Measurements of carbon dioxide and heat fluxes during monsoon-2011 season over rural site of India by eddy covariance technique

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An increase in carbon dioxide (CO_2) concentrations in the atmosphere due to anthropogenic activities is responsible for global warming and hence in recent years, CO_2 measurement network has expanded globally. In the monsoon season (July–September) of year 2011, we carried out measurements of CO_2 and water vapour (H_2O) concentrations along with wind and air temperature over a tropical site in southeast India having rural topography. To collect these observations, the instrumentations used were the sonic anemometer for wind and temperature, and the open path H_2O/CO_2 infrared gas analyzer for CO_2 and H_2O concentrations. Using these observations, we explored the diurnal variability of CO_2 flux along with sensible and latent heat. The CO_2 flux was positive during night-time and negative during daytime and in phase with convective instability. The CO_2 flux relationships with the meteorological parameters such as wind speed, temperature and heat fluxes have been analysed. The seasonal (monsoon) half hour mean of CO_2 flux which was -3.55 μmol m^{-2} s^{-1} indicated the experimental site as a CO_2 sink region (net seasonal uptake). An increase in CO_2 concentrations during weekends was not observed due to unavailability of heavy vehicular traffic.

1. Introduction

The increased concentration of greenhouse gases (GHGs), including carbon dioxide (CO_2), in the atmosphere due to anthropogenic activities is responsible for global climate change and increases in the intensity and frequency of extreme weather events (IPCC 2007). Due to the significant increase in atmospheric CO_2 over the last few decades (Keeling *et al.* 1995; Artuso *et al.* 2009), exchange of CO_2 between the atmosphere and the biosphere and oceans has become a major focus of research through its measurements by different techniques. In the recent study (Artuso *et al.* 2009), the CO_2 concentration showed a linear growth of 1.9 ppm yr^{-1} (parts per million per year) for the

years from 1992 to 2008. Human activities such as fossil fuel emissions, cement production, and land use changes contributed to the noteworthy increase of atmospheric CO_2. The changes in land use, determined a considerable reduction of CO_2 uptake capacity by plants, which amplified the general global increasing trend. The available global CO_2 records are used for predicting its future trend and for planning international policy strategy for its reduction. In order to validate the inventory data, independent methods based on atmospheric measurements have been suggested recently (Gibert *et al.* 2007; Casso-Torralba *et al.* 2008; van der Laan *et al.* 2009; Worthy *et al.* 2009).

Many studies from tropical region (Brummer *et al.* 2008; Lohou *et al.* 2010) and mid-latitudinal

region (Lee and Hu 2002; Pawlak *et al.* 2011; Barr *et al.* 2012) depicted intra seasonal and annual characteristics of CO_2 fluxes over different land surfaces. The urban area acted as a source for CO_2 (Song and Wang 2012). There are very few studies available from the Indian subcontinental region (Dharmaraj *et al.* 2012). The presented results are the first of CO_2 measurement at the site of south-east India, and one of the very few by eddy covariance technique. The aim of this work is to quantify the CO_2 concentrations and fluxes in rural area of south-east region of India. The CO_2 observations are analyzed in terms of its diurnal variability with the progress of monsoon. The correlations of CO_2 flux with meteorological parameters have been proposed. The analysis presented in this study could be helpful to improve how the rural regions of Indian subcontinent are to be incorporated in the air quality and climate models.

2. Experimental site and instrumentation

The Eddy Covariance (EC) system was installed over a station Mahabubnagar (16.44°N, 77.59°E, 498 m a.s.l.) in south-east India in the monsoon period of 2011 as a part Cloud Aerosol Interaction and Precipitation Enhancement Experiment – Integrated Ground Observations Campaign (CAIPEEX-IGOC). The measurement site is on the outskirts of the city at a distance of ∼15 km, with rural characteristics. The population of the Mahabubnagar city is ∼0.158 million and no significant industrial activities are found near the site. Coal, gas and oil consumed for communal and transport purposes generate the main flux of anthropogenic CO_2 within the region. No thermal plant or cement factory is located in the Mahabubnagar district. Thus, strong anthropogenic sources of CO_2 are absent in the immediate vicinity of the measurement site. The vehicular traffic was low with about 10 vehicles passing in one hour. The railway track was at a distance of about 0.5 km in the south with low traffic. The railway route was unelectrified and consumed diesel. One rice mill (unoperational in monsoon) was available at a distance of 1 km in the north. In the surrounding area, people used wood and kerosene for cooking purpose. The Mahabubnagar city, which is the district headquarters is about 15 km away from the experimental site. A small residential locality with 15–20 huts was in the south-west direction at about 0.7 km. A water reservoir, *Koilpatti*, existed at a distance of about 30 km in the south-west. Thus, the contributors for CO_2 production were partially from vehicular and domestic cooking, agricultural practice, etc. The slope of the site was horizontal, one hill (∼800 m high) was located at about 2 km

in the west. Towards west and north, at a distance of about 100 m, thorny plants with a height of about 1 m were available. Towards east and south, at a distance of about 100 m, paddy crop was available with a height of 0.2 m in the month of August which increased to about 0.80 m in September.

The EC system consisted of the CO_2/H_2O open path gas analyzer (Model LI-7500A by Licor Inc.) integrated with 3D sonic anemometer (Model wind master Pro by Gill Instruments). The distance between the sonic anemometer and CO_2/H_2O analyzer was about 20 cm (figure 1). The wind and temperature as well as CO_2 and H_2O observations

Figure 1. Location of the observational site.

were sampled at 10 Hz. Since both the sensors were part of the EC system, and were integrated to single data logger (LICOR), there was no time-lag in measurement by both the sensors. The complete description of both the sensors is given in table 1.

The EC sensors were mounted on 20 m mast as shown in figure 1. The EC observations were taken at 8 m height upto August 4, 2011 and later, the system was shifted to 6 m height to make provision for other measurements at 8 m. The precipitation

Table 1. *Specification of eddy covariance system installed during CAIPEEX-IGOC.*

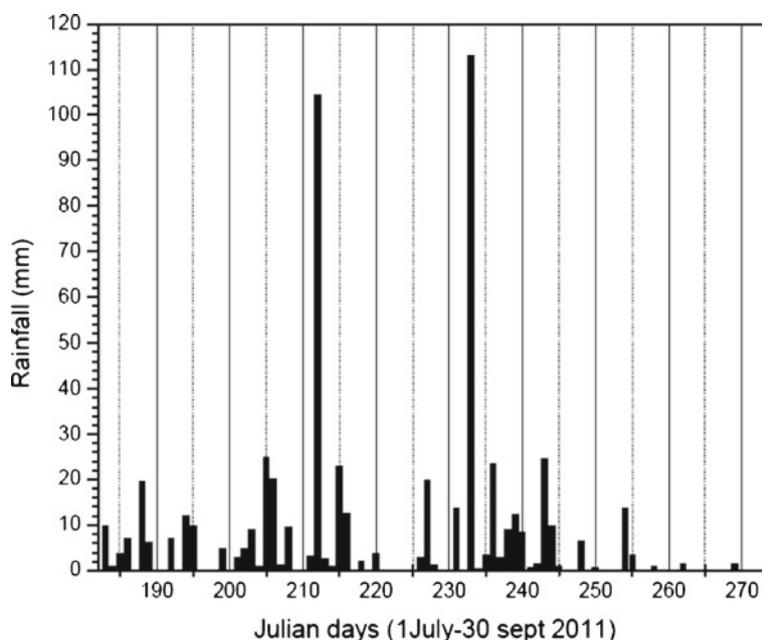| CO$_2$/H$_2$O gas analyzer-Model LI-7500A	3D Sonic anemometer-Model WindPro
Type	**Outputs**
Absolute, open-path, non-dispersive infrared gas analyze	Output rate: 1, 2, 4, 8, 10, 16, 20, 32 Hz
Detector	Sample rate (automatically selected): 20 or 32 Hz
Thermo-electrically cooled lead selenide	Units of measure: m/s, mph, KPH, knots, ft/min
Output rate	Averaging : Flexible 0–3600 s
5, 10, or 20 Hz, software selectable	
Path length	**Wind speed**
12.5 cm	Range : 0–65 m/s
Calibration range	Resolution : 0.01 or 0.001 m/s
For CO$_2$: 0–3000 ppm	Accuracy (12 m/s) (Standard)* : <1.5% RMS
For H$_2$O: 0–60 ppt	Accuracy (12 m/s) (to special order)* # : <1.0% RMS
Accuracy	
For CO$_2$: within 1% of reading	**Wind direction**
For H$_2$O: within 2% of reading	Range: 0–359.9
Zero drift (per $^\circ$C)	Resolution : 1 or 0.1
For CO$_2$: ±0.1 ppm typical; ±0.3 ppm max.	Accuracy (12 m/s) (Standard)* : 2
For H$_2$O: ±0.03 ppt typical; ±0.05 ppt max.	Accuracy (12 m/s) (to special order)* # : 0.5
	Speed of sound
	Range : 300–370 m/s
	Resolution : 0.01 m/s
	Accuracy : < ± 0.5% @20°C
	Sonic temperature range: −40°C to +70°C

Figure 2. Rainfall recorded over Mahabubnagar during July 1 to September 30, 2011.

recorded during the period of observations is shown in figure 2.

3. Estimation of fluxes

The sonic anemometer measured the longitudinal (u), lateral (v) and vertical (w) components of wind and virtual air temperature, where as the LICOR CO_2/H_2O analyser system measured the CO_2 and water vapour concentrations (water vapour mixing ratio-q). The fluctuating components of u, v, w, θ, q and ρCO_2 are derived using following equations.

$$u' = u - \overline{u}, \quad (1a)$$

$$v' = v - \overline{v}, \quad (1b)$$

$$w' = w - \overline{w}, \quad (1c)$$

$$\theta' = \theta - \overline{\theta}, \quad (1d)$$

$$q' = q - \overline{q}, \quad (1e)$$

$$\rho CO_2' = \rho CO_2 - \overline{\rho CO_2}. \quad (1f)$$

The primes represent the fluctuations and over-bar the averages over the period of 30 minutes. Initially, we removed the observations that were made during the rainy hours. The natural wind coordinates were rotated for minimizing the effect of vibrations and deviation of the sensors according to Lee *et al.* (2004). Later, the fluxes were estimated using the following relations:

$$FCO_2 = \overline{w' \cdot \rho CO_2'} \quad (2)$$

$$H = \rho Cp \, \overline{\theta' w'} \quad (3)$$

$$LE = \rho Lv \, \overline{q' w'} \quad (4)$$

$$u_* = \left[\left(\overline{u'w'} \right)^2 + \left(\overline{v'w'} \right)^2 \right]^{\frac{1}{4}} \quad (5)$$

where FCO_2, H, LE are the fluxes of CO_2, sensible heat and latent heat, respectively, u_* is the friction velocity. ρ is the air density, Cp the

specific heat at constant pressure and Lv is the latent heat of vapourization. The observations collected at 10 Hz for 30 minute durations were stored in a single data file which consisted of 18,000 sample points. Each data file is processed separately. The instantaneous observations which have occasional spikes due to both electronic and physical noise were checked in each file for spikes. If some spikes were detected, they were removed and those erroneous data points were replaced with the interpolated value of that observation. In all the available data files, very few files with few spikes were found. An arithmetic mean of 18,000 data samples of each variable is estimated and used to estimate the fluctuating component of that variable as shown in equations 1(a–f). The WPL correction for density effects due to heat and water vapour transfer (Webb *et al.* 1980) and data quality control test for steady state and integral turbulence characteristics (Foken and Wichura 1996) have been applied. Since we used the open-path CO_2/H_2O gas analyzer (Model LI-7500A), the sensor response time delay is ignored.

4. Results and discussion

4.1 *Diurnal variation of CO_2 flux*

The diurnal variations of CO_2 flux vary from rural site to urban site. Over the rural site (free from anthropogenic activities), only one maxima in the CO_2 observations, connected with diurnal convection is observed, but over an urban site, more maximas (Coutts *et al.* 2007) connected with vehicular traffic load, domestic activities, cultural festivals, etc., are observed. Opposite to the observation over rural site, CO_2 flux could be positive during daytime (Coutts *et al.* 2007; Pawlak *et al.* 2011) over an urban area because of insufficient photosynthesis. Figure 3 shows the diurnal variation of (a) CO_2 flux, (b) H_2O flux, (c) CO_2 concentration, (d) H_2O concentration, (e) sensible and latent heat flux and (f) friction velocity observed on September 24, 2011. A pronounced diurnal variation is seen in all the above parameters. The CO_2 flux was observed to be negative (uptake) during daytime and positive in the night-time. The maximum CO_2 uptake was observed in the noon hours (figure 3a) when the intensity of solar radiation was high. Being a rural site, we observed one diurnal maxima (peak) at 10–12 hrs IST in CO_2 flux. During daytime, Lohou *et al.* (2010) observed the CO_2 flux in range of −6 to −20 µmol m^{-2}s^{-1} in rainy season (May–September) over the tropical Nangatchori site in northern Benin, located in a Sudanian–Guinean vegetation-type area, surrounded by woodland, crops and fallow. The CO_2
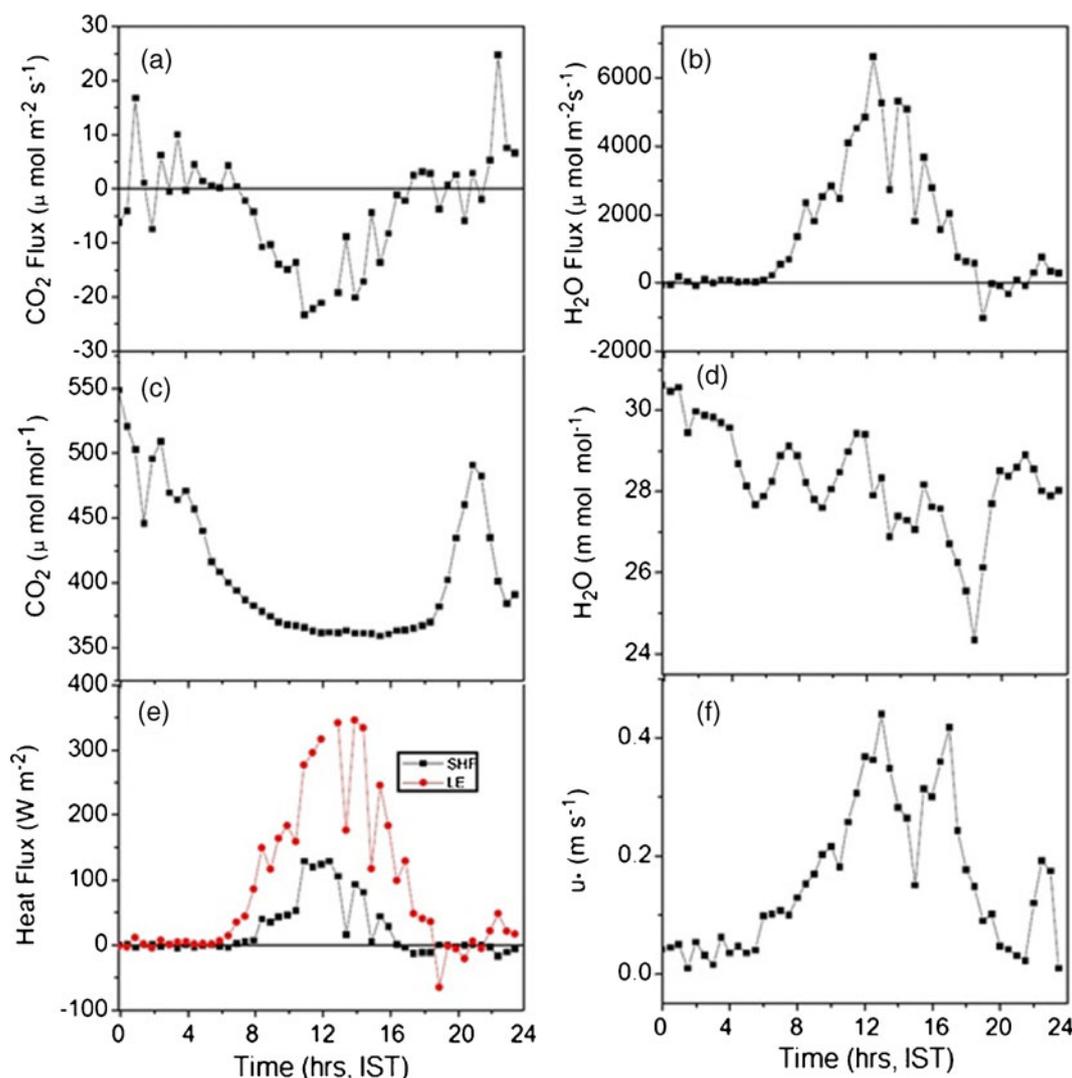
Figure 3. Diurnal variation of (**a**) CO_2 flux, (**b**) H_2O flux, (**c**) CO_2 concentration, (**d**) H_2O concentration, (**e**) sensible and latent heat flux and (**f**) friction velocity observed on September 24, 2011.

flux observed by Lohou *et al.* (2010) corroborated with the result presented in this study. The water vapour flux (figure 3b) showed maxima at noon (1200 hrs, IST).

As seen in figure 3(c), a minimum CO_2 concentration was observed in the afternoon hours and maximum at around midnight (2330–0100 hrs, IST). It is evident that the atmospheric concentrations of trace gases within the boundary layer are controlled to a large extent by intensity of vertical mixing processes (Emeis 2008). During daytime, when strong thermal convection prevails, CO_2 emitted from the surface is diluted in a large volume of well-mixed boundary layer, hence the low CO_2 concentration in the noon hours. After the sunset, vertical mixing is reduced. The diurnal variation of CO_2 reported in this study is in agreement with the results of Reid and Steyn (1997). During the periods of low wind speed, when advection is small, this leads to accumulation of

CO_2 emitted from the surface and its concentrations within the boundary layer start to increase. Hence, the CO_2 concentration was increased in the night-time as seen in figure 3(c). Thus, a CO_2 uptake flux in the noon hours was greater due to the biogenic processes whereas minimum CO_2 concentration was due to the intense convective instability, biospheric photosynthesis and greater boundary layer height. In low friction velocity (0–0.10 ms⁻¹), the CO_2 flux was ranging from −5.0 to +7.0 µmol m⁻²s⁻¹. Two peaks in the CO_2 concentration, one at 2100 hrs and another at 0000 hrs (figure 3c) were observed. Such peaks were not observed on all the days. Sometimes, besides midnight peak value, another peak was noticed at 1000 hrs. Such abnormal peaks could be due to emission of CO_2 by a train passing at that time. The peak shown in figure 3(c) is well pronounced because of the absence of solar radiation and accumulation of CO_2 in stable boundary layer.
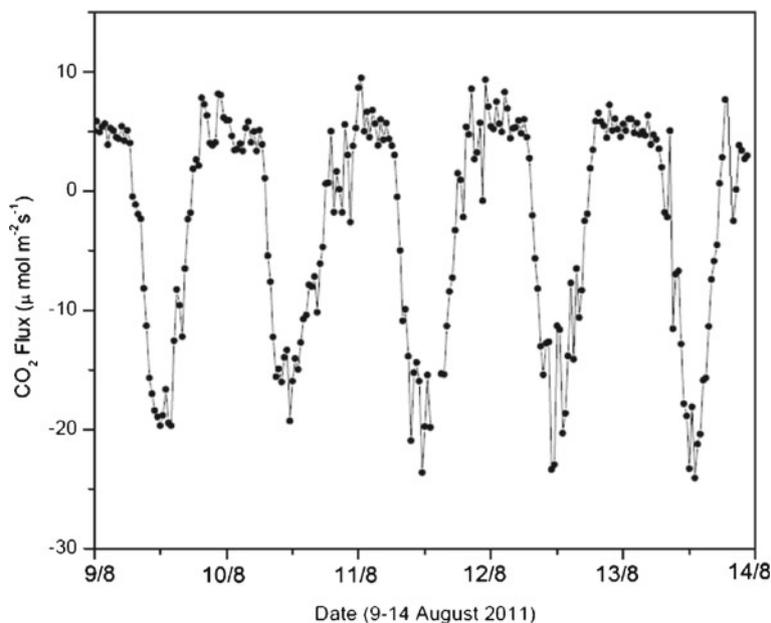
Figure 4. Diurnal variation of CO_2 flux during 9–14 August, 2011 over Mahabubnagar.

However, during noon time, CO_2 concentration is dispersing CO_2 in a large volume of unstable boundary layer. The peak observed at midnight is an undisturbed diurnal maxima which is observed on all days. The water vapour concentration was greater in the midnight hours (figure 3d). The diurnal variation in sensible and latent heat flux (figure 3e) showed greater magnitude in the noon hours due to an intense convective instability. The water vapour flux (figure 3b) and friction velocity (figure 3f) were also greater at this time.

Figure 4 shows diurnal variation of CO_2 flux observed during the non-rainy period of 9–14 August, 2011 over the observational site. The CO_2 flux was in the range of −24.1 to 9.5 µmol m^{-2}s^{-1}. Observed night-time flux in this study is comparable with the results by Lee and Hu (2002) over the mid-latitudinal region of mixed forest on non-flat terrain. They observed positive flux of CO_2 (>23 µmol m^{-2}s^{-1}) frequently at night hours. Kidston *et al.* (2010) observed the CO_2 flux in the range of −6 to 4 µmol m^{-2}s^{-1} in the summer season over Jack Pine forest of Canada. It is also evident that the subtropical plantations are the large carbon sinks (Chen *et al.* 2011). A mean of half hourly CO_2 flux over a period of whole monsoon (July–September) period was observed to be −3.55 ± 9.48 µmol m^{-2} s^{-1}, which indicated that the region of Mahabubnagar is not a source of CO_2, but it is a sink region. The seasonal mean of CO_2 concentration was observed to be 385.90 ± 18.87 ppm. The median for July to September (monsoon season) of CO_2 concentration and CO_2 flux was observed to be 382.52 ppm and −3.10 µmol m^{-2}s^{-1}, respectively. An analysis also
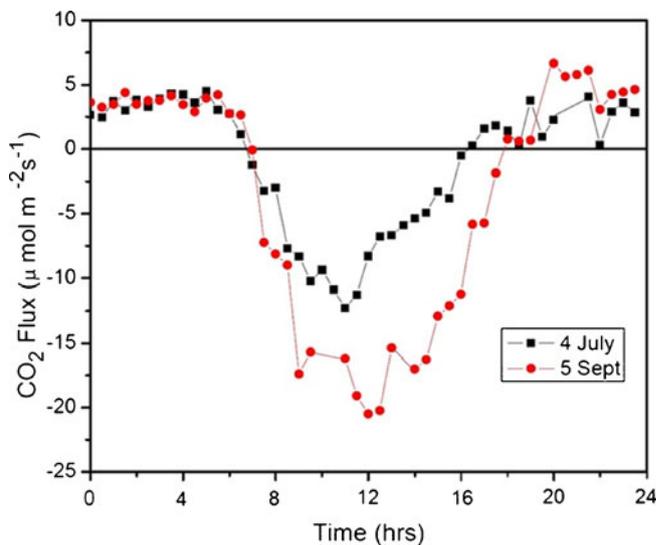

Figure 5. Diurnal variation of CO_2 flux on 4th July and 5th September, 2011.

showed that there was no change in the CO_2 concentration on weekend days due to absence of heavy vehicular traffic.

4.2 *Effect of soil moisture on diurnal variation of CO_2 flux*

It is evident that the vegetation is the net storage/sink of CO_2. The plants use CO_2 in the photosynthesis process. Figure 5 shows the 30 min. CO_2 flux observed on 4th July and 5th September, 2011. The southwest monsoon arrived over the experimental site on 11 June. The observations
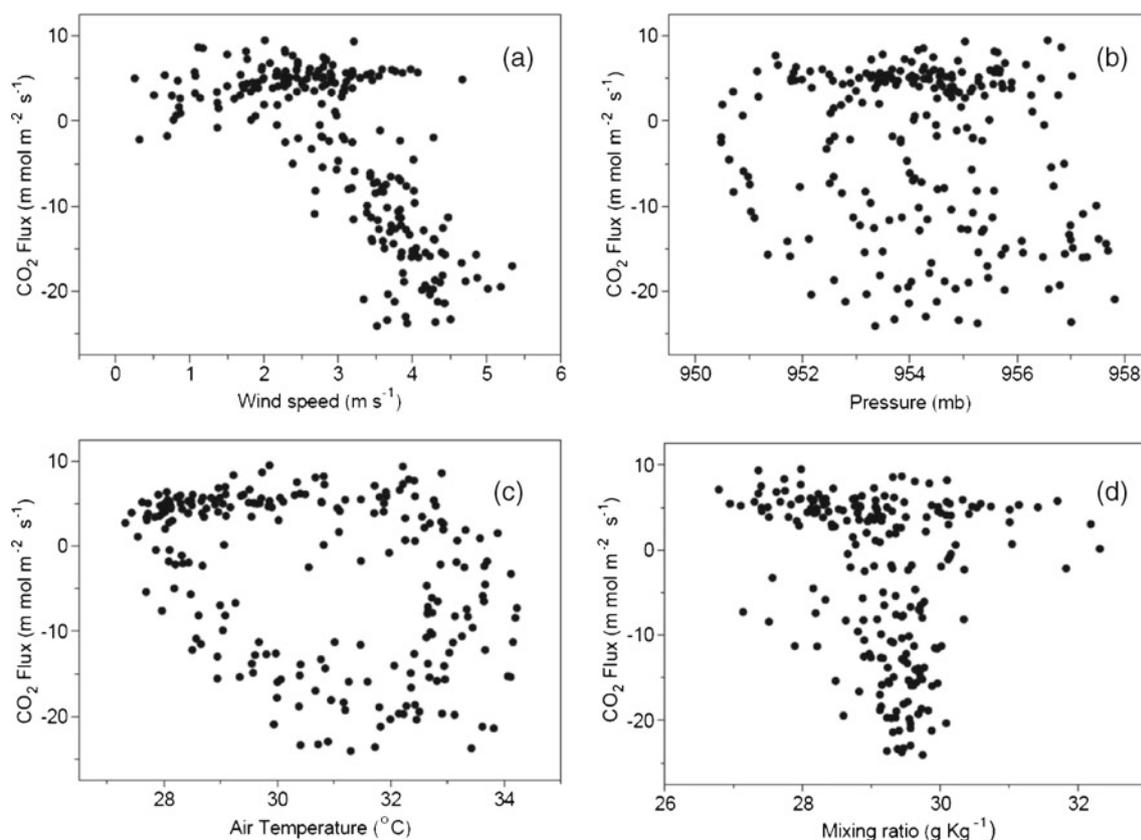
Figure 6. Dependency of CO_2 flux on (**a**) wind speed, (**b**) surface air pressure, (**c**) air temperature and (**d**) mixing ratio.

were started in the first week of July. The soil moisture was considerably low in the first week of July than that of in the month of September. Plants are more developed in September compared to July. In the second part of night (10 PM to 7 AM), the CO_2 flux was nearly constant (figure 5). After sunrise, the CO_2 flux was more in September than in July. During daytime, the maximum uptake of CO_2 was -12.5 μmol m^{-2} s^{-1} in July which increased to -21 μmol m^{-2} s^{-1} in the month of September. The greater CO_2 flux in the month of September was attributed to the enhanced photosynthesis process with availability of greater soil moisture and well developed plants than in the month of July.

4.3 CO₂ fluxes and meteorological parameters

Figure 6(a–d) shows the observed variation of CO_2 flux with wind speed, air pressure, air temperature and mixing ratio, respectively for the period of 9–14 August, 2011. It is interesting to note here that, a CO_2 flux showed relation with wind speed, but not with air temperature, mixing ratio (humidity) or air pressure. For the wind speed <2 ms^{-1}, CO_2 flux was positive with less variation. In this case, with increase of wind speed (and net radiation, sensible and latent heat flux), increase of CO_2

flux is also observed but it becomes more negative (CO_2 uptake becomes more intense) as seen in figure 7(a, b and c). In the mid-latitudinal region too, Merbold *et al.* (2011) expressed poor relationship of CO_2 flux with air temperature, wind speed and air pressure. Contini *et al.* (2012) too expressed poor correlation between CO_2 flux and meteorological parameters due to the influence of the biogenic cycle over the town of Lecce (Italy). The linear relationship of CO_2 flux with sensible heat flux (H), latent heat flux (LE) and net radiation (Rn) is established as $FCO_2 = -0.25*H - 0.35$, $FCO_2 = -0.06*LE + 5.90$ and $FCO_2 = -0.05*Rn + 2.73$, respectively. The relation between FCO_2 and H and LE fluxes is mainly a result of diurnal rhythm of turbulence. This relationship is site specific and valid for the wind speed less than 5 ms^{-1} with CO_2 concentration in the range of 366–452 μmol mol^{-1}. The response from the fluxes of CO_2, sensible and latent heat to the precipitation (113 mm) that occurred over the study area on 21 August (day number 233, see figure 2) have been examined. The sensible and latent heat flux were also increased by $\sim$35 and $\sim$136 W m^{-2}, respectively after passing the rainfall event (see figure 8a). Due to intense rainfall on this day, it is interesting to note that, on the next day (day number 234, 22 August), the daytime CO_2 uptake (negative CO_2 flux) at peak
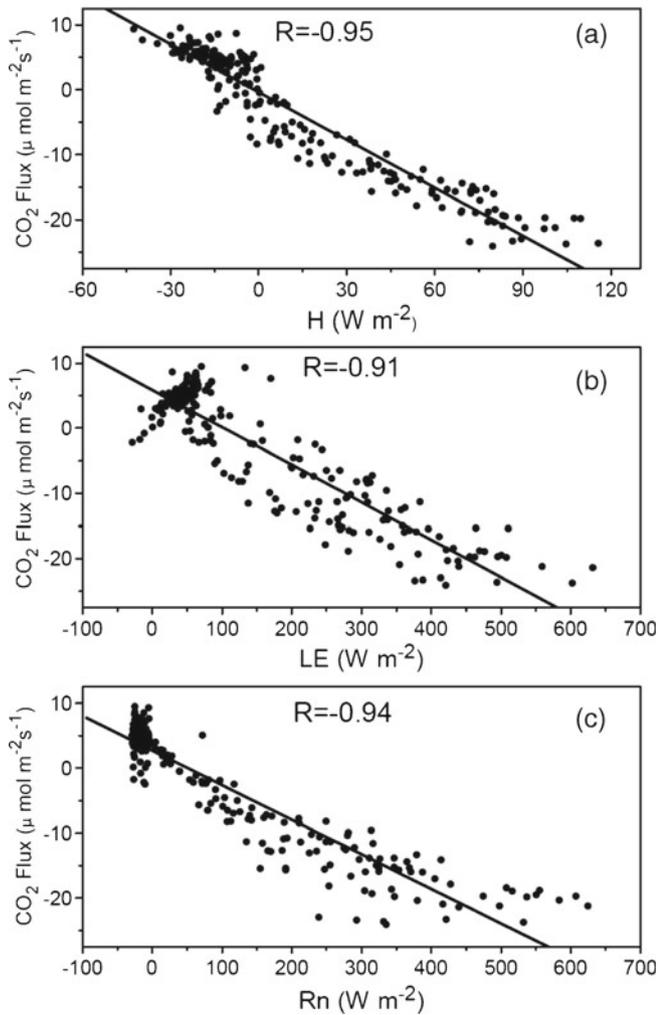
Figure 7. Dependency of CO_2 flux on (**a**) sensible heat flux, (**b**) latent heat flux and (**c**) net radiation.

Figure 8. Diurnal variation of fluxes of (**a**) sensible and latent heat, (**b**) CO_2 flux and (**c**) air temperature observed on 21–22 August, 2011.

hour increased by ~-6.8 µmol m^{-2}s^{-1} as seen in figure 8(b). The change in air temperature due to rain episode is given in figure 8(c). Following the precipitation event, an increase in CO_2 uptake indicates that the regions with high soil moisture can uptake greater amount of CO_2 and utilize efficiently in the photosynthesis process. Otherwise, in few studies from the mid-latitudinal region (Barr *et al.* 2012), in response to hurricane (disturbance), more efficient transport of CO_2 from the surface, and decrease in sensible heat flux was observed. In the present study, the significant increase of latent heat flux was observed. A study (Brummer *et al.* 2008) over the tropical region, i.e., south-west of Burkina Faso, showed the net CO_2 uptake in the monsoon season which corroborates with our findings. From the above findings and discussions, it is appropriate to conclude that the rural part of the Indian subcontinent, particularly during monsoon season, can be a CO_2 sink region.
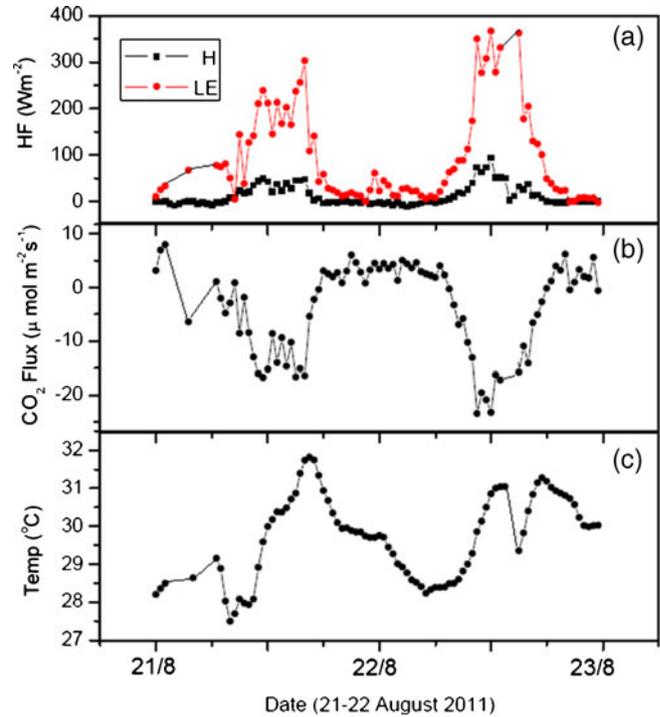
5. Conclusions

CO_2, H_2O concentrations and their fluxes in the rural area of south-east India site (Mahabubnagar) were analysed using the eddy-covariance technique. The result showed that the measurement site, which is rural, is a net sink of CO_2 in the monsoon season. The measured fluxes showed a clear daily pattern correlated with diurnal stability. The effect of the biogenic cycle was clearly visible on CO_2 fluxes. The CO_2 flux showed conclusive relationship with wind speed, net radiation, sensible and latent heat fluxes. However, there was no clear relation of the CO_2 flux with air temperature, water vapour mixing ratio and air pressure as a single parameter. The CO_2 uptake was low at the beginning of monsoon season, but it enhanced towards the end of the season mainly because of enhanced photosynthesis processes with the availability of greater soil moisture.

help in collection of valuable observations used in the analysis.

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