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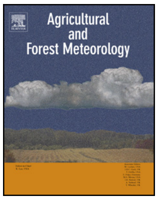

Nocturnal intermittency in surface CO_2 concentrations in sub-Saharan Africa

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ABSTRACT

An exploratory study of CO_2 concentrations and fluxes was conducted during 2013, at a site 12 km North of Harare, Zimbabwe. CO_2 measurements were made over four adjacent fields of differing surface vegetation. The data illustrate the role of atmospheric intermittency as a mechanism for transferring CO_2 between the surface and the atmosphere. At night, limited atmospheric mixing permits CO_2 concentrations to increase to levels well above those conventionally reported (exceeding a spatial average of 450 ppm on some nights), but these high levels are moderated by a periodic intermittency that appears similar to that observed elsewhere and often associated with the presence of strong, synoptic-scale winds aloft (especially low-level jets). The availability of CO_2 data with adequate time resolution facilitates investigation of the general behavior, which is suspected to be a common although rarely observed feature of the lower terrestrial atmosphere. If true, this means that the nocturnal vertical transfer of momentum, heat and mass is not solely through a constrained spectral continuum of turbulence as much as by intermittent bursts, propagating from above and penetrating the surface boundary layer.

1. Introduction

There have been many studies of the exchange of CO_2 between the surface and the atmosphere; indeed there is a large international program (Fluxnet) addressing this issue with globally-distributed sites (q.v. http://fluxnet.ornl.gov/maps-graphics). Inspection of the distribution of Fluxnet sites indicates a paucity of observations in two of the areas of greatest population growth (and hence of the greatest pressure on agriculture): the Indian sub-continent and central Africa. Obtaining understanding to help feed the growing populations in these regions while minimizing adverse environmental impact presents a challenge. Maintaining instrumentation of the kind common in North American and European studies would be technically demanding, and analyzing data in the manner now common to many researchers would require access to uncommon computers.

Nevertheless, there is need to design crop management strategies to improve productivity in an environmentally friendly way. O'Dell et al. (2014) describe an exploratory field investigation conducted in Lesotho, designed to compare long-term CO_2 fluxes over an assortment of surfaces. Subsequently, the experimental activity has been transferred to Zimbabwe, with results that constitute the basis for the analysis presented here. The field installation now reported is far simpler than the set-up favored by most agricultural meteorology researchers. It is designed to require minimal technical expertise, at the lowest feasible cost, while providing data adequate for testing the comparability of CO_2 (and other) fluxes over different agricultural surfaces.

It is not the present intent to analyze the Zimbabwe data in the same detail as is common in similar studies in North America or in Europe (e.g. Salmond, 2005), since such would require instrumentation and data collection more complex than was feasible. Instead, the analysis presented here is intended to draw attention to aspects of the surface boundary layer that are amenable to study without making use of advanced instrumentation or computer resources. It is a demonstration of comparatively simple measurement approaches that might have practical application in demanding circumstances. The micrometeorological flux determinations derived from this study will be presented elsewhere. The focus here will be on the way in which air-surface exchange occurs at night, on the utility of CO_2 records as indicators of

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atmospheric processes, and on the applicability of simplified experimental approaches.

2. Background

The contemporary vision of the processes that contribute to the air-surface exchange of momentum, heat, moisture, and carbon dioxide is that there is a spectrum of turbulent fluctuations of velocity, temperature, humidity and CO_2 concentration such that correlations among them determine the relevant fluxes (q.v. Kaimal et al., 1972). To measure the exchange rates (the fluxes), it is usual to measure the fluctuations in velocity components (primarily w vertically and u horizontally along the mean wind) and the other variables of interest sufficiently rapidly to ensure that the high-frequency end of the flux cospectrum is adequately covered. The necessary frequency is not some universal value, but is determined by the application and the height of measurement. It is typically of the order of 1 Hz. At the low frequency end, there is also no absolute “best value.” The averaging time varies with the intended application, however there are well recognized constraints—(1) that this should not be so long that there is a major change with time, and (2) that it is not so short as to reject flux-carrying fluctuations. In most field work, averaging times of 15 min to 60 min are used.

An alternative methodology relies on measurements of vertical gradients and the application of eddy diffusivities derived from other considerations. In this case, the necessary precision of measurement becomes a major consideration, however the averaging time guidelines remain the same. In the field study reported here, the adoption of a modified Bowen ratio approach to the measurement of CO_2 exchange rates (Kanemasu et al., 1979; Dugas, 1993; and as discussed by O’Dell et al., 2014) permits consideration of data collected and reported as averages over shorter periods (5 min) from which longer averages can be constructed as the need arises. This finer time resolution of the reported data allows an unconventional examination of the dataset, as follows.

3. Experimentation

The study area is at 17.7220° S, 31.0209° E, at an elevation of 1494 m above sea level. It is part of an experimental farm, about 12 km north of Harare (the capital of Zimbabwe), operated by the International Maize and Wheat Improvement Center (CIMMYT). As is shown in Fig. 1, an experimental area about 160 m × 160 m is divided into four squares, each about 0.6 ha. Two of these squares are seeded—one in wheat (*Triticum aestivum*) and the other in blue lupin (*Lupinus angustifolius*). One of the remaining squares is untilled and has been left fallow for one year. The fourth square has been recently tilled, but is unseeded. This distribution of plots has been arranged to quantify differences in CO_2 fluxes from the different plots (with emphasis on the tilled/untilled dichotomy). Centrally over each plot, measurements are made of temperature, humidity, net radiation, surface IR temperature and CO_2 concentrations. Wind speed is measured near the central point of the four plots. All meteorological instrumentation was supplied by Campbell Scientific, Inc., of Logan, Utah. Details of specific instruments are provided elsewhere (O’Dell et al., 2014). Heights of measurement average about 1 m above the top of the local canopy for most of the quantities, and about 3 m for the wind speed.

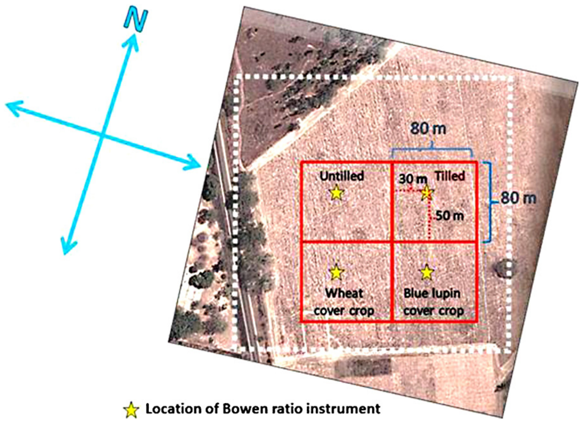

Fig. 1. The experimental area used in the present study.

Sensors are interrogated by a solar-powered (battery backup) data acquisition system at a frequency of 1 Hz. Data are recorded as 5 min averages (thus prohibiting post-event analysis using, for example, frequency spectral or wavelet analyses). Data are routinely transferred for scrutiny at the University of Tennessee. The data record considered here commenced in June 2013 (soon after germination), and extended through the remaining part of the year. Maintenance of the instrumentation has been through the facilities of CIMMYT.

The present focus is to examine the absolute concentration data and to derive evidence for nocturnal intermittency due to synoptic-scale features aloft. Data from the four CO_2 instruments are used here. The number of sensors generates confidence in the averages derived from them. Conspicuous departures in the time series derived from one sensor, relative to the others, has been used as an indicator of questionable data, replaced by linear interpolation. The resulting time sequence of CO_2 average concentrations with 5-min time resolution is the basis for the analysis below.

4. CO_2 concentrations

Fig. 2 shows average CO_2 diurnal cycles for the months of August and November. Corresponding average cycles of air temperature are also shown. As expected, CO_2 concentrations peak at night, when emission is highest and when vertical mixing is minimal. Concentrations are lowest in daytime, when vertical mixing is most effective due to the role of surface heating and the resulting convection. The November peak concentrations are considerably greater than the August, due to the contribution of the wheat plot to the averages considered here. (The amplitude of the wheat diurnal cycle is several times greater than the next largest—blue Lupin. Differences of this kind will be examined elsewhere.)

Also shown in Fig. 2 are ±one standard deviation error bounds. For August, the daytime CO_2 data are far less variable than the nighttime. For November, the variability is considerably greater for the entire diurnal cycle, presumably because of the variability in photosynthetic activity of surfaces in the area. (The wheat and blue Lupin plots were senescent or approaching senescence at that time.) The air temperature records behave differently, in that there is no consistent difference in variability from August to November, although the averages change as expected. Note, however, that the inflexions at dawn are clearly noticeable, about 1 h earlier in November than in August, with consequences also seen in the CO_2 records.

Fig. 3(a) presents a 20-day sample of the CO_2 time record. To clarify the day-night variability, the original 5-min data have been subjected to a 20-min running mean before plotting. Diurnal cycles are obvious, with minimal concentrations occurring in daytime and with maxima at night. Fig. 3(b) is an expanded view of part of the record shown in Fig. 3(a). It is clear that considerable variability occurs at night, but details of this variability are not readily apparent because of the 20-min running mean used. There is obvious fine structure in the data; however, at a level exceeding that observable in the daytime portion of the plot.

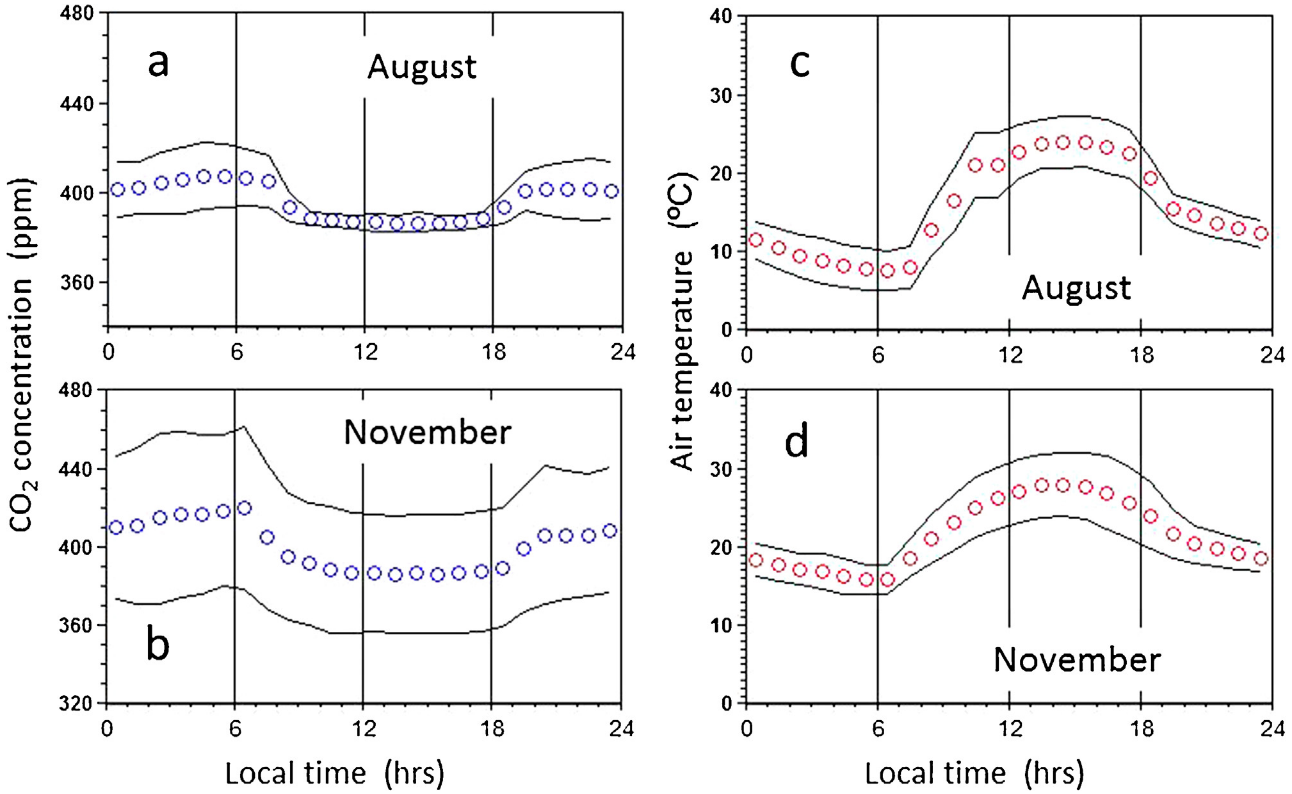

Fig. 2. Average diurnal cycles of CO_2 concentration (the two diagrams to the left) and of air temperature (to the right) for the months of August and November. The points plotted are hourly averages. In each plot the lines indicate the corresponding ±one standard deviation bounds.

The red bars drawn in Fig. 3 indicate periods of readily detectable intermittency of turbulence, which will be examined in a later section.

5. Surface stability

The exceedingly high nighttime concentrations represented in the diagrams of Fig. 3 result from biological exhalation of CO_2 while vertical diffusivity is low. In daytime, vertical mixing is heavily influenced by convection, resulting from radiative heating of the surface. At night, the surface cools to well below air temperature and air in contact with it becomes stably stratified. This stable stratification greatly reduces vertical mixing.

The present dataset includes measurements of wind speed (u), air temperature (T_a), and infrared surface temperature (T_s, obtained using downward-looking infrared thermometers). From these measurements, values of the bulk Richardson number

$$Ri(B) = \frac{(gz/\theta) \times (T_s - T_a)}{u^2} \qquad (1)$$

have been calculated and plotted in Fig. 4 (the two diagrams to the left), along with the corresponding CO_2 concentration data. Here, g is the acceleration due to gravity, z is the height of measurement, and θ is the absolute temperature. One-hour averages are plotted, centered on midnight (for the upper pair of diagrams) and on 04:00 (the lower pair). These two times are selected as examples, as is the period identified for presentation. The association between the nighttime CO_2 concentration and the degree of stratification is clear and convincing. The two panels to the right show a similar correlation, involving the measured net radiation. The overall behavior aligns with expectations—that those occasions with the highest radiative cooling of the surface (i.e. cloud-free nights) permit the strongest surface stratification to occur, with consequent minimal vertical mixing leading to a pooling of emitted CO_2.

Examination of an extended period of data, as shown in Fig. 5, reveals that the nocturnal radiation loss and resulting surface stratification diminishes as time progresses. It is presumed that this results from the vegetation growth at the surface rather than from external forces (such as larger-scale atmospheric factors), but this remains unproven. A longer record of data at the same site will enable a closer examination of this aspect.

6. Intermittency

CO_2 is well recognized to be an informative indicator of surface boundary layer intermittency. The red bars shown in Fig. 3 identify occasions when a particular 5-min average CO_2 concentration is less than the preceding 20-min average by more than 5 ppm. This is used here as a criterion for identifying occurrences of sudden mixing with air aloft, presumably having lower CO_2 concentrations. The criterion is especially relevant at night, when the stable stratification of the lower atmosphere causes near-surface concentrations of CO_2 to grow steadily, until the resulting CO_2 reservoir is exhausted (or at least partially exhausted) by a sudden incursion of (or access to) air with a lower CO_2 level, such as from the layers of air above the surface boundary layer. Classical examinations of this phenomenon (also referred to as “surface renewal,” e.g. Paw et al., 1995) have generated several appropriate “rules of thumb,” among which is the expectation that such events occur about every hour.

The overall behavior is reminiscent of quadrant analyses presented by workers elsewhere (e.g. Katul et al., 2006) and of early observations of “sweeps” and “ejections,” (mainly in the context of forests, Gao et al., 1989; Katul et al., 1997). The behavior now evident is attributed to bursts of turbulence occurring both in daytime and fairly regularly through some (but not all) nighttime hours. At night, surface boundary layer concentrations build up as vertical mixing (and associated dilution) remain minimal, but are rapidly

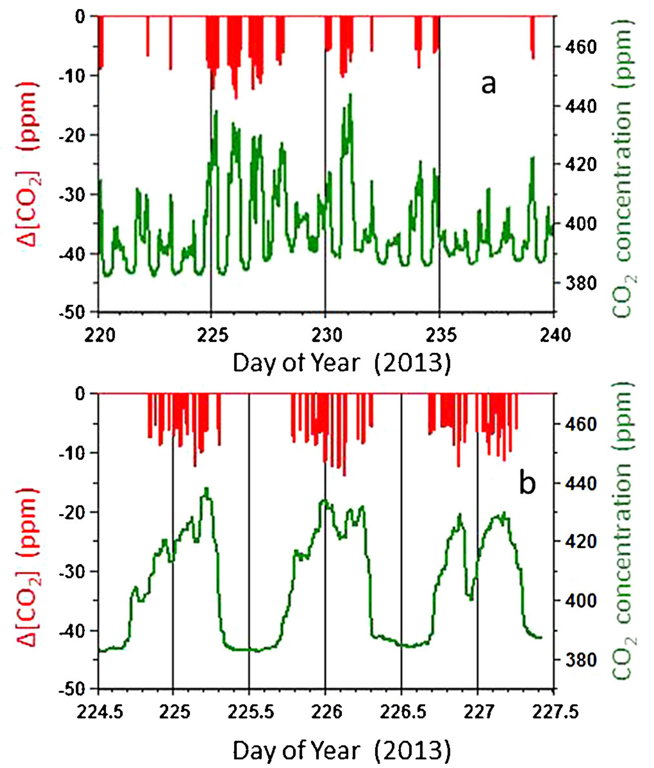

Fig. 3. Examples of the records of average CO$_2$ concentration (in green) for a 20-day period in August (the upper diagram) and for a three-day period extracted from it (the lower diagram). Also indicated (in red) are occasions when the 5-min CO$_2$ average concentration was lower (by at least 5 ppm) than the average of the preceding 20 min. These intermittency data are plotted as the difference between the 5-min observation and the preceding 20-min average. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

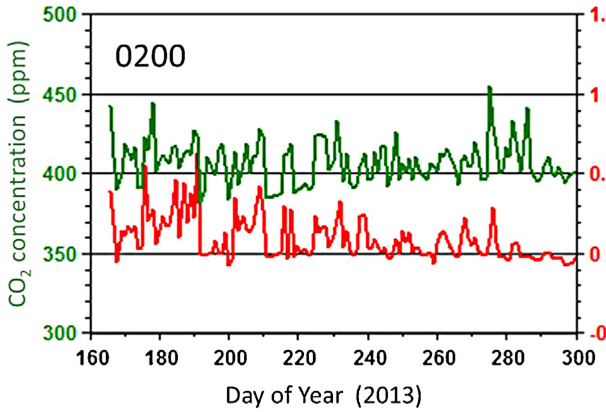

Fig. 5. The extent of CO$_2$ pooling at the surface, illustrated by a longer-term record (average CO$_2$ data in green) and the corresponding surface stratification index (Ri(B), in red). Data plotted represent hourly averages centered at 02:00 h. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

reduced as soon as a burst of turbulence occurs. (Note that such a burst of turbulence could cause a negative departure to be followed by a positive one, but this need not necessarily be the case since the return could be gradual and hence less detectable.) Several authors have addressed this and related phenomena, mainly with a focus on the forest environment (e.g. Baldocchi and Meyers, 1989; Oliveira et al., 2013).

The energy necessary to generate such a burst of turbulence is necessarily aloft, where high winds are characteristic and low-level jets can occur. Such is not the case in daytime, when the dominant source of turbulent energy is the solar heating of the surface and the resulting generation of convection. However, in daytime, somewhat similar intermittent behavior is sometimes observed.

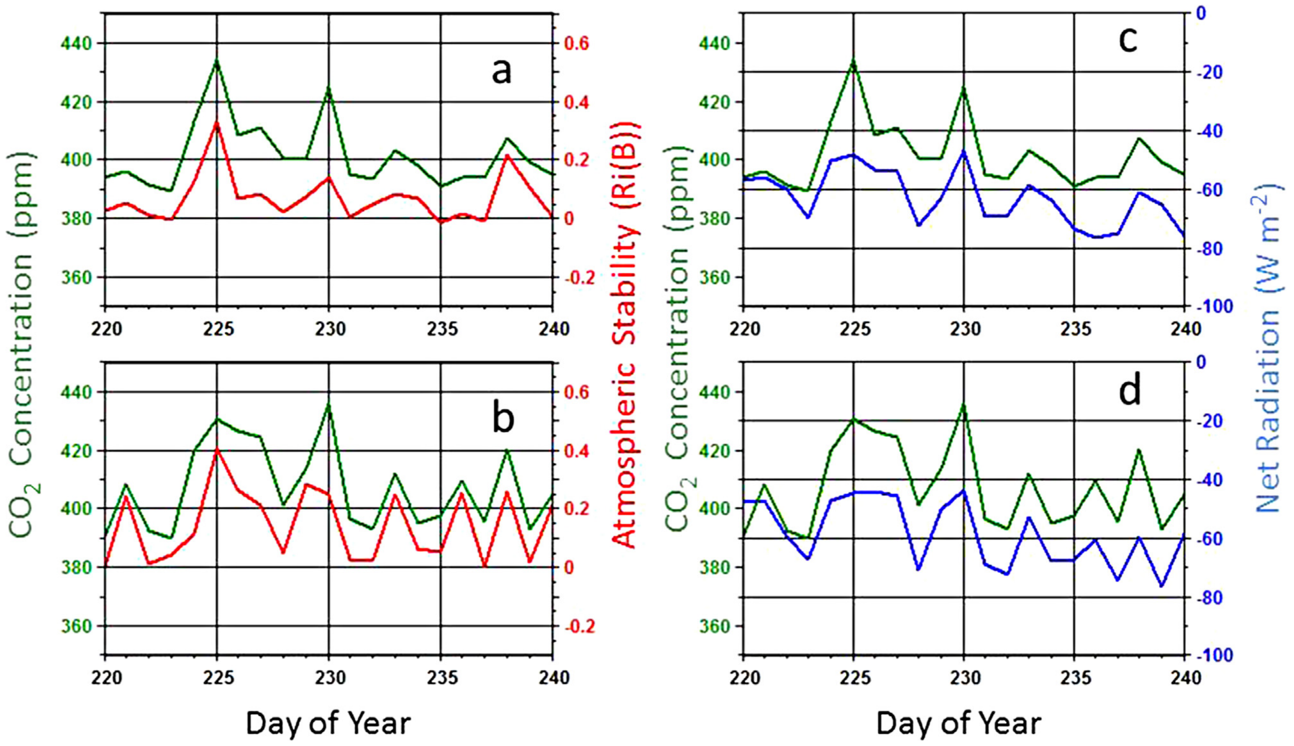

Fig. 4. For the same 20-day period as Fig. 3, a plot of the reported 1 h average CO$_2$ concentrations at midnight (the upper pair of plots) and at 04:00 h (the lower pair). To the left, the CO$_2$ record (in green) is compared with that of surface-layer bulk stability (Ri(B), shown in red); to the right, the comparison is with the reported average net radiation (in blue). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

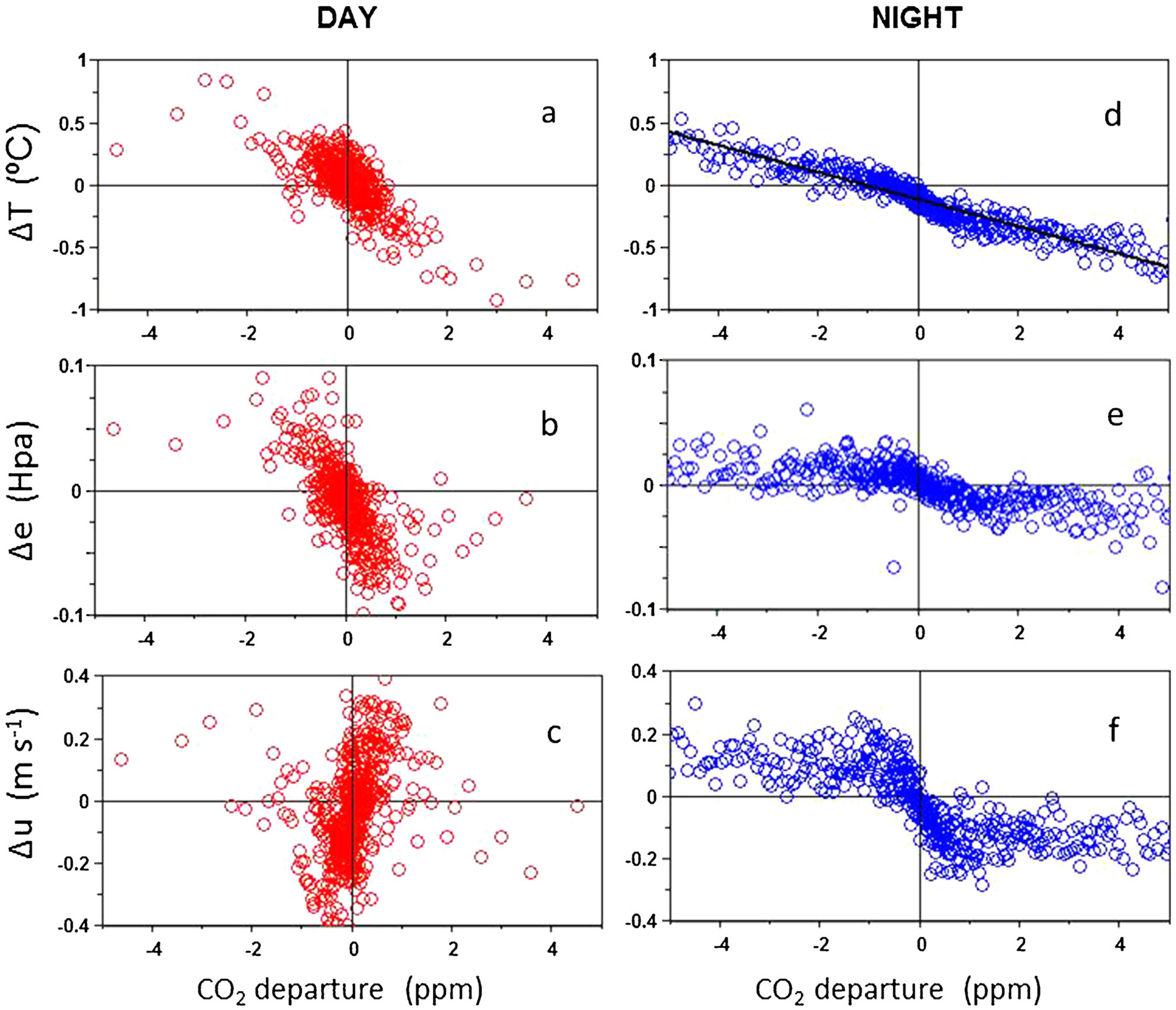

Fig. 6. Building upon the results shown in Fig., now shown are the departures of individual 5-min averages from preceding 20-min averages of temperature, humidity and wind speed (ΔT, Δe and Δu, respectively), plotted against the corresponding differences for CO_2 concentration, without any constraint on the magnitude or the direction of these deviations. The data plotted are averages over groups of 25 observations, constructed sequentially after ordering according to the CO_2 deviation. To the left are daytime data (11:00–16:00 h), to the right are nighttime (23:00–04:00 h).

The overall behavior reported here appears compatible with convention, associating the nighttime bursts of turbulence mainly with “sweeps” and the daytime occurrences mainly with “ejections” (q.v. Paw et al., 1992; Raupach, 1995). The present observations appear to indicate that the nighttime phenomenon in question is widely relevant, as might be expected on the basis of current understanding of the low-level jet and its interactions with the stable boundary layer over land (see Banta, 2008).

The regularity of the events is impressive. In essence, the classical guideline of about one every hour appears to be approximately correct for this site. It is also clear (referring back to Fig. 3) that the most stable conditions are the most likely to be subject to intermittency of the kind addressed here.

7. PBL implications

The Planetary Boundary Layer (PBL) is the lowest part of the atmosphere, which responds to the diurnal cycle of solar radiation affecting the surface. To explore further the relevance of PBL factors, two subsets of data have been generated, intended to represent the central daytime and nighttime periods—11:00–16:00 and 23:00–04:00. Fig. 6 presents the results. All data within the selected time periods have been used: there are no exceedance criteria involved. The values plotted are averages, constructed over sequential groups of 25 runs after sorting according to the CO_2 departure as explained above. The dichotomy between daytime and nighttime is obvious. The plots demonstrate the greatly reduced amplitude of CO_2 intermittences for daytime, relative to night.

The amplitudes associated with the other signals illustrated (humidity and wind speed) also appear greater in daytime than at night. Most striking, however, is the lack of consistent order for the daytime data, and the relative coherence for the nighttime case. This is especially true for the temperature plot (Fig. 6(d)), where a regression line is drawn, representing a linear fit with a slope of 0.09 °C ppm^{-1} and a correlation coefficient of −0.94. In general; however, the three diagrams for the nocturnal case share a common feature, that near the origin the slope is great and the association strong, but outside the central part of the diagram the three meteorological variables appear to approach constant values whereas there is no such constraint influencing the CO_2 case.

Examination of the data reveals many instances in which episodic behavior at night is not evident. When the intermittency occurs, it appears to be a major (if not THE major) mechanism for transferring quantities between the surface and the air aloft, at night. This competes with the conventional view that at night the surface boundary layer becomes sufficiently stratified that vertical exchange is limited to exceedingly low values, because of the setting up of strongly stable layers near the surface. Here it is shown that such stable stratification can be penetrated by bursts of turbulence, presumably originating with the velocity regime aloft.

8. Conclusions

The results presented here demonstrate the utility of simplified experimental strategies for addressing issues of air-surface exchange in challenging circumstances. The value of the resulting data stream is exemplified by the finding that PBL factors appear to modify the exchange, especially at night. The conventional view of nocturnal air-surface exchange invokes an assumption of minimal vertical mixing through nighttime hours, because the surface-layer stratification is then known to be strong and therefore limiting vertical diffusion. This perspective relates the behavior of the surface boundary layer to the surface characteristics surrounding and upwind of the point of observation (e.g. see Launiainen et al., 2007). While this view might be adequate in daytime, when vertical transfer is dominated by convection, the present work illustrates an alternative perspective for the nocturnal case. At night, stability at the surface can permit air aloft to move more freely, promoting the generation of velocity maxima (“low-level jets”) whose speed gradually increases until turbulence is generated by the wind shear (e.g. see Karipot et al., 2006). The resulting burst of turbulence propagates downwards, bringing with it an increase in temperature at the surface and an increase in ground-level wind speed. The coupling of a downburst with a wind speed increase implies a periodic exchange of momentum, possibly irrespective of the detailed characteristics of the surface but instead depending on synoptic-scale factors. The way in which the intermittent exchange reported here relates to the classical view of a turbulence continuum and an application of conventional eddy covariance approaches remains to be explored.

It is clear that the nocturnal intermittency phenomenon is not always present at the site considered here. Final resolution of the questions that necessarily arise will require monitoring of winds aloft, with much the same detail as has been the basis for legacy surface boundary layer studies. Instead of focusing attention on the part of the atmosphere that is most easily observable, the present data indicate that attention should be given to that part where (according to the present interpretation) the important processes might originate.

It is shown here that investigation of CO_2 concentration fluctuations in air near the surface can be very revealing. It is planned to extend the present experimental program, with attention to several factors now evident but not reported here—e.g. the role of local surface variability (here, averages have been used rather than fetch-specific behavior) and, if feasible, the role of synoptic features of the atmosphere. Following the apparent success of the initial field program, the experimental set-up has now been refined to include sonic anemometry.

Two final conclusions are obvious. First, comparatively inexpensive instrumentation and simplified analysis (as reported here) can lead to an improved understanding of what controls air-surface exchange in demographically challenging situations. In this regard, it is hoped that additional simplified field experiments will be conducted, and that the results of these will help the development of improved agricultural strategies appropriate for a wide variety of conditions. Second, whereas the daytime mechanisms and magnitude of atmospheric CO_2 exchange with the surface are relatively well understood, those for the nighttime case are not. In particular, it is incorrect to assume that surface stratification will necessarily minimize average exchange rates of CO_2 over land, since quasi-regular nocturnal intermittency can play an important role. How this phenomenon relates to the exchange of other quantities remains to be assessed, as do its spatial and temporal extents.

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