Vertical Profiles of Carbon Dioxide Concentration in Stable Stratification

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VERTICAL PROFILES OF CARBON DIOXIDE CONCENTRATION IN STABLE STRATIFICATION*

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ABSTRACT

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Atmospheric carbon dioxide concentration ($[CO_2]$) and gradients (ΔCO_2) as well as profiles of wind speed and air temperature were measured from 0.5 to 16 m above ground at Mead, Nebraska. Initial observations indicate that under stable stratified conditions $[CO_2]$ and ΔCO_2 are, to a first approximation, closely related to the concurrent Richardson number. Under near neutral conditions the vertical profiles of $[CO_2]$ are approximately logarithmic. For stable conditions, the plots of $[CO_2]$ against logarithm of height are curvilinear. The profile departure from linearity increases with increasing stability.

INTRODUCTION

Detailed experimental data are needed to better estimate the source and sink strengths for atmospheric CO_2 exerted by terrestrial vegetated surfaces and the buffering effect which these surfaces exert on the global concentration. In a report to the United Nations Conference on the Human Environment (Stockholm, 1972), the Commission on Monitoring, Scientific Committee on Problems of the Environment, International Council of Scientific Unions recommended that atmospheric carbon dioxide concentration and flux data be collected at reference stations world-wide for assessing secular changes of the global climate. In view (in fact, in anticipation) of this, an organized program to regularly observe and analyze patterns in CO_2 concentration and gradients at a well-instrumented rural site has been initiated at one of the University of Nebraska's Agricultural Meteorology Laboratories (Mead, Nebraska).

Here we report the results of carbon dioxide concentration ($[CO_2]$) and

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gradient (ΔCO_2) measurements made at elevations ranging from 0.5 to 16 m above ground in an agricultural location remote from industrial and urban sources of pollution. The effects of thermal stratification on $[CO_2]$ and ΔCO_2 are analyzed and the usefulness of CO_2 as a tracer in micrometeorological as well as in air-pollution research is considered. The work reported here is part of a comprehensive research program, supported by the National Oceanic and Atmospheric Administration, to study the terrestrial sink and source strengths of atmospheric CO_2 in a large agricultural region.

EXPERIMENTAL PROCEDURES

Measurements of $[CO_2]$ and ΔCO_2 were made during the summers of 1970 and 1972 at the University of Nebraska Micrometeorology Research Laboratory at Mead (41° 09′N 96° 30′W; altitude 354 m above m.s.l.). Profiles of $[CO_2]$, wind speed and air temperature were measured simultaneously at elevations between 0.5 and 16 m. The 2-ha experimental field, in which a 19.2 m meteorological tower stands, was planted to soybeans on May 15, 1970, and to oats on August 17, 1972. The surrounding region is almost entirely agricultural land which is planted in season to soybeans, corn, sorghum, alfalfa and pasture grasses in commercial sized fields.

Details of $[CO_2]$ and ΔCO_2 measurements employing two infrared gas analyzers (one absolute and one differential) have been reported elsewhere (Rosenberg and Verma, 1976). Wind speed was measured with Casella Sheppard-type cup anemometers. Air temperature was measured with an assembly of shielded and aspirated thermocouple psychrometers (Rosenberg, 1969) near the crop canopy (0.5—2.0 m) and with a set of shielded, unaspirated differential thermocouples on the tower. Concurrent measurements of wind direction were made.

All meteorological measurements were recorded twice on the quarter hour with an analogue to digital data logging system. A library of computer programs is used to convert these data to parametric forms for further analysis and graphical representation.

RESULTS AND DISCUSSION

Daily CO_2 concentration waves at different elevations

Figs. 1 and 2 show sets of typical daily CO_2 concentration waves measured at 0.5, 1.0, 4.0 and 16 m above ground during the 1972 study. Midday concentrations range from about 318 to 328 ppm at 16 m and from 312 to 320 ppm at 0.5 m. Immediately after sunrise, with the onset of photosynthesis each day, a sharp drawdown in $[CO_2]$ occurs. Concentration at each elevation levels off at about 10 h (solar time) with only slight change until 16h. The transition in the morning from lapse profiles of CO_2 ($\partial C/\partial z < 0$*, or respira-

*$\partial C/\partial z$ = gradient of CO_2 concentration.

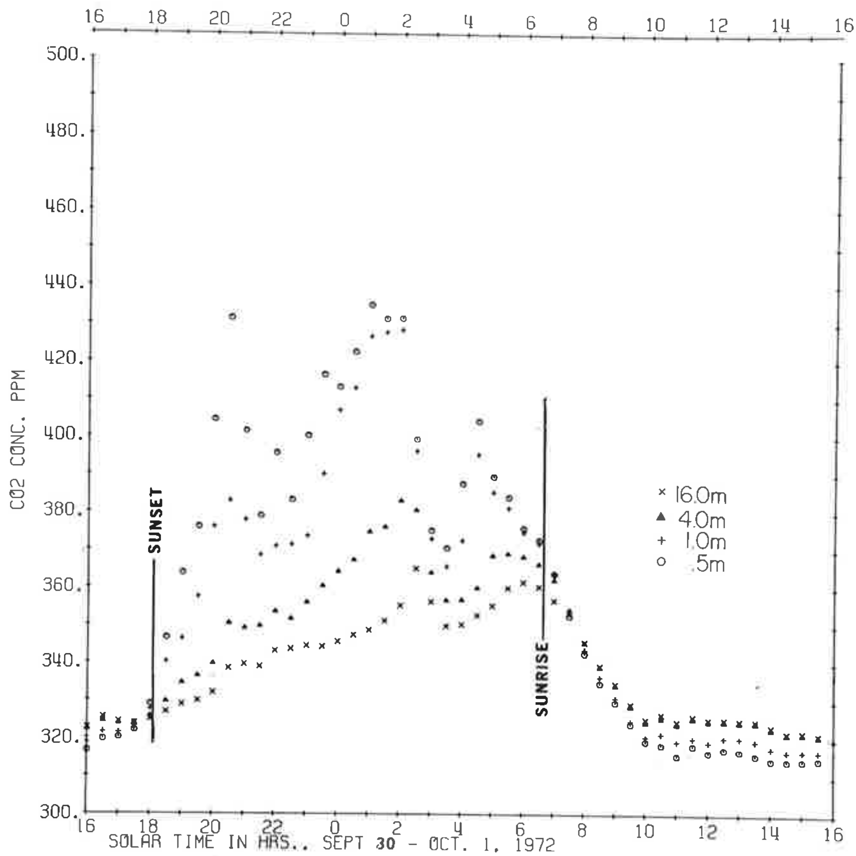

Fig.1. Typical patterns of diurnal CO_2 concentration at varying elevations over cropped land at Mead, Nebraska, Sept. 30—October 1, 1972.

tion conditions) to inversion profiles of CO_2 ($\partial C/\partial z > 0$, or photosynthesis conditions) occurs first at the lower elevations. The change from lapse to inversion is usually sharp and abrupt. The return to a respiration type lapse profile in the afternoon is not so sharply defined. The shape of the diurnal [CO_2] waves and the day-to-day variation depends primarily upon ambient light intensity and wind-speed conditions.

There is considerably less diurnal variation in [CO_2] at an elevation far removed from the crop canopy (e.g., 16 m) as compared to an elevation just above the canopy (e.g., 0.5 m). Typically the amplitude of the CO_2 wave at 0.5 m is 2—4 times that at 16 m.

Nocturnal CO_2 concentration and thermal stratification

[CO_2] at night ranges quite widely and may reach 450—500 ppm at levels close to the crop canopy, especially on calm nights. Wind speed and nocturnal

$[CO_2]$ have been shown to be inversely related (Brown and Rosenberg, 1970; Allen, 1971). However, the accumulation or dispersion of respired CO_2 depends on atmospheric thermal stratification as well as on wind speed. In order to consider both influences, values of a non-dimensional stability parameter — the Richardson number:

$$Ri = g\left(\frac{\partial \theta}{\partial z}\right)\theta^{-1}\left(\frac{\partial U}{\partial z}\right)^{-2}$$

were computed from wind speed and temperature profile data: g = acceleration due to gravity; θ = potential temperature; U = mean windspeed; and z = height above ground. The Richardson number represents the ratio of the rate at which buoyancy forces extract energy from turbulence to the rate at which energy is supplied by wind shear. Therefore, Ri is a measure of the relative importance of thermal effects. Ri is positive under inversion conditions (stable

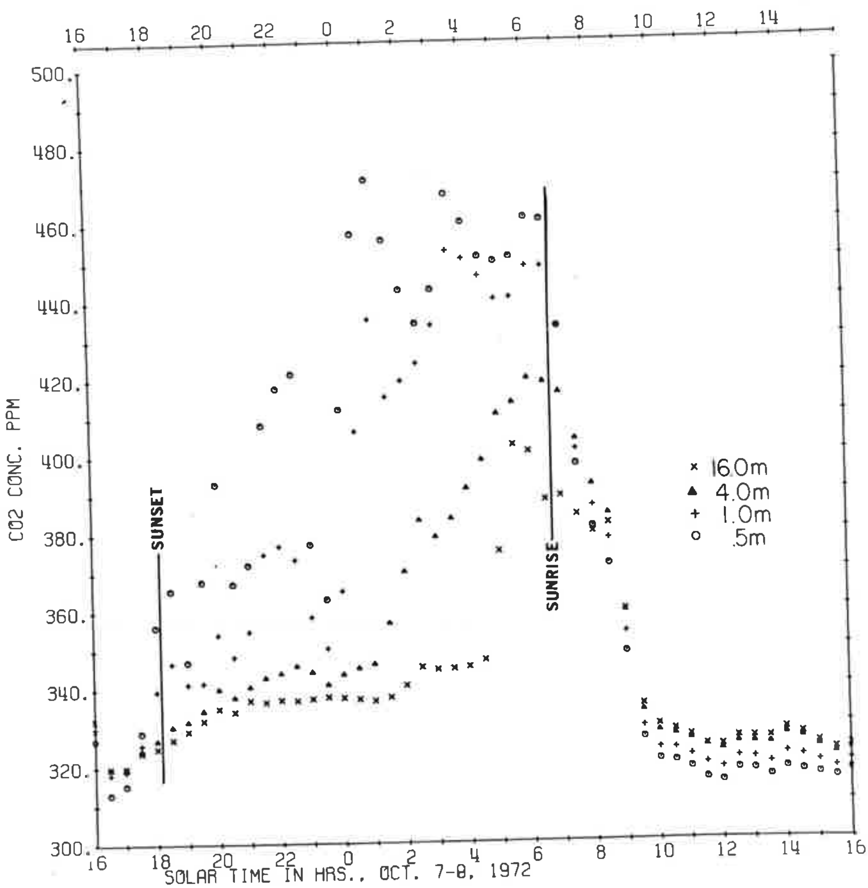

Fig.2. Same as Fig.1 for Oct. 7—8, 1972.

stratification) when turbulence tends to be suppressed, and is negative in lapse conditions (unstable stratification) when turbulence tends to be enhanced.

Figs. 3 and 4 show some typical plots of nocturnal [CO_2] over a soybean canopy in 1970 and the concurrent values of *Ri*. Nocturnal [CO_2] is seen to be strongly dependent upon thermal stability as indicated by *Ri*. *Ri*, therefore, appears to be a controlling parameter for predicting levels of nocturnal [CO_2].

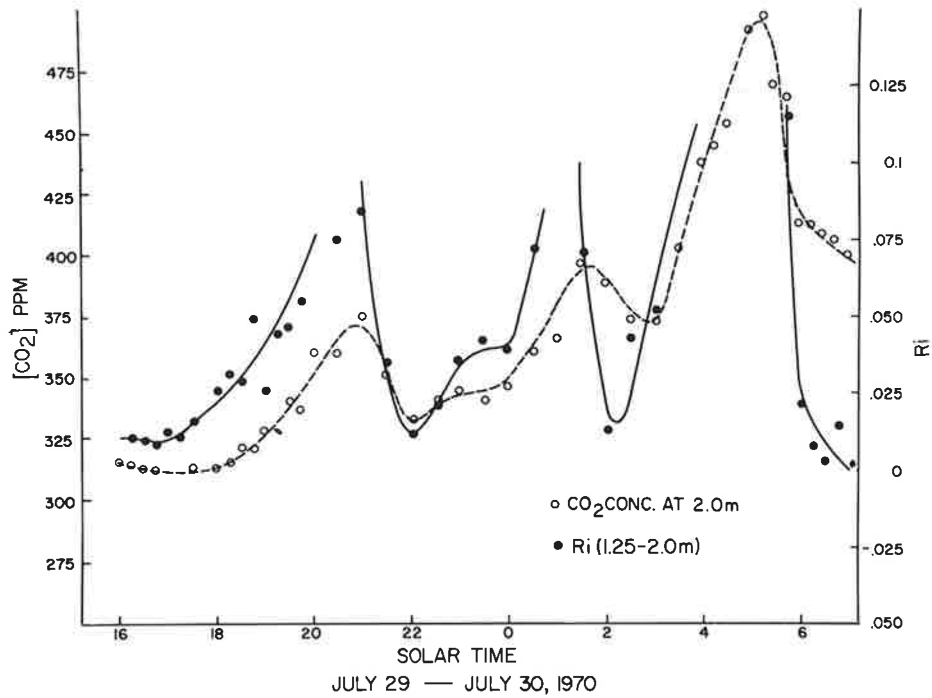

Fig.3. The relation of nocturnal [CO_2] at 2 m and the concurrent *Ri* value. July 29—30, 1970 at Mead, Nebraska.

Figs. 5 and 6 show some typical nocturnal [CO_2] and ΔCO_2 values measured well above the oat field in 1972 (4—16 m). Concurrent values of *Ri* and another suitable stability parameter, ($\Delta\theta/U^2$) are also plotted. Both the CO_2 concentrations and gradients increase and decrease in the same sense as *Ri* and $\Delta\theta/U^2$. [CO_2] maxima and minima coincide with the maxima and minima of *Ri* (or $\Delta\theta/U^2$) but the magnitudes are not necessarily proportional. Proportionality between noctural ΔCO_2 and *Ri* (or $\Delta\theta/U^2$) is somewhat better, however. Since some of our data were first reported (Verma and Rosenberg, 1973; Rosenberg and Verma, 1973) similar results have come to our attention (Pearman and Garratt, 1973).

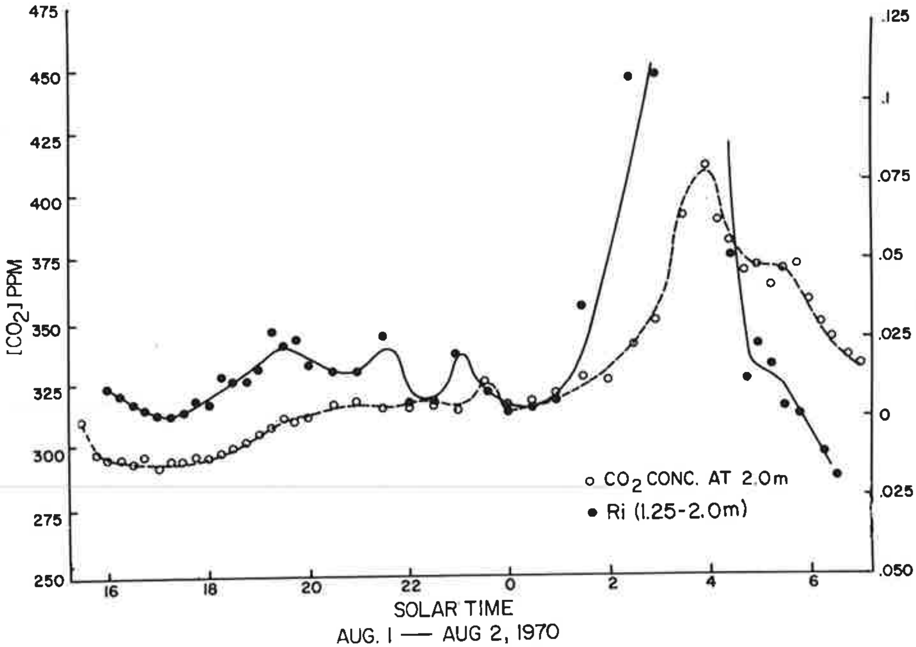

Fig.4. Same as Fig.3 for August 1—2, 1970.

Effect of thermal stability on profiles of CO_2

The effect of atmospheric stability on CO_2 profile shapes is considered in this section. Fig.7 shows a set of CO_2 concentration profiles for various values of the stability parameter, $(\theta_{16} - \theta_4)/U_4^2$. Under near neutral conditions ($|(\theta_{16} - \theta_4)/U_4^2| \leqslant 0.04$) CO_2 profiles (A, A_1, A_2) are approximately logarithmic. Under stable conditions, however, the plots of $[CO_2]$ (B, C, D, and E) are curvilinear functions of the logarithm of height, with concentration increasing rapidly as the ground is approached. An interesting feature is the fact that profile departure from linearity becomes more pronounced with increasing stability. Thus $\partial C/\partial z$ decreases (numerically) less rapidly with height than is consistent with a logarithmic relationship (or with a direct height proportionality).

In order to further study the effect of stability on CO_2 profiles, the ratios of ΔCO_2 measured in two air layers were computed for comparison with a corresponding stability parameter. To avoid the possibility of large errors, data were selected for periods when wind direction was such that no mast interference with the anemometers was likely (SE to SW) and when the individual CO_2 and temperature gradients were greater than 0.3 ppm and 0.25° C, respectively. All data were averaged over half hour periods.

Figs. 8 and 9 are plots of the ΔCO_2 ratio vs. the corresponding stability parameter. Fig.8 describes conditions below 1.75 m and Fig.9 refers to elevations far removed from the canopy (4, 8 and 16 m). Each figure includes data for five nights during fall 1972. In both plots the ratios of CO_2 gradients (elevations indicated) and $\Delta\theta/U^2$ are related by a linear correlation coefficient of about 0.70. The scatter of points tends to increase with increasing value of the stability parameter, possibly because of cessation of turbulence in very stable conditions.

In Figs.8 and 9 values of stability parameters ($\Delta\theta/U^2$ or $\Delta T/U^2$) are presented instead of "local" Richardson numbers since the gradients of wind speed required to compute the latter were not available. The stability parameter ($\Delta\theta/U^2$) represents a "bulk" Richardson number (Lettau, 1957). Deacon (1953) has shown that the temporal variations of the "bulk" Richardson number are uniquely related to those of the "local" Richardson number of the corresponding layer.

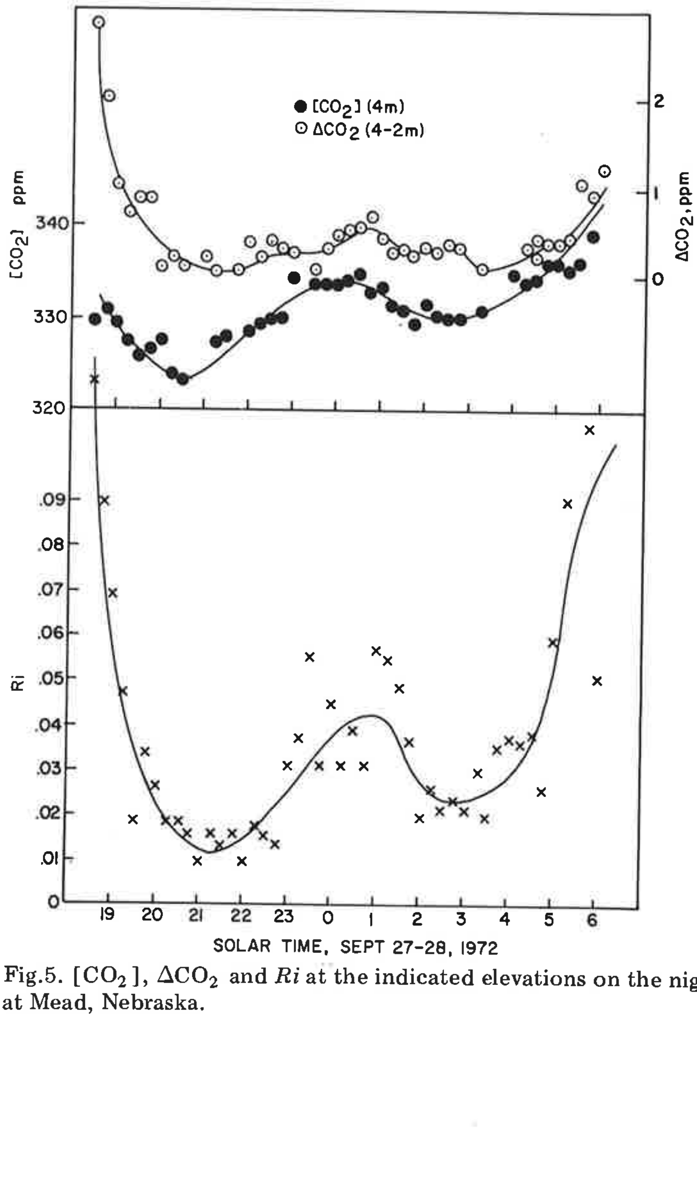

Fig.5. [CO_2], ΔCO_2 and Ri at the indicated elevations on the night of Sept. 27—28, 1972 at Mead, Nebraska.

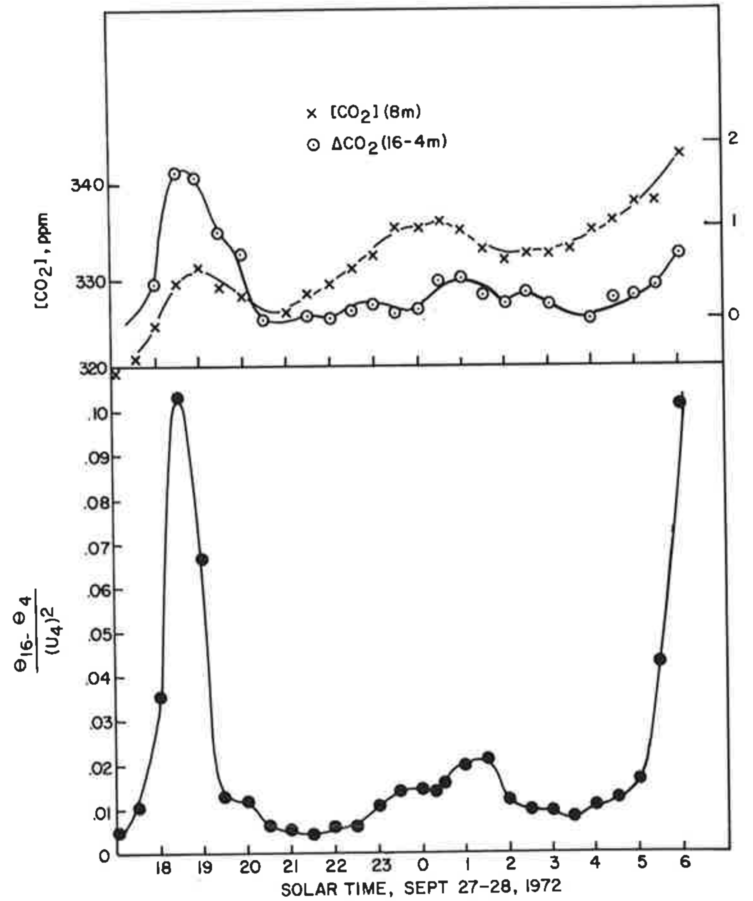

Fig.6. $[CO_2]$, ΔCO_2 and the stability parameter $(\theta_{16} - \theta_4)/(U_4)^2$ at the indicated elevations on the night of Sept. 27—28, 1972 at Mead, Nebraska.

Even though the results in Figs. 8 and 9 show some scatter, it is obvious that the ratio of CO_2 gradients, both near as well as far above the crop canopy are, under stable conditions, strongly dependent on the Richardson number. In an earlier micrometeorological investigation, Deacon (1953) reported a similar dependence for gradients of wind speed and air temperature.

SUMMARY AND CONCLUSIONS

Nocturnal CO_2 concentrations are strongly dependent upon the concurrent value of the Richardson number. This finding should be equally applicable to other atmospheric entities, including pollutants, and thus be useful in the prediction of air pollution hazards, especially under inversion conditions. Some previous studies have demonstrated correlation between $[CO_2]$ and concentrations of several atmospheric pollutants such as NO, NO_2, HC, SO_2 as well

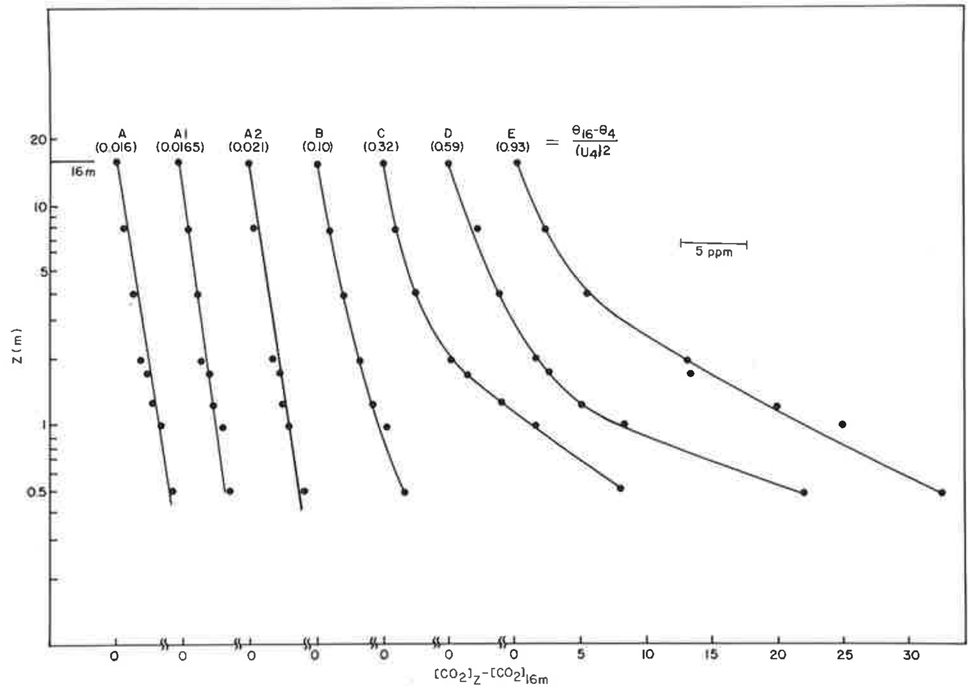

Fig.7. $[CO_2]$ profiles as a function of the indicated stability parameter.

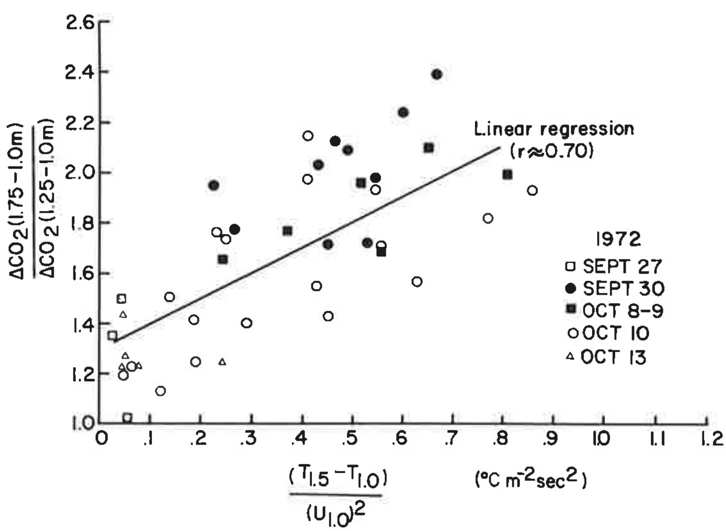

Fig.8. The ratio of CO_2 gradients at different levels near the ground as a function of the indicated stability parameter.

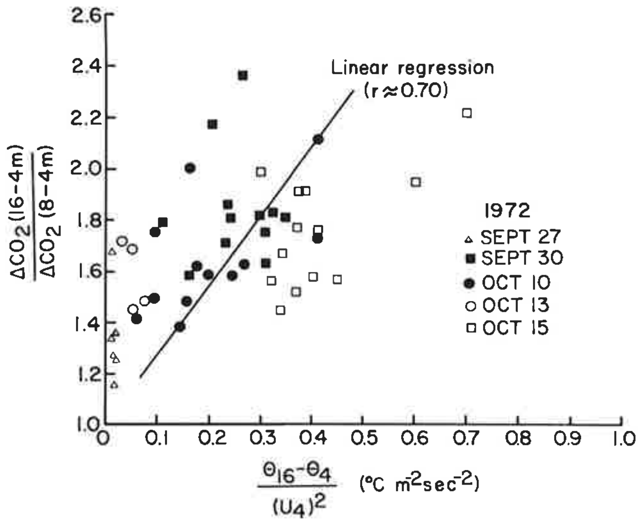

Fig.9. The ratio of CO_2 gradients at different levels well above the ground as a function of the indicated stability parameter.

as smoke and turbidity (Besson and Pelletier, 1959; Ba'ez and Fournier d'Albe, 1959; Clark and Faoro, 1966). Also, Clark and Faoro (1966), and Clark (1969) pointed out that CO_2 may have utility as a gross indicator of total pollution in an urban area during the afternoon hours and in cold climates at any hour of the day. In view of such findings and considering that CO_2 is an easily measured, relatively stable constituent of the atmosphere ($[CO_2] \approx$ 300—500 ppm), the possibility that CO_2 may be used as an indicator of atmospheric pollution should be given serious consideration.

Under near-neutral conditions the vertical profiles of $[CO_2]$ are approximately logarithmic. For stable conditions, however, the plots of $[CO_2]$ against logarithm of height are curvilinear. The departure from linearity increases with increasing stability. Analysis of CO_2 concentration and gradient data measured at different elevations with the corresponding stability parameter indicates that the $[CO_2]$ profiles are, to a first approximation, closely related to the values of the Richardson number. This property has previously been established for the profiles of wind speed and air temperature.

Such pioneer workers as Monteith and Szeicz (1960), Inoue (1964), and Munn (1966) were optimistic that CO_2 might be used as a tracer in micrometeorology. At night CO_2 gradients are large and fluxes are relatively constant (Monteith and Szeicz, 1960; Munn, 1966). The nocturnal flux of CO_2 above vegetation is probably less sensitive to changes in meteorological conditions than is any other process of diffusion. CO_2 micrometeorology therefore offers a potential for evaluating the effects of thermal stratification on turbulent transport, especially in very stable conditions. We hope that the data presented here will stimulate interest in practical applications of CO_2-micrometeorology.

ACKNOWLEDGEMENTS

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REFERENCES

Allen Jr., L. H., 1971. Variations in carbon dioxide concentration over an agricultural field. Agric. Meteorol., 8: 5—24.

Ba'ez, A. and Fournier d'Albe, E. M., 1959. Carbon dioxide in study of medium scale diffusion. Adv. Geophys., 6: 417—419.

Besson, D. and Pelletier, F., 1959. Atmospheric pollution in the Paris area. Proc. Diamond Jubilee, Int. Clean Air Congr., London, pp. 122—129.

Brown, K. W. and Rosenberg, N. J., 1970. Concentration of CO_2 in the air above a sugar beet field. Mon. Weather Rev., 98: 75—82.

Clark, J. F., 1969. A meteorological analysis of carbon dioxide concentrations measured at a rural location. Atmos. Environ., 3: 375—383.

Clark, J. F. and Faoro, R. B., 1966. An evaluation of CO_2 measurements as an indicator of air pollution. J. Air Pollut. Control Assoc., 16: 212—218.

Deacon, E. L., 1953. Vertical profiles of mean wind in the surface layers of the atmosphere. Meteorol. Off. Geophys. Mem., 92.

Inoue, E., 1964. Turbulent fluctuations in atmospheric CO_2 concentration over the vegetated fields. Stud. Oceanogr., p. 232—237.

Lettau, H. H., 1957. Computation of Richardson numbers, classification of wind profiles, and determinations of roughness parameters. In: H. H. Lettau and B. Davidson (Editors), Exploring the Atmosphere's First Mile. Pergamon, London, Vol.1.

Monteith, J. L. and Szeicz, G., 1960. The carbon-dioxide flux over a field of sugar beets. Q. J. R. Meteorol. Soc., 86: 205—214.

Munn, R. E., 1966. Descriptive Micrometeorology. Academic Press, New York, N.Y., 245 pp.

Pearman, G. I. and Garratt, J. R., 1973. Carbon dioxide measurements above a wheat crop, 1. Observations of vertical gradients and concentrations. Agric. Meteorol., 12: 13—25.

Rosenberg, N. J. and Verma, S. B., 1973. Terrestrial source and sink strengths for atmospheric carbon dioxide in an agricultural region. Progress Report on Contract 2—35385, submitted to the Environmental Data Service, National Oceanic and Atmospheric Administration, U.S. Department of Commerce.

Rosenberg, N. J. and Verma, S. B., 1976. A system and program for monitoring CO_2 concentration, gradient and flux in an agricultural region. Agron. J., 68: 414—418.

Rosenberg, N. J. et al., 1969. Research in Evapotranspiration. Report to the Office of Water Resources Research on Project A—001 NEB, 153 pp. Horticulture Progress Report No. 73 Univ. of Nebraska, Lincoln, Nebr.

Verma, S. B. and Rosenberg, N. J., 1973. Systematized monitoring of CO_2 concentration and gradients in an agricultural region and implication with respect to air pollution. Abstract, WMO/WHO Technical Conference on Observation and Measurement of Atmospheric Pollution, Helsinki, Finland (30 July to 4 August 1973).