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Atmospheric Carbon Dioxide Levels in Garhwal Himalaya, India

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Abstract: Measurements of atmospheric CO_2 were made in the mountainous region of Srinagar-Garhwal, India (January to December 2006). Concentrations of CO_2 averaged 393±4.9 ppm in 2006. Daily variations of CO_2 values showed minimum during the daytime (376.2 ppm) and peaked in the morning/evening (410.1 ppm). At monthly intervals, the CO_2 values varied from 367±11.14 (May) to 425.2±13.54 ppm (March). If divided on a seasonal basis, the values declined to minimum amounts in post-monsoon (389.9±9.0 ppm) and reached maximums during winter (397.1±11.6 ppm). Although phenology is significant in controlling CO_2 levels, short-term changes cannot be explained without the anthropogenic perturbations (e.g., vehicular pollution and forest fires). The CO_2 concentrations in Srinagar-Garhwal (393.4 ppm) were generally higher than those of other major monitoring locations around the world.

Keywords: Carbon dioxide, Diurnal, Garhwal Himalaya, Forest fires

Introduction

Carbon dioxide is a trace gas in the earth's atmosphere that exchanges between major environmental reservoirs such as the oceans and the biosphere. Although CO_2 is the second most abundant greenhouse gas after water vapour, it is the greatest contributor to global climate change (Bolin et al., 1986; Houghton et al., 1996). Since the beginning of the industrial revolution, industrial demands for energy have led to the release of vast quantities of carbon dioxide into the earth's atmosphere.

Since the initial monitoring of CO_2 in late 19th century, it has steadily been increasing (i.e., from 280 ppm before the industrial revolution to 380 ppm today) (IPCC, 2007). The annual emissions of atmospheric CO_2 have grown by 80% between 1970 and 2004 (IPCC, 2007). An average increase rate of CO_2 was maintained at 1.4 ppm yr^{-1} from 1960 to 2005 (IPCC, 2007). The rate of increase in the last 10 years (1995-2005) was 1.9 ppm yr^{-1}, showing the highest growth rate since the initiation of direct measurements (IPCC, 2007).

The major sources of carbon dioxide is often designated to fossil fuel combustion (Denning et al., 1995; Colombo et. al., 2000). Other sources of atmospheric CO_2 include plants, animals, microbial respiration, ocean emission, and land use change. As such, fossil fuel combustion and cement production contributed to its emissions by 70% over the last 30 years (Prentice et al., 2001; Marland et al., 2006).

This growth rate of CO_2 became the main cause of global warming, affecting climate change on both a regional and global scale. Detailed information concerning the source/sink of greenhouse gases and their emission strengths has been one of the major goals of global climate study. Because the distribution of CO_2 is subject to geographical and temporal variations (Keeling, 1961; Pales and Keeling, 1965; Inoue and Matseuda, 1996), model predictions with relatively wide geographical coverage were not useful in accurately quantifying CO_2 exchange on a global

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scale (Massarie and Tans, 1995; Keeling et al., 1995). Because of these limitations, researchers have worked to build a CO_2 database to cover diverse environmental conditions (Levin, 1987; Levin et al., 1995; Schmidt et al., 1996). For instance, continuous measurements of CO_2 (and the related isotopic carbon ratios) have been reported in the Krakow region in Poland (Kuc, 1991) and in the K-puszta region in Hungary (Haszpra, 1995). However, despite the importance of CO_2 data acquisition, the database of CO_2 distribution on hilly areas is relative sparse.

This paper reports the results of CO_2 measurements taken in the atmosphere of Srinagar Garhwal which is a semi urban and subtropical humid region in the Northwest Himalaya in India. The purpose of this study is to evaluate the carbon dioxide concentration levels and its temporal variabilities in the hilly region of Garhwal Himalaya in Srinagar Garhwal, India. The results of this work will provide some insights into the environmental behavior of CO_2 in mountainous areas.

Materials and Methods

The CO_2 concentration data were collected using an infrared CO_2 gas analyzer (LI- 820, LI-COR, USA). Air was drawn at a flow rate of 1 L min^{-1} through an air filter (Balston 25 Micron) attached to non-CO_2 absorbing Teflon tubing into a gas analyzer. The sampling interval was 30 seconds, and the data were recorded hourly with a data logger (LI-1400, LI-COR, USA). The incoming air was passed through a column of magnesium perchlorate to eliminate possible interference due to water vapour. The CO_2 gas analyzer was calibrated weekly by checking span and zero values with CO_2 calibrant gas (505 ppm). The measurement range of CO_2 with the NDIR analyzer was 0-1000 ppm with an accuracy of <2.5% and a total drift of <0.4 ppm/°C at 370 ppm. The CO_2 values recorded at hourly intervals were converted into daily or monthly values for the analysis of temporal variabilities at different intervals.

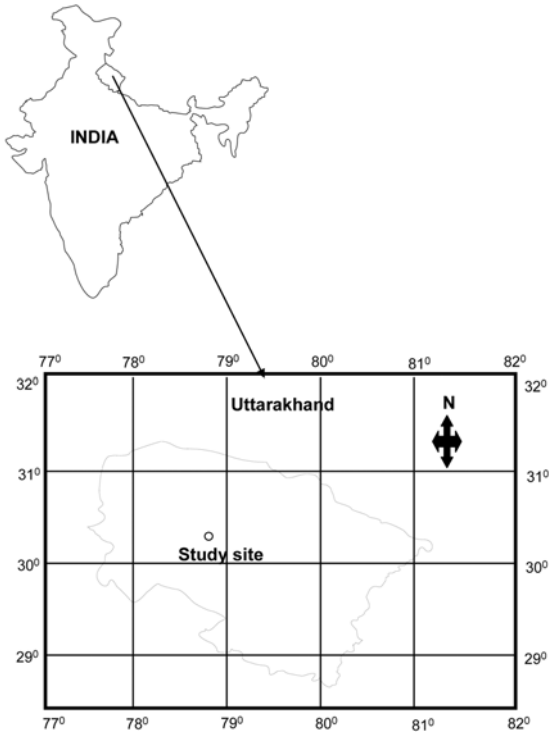

Fig. 1. Location map of the study site.

Results and Discussion

General pattern of carbon dioxide distribution at study site

This study was conducted in Srinagar Garhwal, a town situated on the bank of the Alaknanda river in the Garhwal district of the Uttarakhand Himalayan region in India (Fig. 1). Carbon dioxide concentrations were recorded at the Garhwal Unit at the G.B. Pant Institute of Himalayan Environment and Development, Srinagar-Garhwal (altitude of 570 m above mean sea level, latitude 30°13"; longitude 78°46"). Concentrations of CO_2 in air were monitored at 1.5 m above ground at hourly intervals (for up to 22 hrs: 0600 to 0400, Indian standard time (IST)) throughout the study period (January to December 2006). The study area has a humid subtropical climate with hot summers and cool winters and an annual average rainfall of 1000 mm. The area has subtropical tree species such as

Table 1. Statistical summary of atmospheric CO_2 (ppm) recorded in SG Himalaya (Jan-Dec 2006)

(a) Comparison across seasons

	Winter (Nov-Feb)	Summer (Mar-June)	Monsoon (July-Aug)	Post monsoon (Sept-Oct)	All
Mean	397.1	392.7	393.2	389.9	393.4
Median	397.6	396.0	393.4	390.2	394.4
SD	11.6	11.6	9.4	9.0	10.7
Minimum	378.6	374.3	379.4	375.6	377.0
Maximum	415.5	407.6	409.9	405.6	409.6
N	12	12	12	12	12

N denotes number of data considered for descriptive statistics

(b) Monthly comparison (N=12)

Months	Mean	Median	SD	Minimum	Maximum	SE	RA
Jan	402.4	398.6	13.5	379.8	425.2	3.9	11.28
Feb	398.1	399.2	12.1	379.9	415.8	3.5	9.01
Mar	392.8	397.6	12.3	374.7	408.0	3.6	8.49
Apr	400.8	403.0	15.5	380.3	423.2	4.5	10.71
May	391.6	393.5	13.8	367.0	410.1	4.0	11.01
Jun	390.5	389.4	13.3	373.7	409.7	3.8	9.22
Jul	389.8	390.5	8.23	378.8	403.5	2.4	6.35
Aug	387.7	387.7	8.15	378.6	404.8	2.4	6.76
Sep	388.0	388.9	11.1	367.0	405.1	3.2	9.82
Oct	390.6	393.1	10.1	374.5	402.5	2.9	7.17
Nov	392.1	393.9	12.2	375.2	408.5	3.5	8.50
Dec	395.8	396.1	11.1	379.5	412.3	3.2	8.29

SE denotes standard error
RA denotes relative amplitude

Pinus roxbhurgii, *Mangifera indica, Melia azidarach, Celtis tetrandra*, *etc.*

The concentration data of atmospheric CO_2 have been collected continuously from various locations around the world since measurements at Antarctica and Mauna Loa observatory (Hawaii) were taken in 1958. In India, CO_2 was monitored for the first time in the air and soil layers near the ground in 1941 (Mishra, 1950): The study was conducted to measure CO_2 in the open as well as crop fields. The longest monitoring of atmospheric CO_2 in India was first done at Cape Rama, a maritime site located on the west coast of India for a 10 year period (1993 and 2002: Bhattacharya et al., 1997).

This study is the first to measure atmospheric carbon dioxide in the hilly region of Srinagar Garhwal, Uttarakhand. Table 1 shows the basic statistical parameters of CO_2 data monitored. The mean value for CO_2 measured in this study was 393.4 ±10.7 ppm.

Diurnal variation in Carbon dioxide levels

To assess the diurnal variation of CO_2, the data obtained above the ground at 2 hour intervals were plotted and examined. In Fig. 2a, the CO_2 concentrations for each two hour interval are compared diurnally using the data sets. The CO_2 levels at this site maintained a diurnal pattern that was consistent enough to show the highest values (410.1 ppm) in the early morning (0600 hr) and lowest values (376.2 ppm) in the afternoon (1600 hr) with a relative amplitude of 8.72%. Figure 2b depicts the diurnal pattern of CO_2 across months of the year in 2006. The differences in hourly CO_2 concentration levels varied significantly between minimum (367.0 ppm in May) and maximum values (425.2 ppm in January). If the strengths of diurnal variation were compared by relative amplitude (RA) values between different months, the RA values ranged from 6.34 (July) to 11.28% (January). The maximum RA value in January

was the result of a high variation in daytime drops and early morning increases in CO_2 during winter. When diurnal patterns were compared across seasons, the results showed a daily maximum CO_2 (415.5 ppm) during winter.

The diurnal cycle of CO_2 generally exhibits a maximum at night (or morning) and a minimum during the daytime (Schnell et al., 1981; Baez et al., 1988; Yi et al., 2001). The nighttime maximum of CO_2 in rural areas has linked to respiration by plants (and animals) and emissions from soil. In contrast, the daytime minimum has been explained by photosynthesis (Spittlehouse and Ripley, 1977; Baez et al., 1988; Nasrallah et al., 2003). These phenomena can also be partially explained by changes in meteorological conditions, as the height of the mixing layer increases with stronger solar radiation (Aikawa et al., 1995). In contrast, diurnal variations of CO_2 in urban areas can also be affected by perturbations due to man-made activities (burning of fossil fuels and vehicular emission (Baez et al., 1988; Inoue and Matsueda, 2001; Idso et al., 2002).

Many previous studies based on long-term monitoring of CO_2 also indicated that CO_2 fluctuates both diurnally and seasonally (Woodwell, 1978; Keeling et al., 1984; Fung et al., 1987). The average relative amplitude in this study was 14.7% between the daytime decline and early morning increase. This RA value is smaller than those measured in the Savannah regions (21.6%) and tropical rain forests (25.4%) (Schnell et al., 1981). It is however comparable to values measured in Basel city, Switzerland (15.5%) (Vogt et al., 2006), while larger than the urban area of Chicago with RA values of 9.02% (Grimmond et al., 2002) or four different sites in Phoenix (2.85-7.86%: Day et al., 2002). Differences in the magnitude of RA values may be ascribable to the strength of biospheric photosynthesis, respiration, mixing conditions, and emissions anthropogenic sources (Pales and Keeling, 1965; Inoue and Matsueda, 1996). Considering the magnitude of diurnal fluctuations in the study area, variability in CO_2 may have significant implications on the vegetation of the region because of its impact on plant photosynthesis (Veste and Herppich, 1995).

Seasonal Variations in Carbon dioxide levels

Seasonal patterns of CO_2 were evaluated by sorting the data into 4 seasons. As shown in Fig. 3, a clear cycle is apparent with a maximum in winter and minimum during summer season. During the study year, CO_2 concentrations showed the highest value at 397.1±11.6 ppm during the winter (Nov-Feb). The CO_2 values were similar between summer (March-June: 392.7±11.6 ppm) and the monsoon season (July-August: 393.2±9.4 ppm). The lowest CO_2 values were noted in the post-monsoon (Sept-Nov) at 389.9±9.0 ppm. The results of a z-test showed that mean seasonal concentrations were statistically insignificant from all possible matching pairs.

To learn more about seasonal variabilities of CO_2, concentrations, the data were compared at monthly intervals. The maximum concentration of atmospheric CO_2 was recorded during the month of January (402.4 ±13.54 ppm), while the lowest value of 387.7 ppm was measured in August (Table 1). If the relative amplitude of monthly variation is estimated using all the monthly mean data, it is 3.72%. As such, temporal variability of CO_2 is most significant over short-term diurnal intervals. There are a number of factors that can affect the concentrations of CO_2 in the surface layer near the ground over extended scales (e.g., monthly interval). These include plant respiration, micro-biological and chemical processes in the soil layers, diffusion of the soil air CO_2 from the topmost layer of soil, photosynthesis and rainfall. Turbulence in the atmosphere is also important, as it can prevent a build-up of CO_2 in the surface layer.

During the summer season, CO_2 concentration reached a minimum level, as the biosphere acts as a net sink of atmospheric CO_2. Although greater amounts of CO_2 are absorbed through vegetation from photosynthesis, the amount released through respiration decreases with the suppression of microbial activities. The relative growth of CO_2 during winter as shown in this study, is comparable to the patterns seen in previous studies in Denmark, Norway, and Sweden

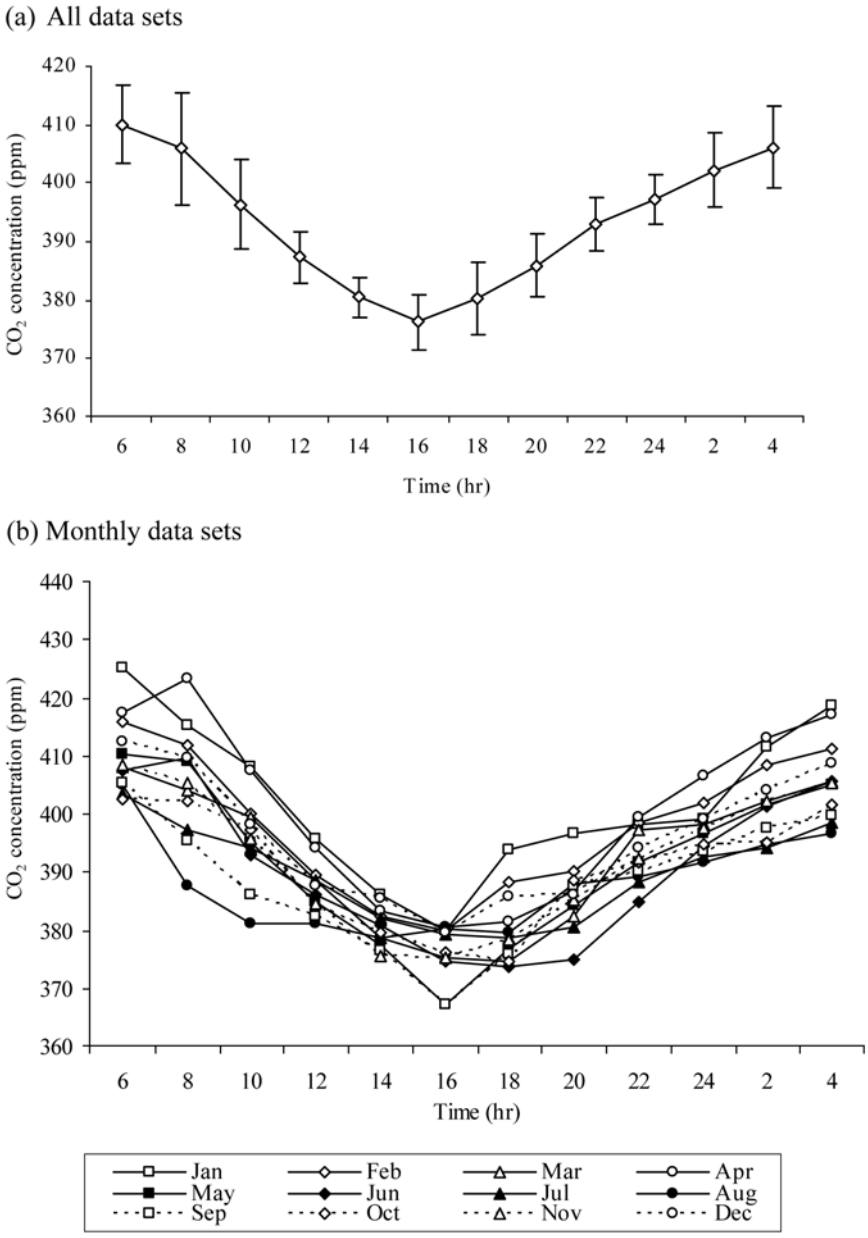

Fig. 2. Diurnal variation in atmospheric CO_2 for hourly measurements of CO_2 data sets (Indian standard time). Error bars denote standard error (SE).

(Fonselius et al., 1956) as well as several rural areas in the Northern Hemisphere (Bolin and Keeling, 1963; Woodwell, 1978; Keeling et al., 1996; Pataki et al., 2003). On the other hand, the photosynthetic activity of plants can stimulate CO_2 uptake during April-September; but it gradually declines, reaching a minimum in winter (Bhadula et al., 1995). The unusually high levels of CO_2 during the month of April were likely caused by the transport of CO_2 that is released by frequent forest fires that occur in many parts of the Garhwal Himalaya during that time of the year.

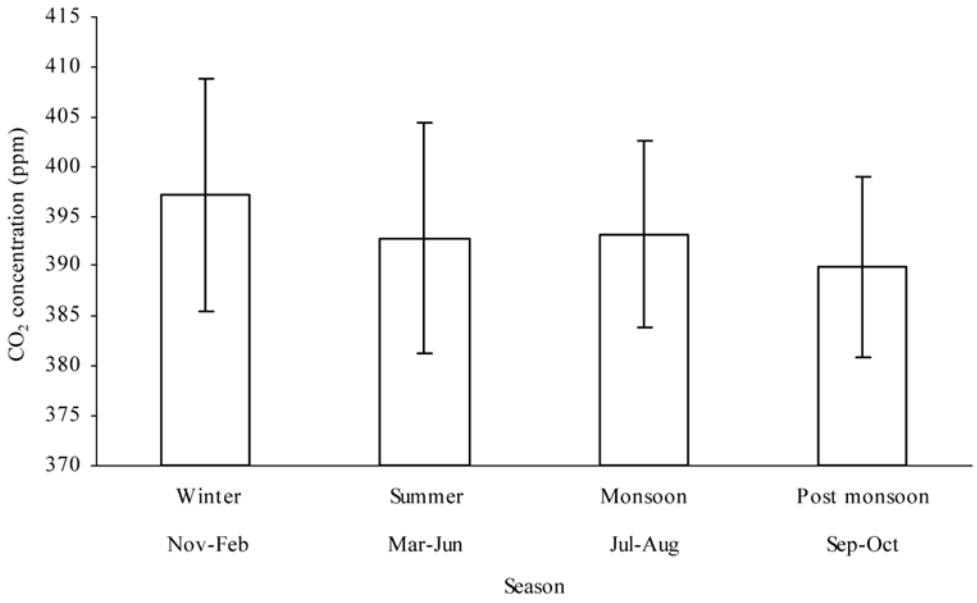

Fig. 3. Seasonal variations in atmospheric carbon dioxide levels in SG Himalaya, India (2006).

Comparison with previous studies of CO_2 Concentration

In an attempt to understand the factors controlling the distribution of CO_2 under various environmental conditions, we examined our monitoring data obtained from the mountainous area of Garhwal Himalaya, India with those reported from other parts of the world. Table 2 summarizes the yearly carbon dioxide values, measurements conditions, detection method, and amplitude of CO_2 data for all comparable data sets. For this comparative analysis, all the reference data were taken from the data sets in 2006 from the WMO global atmosphere watch, world data centre for greenhouse gases (WDCGG).

The annual mean concentrations of CO_2 for all the recording stations except Romania (368.3 ppm) were above the global background concentrations of CO_2 (380 ppm). Figure 4 depicts the absolute concentrations and relative amplitude of CO_2 measured from the stations examined for comparative purposes. The mean CO_2 concentration for the Indian Himalaya during the study year was the highest (393.4 ppm), when compared to the stationary stations in Germany (386.15 ppm), Norway (383.07 ppm), Kazakhstan (38.4 ppm), Russia (384.6 ppm) and Mongolia (383.7 ppm) stations. The relative amplitude of the CO_2 values for the comparative data can be estimated as the difference between the maximum and minimum values (amplitude) over mean. The relative amplitude of our study site was similar (3.74%) to the RA recorded in Germany (3.88%) and Norway (3.92%). A strong similarity in seasonal CO_2 patterns (e.g., maximum during winter and minimum in summer) was observed from most stations.

Figure 5 shows the comparison of the monthly mean values of CO_2 measured at different stations around the world. Pallas-Sammaltunturi (Finland) and Mt. Kenya (Kenya) represent the global CO_2 concentration sites, whereas all the other stations for regional CO_2 concentration. Among the sites shown in the Table 2, a number of stations including Sonnblick, Deuselbach, Fundata, Ulaan Uul, and Sary taukum, represent mountainous sites. All of these stations are stationary and free from direct effects of anthropogenic sources. The annual mean CO_2 concentration for mountainous sites, if derived using all those data sets, was much lower (384.2 ppm, range: 381.7-386.2 ppm) than in this work (393.2 ppm). The data from our study site as well as those of the other mountainous

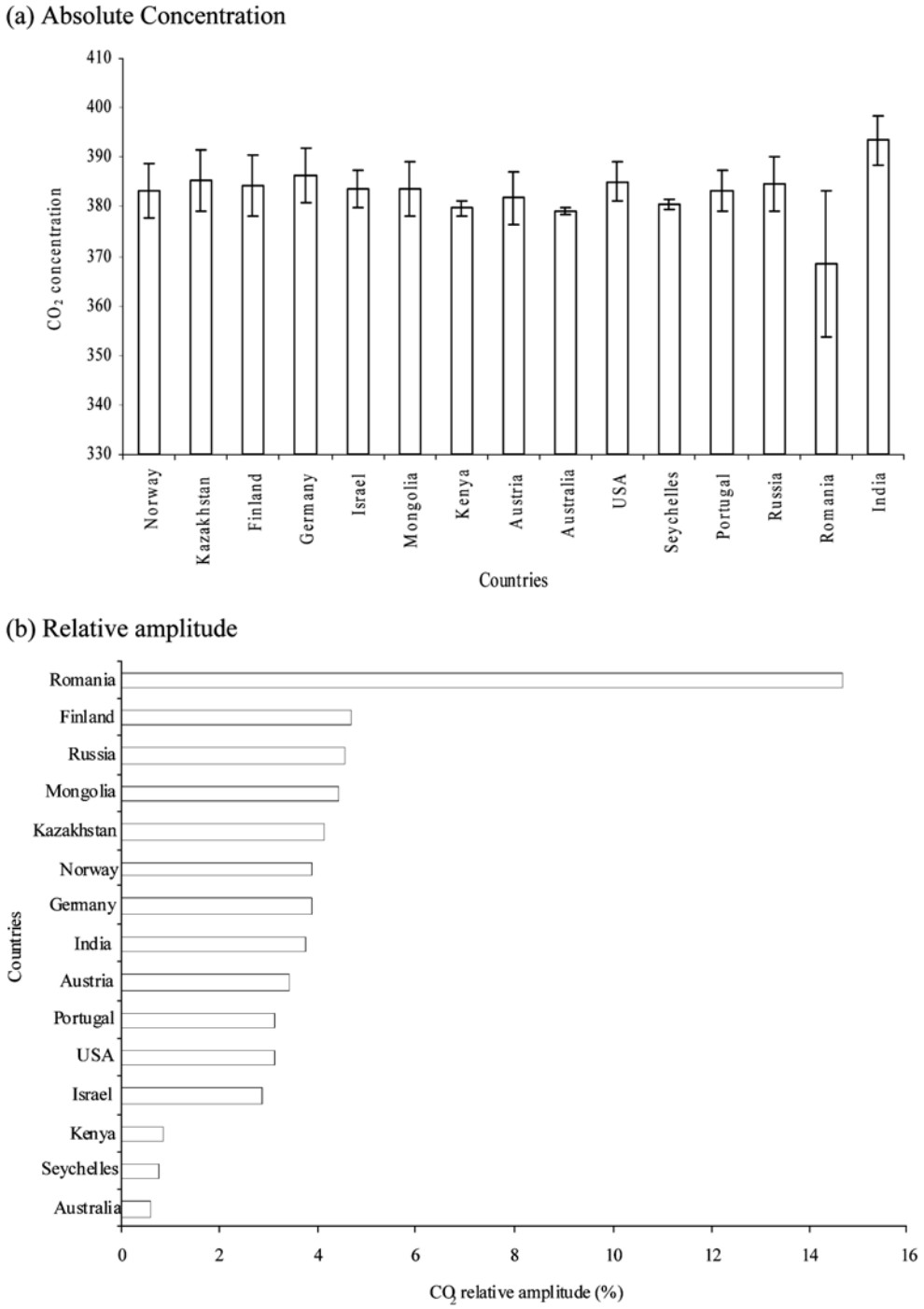

Fig. 4. CO_2 concentration and relative amplitude of CO_2 between this study and others.

sites (like Sary taukum, Sonnblick, and Fundata) show increases in CO_2 concentration from September to January and minimums in August. If the relative amplitude values are compared across the mountainous sites (3.41-4.43%), their values are analogous to our results (3.74%).

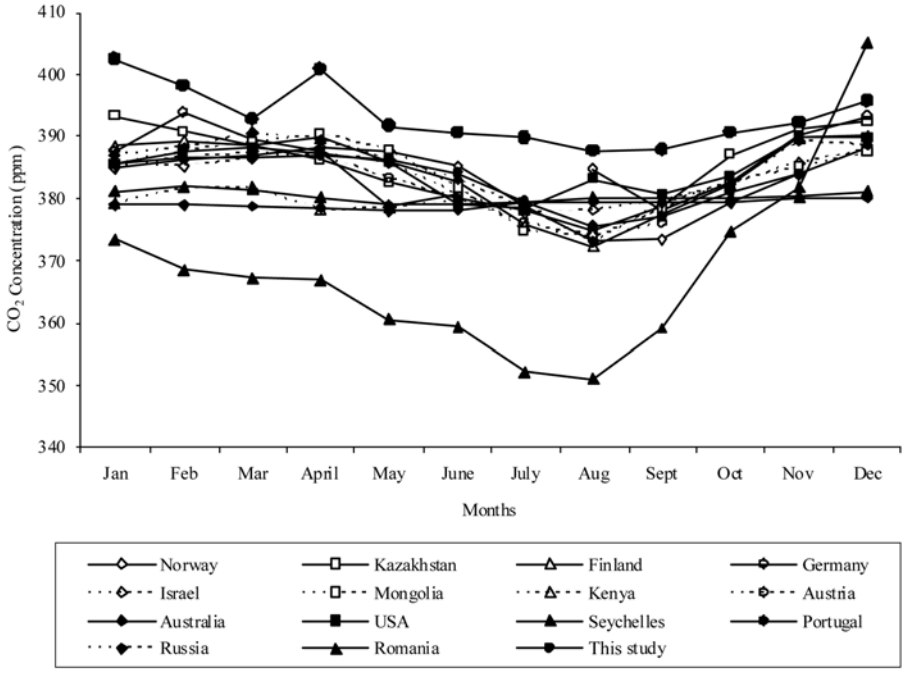

Fig. 5. Month- to- month variation of CO_2 in all stations selected for comparison.

Table 2. Comparison of the mean CO_2 concentrations measured around the world

City/Station	Recording Year	Method	Sampling Type	No of Sampling Months	Average (ppm)	SE	Amplitude (ppm)	Relative Amplitude (%)
Australia (Cape Fergusson)	2006	GC (FID)	Flask	12	379.10	0.2	2.2	0.59
Austria (Sonnblick)	2006	NDIR	Continuous	9	381.71	1.8	13.0	3.41
Finland (Pallas-Sammaltunturi)	2006	NDIR	Continuous	12	384.38	1.8	18.0	4.68
Germany (Deuselbach)	2003	GC (FID)	Continuous	11	386.15	1.7	15.0	3.88
Israel (Sede Boker)	2006	NDIR	Flask	12	383.57	1.1	11.0	2.87
Kazakhstan (Sary Taukum)	2006	NDIR	Flask	12	385.35	1.8	16.0	4.15
Mongolia (Ulaan Uul)	2006	NDIR	Flask	12	383.66	1.6	17.0	4.43
Kenya (Mt. Kenya)	2006	NDIR	Flask	7	379.63	0.5	3.3	0.86
Norway (Zeppelinfjellet)	2006	NDIR	Continuous	12	383.07	1.6	15.0	3.92
Portugal (Terceira Island)	2007	NDIR	Flask	11	383.06	1.2	12.0	3.13
Russia (Teriberka)	2006	NDIR	Flask	11	384.63	1.6	17.6	4.58
Seychelles (Mahe Island)	2006	NDIR	Flask	12	380.42	0.3	3.0	0.79
USA (Southern Great Plains)	2006	NDIR	Flask	12	384.98	1.1	12.0	3.12
Romania (Fundata)	2005	NDIR	Continuous	12	368.32	4.3	54.1	14.69
India (Srinagar Garhwal)	2006	NDIR	Continuous	12	393.35	1.4	14.7	3.74

GC (FID) denotes Gas chromatograph with flame ionization detector
NDIR denotes Nondispersive infrared sensor
Source: The data, except the values recorded in this study, were obtained from WMO global atmosphere watch, World data centre for greenhouse gases (WDCGG).

Conclusion

In this study, the temporal variations in atmospheric carbon dioxide in the mountainous region of Srinagar Garhwal were investigated using data sets collected continuously from Jan. to Dec. 2006. Diurnal

variations of CO_2 were characterized by growth at night. Examination of seasonal variations revealed higher CO_2 concentrations in winter and lower values following the monsoon season as green plants absorb atmospheric CO_2 (through photosynthesis) during this time. When the diurnal variations were assessed across different months, the patterns confirmed the combined effect of biogenic and meteorological factors. The annual mean carbon dioxide concentration in Srinagar Garhwal was much higher (393 ppm) than the global mean atmospheric CO_2 value of 380 ppm and the mean values of other mountainous areas (384.2 ppm). This work is the first report on continuous monitoring of CO_2 in Garhwal Himalaya, India. According to our analysis, it may be important to explain the possible cause of the high CO_2 levels in this clean area. As the troposphere baseline data of CO_2 concentration had not been previously measured over the Himalayan region, precise measurements of atmospheric CO_2 are needed over an extended period. These measurements can offer more insight into the factors governing CO_2 concentration under diverse environmental settings.

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