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Carbon dioxide concentrations over a native grassland in Saskatchewan

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ABSTRACT

Variations in the surface boundary layer carbon dioxide concentration (⟨CO_2⟩) during the 1971 growing season have been analyzed in terms of three periodicities. The *diurnal* periodicity has an amplitude maximum in the vegetation canopy, of up to 100 vpm, and this diminishes with increasing height above the surface. This variation is driven by the daytime intake of carbon dioxide by the vegetation in photosynthesis and the nighttime release through plant and soil respiration. Spectral analysis of the ⟨CO_2⟩ shows the presence of *irregular variations*, with periods between 3 and 5 days, that appear to be related to synoptic scale weather patterns. Highest ⟨CO_2⟩ is found in air that has most recently come from the Pacific Ocean and ⟨CO_2⟩ decreases with longer trajectories over land causing a difference of up to 7 vpm in the daily minimum. A 28 vpm decrease in mean daily ⟨CO_2⟩ from June to September is considered part of the *annual* ⟨CO_2⟩ variation.

Introduction

In recent years man has come to realize more and more the importance of carbon dioxide in the atmospheric environment, not only for its role in photosynthesis but also for its effects on the global climate. The influence of human technology on the concentration of carbon dioxide (abbreviated as ⟨CO_2⟩) in the atmosphere has received considerable attention, e.g. Keeling (1973), Smil & Milton (1974), Hoffert (1974). The effects of an increase in ⟨CO_2⟩ range from changes in the radiation balance of the earth resulting in modification of the climate (Sawyer, 1972), to changes in the calcium carbonate balance in the sea resulting in the dissolving of coral reefs and the shells of other calcareous organisms (Fairhall, 1973). To recognize, evaluate, and ultimately, predict the effects of man-induced changes in ⟨CO_2⟩ we must first understand the nature of natural variations in ⟨CO_2⟩ in the biosphere. This is most readily realized in regions remote from industrial and other human sources which tend to obscure the natural variations.

Measurements of the ⟨CO_2⟩ have been made in many regions of the earth's atmosphere and oceans; e.g. in the surface boundary layer over crops (Brown & Rosenberg, 1970; Allen, 1971; Pearman & Garratt, 1973a; Rosenberg & Verma, 1974) and natural vegetation (Bischof, 1960; Pales & Keeling, 1965; De Maio et al., 1966; Clarke, 1969; Johnson & Kelley, 1970; von Paller, 1971); over and in the oceans (Keeling, 1968; Akiyama, 1969; Miyake & Sugimura, 1969; Kelley & Hood, 1971; Liakhin, 1971); and in the upper troposphere and stratosphere (Bischof & Bolin, 1966; Bolin & Bischof, 1970; Bischof, 1973; Garratt & Pearman, 1973a,b; Pearman & Garratt, 1973b). Bolin & Keeling (1963) summarized a large number of atmospheric and oceanic measurements of ⟨CO_2⟩ made over the globe. Systematic variations of the ⟨CO_2⟩ in the atmosphere with season, latitude, longitude and altitude have been observed and related to the distribution of sources and sinks which exist at the surface of the earth.

Variations in the ⟨CO_2⟩ over vegetated surfaces have been described by many investigators in terms of three major periodicities. Two of these, the diurnal and annual, are regular while the third includes periodicities between one day and several weeks. The diurnal cycle has a maximum ⟨CO_2⟩ at night and a minimum usually during the afternoon. This variation is in response to the daytime uptake of carbon dioxide, in photosynthesis, by the vegetation canopy and the nighttime release through plant and soil respiration (Brown & Rosenberg, 1970; Allen, 1971; Georgiyevskiy & Khalikova, 1971). The greatest amplitude of the diurnal cycle occurs inside the vegetation canopy. The amplitude decreases rapidly away from the surface, although it is still conspicuous at 125 to 150 m (Chapman et al., 1954; Woodwell et al., 1973).

The $\langle CO_2 \rangle$ variations of irregular periodicity are related to large-scale mixing processes in the free atmosphere and are usually associated with characteristic features of weather systems such as airmasses and fronts (Bolin & Bischof, 1970; Johnson & Kelley, 1970); analogous to changes in atmospheric humidity. Callendar (1940) and Buch (1948) noted differences in the surface boundary layer $\langle CO_2 \rangle$ of the air in various airmasses, air of arctic origin having lower values than air of tropical origin. However, these early measurements of $\langle CO_2 \rangle$ were often unreliable, being subject to large errors due to contamination of the samples, and the measurement techniques used (Callendar, 1958). Also, it is to be expected that the trajectory, as well as the origin of the air, determines the surface boundary layer $\langle CO_2 \rangle$. Garratt & Pearman (1973b) found that day-to-day variation in midday $\langle CO_2 \rangle$ in the surface boundary-layer at two sites in southeast Australia were due to changes in air trajectory. Woodwell et al. (1973), on the northeastern seaboard of the U.S.A., Johnson & Kelley (1970), on the Arctic coast of Alaska, and Goldman (1974), at Mauna Loa, Hawaii, noted similar effects. Kelley (1969) found a reduction in $\langle CO_2 \rangle$ at the 500 hPa (500 mb) level between the west coast of North America and the interior of the continent.

Bolin & Keeling (1963), Woodwell et al. (1973) and others noted that the annual cycle has a minimum during summer or early autumn in the northern hemisphere due to the removal of atmospheric carbon dioxide in photosynthesis and its incorporation into plant tissue. The maximum concentration occurs in late winter to late spring as the carbon dioxide is replenished through the burning of fossil fuel, by mixing by air from over the oceans which act as "reservoirs" for carbon dioxide and by decomposition of plant material. The amplitude of this cycle decreases with height and there is a phase lag through the troposphere and into the stratosphere. The amplitude is also latitude dependent (Bolin & Bischof, 1970). Woodwell et al. found that the winter maximum at Brookhaven, N.Y. was not clearly defined, probably due to a large urban influence. Bischof (1960) found two peaks instead of one in the annual $\langle CO_2 \rangle$ of the surface boundary layer at various sites in Scandinavia between 1955 and 1959. There was considerable variation in the time of occurrence of these peaks from year to year and from station to station. However, the measurement techniques used are subject to large errors and the results must be used only with reservation.

Bolin & Keeling (1963) and Garratt & Pearman (1973b) noted that there was only a small annual variation in the $\langle CO_2 \rangle$ of the free atmosphere in the southern hemisphere, probably because much of this hemisphere is oceanic. Pearman & Garratt (1973b) claim that even the air in the surface boundary layer is influenced to only a small degree by terrestrial carbon dioxide sources and sinks.

As well as the three periodic variations described above, there is also a gradual increase in mean annual $\langle CO_2 \rangle$ (Brown & Keeling, 1965; Pales & Keeling, 1965; Bischof, 1973). This is believed to be a result of the addition of carbon dioxide to the atmosphere through the combustion of fossil fuels. It has been estimated (Bolin & Bischof, 1970) that about two-thirds of the generated carbon dioxide is assimilated by vegetation or absorbed by the oceans, with the latter predominating. This yearly increment, which was about 0.5 parts per million by volume (vpm) in 1963, has increased through the last decade and is now in excess of 1 vpm (Bischof, 1973; Woodwell et al., 1973; Goldman, 1974).

In the present paper, measurements of $\langle CO_2 \rangle$ over a mixed grass prairie of the northern Great Plains of North America are presented. An analysis is made of the three periodic variations described above, particularly those of diurnal and irregular periodicities.

Methods

The $\langle CO_2 \rangle$ data used in this study were obtained during the summer of 1971 at the Matador Project research site in southern Saskatchewan, Canada, (Lat. 50°42′N, Long. 107°43′W), as a part of the Canadian contribution to the International Biological Programme. The study area was situated on the bed of a former glacial lake. The land is flat, rising gradually to the north to a range of hills 120 m above the plain at a distance of 8 km. Two to three kilometres to the south there is an abrupt drop of about 120 m to the valley of the South Saskatchewan River. The vegetation is representative of the Agropyron-Koeleria faciation of the Stipa-Bouteloua association of the Mixed-Grass Prairie (Coupland, 1961). The study site forms part of over 25,000 ha of untilled grassland. On the basis of usual fetch-to-height relationships (Dyer, 1968), all measurements were made within the surface boundary layer of the grassland. The macro- and microclimate, soils, and the vegetation of the region have been described in various Project Technical Reports, and summaries may be found in Ripley and Saugier (1974) and Ripley & Redmann (1976). The site is many hundreds of kilometres from any significantly large man-made carbon dioxide source.

The $\langle CO_2 \rangle$ data were collected as part of an extensive micrometeorological measurement programme and were used primarily to provide non-destructive estimates of plant productivity. Although $\langle CO_2 \rangle$ was measured at a number of heights, only that at the highest level, 6.5 m above the soil surface, is used in the present paper. The vegetation canopy was about 0.3 m in height although for vegetation–atmosphere transfer processes its effective height was about 0.2 m (Spittlehouse & Ripley, 1974). The data on which this report was based are available in a summarized form in Ripley & Saugier (1973). The complete data are on file in the data-bank of the Canadian IBP Grassland Biome Centre at the University of Saskatchewan, and copies can be obtained from the authors.

The carbon dioxide sampling and measurement system has been described in detail in Ripley et al. (1973) and Saugier & Ripley (1974) and is only briefly described here. Air was drawn from the sampling nozzles through heated insulated copper tubing by stainless steel metal-bellows pumps. This was at a constant flow rate of $10\ \mathrm{l\ min^{-1}}$. Solenoid valves, actuated automatically, sequentially switched channels once each minute allowing a flow of $1\ \mathrm{l\ min^{-1}}$ through the differential infra-red gas analyzer (Maihak UNOR 5). Each level was sampled once every six minutes. The output of the analyzer was integrated for the last 30 seconds of each one-minute sampling period and recorded on magnetic tape by the micrometeorological data acquisition system.

Water vapor was removed from the air with magnesium perchlorate desiccators prior to analysis of the $\langle CO_2 \rangle$. Consequently a volume correction had to be made (Parkinson, 1971). To facilitate this, the dew-point temperature of the air was measured by passing a sample of the air through a dew-point hygrometer. The $\langle CO_2 \rangle$ was then determined in volume parts per million of *moist* air using the following formula:

$$\langle CO_2 \rangle_{\mathrm{moist}} = \langle CO_2 \rangle_{\mathrm{dry}} \cdot (1 - e/p)$$

where e = vapour pressure of the air, and
p = atmospheric pressure

The absolute and differential sensitivities of the analyzer were determined at least once a month using test gas mixtures of carbon dioxide in nitrogen, with concentrations ranging from 280 to 370 vpm. The actual concentrations of these gases were determined by K. M. King of the University of Guelph by comparison with mixtures coming from Wösthoff pumps. There was a gradual, smooth decrease in the sensitivity of the analyzer, of about 10% over the five months of operation. The accuracy of the measured $\langle CO_2 \rangle$ was ± 0.1 vpm.

$\langle CO_2 \rangle$ data were obtained between 10 June and 28 September 1971, and summarized as half-hourly means for analysis. Inevitably there were gaps in the data record due to system maintenance and calibration and occasional power-supply interruptions.

It should be noted here that many published reports on atmospheric and oceanic $\langle CO_2 \rangle$ present the data in vpm of *dry* air. In the upper part of the troposphere and in the stratosphere the difference between the $\langle CO_2 \rangle$ of dry and moist air is usually very small. However at 6.5 m, on a normal summer day, the $\langle CO_2 \rangle$ of moist air may be about 15 vpm lower than that of dry air. As it is the moist air concentration gradient that drives the diffusion processes, the present $\langle CO_2 \rangle$ data were required to be in terms of volume of moist air as they were originally used for carbon dioxide flux calculations.

A spectral analysis of the $\langle CO_2 \rangle$ data was carried out in order to separate the diurnal and longer-period variations. The spectrum of a series of observations taken at regular intervals of time displays the contributions to the total time series of each of the various frequencies, or periods, in the time series. Spectral density is presented as the autospectrum, which is the ratio of the spectral density of a particular frequency to the total density of the complete spectrum (Jenkins & Watts, 1968). The equivalence between the spectra of two time series is measured by a co-spectrum, and is represented here by the coherence. The coherence is bounded by 0 and 1; it is analogous to a correlation coefficient (Tilley & McBean, 1973). The phase angle, or angle of lag or lead between the frequencies of two time series was also calculated. The computer program for determining the spectrum uses a fast-Fourier-transform, "detrends" the data, and fits a 10% "taper" to the data using a "cosine bell" (Bingham et al., 1967; Munn, 1970, section 7).

The spectral analysis was performed on hourly $\langle CO_2 \rangle$, atmospheric pressure, and 10 m windspeed at the climatological site 1.5 km away; there being too many gaps in the windspeed data at the micrometeorological site. Gaps in the $\langle CO_2 \rangle$ data of less than half a day were filled by linear interpolation. Longer-period gaps were filled with the 10-day mean hourly $\langle CO_2 \rangle$ centered around that day. Only data for July 4 to September 26 were suitable for spectral analysis.

The $\langle CO_2 \rangle$ data have also been presented in the form of ten-day running and monthly means. Only days with less than one-third of the data missing were used.

Results and Discussion

A plot of the $\langle CO_2 \rangle$ against time for several days in July (Fig. 1a) clearly shows the diurnal cycle. During this period the large diurnal variation makes it difficult to identify any other periodic variations. By the end of August the diurnal variation has almost disappeared (Fig. 1b) and longer period variations are becoming evident. The spectral analysis (Fig. 2) clearly shows the presence of both diurnal variations and irregular longer period variations. The length of the available data record is insufficient to give reliable transforms for periods longer than about six days.

For the data as a whole (Fig. 2a) the diurnal period shows as a much stronger peak than the irregular variations. If the data are separated into two distinct periods, July 4 to August 14 (Fig. 2b) and August 16 to September 26 (Fig. 2c), the irregular variations become relatively stronger later in the year as the strength of the diurnal variation decreases. This is shown even more clearly in Fig. 2d, for September 6 to 26, where the autospectral density of the diurnal peak is only one-sixth as large as it was for the July 4 to August 14 period, and the autospectral density of the irregular variations has more than doubled in magnitude. The increase in strength of the peaks of the irregular periodic variations and concurrent decrease in the strength of the diurnal peak, plus the general shape of the transform, suggest that these irregular variations are not due to "leakage" harmonics of the diurnal cycle; nor can they be ascribed to measurement system disturbances, such as new desiccant, calibration, and power interruptions. Unfortunately, no sufficiently reliable statistical technique could be found to test the significance of the autocorrelations. However, the general shape of the $\langle CO_2 \rangle$ transform and the correlations with windspeed, atmospheric pressure and wind direction (Table 1) suggest that the peaks are real and do not merely represent random noise in the data.

Although the data record was not long enough for spectral analysis to show the annual cycle, part of this cycle can be seen in plots of the mean daily and monthly $\langle CO_2 \rangle$ (Figs. 3 and 4).

The Diurnal Cycle: In June and July the amplitude of the diurnal cycle inside the vegetation canopy was frequently greater than 100 vpm (Ripley & Saugier, 1973). This cycle was still strong at the 6.5 m height, with the amplitude frequently exceeding 40 vpm (Fig. 1a). The amplitude of the diurnal cycle decreased through the summer and by late-summer was between 10 and 20 vpm in the canopy (Ripley & Saugier, 1974) and generally less than 10 vpm at 6.5 m (Figs. 3 and 4). This drop was due primarily to a decrease in the amount of soil respiration and in the photosynthetic rate of the vegetation, resulting from increasing soil moisture stress, and a decrease in the amount of photosynthesizing plant material (see Ripley & Saugier, 1974, Figs. 9 and 13).

The windspeed and the shortwave radiation flux strongly influence the amplitude of the diurnal cycle (Figs. 1a and 1b). Similar relationships have been noted by Brown & Rosenberg (1970) over sugar beet and Allen (1971) over corn. The coherence data (Fig. 2) show, as expected, that the diurnal variation in windspeed is highly correlated with $\langle CO_2 \rangle$ but lags by about 14 hours.

At night the $\langle CO_2 \rangle$ varies inversely with the

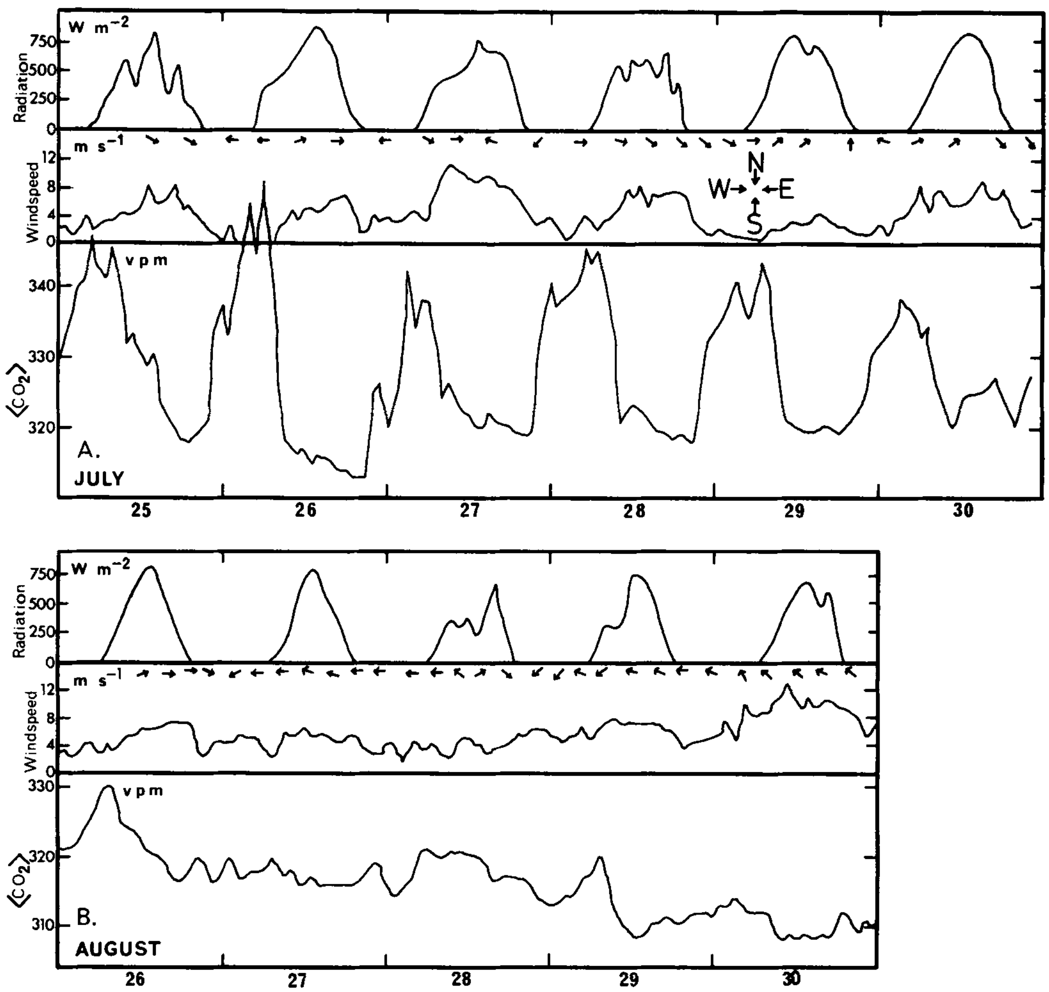

Fig. 1. Variation of atmospheric carbon dioxide concentration at a height of 6.5 m, windspeed at a height of 10 m and, incoming solar radiation at the Matador Field Station for two periods during 1971: A. July 25–30, and; B. August 26–30. The arrows under the radiation trace indicate wind direction.

windspeed. This effect is related to atmospheric stability. The turbulent diffusivity decreases with increasing stability (decreasing windspeed), resulting in a reduction in transfer of the respired carbon dioxide through the surface boundary layer and a build up in the $\langle CO_2 \rangle$. This is particularly noticeable for the more stable situations (Richardson number greater than about 0.05). Pearman & Garratt (1973a) and Rosenberg & Verma (1974) have also noted this relationship between nighttime $\langle CO_2 \rangle$ and atmosphere stability. However, other environmental parameters, such as air and soil temperatures and soil moisture are also important, because they influence the nighttime $\langle CO_2 \rangle$ through soil and plant respiration.

During the daytime, changes in the shortwave radiation flux have a greater effect than changes in windspeed. A decrease in the radiation flux causes the $\langle CO_2 \rangle$ to increase due to a decrease in the photosynthetic uptake of carbon dioxide. Higher windspeeds increase the $\langle CO_2 \rangle$ by enhancing the transport of carbon dioxide from the free atmosphere to the surface boundary layer.

The diurnal cycle is not symmetrical (Figs. 1 and

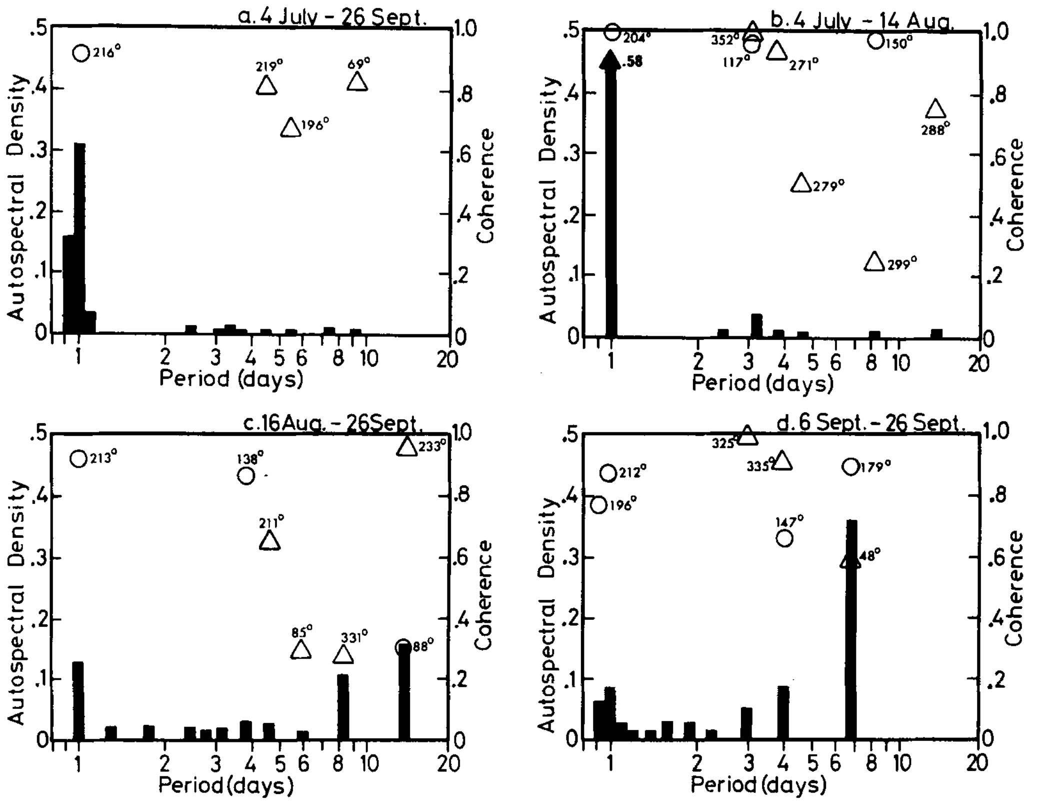

Fig. 2. Autospectra of 6.5 m carbon dioxide concentration (bars); coherence and phase angle between $\langle CO_2 \rangle$ and 10 m windspeed (circles), and $\langle CO_2 \rangle$ and atmosphere pressure (triangles). Phase angle is written as the angle in degrees by which $\langle CO_2 \rangle$ leads windspeed or pressure. For clarity, periods with autospectral densities less than 0.01 are not shown. Correlations for periods longer than six days are unreliable due to the limited time span (80 days) of the data record.

3). The daily maximum $\langle CO_2 \rangle$ occurs between 0500 and 0700 solar time, resulting from the gradual build-up of respired carbon dioxide through the night being curtailed as photosynthesis commences and the windspeed increases. The daily minimum concentration occurs during the late afternoon and the curve is flattened during the daytime.

Irregular Period Variations: Through most of the summer the contribution of the irregular variations (periods between 3 and 5 days) of $\langle CO_2 \rangle$ to the total variation of the $\langle CO_2 \rangle$ was small. However, by September, the spectral density of the diurnal amplitude was much reduced and the irregular variations became more prominent, though they too had diminished.

Peaks in the $\langle CO_2 \rangle$ autospectra at periods between 3 and 5 days show high conherences with the equivalent autospectra of windspeed and atmospheric pressure. The variations in windspeed and pressure over this range of periods are largely due to the passage of weather systems over the region. It is hypothesized that the corresponding variations in $\langle CO_2 \rangle$ are also related to the passage of these weather systems.

Variations in atmospheric pressure and windspeed with weather patterns are the basis of synoptic meteorology, and their influence on the concentration of gases and particles in the surface boundary layer have been noted by many authors. For example, Tilley & McBean (1973) suggested that 3-day cycles in corresponding windspeed and sulfur dioxide concentration spectra for Ottawa, Canada, were the result of the passage of low pressure systems over the region.

Intervals of 3 to 5 days between the passage of successive low or high pressure systems are usual over this region of Canada during the summer.

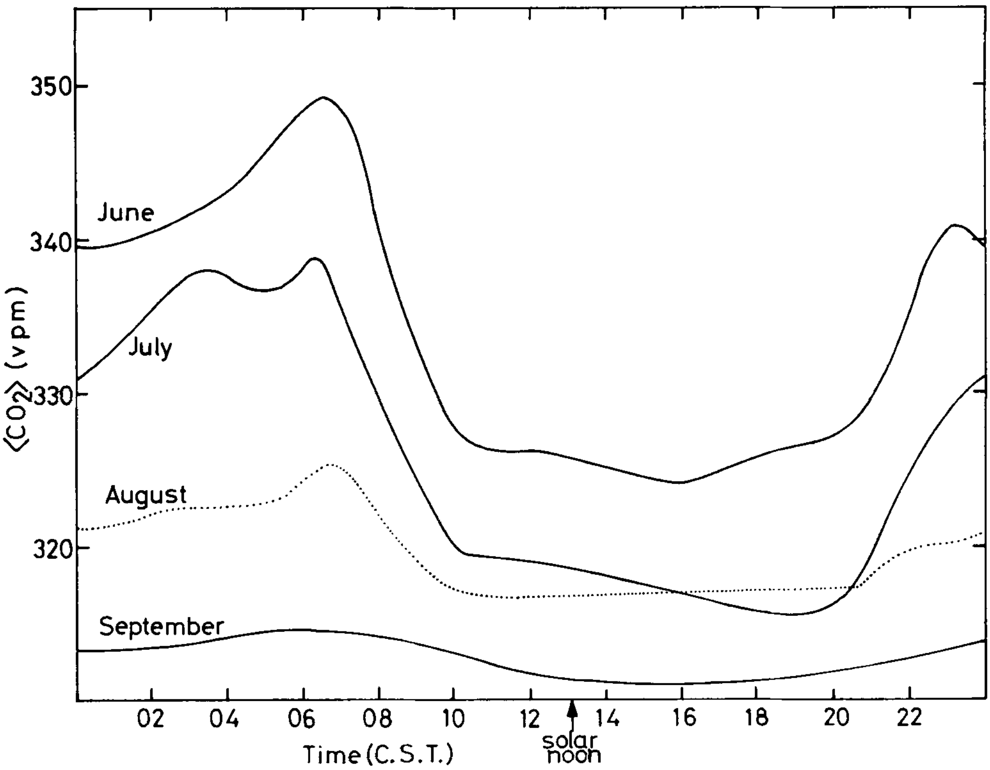

Fig. 3. Diurnal variation of monthly mean carbon dioxide concentration at 6.5 m above the ground during the summer of 1971 at the Matador Field Station.

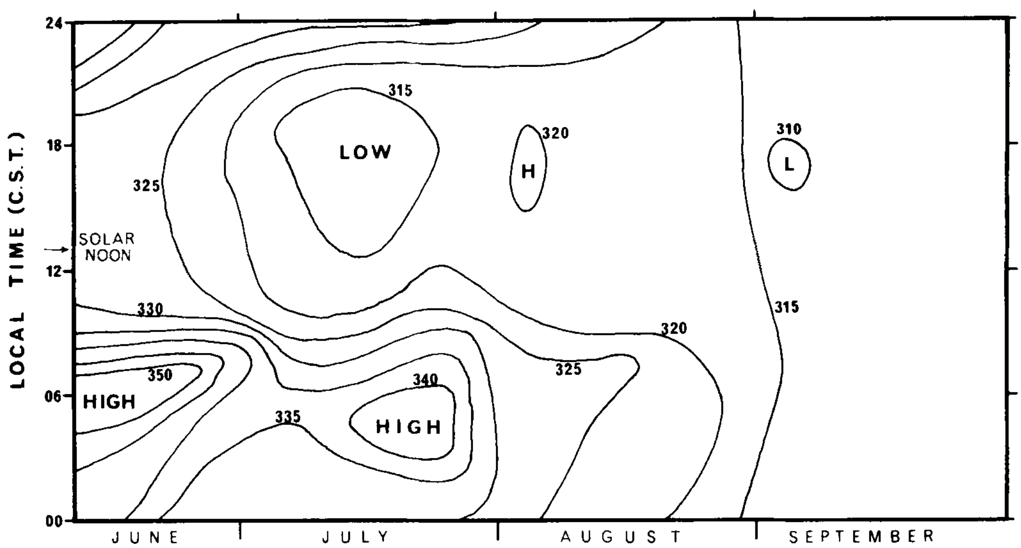

Fig. 4. Diurnal and seasonal variation of $\langle CO_2 \rangle$ at a height of 6.5 m during the summer of 1971 at the Matador Field Station. The data points used to prepare the diagram were 10-day means of the concentrations for each half-hour.

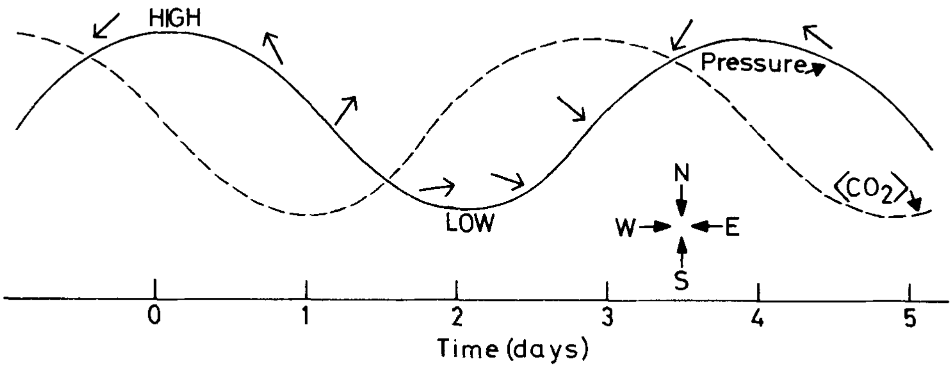

Fig. 5. Schematic representation of observed relationship between $\langle CO_2 \rangle$, atmospheric pressure and wind direction.

However, periods in the range of 6 to 12 days also occur, though the data record used in this study is not long enough to permit a reliable analysis of these periods. Also, the wide range of periodicities of occurrence of the weather systems result in the peaks in this region of the spectrum not being very strong.

The phase difference between the corresponding peaks in the autospectra of $\langle CO_2 \rangle$ and atmospheric pressure (Fig. 2) lead one to expect that westerly winds would have a higher $\langle CO_2 \rangle$. In general, pressure lags $\langle CO_2 \rangle$ by a phase angle of 200 to 300 degrees, thus a maximum in the $\langle CO_2 \rangle$ cycle is attained following the passage of a center of low pressure across the region; and, due to circulation within the low, the winds are from 220° to 320°. Conversely, the passage of a high pressure center is associated with winds from 70° to 180° and the attaining of a minimum in the $\langle CO_2 \rangle$ cycle. This is schematically represented in Fig. 5.

We found here, as did Tilley and McBean, that with available techniques it was not possible to perform a spectral analysis on the wind direction data due to the discontinuity through north. Consequently, a subjective comparison was made between wind direction and daytime $\langle CO_2 \rangle$. As the $\langle CO_2 \rangle$ is less variable during the daytime than during the night, the minimum daytime $\langle CO_2 \rangle$ and corresponding wind direction were compared, using only data where the wind had been blowing from one direction $\pm 23°$ for 4 to 6 hours prior to the measurement, as in Woodwell et al. (1973).

During the summertime, at the study area, the wind blows from either 100° to 145° (ESE) or 270° to 315° (WNW) about 80% of the time, with the latter direction predominating (Ripley, 1973). Air from the WNW had a higher $\langle CO_2 \rangle$ than that from the ESE with the difference decreasing through the summer (Table 1). Johnson & Kelley (1970), Garratt & Pearman (1973b), and Goldman (1974) found differences in $\langle CO_2 \rangle$ with wind direction in the surface boundary layer and noted that air that had travelled the longest distance over land had the lowest $\langle CO_2 \rangle$ due to a longer period of removal of carbon dioxide from the atmosphere by vegetation photosynthesis. In this research, trajectory analysis indicated that air from both directions originated over the northern Pacific Ocean (Fig. 6). However, air from the ESE has had a longer residence time, by up to 4 days over the continent, originally passing over the area from the WNW and then returning, as the pressure pattern changed. Consequently, ESE air underwent greater modification; more carbon dioxide having been removed by photosynthesis. Another explanation would be that there is a significant difference in efficiency of vertical mixing between the WNW and ESE situations. Greater eddy diffusivities for the WNW case would result in a smaller depression in

Table 1. *Mean monthly $\langle CO_2 \rangle$ and standard deviation for the two predominant wind directions, June–September 1971*

Wind direction was constant $\pm 23°$ for the 4 to 6 hours prior to the minimum $\langle CO^2 \rangle$ being reached. Concentrations are in vpm of moist air. Figure in brackets is number of data points

Month	100° to 145°, ESE	270° to 315°, WNW
June	317.0 ± 0.5 (3)	324.1 ± 1.5 (8)
July	309.3 ± 0.3 (3)	314.5 ± 0.8 (17)
August	313.5 ± 0.9 (12)	315.2 ± 1.5 (6)
September	308.3 ± 1.3 (3)	308.5 ± 0.5 (10)

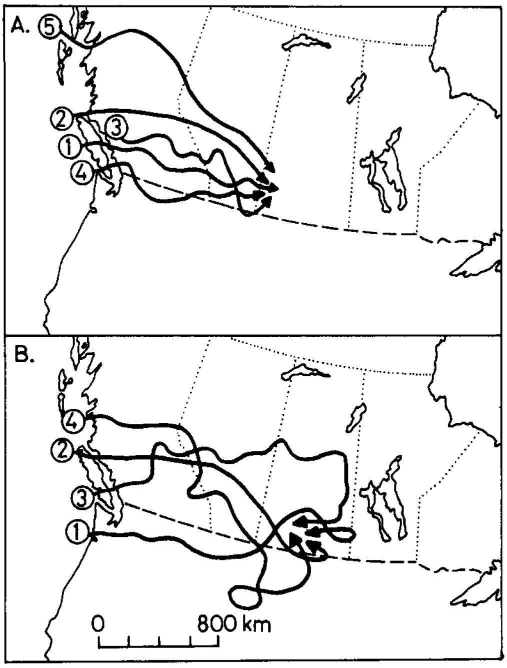

Fig. 6. Examples of trajectories of air arriving at the Matador Field Station on a number of summer days during 1971. A. Arriving with westerly to northwesterly winds: ① 4–11 June; ② 3–7 July; ③ 22–29 July; ④ 14–20 August; ⑤ 12–15 September. B. Arriving with easterly to southeasterly winds: ① 12–19 June; ② 3–9 July; ③ 20–29 August; ④ 13–24 September. For each example the range of dates indicates the period taken for the air parcel to move from the coast to the Field Station.

concentration, below the free atmosphere level, compared with the ESE situation.

By late summer the difference in $\langle CO_2 \rangle$ between the two wind directions had decreased considerably. This was probably the result of a general reduction in photosynthetic activity of the vegetation. The spectral analysis indicates that there were still some irregular variations in September (Fig. 2d) although the limited amount of available data (Table 1) shows no significant difference in $\langle CO_2 \rangle$ between the two wind directions.

Wind direction also has an influence on the moisture content of the air passing over the site. Air from the WNW, having a more northerly trajectory than air from the ESE, may be expected to have a lower absolute moisture content and if WNW and ESE air had the same $\langle CO_2 \rangle$ per volume of dry air, WNW air would have higher measured $\langle CO_2 \rangle$ per volume of moist air.

Windspeed may influence the period and amplitude of the irregular variations in $\langle CO_2 \rangle$. The irregular variations in the windspeed lag the coherent $\langle CO_2 \rangle$ variations by a phase angle of 100 to 140 degrees, and as expected, these variations in windspeed are almost completely out of phase with the variations in atmospheric pressure. If windspeed is influencing the $\langle CO_2 \rangle$ it is probably through changes in turbulent mixing of the air, just as with the diurnal variations.

In conclusion, the surface boundary-layer atmospheric humidity and possibly windspeed aspects of the synoptic weather pattern, as well as photosynthetic depletion of the atmospheric carbon dioxide, appear to be related to the observed variation of $\langle CO_2 \rangle$ with wind direction.

Annual Variation: A decrease in the amplitude of the diurnal variation of $\langle CO_2 \rangle$ through the summer can be seen in Figs. 3 and 4. A general decrease in the mean concentration, through the summer, can be seen in Fig. 7, and Tables 1 and 2. The ten-day running means (Fig. 7) show that the decrease is not regular. This is because the $\langle CO_2 \rangle$ was determined in the surface boundary layer and local effects of vegetation photosynthesis are superimposed on the northern hemisphere free atmosphere summer decrease shown in Bolin & Keeling (1963). The dip in the curve in July coincides with a period of maximum photosynthesis of the grassland, determined from the carbon dioxide profile (Ripley & Saugier, 1974).

The minimum ten-day mean $\langle CO_2 \rangle$ occurred in mid-September. This is in agreement with many other measurements made in the northern hemisphere (see Bolin & Keeling, 1963). This minimum value was 28 vpm lower than the maximum value observed in mid-June.

Summary

Measurements of $\langle CO_2 \rangle$ at 6.5 m over a prairie grassland in Saskatchewan during the summer of 1971 show a strong diurnal cycle. The maximum concentration occurs around 0600 solar time and a minimum is found in the afternoon. The amplitude of this diurnal cycle is negatively correlated with the windspeed at night and shortwave radiation

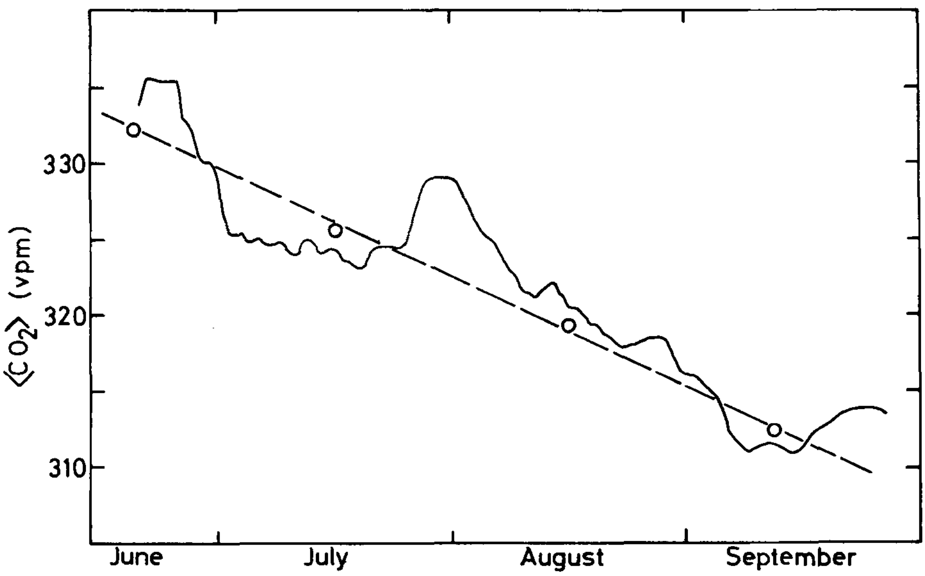

Fig. 7. Seasonal variation of the 10-day running mean ⟨CO_2⟩ at Matador (solid line). The circles represent monthly means and the dashed line is a straight line fitted to these monthly means.

Table 2. *Mean monthly* ⟨CO_2⟩ *and standard deviation in vpm of moist air*

Only days with more than two-thirds of the half-hour summaries available were used. Figures in brackets are number of days

Month	Mean ⟨CO_2⟩
June (8)	332.1 ± 0.5
July (20)	325.4 ± 0.4
August (23)	319.1 ± 0.2
September (26)	312.3 ± 0.1
Overall Mean	322.2 ± 4.2

flux during the daytime. The amplitude decreases through the summer from around 40 vpm in June to less than 10 vpm in September.

Spectral analysis of the ⟨CO_2⟩ indicates weak, irregular variations. Those with periods between 3 and 5 days had a high coherency with windspeed and atmospheric pressure data. The ⟨CO_2⟩ appears to be dependent on wind direction. The ⟨CO_2⟩ was greater when the wind was from 270° to 315° (WNW) than from 100° to 145° (ESE), the two predominant summer wind directions. The phase lag between coherent ⟨CO_2⟩ and atmospheric pressure cycles substantiates this. The reason for this difference appears to be that air from ESE has had a longer residence time, by 2 to 4 days, over the continent with the result that more carbon dioxide has been removed through vegetation photosynthesis.

Part of the annual ⟨CO_2⟩ cycle for the northern hemisphere is visible in the data. The ⟨CO_2⟩ decreases during the summer from a daily mean of about 335 vpm of moist air in June to 311 vpm in mid-September. There is a dip in the curve in July which corresponds to a period of maximum photosynthesis of the grassland vegetation, maximum green canopy biomass and favorable soil moisture.

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КОНЦЕНТРАЦИИ ДВУОКИСИ УГЛЕРОДА НАД ЕСТЕСТВЕННЫМ ТРАВЯНЫМ ПОКРОВОМ В САСКАТЧЕВАНЕ

Вариации концентрации двуокиси углерода ($\langle CO_2 \rangle$) в приземном слое воздуха в течении сезона вегетации 1971г. были проанализированы в терминах трех периодичностей. Суточная периодичность имеет максимум амплитуды внутри слоя растительного покрова, достигаюший $100 \cdot 10^{-4}$ и уменьшаюшийся с ростом высоты. Эта вариация вызывается потреблением углекислого газа днем растительностью В процессе фотосинтеза и высвобождением его ночью при респирации растительностью и почвой. Спектральныйа нализ значений $\langle CO_2 \rangle$ указывает на присутствие нерегулярных вариаций с иериодами между 3 и 5 днями, что представляется связанным с синоптическими масштабами погоды. Наибодьшие значения $\langle CO_2 \rangle$ найдены в воздухе, только что пришедшем с Тихого океана и величины $\langle CO_2 \rangle$ уменьшаются по мере увеличения длины траекторий воздушных масс над сушей, вызывая различия до $7 \cdot 10^{-6}$ в суточном минимуме. Уменьшение в средних суточных значениях $\langle CO_2 \rangle$ на $28 \cdot 10^{-6}$ с июня по сентябрь рассматривается как часть годичной вариации величины $\langle CO_2 \rangle$.