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# Variations in atmospheric Carbon Dioxide and its association with rainfall and vegetation over India

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## HIGHLIGHTS

► $CO_2$ variation in relation to changes in rainfall-vegetation were studied over India.
► Rainfall and monthly mean $CO_2$ concentrations are well correlated.
► Negative correlation is seen between $CO_2$ concentration and vegetation.
► $CO_2$ shows higher magnitude increasing trend than the decreasing trend of NDVI.

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## ABSTRACT

In this paper we have studied variability and growth rate of surface observed atmospheric Carbon Dioxide ($CO_2$) concentrations over Cape Rama, west coast of India and its association with rainfall and vegetation over this region. Cape Rama is a maritime site which experiences a seasonal reversal wind pattern receiving air masses having marine (continental) signatures during summer (winter) monsoon season. This study reveals that summer monsoon (JJAS) precipitation and monthly values of atmospheric $CO_2$ concentration during the season are well correlated. Negative correlations are seen with $CO_2$ concentrations of concurrent months of the season as well as subsequent months. However the magnitudes of correlation coefficients are decreased till hot pre-monsoon season (MAM). Annual cycle and interannual variability show negative relationship between $CO_2$ concentration and vegetation over the region. $CO_2$ concentration shows increasing trend and NDVI shows decreasing trend. However, the magnitude of increasing trend of $CO_2$ concentration is higher. Amplitude of decreasing phase of vegetation is higher than the amplitude of increasing phase. Though the results show certain link between $CO_2$ and climate variability, further examination with dense and longer data may be needed to confirm the result.



## 1. Introduction

Atmospheric Carbon Dioxide ($CO_2$) has become the largest contributor among all anthropogenic greenhouse gases to warming of the global climate (IPCC, 2002, 2007). Developing countries account for 73% of the global emissions growth rate in 2004 (Raupach et al., 2007). According to the Ministry of Power, Govt. of India, 54.6% of the electricity produced in India in 2009–2010 was generated by burning coal, which is the most carbon-intensive of all fossil fuels. For instance, total emissions of carbon dioxide from power sector in India have risen from 469.7 Tg-$CO_2$ in 2005–2006 to 579.8 Tg-$CO_2$ in 2009–2010 (CEA, 2011). Some of these emissions are compensated by vegetation uptake (Lal and Singh, 2000). Estimates of total fossil fuel $CO_2$ emissions from India, which Carbon Dioxide Information Analysis Center (CDIAC) lists as 189 TgC in 1990, 324 TgC in 2000, 385 TgC in 2005 & 440 in 2007, and state that the annual rate of increase is ~7 percent per year (Boden et al., 2010).

Accumulating evidences suggests that increasing level of atmospheric $CO_2$ could change in rainfall patterns (EPA, 1983). However, increased atmospheric $CO_2$ concentration may cause warmer atmospheric temperature and higher atmospheric water vapor content, but not necessarily more precipitation. Several studies in the past have found that rainfall over the Indian summer monsoon domain intensifies as the atmospheric $CO_2$ increases (Fan et al., 2011; Cherchi et al., 2010; Annamalai et al., 2007; Kumar et al., 2006; Ueda et al., 2006; May, 2004; Meehl and Arblaster, 2003; Allen and Ingram, 2002). Whereas, few studies e.g. Ashfaq et al., 2009 suggest reduction

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of Indian summer monsoon rainfall associated with anthropogenic increases in greenhouse gas concentrations.

The association between atmospheric $CO_2$ and rainfall and vegetation over India is a critical question. Indian subcontinent is a portion of monsoon Asia where a significant seasonal shift of wind patterns occurs throughout the entire area and is covered by a range of ecosystems including tropical forests and tundra in Himalayan Mountains (Tian et al., 2003). These ecosystems contribute significantly in global terrestrial net primary productivity (Melillo and Gosz, 1983; McGuire et al., 2003). On the other hand, India is supporting a population of around 1.2 billion and experiencing a steep rise in energy demand. Therefore Indian subcontinent is of critical importance to the understanding of how climate drivers and elevated atmospheric $CO_2$ interacts to influence the functioning of ecosystem and biosphere. Given the dependence of large populations on monsoon rainfall, the response of Indian summer monsoon dynamics to elevated atmospheric greenhouse gas concentrations is an issue of both scientific and societal importance. More information on how the biosphere associates with atmospheric $CO_2$ is needed to understand the Earth's carbon cycle. Consequently studies should be undertaken to delineate the relations between atmospheric $CO_2$ concentrations and changes in climate drivers such as rainfall and vegetation. In this study we investigate with available data sets to examine how variations in atmospheric $CO_2$ observations (Bhattacharya et al., 2009; Tiwari et al., 2011) are associated with rainfall and vegetation over Cape Rama, India.

## 2. Data

### 2.1. Carbon Dioxide ($CO_2$)

Atmospheric $CO_2$ observations during February 1993 to October 2002 used in this study, are from a coastal station Cape Rama (15.1° N, 73.8° E), 80 km south of Panaji Goa located at the west coast of India (Fig. 1). Cape Rama is a maritime site located on flat rocky terrain 60 m above sea level and overlooks the sea. The site is free of any vegetation over a scale of 50 m from all sides and is few hundred meters away from sparse habitation. It is a unique site which experiences a seasonal reversal wind pattern. During South West (SW) monsoon it receives airmasses having marine signatures while during winter North East (NE) monsoon period it receives continental signature from Indian subcontinent (Fig. 1). The meteorological data from Panaji Goa show that the zonal wind direction in the afternoon (sampling time) is onshore and morning is offshore all year around (Bhattacharya et al., 2009). However, the morning air mass re-circulates as a sea breeze in the afternoon after mixing over a large oceanic fetch. The wind speed at the time of sampling is 10–12 $ms^{-1}$ during SW monsoon and 4–6 $ms^{-1}$ during rest of the months (Bhattacharya et al., 2009; Tiwari et al., 2011).

Air samples in two separate 0.5 ml glass flasks were collected 6 m above ground bi-monthly at absolute pressure of 190 kPa. Air sampler is a specially designed devise that dries the sample using $MgClO_4$ and monitors local wind speed and winds direction. Filled glass flasks were analyzed at CSIRO Atmospheric Research GASLAB (Global Atmospheric Sampling LABoratory) in Australia for concentration of trace gasses $CO_2$, $CH_4$, $N_2O$ etc. by gas chromatography method. Sample collection strategies and analytical methods are described elsewhere (Francy et al., 1996, 2003).

### 2.2. Rainfall

High-resolution (1°latitude × 1°longitude) gridded daily rainfall datasets for Indian region during 1951–2003 (Rajeevan et al., 2005, 2006) are extensively used for research studies (Goswami et al., 2006; Krishnamurthy and Shukla, 2008). The dataset is based on rainfall data of 1803 stations each with at least 90% data availability. Rainfall data extracted for Cape-Rama location (15.1° N, 73.8° E) are for the period 1993–2002. Monthly time series of rainfall are further analyzed to see annual cycle, variability and its association with variation in $CO_2$ over Cape Rama.

### 2.3. Vegetation

The NDVI land data set used in this study are from NOAA/AVHRR (Leeuwen et al., 1999) and MODIS/AQUA (Huete et al., 2002) at 1 × 1° (latitude by longitude) horizontal and monthly temporal resolution for the period of 1981–2000 and 2000–2010 respectively. Data are available via the Internet at http://eosdata.gsfc.nasa.gov/. The NDVI is satellite-derived surface greenness values (Bounoua et al., 2000); produced using the measurements from Advanced Very High Resolution Radiometer (AVHRR) on board the NOAA polar orbiting meteorological satellites and Moderate-resolution Imaging Spectrometer (MODIS) onboard NASA/AQUA earth observing system. MODIS is referred to as a composite approach to the existing NOAA/AVHRR derived NDVI which is extended my MODIS data to provide longer-term record. The reflectance is measured from channel 1 (visible: 0.58–0.68 m) and channel 2 (near infrared: 0.725–1.0 m) is used to calculate the index. The NDVI value is defined as the ratio of the difference to the total reflectance.

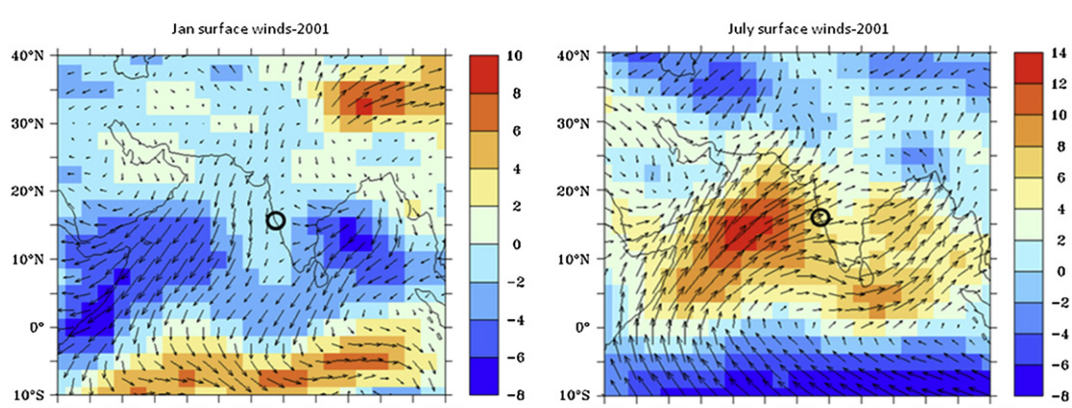


**Fig. 1.** Location of Cape Rama, India marked with a black circle. Background shades present NOAA NCEP-derived monthly mean u-wind at the surface during winter (left panel) and monsoon month (right panel). Arrows indicate wind direction.

$$\text{NDVI} = (\text{channel } 2 - \text{channel } 1)/(\text{channel } 2 + \text{channel } 1)$$

Green leaves commonly have larger reflectance in the near infrared than in the visible range. Clouds, water, and snow have larger reflectance in the visible than in the near infrared range, so that negative values of vegetation index corresponds to snow or ice cover, whereas the difference in reflectance is almost zero for bare soils such as deserts. So as a result, NDVI values can range from $-1.0$ to 1.0 but typical ranges are from 0.1 to 0.7, with higher values associated with greater density and greenness of plant canopies. Calculations of NDVI for a given pixel always result in a number that ranges from minus one ($-1$) to plus one ($+1$); however, no green leaves gives a value close to zero. A zero means no vegetation and close to $+1$ (0.8–0.9) indicates the highest possible density of green leaves. More details of the processing methods used in generating the data set can be found in James and Kalluri (1994). Because our objective is to investigate the large-scale features in climate and NDVI, we used the coarser monthly data sets to suppress the noise usually existing in the high spatial resolution data. The seasonal mean was averaged for April and May at each grid. Grids having insufficient data (nv18) or low mean NDVI (0.05) were removed from the data set. Similar to rainfall data, NDVI data also extracted for the Cape Rama locations and analyzed further to see annual cycles, variability and its association with $CO_2$ variation.

## 3. Results and discussions

Since the industrial revolution, there has been a marked increase in the emission of Greenhouse gases mainly $CO_2$ in the atmosphere, raising the atmospheric temperatures near the surface of the earth. Concentration of Carbon Dioxide varies seasonally and also considerably on a regional basis, especially near the surface. Global mean surface temperatures have risen by $0.74 \pm 0.18$ °C as estimated by a linear trend over the recent 100-year period 1906–2005. The rate of warming over the last 50 years in this period is almost double that over the entire 100 years, that is, $0.13 \pm 0.03$ °C versus $0.07 \pm 0.02$ °C per decade (IPCC, 2007). India has the second largest population, one of fastest growing economies and is ranked third in Greenhouse gases emissions by fossil-fuel burning in the world. Over India, till to date monitoring of atmospheric $CO_2$ concentration is very little. Tiwari et al. (2011) reanalyzes pioneering atmospheric $CO_2$ observations at Cape Rama, India during the period from February 1993 to October 2002. Their study also reveals that $CO_2$ concentrations over Cape Rama have been consistently increasing. However basic aim of their study was to compare three forward transport models to simulate atmospheric $CO_2$ and separate tracers of terrestrial and oceanic fluxes, and fossil-fuel emissions. In this study an attempt is made to study variability of Carbon Dioxide over Cape Rama India and its association with rainfall and vegetation on seasonal as well as inter annual scale.

### *3.1. Mean annual cycle of Carbon Dioxide ($CO_2$)*

Fig. 2 shows mean annual cycle of $CO_2$ over Cape Rama, India. It is based on daily data for the period 1993 to 2002. For each day of calendar year, average values of $CO_2$ are computed. Annual cycle is further smoothed by fitting 9° polynomial. Since January, $CO_2$ concentration starts increasing till the end of winter season in February. During pre-monsoon months (MAM), which is the hottest season over the region, it decreases. This decrease in $CO_2$ concentration is further continued and attains its first minima in the month of July, which is an active summer monsoon month. Slight increase is seen till the end of September and further it attains second minima in the month of November, associated with rainfall activities over the region during winter monsoon. Thus the annual cycle generally shows impact of seasonal variability of climate over the region. During rainy season, there is an increase in vegetation over the region which causes decrease in $CO_2$ concentration. So the first minima in $CO_2$ occur during summer monsoon. Further rainfall activities during winter monsoon causes to attain secondary minima. As rainfall activities during this season favors in further growing of existing vegetation, therefore this second minima show lowest values of $CO_2$ concentration over the region. The concentration further increases as there are no further rainfall activities over the region.

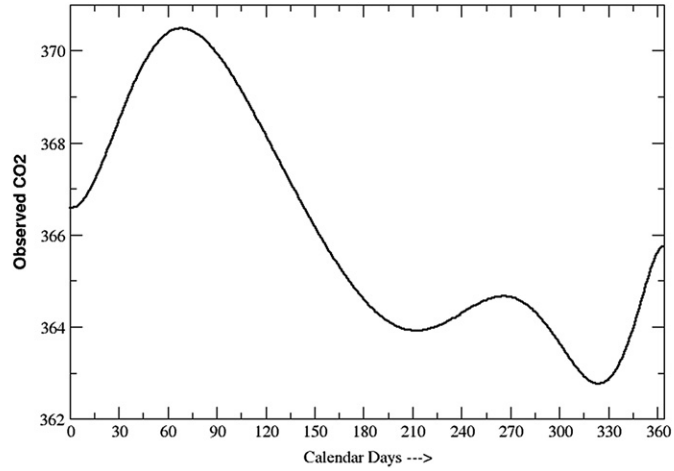


**Fig. 2.** Mean annual cycle of $CO_2$ over Cape Rama based on daily data for the period 1993–2002.

Though the Fig. 2 shows daily mean pattern of $CO_2$ concentration over Cape Rama, there exists year to year variability in $CO_2$. This variability is measured in terms of standard deviation (Fig. 3). In general, mean monthly pattern of standard deviation shows opposite features which are seen in mean annual cycle. This clearly indicates that lower variability in $CO_2$ occurs during the months of higher concentration and vice versa. It is seen that lower concentration in $CO_2$ are associated with rainfall activities during summer and winter monsoon. The most important characteristic of the climate of the region is the occurrence of monsoon, with associated seasonal reversal of wind distribution. Both summer and winter monsoon are the main sources of water.

Variability in $CO_2$ concentration over Cape Rama is also studied in terms of day to day incremental changes. For this daily incremental changes in $CO_2$ concentrations are computed as $\sum CO_2(t)-$

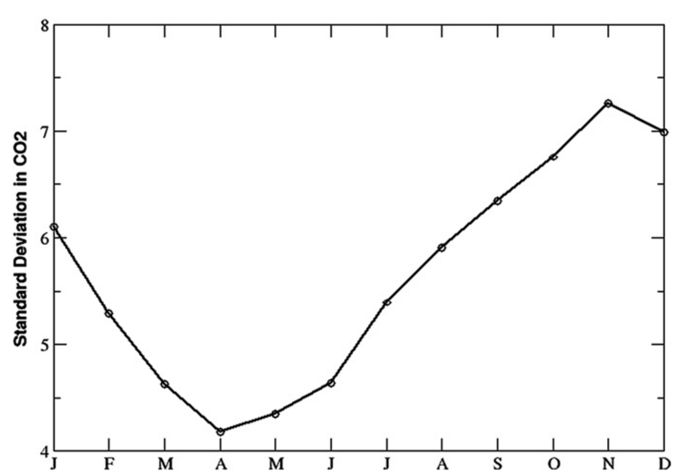


**Fig. 3.** Variability in $CO_2$ over Cape Rama computed as standard deviation.

$CO_2(t-1)$, $t = 2.........n$, where '$n$' is number of days in month. These incremental changes are averaged over entire period (1993–2002) on monthly basis to understand its general characteristics (Fig. 4). Figure shows two alternate epochs of increasing and decreasing phase of $CO_2$ over Cape Rama and the rate of increase/decrease of incremental change decreases in each phase and further it changes the phase. Though continuous increase in $CO_2$ level is seen in earlier section (Fig. 2) during winter season, incremental changes show the rate of increase is slow in the month of February (Fig. 4). Similarly highest decrease is seen in the month of April and the rate of decrease in $CO_2$ is further decreasing continuously till the month of July.

### 3.2. Interannual variability

As seen in previous section, $CO_2$ levels exhibit intra-seasonal as well as inter annual variability over Cape Rama. This has been further examined in detail using daily time series of $CO_2$ over Cape Rama for the entire period under study from 1993 to 2002. Interannual variability is examined in terms of their day to day incremental changes computed as $CO_2$ (day)–$CO_2$ (previous day). It is well known that since the industrial revolution, there has been a marked increase in the emission of $CO_2$ in the atmosphere. However it is important to note from the Fig. 5 that the seasonality of $CO_2$ is decreased continuously. Magnitude of peak values of both increasing and decreasing phase of $CO_2$ during earlier period is higher compared to recent period. Rainfall activity during initial two years (1993 and 1994) was above normal and during last four years (1999–2002) rainfall activity was below normal.

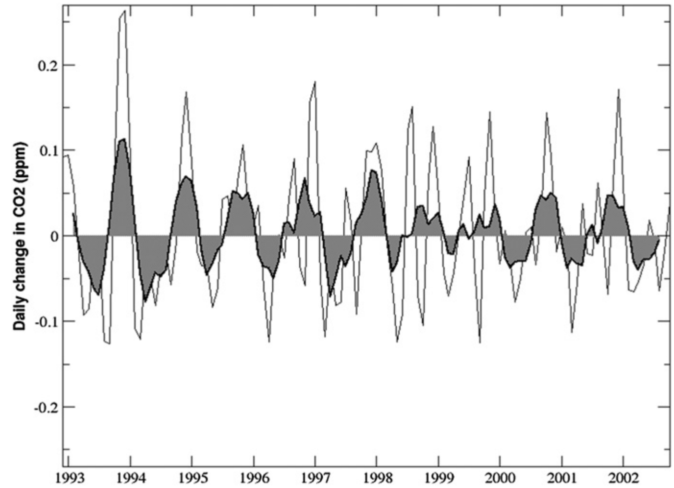


**Fig. 5.** Interannual variability of daily variation in $CO_2$ levels ($\sum CO_2\ (t) - CO_2\ (t-1)$, $t = 1.........n$, where $n$ is number of days in month) during 1993–2002, shaded region represents smoothed values.

### 3.3. Link between Carbon Dioxide and rainfall

It is interesting to note the direct as well as indirect causes of carbon sink. It is known that vegetation growth absorbs $CO_2$ from the air, causing the carbon sink. However, water is essential component in growth of vegetation and hence the connection between water availability and vegetation growth is obvious. Therefore further analysis is done to see the link between rainfall and $CO_2$ concentration over Cape Rama.

Along the west coast, the orientation of the Western Ghats is from north to south. Therefore the southwest monsoon winds, which strike the Ghats from southwesterly direction, shed most of their moisture on the windward side of mountains. Cape Rama is located along the west coast, therefore annual cycle of rainfall over Cape Rama shows high rainfall values during southwest monsoon months from June to September. During October, active month of northeast monsoon or winter monsoon over India, Cape Rama experiences some rainfall activity, but rests of months are comparatively dry. Connection between the plant growth due to natural water availability and $CO_2$ is well reflected in annual cycle of Carbon Dioxide and precipitation (Fig. 6). Figure shows inverse pattern till the end of the rainy summer monsoon season (JJAS). Further there is slightly decrease in precipitation with decrease in $CO_2$. Thus the summer monsoon is of paramount importance as it contributes about 80%–90% of the annual rainfall. It provides water for agriculture, vegetation and replenishment of water resources to be used during the rest of the year when the region is generally under dry conditions.

It is seen that the summer monsoon (JJAS) is the main rainy season for the region, which provides the water for vegetation during the season as well soil moisture for the rest of the season when it is generally dry. Therefore concurrent inverse relationship between $CO_2$ and Rainfall is obvious, as increased vegetation sinks $CO_2$ levels (Fig. 7). Initially during the month of June vegetation start increasing with availability of water and as vegetation increases there is a sink in $CO_2$ levels. Vegetation sustain further with initial soil moisture gained by the main rainy season. Therefore there exist negative relationship between summer monsoon rainfall (JJAS) precipitation and monthly values of Carbon Dioxide concentration during the season as well as $CO_2$ in the subsequent months. However the magnitudes of correlation coefficients are decreased till hot pre-monsoon season (MAM).

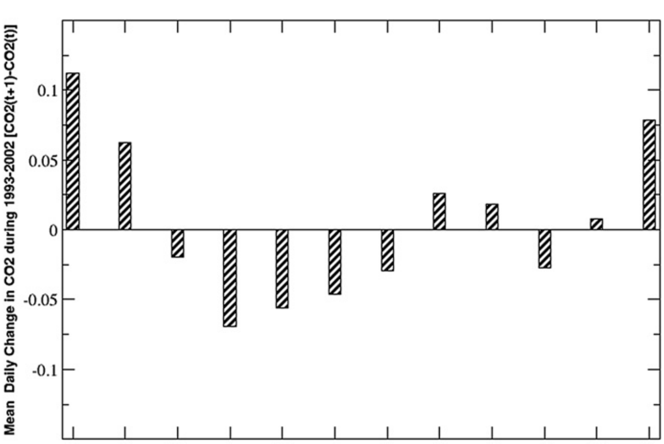


**Fig. 4.** Monthly mean changes in daily $CO_2$ levels over Cape Rama during 1993–2002 computed as $\sum CO_2(t) - CO_2(t-1)$, $t = 2.........n$, where $n$ is number of days in month.

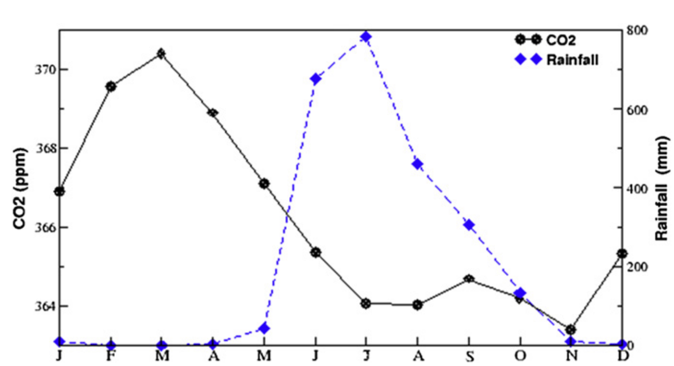


**Fig. 6.** Annual cycle of $CO_2$ (ppm) superimposed with annual cycle of rainfall (mm) over Cape Rama based on the data for 1993–2002.

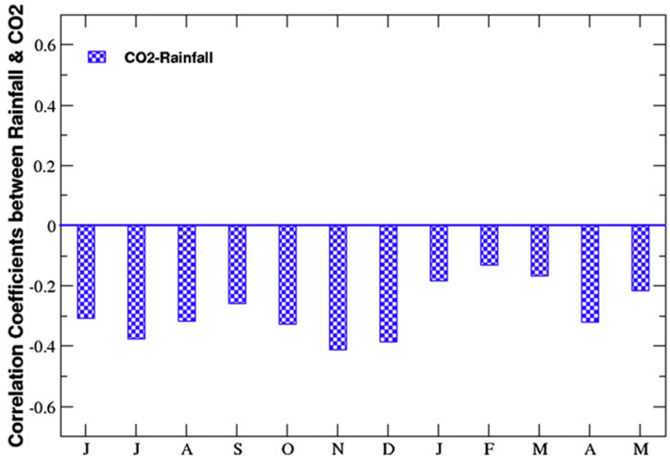


**Fig. 7.** Correlation coefficients between monthly $CO_2$ and summer monsoon rainfall over Cape Rama based on data for the period 1993–2002.

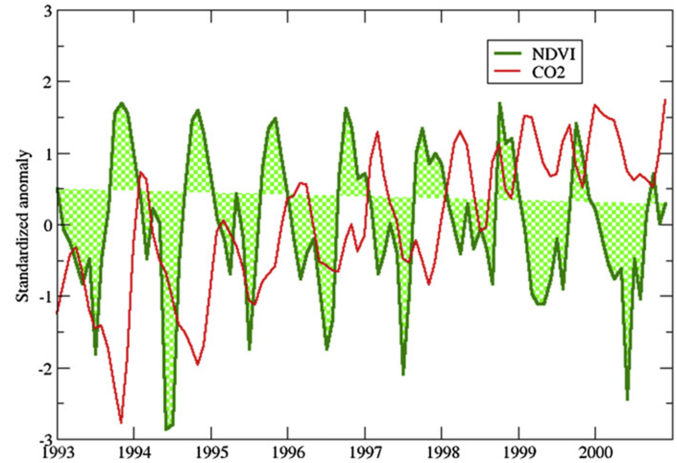


**Fig. 9.** Interannual variability in NDVI and $CO_2$ over Cape Rama in terms of their standardized anomalies during 1993–2000.

### 3.4. Link between Carbon Dioxide and vegetation

Plants require Carbon Dioxide to conduct photosynthesis. Each year when the terrestrial vegetation of the Northern Hemisphere waxes and wanes in vigor along with the seasons, it removes considerable amount of $CO_2$ from the atmosphere in its productive growing phase, while it returns $CO_2$ to the air when it dies and decomposes. This phenomenon creates a seasonal ripple in the atmospheric $CO_2$ concentration, as it drops a few ppm when land plants are growing vigorously and raises a similar amount when the majority of these plants are senescing.

Summer and winter monsoon months, well-known for its regularity and dependability on the seasonal scale, the rainfall associated with it does show significant variation on various scale, it also have a strong impact on crops (e.g. Parthasarathy and Pant, 1985; Parthasarathy et al., 1992; Kulshrestha, 2002; Selvaraju, 2003; Krishna Kumar et al., 2004; Gadgil, 1996; Webster et al., 1998; Kriplanai and Pankaj Kumar, 2004; Revadekar and Kulkarni, 2008; Revadekar and Preethi, 2011; Preethi and Revadekar, 2012). Variability in seasonal rainfall over the region and its impact on vegetation contributes toward the high variability in $CO_2$ over the region during this season.

Because of the succession on both temporal and spatial scale, many studies attempted study on the relation between satellite based vegetation data and climate (Myneni et al., 1996, 1998; Tucker et al., 2001; Zhou et al., 2001; Zhihui et al., 2007). Over Indian region Revadekar et al. (2012) have shown that during drought years, there is decrease in vegetation during all months, while opposite features are shown during flood years. Many other researchers have also studied the variability of vegetation and its relation to meteorological parameters over the Indian region (Singh and Kogan, 2002, Singh et al., 2003; Sarkar and Kafatos, 2004; Prasad et al., 2007; Krishna Prasad et al., 2008; Saikia, 2009). In view of above, it is obvious to see inverse relationship between vegetation and $CO_2$ concentration (Fig. 8). Annual cycles of vegetation and $CO_2$ concentration show clear opposite patterns in their monthly values, except during May, June and July. During these months there is a decrease in $CO_2$ though there is decrease in vegetation. This may be due to dispersion of $CO_2$ with the onset of summer monsoon over the country.

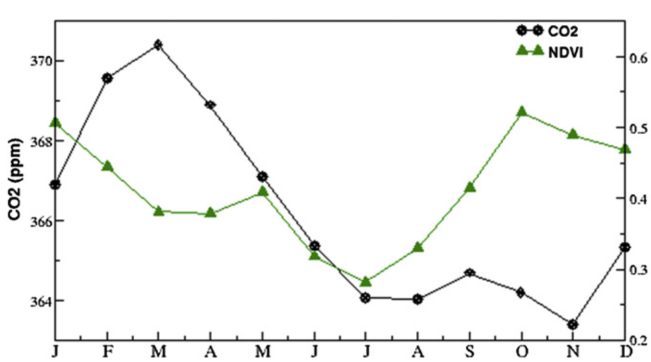


**Fig. 8.** Annual cycle of $CO_2$ (ppm) superimposed with annual cycle of NDVI over Cape Rama based on the data for 1993–2002.

Over India, the mean maximum as well as minimum temperatures have increased by about 0.2 °C per decade during the period 1971–2003 for the country as a whole (Kothawale and Rupa Kumar, 2005). It is well known that since the industrial revolution, there has been a marked increase in the emission of Greenhouse gases mainly $CO_2$ in the atmosphere, raising the atmospheric temperatures near the surface of the earth. Time series of $CO_2$ over Cape Rama seen from Fig. 9 also show continuous increase in $CO_2$ from 1993 to 2002. To understand the link between increase in $CO_2$ and vegetation, this time series is constructed in terms of standardized anomalies of Carbon Dioxide and is superimposed with standardized anomalies of NDVI. Increase in $CO_2$ is associated with decrease in vegetation however the rate of increase in $CO_2$ is higher magnitude than the decreasing rate of NDVI. It is interesting to note that amplitude of decreasing phase of vegetation is higher than the amplitude of increasing phase. Opposite features are seen in standardized anomalies of Carbon Dioxide.

## 4. Summary and conclusions

In this paper, an attempt is made to study variability and growth rate of atmospheric $CO_2$over Cape Rama India and its association with rainfall and vegetation over the region. Since January $CO_2$ concentration start increasing till the end of winter season in February. During pre-monsoon months (MAM), which is the hottest season over the region, it decreases. This decrease in $CO_2$ concentration is further continued and attains its first minima in the month of July. Slight increase is seen till the end of September and further attains is secondary minima in the month of November. Mean monthly pattern of standard deviation is similar to mirror image of mean annual cycle, indicating higher concentration months shows lower variability and vice versa. In addition to this intra-seasonal and inter-seasonal variability of $CO_2$, there exists inter-annual variability, which suggests consistent increase in $CO_2$ concentrations over the region. Study reveals that summer monsoon rainfall (JJAS) precipitation and monthly values of Carbon Dioxide concentration during the season are well correlated. Negative correlations are seen with $CO_2$ concentrations of concurrent months of the season as well as subsequent months. However the magnitudes of correlation coefficients are decreased till hot pre-monsoon season (MAM). This is mainly because, the connection between water availability and plant growth is obvious, and vegetation growth absorbs $CO_2$ from the air, causing the carbon sink. Annual cycle and interannual variability show negative relationship between $CO_2$ concentration and vegetation over the region. However, Carbon Dioxide shows higher magnitude increasing trend than the decreasing trend of NDVI. Amplitude of decreasing phase of vegetation is higher than the amplitude of increasing phase. Opposite features are seen in standardized anomalies of Carbon Dioxide. This study is unique in its nature whereas longer and dense network data set may be required to confirm the results.

## Acknowledgments

Atmospheric $CO_2$ measurements at Cape Rama India are crucially dependent on the sophisticated methods and equipment developed and maintained in CSIRO GASLAB Australia. In this context, we are extremely thankful to Ray Langenfelds, Paul Krummel, Paul Steele, and D.V. Borole. We thank to the Director IITM for encouragement and support to carry out this work.

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