Seasonal and interannual variability of CO\textsubscript{2} above the moist tropical forest of southern Vietnam

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Abstract. The paper presents the results of a study of seasonal and interannual variability of CO\textsubscript{2} concentration above the moist tropical forest in southern Vietnam. Experimental data were collected during year-long observation of CO\textsubscript{2} directly in the forest from 2012 to 2017. All data were obtained through the use of an air intake tube, placed on a metal tower at a height of 46 m and connected to a Li-Cor 820 gas analyzer (Li-Cor Inc., USA) located in a building at the foot of the tower. The values of the concentration were recorded with a resolution of 1 second; for further analysis, all data was averaged to 0.5 h values. Statistical processing based on the Fourier analysis allowed to evaluate the main characteristics of the annual distribution of CO\textsubscript{2} concentration, such as the amplitude and phase, as well as to analyze their variability over the years. The results of the study showed a presence of a well-determined annual course of CO\textsubscript{2} concentration above the canopy of the moist tropical forest.

1. Introduction
The concentration of greenhouse gases such as carbon dioxide (CO\textsubscript{2}) is governed by numerous abiotic and biotic factors, including key atmospheric parameters, biophysical vegetation and soil properties [1-4]. The modern time series of atmospheric CO\textsubscript{2} concentrations (C\textsubscript{CO2}) include three types of dynamics. First, increasing trends of atmospheric CO\textsubscript{2} concentrations have been observed due to an increase in anthropogenic CO\textsubscript{2} emissions. Second, there are seasonal (periodic) variations caused by biosphere
processes in terrestrial ecosystems and atmospheric circulation (climatic seasonal changes). Finally, there are irregular (random) or quasi-regular variations associated with climatic fluctuations (such as El Niño), large-scale interactions in the atmosphere-ocean system and volcanic eruptions. The appropriate differentiation and further interpretation of each component have an important fundamental role in understanding and quantifying both the sinks and sources of atmospheric CO$_2$ as well as its temporal variability [5].

Intact tropical ecosystems are estimated to uptake half of the CO$_2$ of volume for all the world’s vegetation [6, 7]. However, biogeophysical and biogeochemical studies in the biome of tropical forests are still rare. Seasonal tropical forests, which are underrepresented in literature in comparison with rain forests, may demonstrate significant differences in carbon cycling due to the prominent seasonal course of the moisture regime.

The main goal of the study is to estimate the seasonal and interannual variability of CO$_2$ concentration above the canopy of a mature semi-evergreen tropical seasonal forest of southern Vietnam. These CO$_2$ concentration studies are a part of the complex environmental research conducted by the Joint Russian-Vietnamese Tropical Research and Technology Center on the territory of Vietnam.

2. Object and methods

2.1. Experimental site

Measurements of gas concentrations were carried out in southern Vietnam in Cát Tiên National Park, which was established in 1992 and recently became one of the two central parts of Đồng Nai biosphere reserve. The measurement site (11°27'N, 107°24'E, 140 m. a.s.l.) is located in tropical lowland seasonal semi-evergreen forest. The forest in this reserve is a primary forest, but it has been disturbed by selective logging and exploiting of non-timber products for years until 1992 [8-10]. Specifically, thick trees with diameter at a height of 90-120 cm were often cut to shape clearings [10]. However, the native vertical structure with 3 to 5 canopy levels and rich biodiversity did survive [10]. The average height of the canopy is 36-37 m, while emergent trees reach 45 m. The measurements conducted with AccuPAR LP-80 ceptometer (Decagon Devices, USA) produced leaf area index (LAI) of 5.1±0.9 m$^2$ m$^{-2}$, with slight decrease of the values in a dry season. The dominant species of the upper levels of the canopy are drought-deciduous Lagerstroemia calyculata (Lythraceae), Haldina cordifolia (Rubiaceae), Tetrameles nudiflora (Datiscaceae), Afzelia xylocarpa (Caesalpiniaceae), Sterculia cf. cochinchinensis (Sterculiaceae); however, the species of medium and lower levels are predominantly evergreen [10]. Herb cover is patchy. In a wet season, lows are deluged after showers soil becomes saturated with water and puddles are formed. In a dry season, the ground water level drops by 5 to 8 m, and the soil dries up and cracks. Specifically, soils in this forest are District Skeletic Rhodic Cambisol (Clayic) as classified by Reference Base for Soil Resources. They are well-drained, formed at extensively weathered basalts and tuffs with volcanic ash [11-12]. Organic carbon content in the upper layer is 2-3% and nitrogen content is 0.45–0.22% [12]. Due to the base rock composition, soils are rich with phosphorus and potassium [12]. The climate is tropical monsoon with wet summer and dry winter, which is equivalent to Am in Köppen–Geiger climate classification system [13]. According to Đồng Xoài weather station located in 57 km from the site, during the period 1980–2010 the mean annual precipitation and temperature were 2518 mm and 26.4 °C, respectively [14]. Four months (from December to March) have rain totals lower than 100 mm mon$^{-1}$. Furthermore, three distinct seasons may be identified: wet season (May-October), cool-dry season (November-January) and hot-dry pre-monsoon season (February-April).

2.2. Experimental CO$_2$ data

Experimental data were obtained during long-term observations of C$_{CO2}$ over the canopy of the moist tropical forest. An air intake probe equipped with a heated inlet filter and a mixing volume was placed on a metal tower at a height of 46 m. Air was constantly pumped with a flow rate of about 200 ml min$^{-1}$.
through a tube with a diameter of 1/4 inch and transported to Li-Cor 820 gas analyzer (Li-Cor Inc., USA) located in a building at the foot of the tower. The values of the concentration were recorded with a resolution of 1 second on a CR1000 data logger (Campbell Scientific Inc., USA). For further analysis, all data were averaged to 0.5 h values.

Figure 1. Location of the study site (contour map credits: Wikipedia; satellite image credits: CNES/Airbus 2018, DigitalGlobe 2018).

Figure 2. Seasonal tropical forest in wet (left panel) and in dry (right panel) seasons. Southern Vietnam, Cát Tiên National Park.

2.3. Statistical processing
The $C_{CO2}$ data that were used for further analysis represent a discrete time series collected in 0.5 hour increments. The analysis of seasonal and interannual dynamics of $C_{CO2}$ is based on the methodology
The method was tested by a number of researchers on a large experimental material [16-25].

Only the daily values of $\text{C CO}_2$ averaged for the period of 13:00 – 16:30 hours were taken into consideration. The choice of daily values of $\text{C CO}_2$ is conditioned by the specifics of daily dynamics of $\text{C CO}_2$. In general, daytime is characterized by stability of $\text{C CO}_2$ for several hours [26].

The time series averaged for daytime $\text{C CO}_2$ was approximated by the function (1):

$$F_t = a_0 + b_0 t + \sum_{n=1}^{5} (a_n \sin \left(\frac{2\pi t}{T_n}\right) + b_n \cos \left(\frac{2\pi t}{T_n}\right)),$$

where $t$ is time in days from January 1, 2012 to December 31, 2017, $a_0$, $b_0$ – trend coefficients (linear regression), $a_n$, $b_n$ – harmonic weights, $T_n$ – harmonic periods: $T_1=365$, $T_2=182.5$, $T_3 =121.66$, $T_4 = 2190$, $T_5 = 1095$ days.

The function includes a linear trend and cyclic components, which are a polynomial of the first degree and the sum of the harmonics of the Fourier series. The parameters of the trend equation were found by the method of least squares; the coefficients and weights of harmonics were found by the Fourier transform.

As a result, the calculated time series of $\text{C CO}_2$ was obtained, which is the sum of five harmonics and a linear function. At the next stage, residuals were determined as the difference between the observed values of $\text{C CO}_2$ and the values calculated by the function (1).

The value of $3\sigma$ determined from a number of residues ($\sigma$ is the standard deviation) was used further as a criterion for estimating “emissions” over the entire time series [27]. Additionally, anomalous $\text{C CO}_2$ values were temporarily removed from the time series. Thus, a new time series was obtained in which the abnormal (high and low) values of $\text{C CO}_2$ were excluded. The procedure for approximating the observations by function (1) and calculating the residuals was repeated 4 times until all “outliers” were found and eliminated.

Furthermore, the (final) series of residues obtained after 4 procedures was subjected to low-pass filtering using a fast Fourier transform. To perform this procedure, the original series of data was converted into a frequency form through a fast Fourier transform and then filtered and returned to its original format using the inverse Fourier transform. Low-pass filtering of residues was carried out 1 time with a smoothing period of 547.5 days. Further analysis included the following series:

1) Smoothed time series in which only short-term variations are excluded. It is the sum of the values of $\text{C CO}_2$ concentration calculated by formula (1) and the residues obtained by low-pass filtering with a period of 547.5 days.

2) Long term trend – a time series in which annual seasonality is excluded. It is the sum of $\text{C CO}_2$ values calculated only for the first part of function (1) (polynomial of the first degree) and residues obtained by low-pass filtering with periods of 2190,1095, 730, 547.5 days.

3. Results and discussion

The results of $\text{C CO}_2$ observations above the canopy of the moist tropical forest are presented in figure 3. Long-term observations showed the presence of a well-defined annual course of $\text{C CO}_2$. The maximum $\text{C CO}_2$ was observed during dry period; minimum – during the wet period (end of August – beginner of September).

Quite frequently, seasonal and interannual variability is characterized using the detrended time series to estimate the amplitude of $\text{C CO}_2$ (seasonal and annual) and phase [28, 29]. The seasonal amplitude of $\text{C CO}_2$ measured directly above the forest canopy is an indirect indicator of the ratio of gross primary production and ecosystem respiration. For forest ecosystems in general including the boreal forests that are characterized by a period of lack of photosynthesis in winter, seasonal amplitude is defined as the difference between the values of $\text{CO}_2$ concentration at the moment of its intense decline in the spring
and the minimum $C_{CO_2}$ values observed during the period of active vegetation. The annual amplitude is determined by the difference between the maximum and minimum values of $C_{CO_2}$ and is determined, inter alia, by the amount of winter CO$_2$ emissions.

![Figure 3. Long-term course of daily daytime average CO$_2$ concentration above the moist tropical forest in southern Vietnam (blue marker), green line - smoothed time series (see function 1).](image)

The seasonality phase is the period of time when the $C_{CO_2}$ in the detrended series is in the period of negative values. For the boreal forest region, the date of transition of $C_{CO_2}$ values through zero is used as an indicator of the start of CO$_2$ photoassimilation in the studied region. However, this date cannot be considered the beginning of photosynthesis [29].

For the tropical region, in conditions when the assimilation of CO$_2$ is year-round, there is no period in the annual course of $C_{CO_2}$ for which only CO$_2$ emission is characteristic. Therefore, the annual variation in concentration coincides with the seasonal one (figure 4).

![Figure 4. Average long-term seasonal course of CO$_2$ concentration above the moist tropical forest of southern Vietnam in 2012-2017. The course is estimated using a detrended smoothed series of daily CO$_2$ concentrations.](image)
Average annual amplitude of $C_{CO_2}$ over the canopy of a forest for the observation period (2012 – 2017 years) was 14.2 ± 1.2 ppm (Table 1). The maximum amplitude for the observation period was 8.5 ppm, the minimum – 10.0 ppm. The duration of the phase (the values of the detrended series correspond to negative concentration values) was 236 ± 25.

Table 1. The annual CO$_2$ concentration amplitude, minimum, maximum and duration of phase for seasonal tropical forest of southern Vietnam in 2012 – 2017 *

| Year | Minimum [ppm] | Maximum [ppm] | Annual amplitude [ppm] | Phase [days] |
|------|---------------|---------------|------------------------|--------------|
| 2012 | -7.9          | 6.0           | 13.9                   | 240          |
| 2013 | -10.0         | 5.1           | 15.1                   | 250          |
| 2014 | -8.3          | 4.3           | 12.7                   | 253          |
| 2015 | -4.9          | 8.5           | 13.5                   | 190          |
| 2016 | -8.3          | 7.8           | 16.0                   | 225          |
| 2017 | -9.4          | 4.4           | 13.9                   | 259          |
| Averaged value | -8.1±1,8 | 6.0±1,8 | 14.2±1,2 | 236±25 |

* The data presented in Table 1 are based on detrended smoothed time series.

According to our observations, the amplitude of the $C_{CO_2}$ in the seasonally humid tropical forest is less than the amplitude of $C_{CO_2}$ in the boreal forests, which is estimated at 22–28 ppm [30–33]. The phase duration in the seasonal tropical forest significantly exceeds the phase duration for the boreal forest zone, which is estimated at 133 days [25, 30-33].

According to estimates of the net ecosystem production (NEP) the seasonal tropical forest is a strong CO$_2$ sink for the atmosphere [34]. The NEP of the studied moist tropical forest is comparable with that of tropical rainforests. To study the role of seasonal forests in the balance of greenhouse gases would require the development and maintenance of long-term observations of $C_{CO_2}$ and CO$_2$ fluxes.

4. Conclusion

The analysis of long-term continuous observations of the CO$_2$ concentration over the canopy of the moist tropical forest showed the presence a well-defined annual course with maximums and minimums in the dry and wet periods respectively. Statistical processing made it possible to evaluate the main characteristics of the annual variation, such as the amplitude and phase of seasonality. The amplitude of CO$_2$ over the seasonal tropical forest is less than the amplitude over the boreal forests, and the phase duration significantly exceeds the phase duration in the boreal forests.

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