours of the day when instability starts developing; the calculation becomes inaccurate when the level of radon concentration falls to the order of magnitude existing at the beginning of the increase.

The equivalent mixing height value is different from the inversion layer thickness. h_e is a quantitative parameter of the intensity of the vertical diffusion through the nocturnal stable layer.

Two types of results were obtained: 1) a comparison between the sodar echoes and the value of h_e determined with radon over the stable periods; 2) a comparison between the values of h_e obtained over an urban site and over the suburban site.

4. Experimental results

Description of sites. Two series of measurements were carried out, the first between May and October 1976 and the second in January and February 1977. Identical equipment was used for the simultaneous measurement of radon at two sites: the first, called "urban" henceforth, was located in the heart of the city where the average height of the buildings is from 10 to 15 m; the second, called "suburban," was situated on the University campus, in an area where the buildings are very scattered, at 8 km from the town center. The sodar was installed in the urban site for the 1976 measurements and in the suburban site for those of 1977. The air temperature was measured at 1 m above ground level at the sodar site.

Comparison of sodar echoes and values of h_e. The study situations were classified according to the radon variation observed.

a. *Cases where radon indicates no change in the atmospheric stability*

All the cases in which the low variation of radon does not allow calculation of h_e are collected in this group, i.e., cases where there is no daytime variation in the vertical stability (only 14 cases for the overall experiment). In seven of these cases there are no sodar echoes (eg., Fig. 3) during the nocturnal period; the information given by radon and by sodar are therefore in agreement.

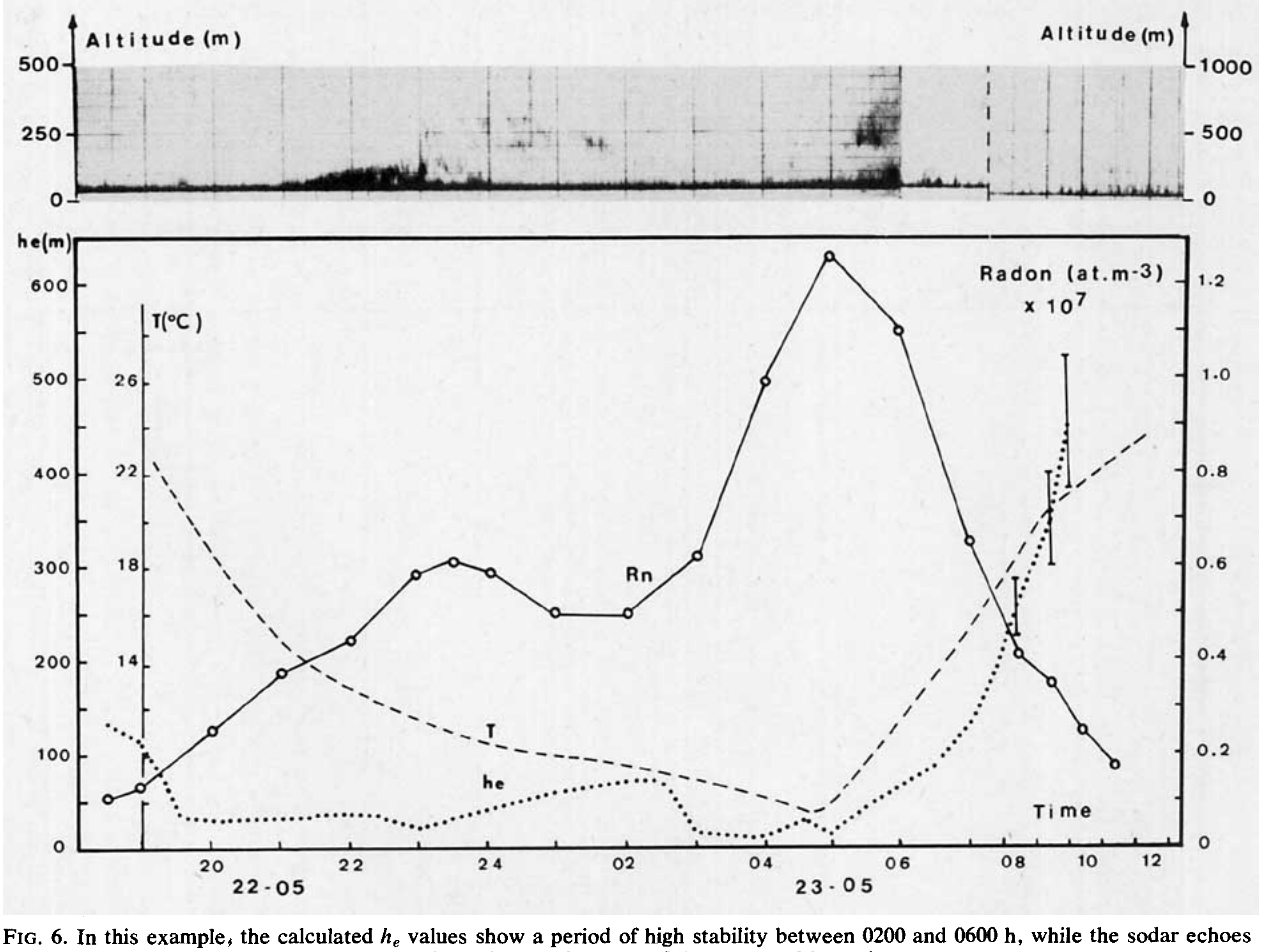

FIG. 6. In this example, the calculated h_e values show a period of high stability between 0200 and 0600 h, while the sodar echoes occur only during the first part of the nocturnal inversion.

In the seven remaining cases, however, all in January and February, there are sodar echoes (Fig. 4). Some similarities can be pointed out: absence of night cooling, frequent rain (shown on the sodar facsimile by vertical black lines . . .). Therefore, there was no typical nocturnal inversion layer due to cooling of the ground and we cannot explain the occurrence of sodar echoes. Unfortunately, no vertical temperature profile data were available.

b. *Cases where radon does indicate a change in the vertical stability*

This situation occurs most frequently. Here, radon concentration shows a diurnal variation which allows calculation of the variation of h_e during the nocturnal stable period. In most of these cases there are sodar echoes corresponding to an inversion layer. An example is given in Fig. 5; the nocturnal inversion due to cooling of the ground is shown by sodar echoes between 2200 and 0600 local time; during this period the value of h_e remains lower than 50 m, pointing out the very weak vertical diffusion in this layer. The example of Fig. 5 is typical of most of the situations occurring during the night. However, in some cases radon and sodar do not give the same information. An example of this situation is given in Fig. 6; the beginning of the nocturnal stability, at about until 2300 LT is characterized by sodar echoes (inversion layer) and a radon concentration increase. The value of h_e is roughly 40 m; then between 2300 and 0200 there is an increase in the vertical diffusion (h_e rises from 30 to 70 m) and the sodar echoes vanish. From 0200, radon indicates high stability (h_e drops to 20 m) whereas sodar gives no visible echo. A second example is given in Fig. 7; a sodar echo corresponding to a stable layer with relatively strong diffusion ($h_e \approx 130$ m) is seen until 0300; after this time, however, the vertical diffusion is very weak (h_e does not exceed 10 m) and the sodar echoes display a discontinuous vertical structure. These two examples give a clear illustration of cases in which radon can be used to track changes in the vertical stability, whereas the sodar recording is more difficult to interpret.

Finally, in 7 cases no strong sodar echoes were observed in spite of large accumulations of radon during the nocturnal periods (Fig. 8). In the two examples shown, the temperature variation and the radon-calculated h_e value indicate the existence of an inversion layer. The fact that this layer induces

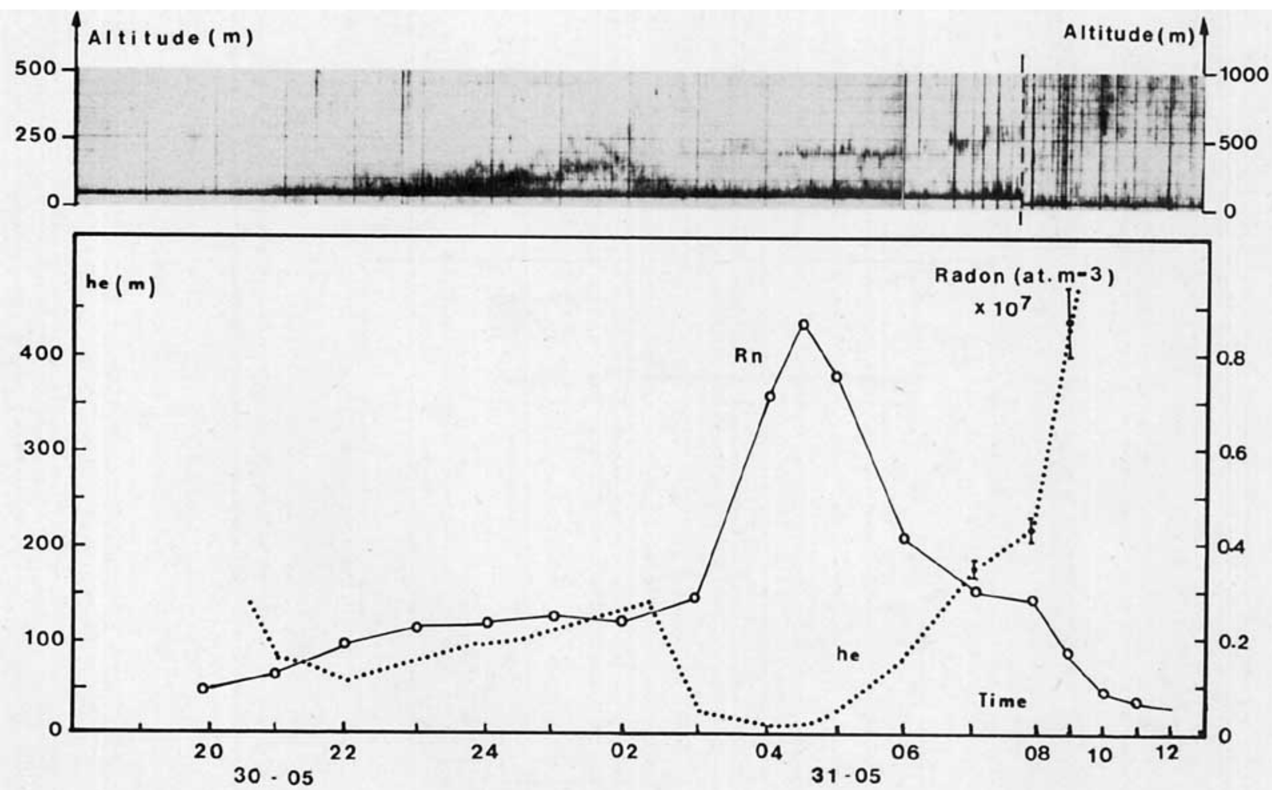

FIG. 7. In this example, the nocturnal period present a moderate stability until 0300 ($h_e \approx 100$ m), and a high stability ($h_e \sim 10$ m) between 0300 and 0500. On the contrary, the sodar echoes are higher during the first part of the night.

weak sodar echoes could be due either to its shallowness (the sodar detection threshold being situated at about 70 m) or to absence of wind shear. Whatever the reason, the use of sodar alone would not have allowed the detection of a period of such very strong vertical stability.

c. *Vertical stability changes above an urban site*

During the whole experimental period two identical radon systems were used, one in the urban site and the other in the suburb site. It was thus possible to compare the vertical stability over the two sites. Since two sodars were not available, identical values of radon flux ϕ_0 at both sites have been assumed.

What would be the consequence of different radon fluxes at each site? First, the relative variation of h_e would not be affected, for it does not depend on radon flux value. Second, this difference is more likely to occur in winter, when radon flux can be higher at the urban site. Therefore the formulated assumption (equality of the radon flux at each site) could result in underestimating the calculated value of h_e at the urban site.

The average daily radon concentration variation

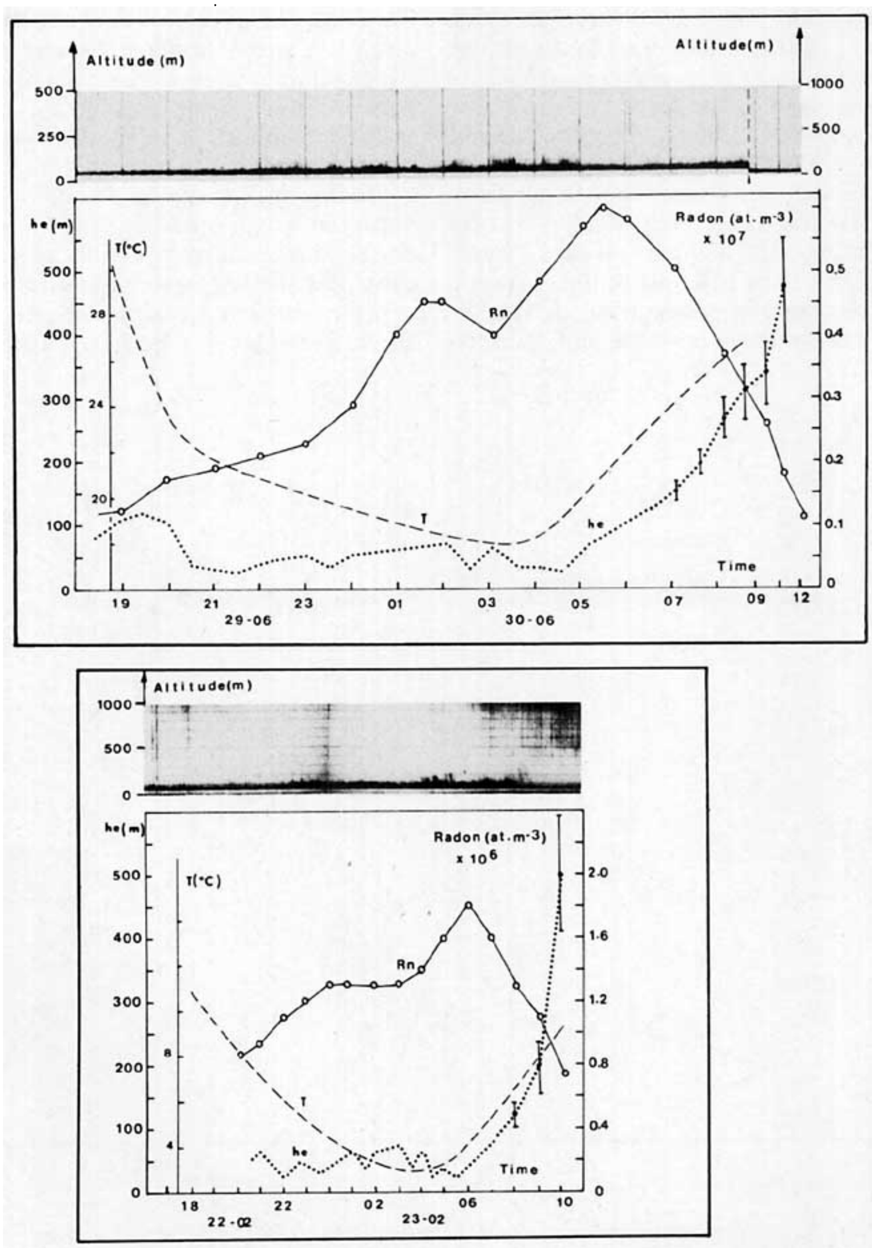

FIG. 8. Two examples with strong stability ($h_e \approx 50$ m) and small echoes sodar.

on the two sites is shown in Fig. 9. Whatever the season, the night accumulation of radon is higher at the suburban site: this indicates weak nocturnal stability at the urban site.

Two points are of interest: 1) The times of maximum radon concentration (corresponding to the end of nocturnal stability) at both sites are about one hour apart; this phenomenon is most noticeable in September when the maximum occurs at 0600 LT at the suburban site and at 0800 at the urban site. 2) A similar shift can be observed, except in June–July, between the times of minimum radon concentration at the end of the afternoon. For the two other periods, stability starts at the suburban site roughly one hour before the urban site. Thus another difference between the two sites can be noticed: the rate of increase of the vertical stability at the end of the afternoon is higher over the suburban site.

The modification of the vertical stability over an urban site can be revealed by calculating the "equivalent mixing height" h_e. In this comparison, only the periods of nocturnal stability over which h_e was calculated for both sites have been retained. The average values of h_e obtained at different hours

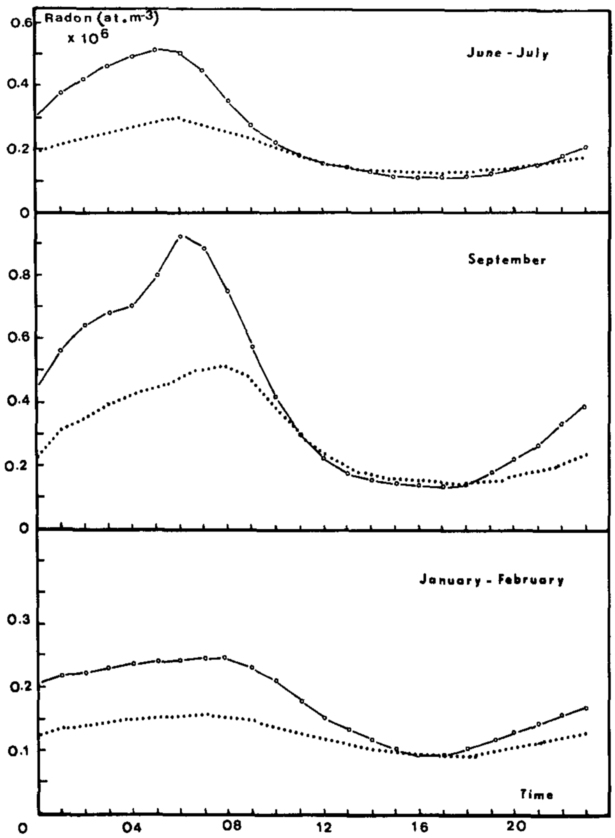

FIG. 9. Diurnal variation of average hourly radon concentration for several months (urban site, dotted curve; suburban site, circles).

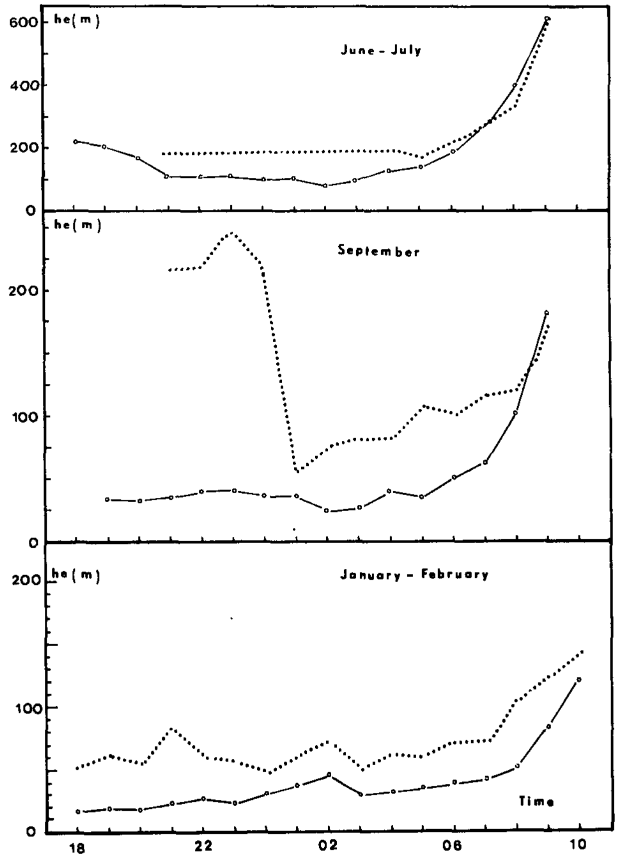

FIG. 10. Average hourly value of the equivalent mixing height h_e at different hours of the day (urban site, dotted curve; suburban site, circles).

during the stable period are shown in Fig. 10. The following comments should be noted:

- Whatever the period under consideration, the equivalent mixing height h_e is greater over the urban site during nocturnal stability. The largest differences are found in January, February and September; during this month the vertical stability over the urban site has a fairly high h_e value until 2400 h (between 200 and 250 m); according to Eq. (4) this corresponds to an equivalent exchange coefficient within the layer of about 3 to 5 $m^2 s^{-1}$; afterward the h_e values fall below 100 m.
- It can be considered that as the values of h_e become identical over the two sites the vertical stabilities are identical. This occurs at about 0700 h in June–July, roughly 0900 h in September, and after 1000 h in January–February.
- The vertical stability is greatest for both sites in September (except for the first part of the night in the town center) and in January–February. During both periods h_e always remains lower than 100 m over the urban site and lower than 50 m over the suburb; this corresponds to equivalent exchange

coefficients for the layer of the order of 0.3 and 0.08 $m^2 s^{-1}$, respectively.

5. Conclusion

The aim of this study was to present a method that makes possible the quantitative measurement of the intensity of vertical diffusion during periods of stability. The method used associates the continuous measurement of radon concentrations at ground level and the use of monostatic sodar.

The value of the equivalent mixing height h_e is calculated using the variation of radon; h_e is a quantitative parameter of the atmospheric vertical diffusion for a pollutant emitted at ground level. It is shown that h_e can be related to the value of a global exchange coefficient of the inversion layer (or stable layer).

The monostatic sodar itself allows the nocturnal inversion layer to be displayed.

Both systems were operated simultaneously over several months at both sites. In most cases the appearance of nocturnal inversion layers was indicated both by the sodar echoes and by a large decrease of the h_e value calculated by radon measurement. In other cases, however, it is seen that the use of sodar alone can lead to failure to detect certain stable periods which are nevertheless clearly indicated by radon measurements. So the simultaneous use of continuous radon measurements and of a sodar gives a reliable method for the monitoring of vertical stability above a site. It should be remembered that the vertical stability is an important factor in the dispersion of pollutants during the night.

Finally, through the comparison of simultaneous measurements made above the urban and the suburban sites, the modification of nocturnal vertical stability was shown. The times when the stable periods begin and end do not correspond at the two sites. The nocturnal stability over the urban site is weaker, whatever the season.

Acknowledgements. We would like to thank the C.N.E.T.-C.R.P.E., who kindly loaned us and maintained the sodar used in this investigation. We would also like to thank the Direction Departementale des Postes de la Haute-Garonne for their kind permission to install the sodar on the flat roof of the Main Post Office of Toulouse.

REFERENCES

Beran, D. W., W. H. Hooke and S. F. Clifford, 1973: Acoustic echo sounding techniques and their application to gravity wave, turbulence and stability studies. *Bound. Layer Meteor.*, **4,** 133–154.

Cohen, L. D., S. Barr, R. Krablin and M. Newstein, 1972: Steady-state vertical turbulent diffusion of radon. *J. Geophys. Res.*, **77,** 2654–2668.

Druilhet, A., and J. Fontan, 1974: Utilisation du radon comme indicateur de l'intensité des échanges près du sol. *Bound. Layer Meteor.*, **1,** 146–170.

Fontan, J., D. Blanc and A. Bouville, 1962: Emploi d'un système de coincidences dans le dosage sélectif du radon et du thoron atmosphérique. *J. Phys. Radium*, **23,** 233–240.

——, D. Guedalia, A. Druilhet and A. Lopez, 1979: Une méthode de mesure de la stabilité verticale de l'atmosphère près du sol. *Bound.-Layer Meteor.*, **17,** 3–14.

——, A. Druilhet, A. Lopez, M. J. Bernis and G. Cautenet, 1976: Surveillance de la stabilité verticale dans un site urbain. *Pollut. Atmos.* **71,** 231–240.

Guedalia, D., 1975: Détermination des échanges verticaux de matière dans la couche limite planétaire. Thèse de doctorat N° 659, Université de Toulouse, France, 85 pp.

——, J. L. Laurent, J. Fontan and A. Druilhet, 1970: Emanation of radon-220 from soils. *J. Geophys. Res.*, **75,** 357–369.

——, A. Ntsila, J. Fontan and A. Druilhet, 1978: The variation of atmosphere stability by means of radon measurements and of a sodar monitoring. *Proc. Third Natural Radiation Environment Symposium,* April, Houston (in press).

Hosler, C. R., 1968: Urban rural climatology of atmospheric radon concentration. *J. Geophys. Res.*, **73,** 1155–1166.

Meetham, A. R., 1950: Natural removal of pollution from the atmosphere. *Quart. J. Roy. Meteor. Soc.*, **76,** 359–371.

Monin, A. S., 1962: Characteristics of the scattering of sound in a turbulent atmosphere. *Sov. Phys. Acoust.*, **7,** 370–373.

Parry, H., M. Sanders and H. Jensen, 1975: Operational applications of a pure acoustic sounding system. *J. Appl. Meteor.*, **14,** 67–77.

Pearson, J. E., 1965: Emanation of Rn-222 from soils and its use as a tracer. *J. Geophys. Res.*, **70,** 5279–5290.

Tombach, I., P. B. Ready and R. L. Baboolal, 1973: Use of a monostatic acoustic sounder in air pollution estimates. *Proc. 2nd Joint Conf. Sensing of Environmental Pollutants*, Instrum. Soc. Amer. Washington DC, 139–149.

Van Gogh, R. G. and P. Zib, 1978: Comparison of simultaneous tethered balloon and monostatic acoustic sounder records of the statically stable lower atmosphere. *J. Appl. Meteor.*, **17,** 34–39.