Earth Syst. Dynam. Discuss., 5, 63–81, 2014
www.earth-syst-dynam-discuss.net/5/63/2014/
doi:10.5194/esdd-5-63-2014

Earth System Dynamics Discussions
Open Access

Explaining the seasonal cycle of the globally averaged CO_2 with a carbon cycle model

G. A. Alexandrov

A. M. Obukhov Institute of Atmospheric Physics, Russian Academy of Sciences, Pyzhevsky 3, 119017, Moscow

Received: 23 November 2013 – Accepted: 17 December 2013 – Published: 6 January 2014

Correspondence to: G. A. Alexandrov (g.alexandrov@ifaran.ru)

Published by Copernicus Publications on behalf of the European Geosciences Union.

Abstract

The discrepancy between simulated and observed globally averaged monthly atmospheric concentrations of carbon dioxide could be attributed either to deficiencies in the observation network or to inadequacies in the global carbon cycle models. This paper shows that model results could be brought closer to observations by improving model components that describe the seasonal changes in the storage of quickly decaying fractions of litter.

1 Introduction

The global mean monthly atmospheric concentrations of carbon dioxide provided by NOAA/ESRL (Conway and Tans, 2012) show that the carbon storage of the atmosphere undergoes regular seasonal changes. The amplitude of seasonal variations in the atmospheric carbon storage puts certain constraints on the choice of parameters in the models of global carbon cycle and the joint carbon–climate models. It would be natural to expect that models are tuned to reproduce the CO_2 growth curve – the basic scientific evidence of the global change, but this not the case. One may find papers demonstrating that carbon cycle models coupled with atmospheric transport models could reproduce seasonal cycle of CO_2 concentrations at some locations (Heimann et al., 1998; Dargaville et al., 2002; Randerson et al., 2009). However, it is difficult to find an article comparing simulated seasonal variations in the atmospheric carbon storage with the globally averaged monthly concentrations of carbon dioxide reported by NOAA/ESRL. A recent article (Chen, 2011) reporting the results of such comparison brings bad news: the observed amplitude of seasonal variations in the atmospheric carbon storage is larger than simulated. Where does the discrepancy come from? The results from simple model experiments presented here partly address this question.

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2 Methods

2.1 Net carbon exchange between the atmosphere and other pools

2.1.1 Observations

The seasonal cycle of the atmospheric carbon storage reflects the seasonal cycle of the net carbon exchange between the atmosphere and other pools. The de-trended net exchange (N_a) is derived from the de-trended atmospheric carbon storage (dC_a), which in its turn is calculated from the de-trended globally averaged monthly concentrations of carbon dioxide in the atmosphere ($d[CO_2]$) reported by NOAA/ESRL (Conway and Tans, 2012): $dC_a(m) = 2.13 \times d[CO_2](m)$. Since $dC_a(m)$ is the value of dC_a in the middle of the month m, the value of dC_a in the beginning of the month m is calculated as the mean of its values in the middle of this month and in the middle of the preceding month, that is, as $(dC_a(m-1) + dC_a(m))/2$, and the value of dC_a in the end of the month m is calculated as the mean of its values in the middle of this month and in the middle of the following month, that is, as $(dC_a(m) + dC_a(m+1))/2$. Then $N_a(m)$ is calculated as the difference between the value of dC_a in the end of the month m and its value in the beginning of the month m:

$$N_a(m) = \frac{dC_a(m) + dC_a(m+1)}{2} - \frac{dC_a(m-1) + dC_a(m)}{2} \tag{1}$$

that gives

$$N_a(m) = \frac{dC_a(m+1) - dC_a(m-1)}{2}. \tag{2}$$

The accuracy of monthly N_a estimates is determined by the accuracy of monthly $d[CO_2]$ estimates. Since monthly $d[CO_2]$ estimates are derived from local observations (Masarie and Tans, 1995), the accuracy of monthly N_a estimates depends on the adequacy of the observation network.

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2.1.2 Modelling

The monthly N_a estimates could be also calculated using the following equation:

$$N_a(m) = -\mathrm{GPP}(m) + R_a(m) + R_h(m) + v_a(m) \tag{3}$$

where GPP, R_a, and R_h are gross primary production, autotrophic respiration, and heterotrophic respiration of the terrestrial ecosystems, and v_a is net carbon exchange between the atmosphere and remaining carbon pools.

The seasonal cycle of GPP, R_a, and R_h is simulated here using the concepts of the MONTHLYC model (Box, 1988) and the global fields of monthly actual evapotranspiration (Willmott, 1985) and monthly air temperature (Leemans and Cramer, 1991) gridded at a $0.5^\circ \times 0.5^\circ$ resolution.

The seasonal cycle of GPP is determined in the MONTHLYC model by the monthly actual evapotranspiration, AET(m):

$$\mathrm{GPP}(m) = \frac{\mathrm{AET}(m)}{\sum_{m=1}^{12} \mathrm{AET}(m)} \mathrm{GPP}_{\mathrm{ann}} \tag{4}$$

where $\mathrm{GPP}_{\mathrm{ann}}$, the annual GPP, is derived from the Montreal NPP model.

The Montreal NPP model relates annual net primary production ($\mathrm{NPP}_{\mathrm{ann}}$, in $\mathrm{g\,C\,m^{-2}\,yr^{-1}}$) to annual actual evapotranspiration ($\mathrm{AET}_{\mathrm{ann}}$, in $\mathrm{mm\,yr^{-1}}$) (Box, 1988):

$$\mathrm{NPP}_{\mathrm{ann}} = 1350 \cdot (1 - e^{-0.0009695 \cdot (\mathrm{AET}_{\mathrm{ann}} - 20)}) \tag{5}$$

and $\mathrm{GPP}_{\mathrm{ann}}$ is derived from $\mathrm{NPP}_{\mathrm{ann}}$ using the empirical equation (Box, 1988)

$$\mathrm{GPP}_{\mathrm{ann}} = -1863 \cdot \ln(1 - \mathrm{NPP}_{\mathrm{ann}}/1350) \tag{6}$$

that gives

$$\mathrm{GPP}_{\mathrm{ann}} = 1.8062 \cdot (\mathrm{AET}_{\mathrm{ann}} - 20) \tag{7}$$

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The monthly values of R_a in the MONTHLYC model are proportional to $Q_{10}^{\frac{T(m)-10}{10}}$ ($Q_{10} = 2$):

$$R_a(m) = \frac{Q_{10}^{\frac{T(m)-10}{10}}}{\sum_{m=1}^{12} Q_{10}^{\frac{T(m)-10}{10}}} R_{a,ann} \tag{8}$$

where $T(m)$ is monthly air temperature and $R_{a,ann}$ is the annual autotrophic respiration calculated as the difference between GPP_{ann} and NPP_{ann}:

$$R_{a,ann} = GPP_{ann} - NPP_{ann} \tag{9}$$

The monthly values of heterotrophic respiration from each litter pool depend in the MONTHLYC model on the rates of litter decay and the storage of litter:

$$R_{h,i}(m) = r_i(m)s_i(m) \tag{10}$$

where the monthly values of decay rates are proportional to monthly values of AET:

$$r_i(m) = \frac{AET(m)}{\sum_{m=1}^{12} AET(m)} r_{a,i} \tag{11}$$

and $r_{a,i}$ depends on the annual amount of AET (Box, 1988) as follows:

$$r_{a,i} = r0_{a,i} \cdot 10^{-1.4553+0.0014175 \cdot AET_{ann}} \tag{12}$$

The monthly values of litter storages satisfy in the MONTHLYC model the following difference equations:

$$s_i(m+1) = s_i(m) + p_i(m) - r_i(m)s_i(m) \tag{13}$$

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where $p_i(m)$ is the input of organic matter to the ith pool of litter. They are found by iterations.

Up till now all of the modelling formulation directly follows Box (1988). Modifications that I introduced to the MONTHLYC model were as follows.

Whereas Box (1988) used 3 litter pools: above-ground true litter (mostly leaves), root litter, and large woody debris (deadfall), I instead use two pools: the pool of slowly decaying fractions and the pool of quickly decaying fractions. The annual heterotrophic respiration is, thus, divided into heterotrophic respiration related to slowly decaying fractions of litter ($R_{\mathrm{h,s}}$) and that related to quickly decaying fractions ($R_{\mathrm{h,q}}$). The seasonal changes in the storage of slowly decaying litter are small in comparison to its average value, and so the seasonal cycle of $R_{\mathrm{h,s}}$ reflects that of the rate of decay, which is assumed to be proportional to AET(m).

$$R_{\mathrm{h,s}}(m) = \frac{\mathrm{AET}(m)}{\sum_{m=1}^{12} \mathrm{AET}(m)} R_{\mathrm{h,s,ann}} \quad (14)$$

and

$$R_{\mathrm{h,s,ann}} = (1 - \phi)\mathrm{NPP}_{\mathrm{ann}} \quad (15)$$

where ϕ is the share of quickly decaying fractions in the litterfall, and $R_{\mathrm{h,s,ann}}$ is the part of heterotrophic respiration related to slowly decaying fractions of litter, which in the case of de-trended carbon cycle is equal to the corresponding part of $\mathrm{NPP}_{\mathrm{ann}}$.

The storage of quickly decaying fractions is sensitive to the seasonal pattern of litterfall. Since deciduous trees shed leaves in the end of growing season, the part of heterotrophic respiration which is related to quickly decaying fractions may depend on the substrate availability. The seasonal changes in the storage of quickly decaying fractions of litter (s) are modelled here by the ordinary differential equation:

$$\frac{\mathrm{d}s}{\mathrm{d}t} = -r(t)s \quad (16)$$

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where $r(t)$ is the rate of litter decay, and t is the time elapsed since the end of growing season. The periodical continuous function $r(t)$ interpolates the $r(m)$ values ($r(m+12) = r(m)$), which are proportional to monthly values of AET.

If litterfall occurs only in the end of growing season, then $s(0) = s(12) + p$, where p is equal to $\phi \cdot \mathrm{NPP_{ann}}$. In this case,

$$s(n) = \frac{\phi \cdot \mathrm{NPP_{ann}}}{1 - e^{-\int_0^{12} r(t)\mathrm{d}t}} e^{-\int_0^{n} r(t)\mathrm{d}t} \tag{17}$$

where n is the number of months elapsed since the end of growing season.

The storage of quickly decaying litter in a given month m is calculated using the equation

$$S(m; m_0) = \frac{\phi \cdot \mathrm{NPP_{ann}}}{1 - e^{-\int_{m_0}^{m_0+12} r(t)\mathrm{d}t}} e^{-\int_{m_0}^{m} r(t)\mathrm{d}t} \tag{18}$$

where m_0 is the last month of the growing season and $m \geq m_0$. If $m < m_0$, then $S(m; m_0)$ is calculated as follows:

$$S(m; m_0) = \frac{\phi \cdot \mathrm{NPP_{ann}}}{1 - e^{-\int_{m_0}^{m_0+12} r(t)\mathrm{d}t}} e^{-\int_{m_0}^{m+12} r(t)\mathrm{d}t} \tag{19}$$

Consequently, heterotrophic respiration related to decomposition of quickly decaying litter is calculated using the following equation:

$$R_{\mathrm{h,q}}(m) = r(m) S(m; m_0) \tag{20}$$

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where the geographic distribution of m_0 is derived from the assumption that the growing season in the deciduous forests of Northern Hemisphere normally ends when monthly air temperature goes below 10 °C (that is, in September or October), and that in some other ecoregions, the end of growing season may occur due to the lack of precipitation, e.g., when monthly AET goes below $20\,\mathrm{mm\,month^{-1}}$.

GPP, R_a, and R_h are the major drivers of the seasonal changes in the atmospheric carbon storage. The amplitude of seasonal changes in the carbon exchange between the atmosphere and the ocean is relatively small (e.g., Chen, 2011). The same can be said about the seasonal changes in the emissions from fossil fuels burning. Hence, one could assume that $-\mathrm{GPP}(m)+R_a(m)+(1-\phi)R_{h,s}(m)+\phi R_{h,q}(m)$, may give a good approximation of $N_a(m)$ under some choice of ϕ and Q_{10} values. This assumption was tested by numerical experiments. The results are discussed below.

3 Results and discussion

The global monthly GPP calculated using Eqs. (4)–(7) has a peak when N_a has a dip (Figs. 1 and 2), supporting the view that seasonal cycle of the globally averaged atmospheric CO_2 concentration reflects the seasonality of plant activity (Keeling et al., 1996). The effect of GPP is reduced, however, by autotrophic respiration (R_a) that has a peak at the same month as GPP. The part of the heterotrophic respiration that results from the decay of slowly decaying fraction of litter ($R_{h,s}$) also has a peak at the same month as GPP. If there were no quickly decaying litter fractions, the amplitude of the seasonal changes in the net exchange between the atmosphere and the terrestrial part of the biosphere would be very narrow if compared to that of N_a (Fig. 3). Taking into account the substrate availability allows us to reconcile the amplitude of the seasonal changes in the net exchange between the atmosphere and the terrestrial part of the biosphere with that of N_a (Fig. 4) and thus to explain the seasonal cycle of the atmospheric carbon storage (Fig. 5).

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The results of this study confirm the hypothesis that seasonality of Net Ecosystem Production (NEP) depends strongly "on the time at which plant substrate becomes available as a food source for the various organisms that comprise the heterotrophic community" (Randerson et al., 1996). The climatic conditions which are favourable for the high rate of NPP are also favourable for the high rate of heterotrophic respiration. There should be something that disrupts the balance between the organic matter decay and production in boreal ecosystems and leads to a pronounced seasonality of NEP. This study shows that the shift between the phase of NPP seasonal cycle and the seasonal cycle of litterfall production may have such effect.

The models and submodels of litterfall production (e.g., Randerson et al., 1996; Potter et al., 1993; Box, 1988; Esser, 1987; Ito and Oikawa, 2002; Eliseev, 2011) often deal with such components as coarse woody debris, fine woody debris, leaf debris and so on. In this study all litter components were aggregated in two pools: slowly decaying fractions and quickly decaying fractions. The latter pool was assumed to be refilled once per year (Fig. 6) and depleted in summer. During the period of the pool depletion heterotrophs decomposing quickly decaying fractions become substrate-limited. This causes a decrease in monthly heterotrophic respiration below that expected from a model that does not take into account the effects of substrate availability. The decrease, which is referred to as substrate limitation (Randerson et al., 1996), depends on the share of quickly decaying fractions in the litterfall. If 70 % of annual respiration in each grid cell results from the decomposition of quickly decaying fractions, then the amplitude of the seasonal changes in the modelled net exchange between the atmosphere and the terrestrial part of the biosphere becomes large enough to explain the seasonal cycle of the atmospheric carbon storage.

Such a high ratio of annual $R_{h,q}$ to annual R_h does not seem completely unrealistic. In some models of litterfall production the share of leaf and fine root litter varies from 30 to 55 %. Since quite a large portion of leaf and fine root litter formed by quickly decaying fractions, 70 % share of quickly decaying fractions in the total litterfall is unprecedentedly high but not impossible, at least theoretically.

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The ratio of annual $R_{h,q}$ to annual R_h that reconciles the observed and modelled net exchange between the atmosphere and the terrestrial part of the biosphere could become even higher if one would use a more conservative method for modelling litterfall seasonality. The assumption that the pool of quickly decaying fractions is refilled once per year simplifies reality. The input to this pool may occur during the vegetation period, especially in the regions where the share of evergreen vegetation is large.

One can decrease the ratio of annual $R_{h,q}$ to annual R_h needed to reconcile the observed and modelled net exchange between the atmosphere and the terrestrial part of the biosphere by decreasing the Q_{10} factor of respiration. The results similar to shown at the Fig. 4 could be obtained at $Q_{10} = 1.5$ and $R_{h,q}/R_h = 0.6$, $Q_{10} = 1.2$ and $R_{h,q}/R_h = 0.55$, and $Q_{10} = 1.0$ and $R_{h,q}/R_h = 0.5$.

Before concluding the discussion of the obtained results, some words should be said about the motivation of the study. It was motivated by the lack of research articles proving that the seasonal cycle of the globally averaged monthly atmospheric concentration of CO_2 could be explained by the net exchange between the atmosphere and the terrestrial part of the biosphere. The results of the study suggest that this is possible in principle; however, some components of the global carbon cycle models may need improvement. Such conclusion could be considered as a kind of "existence theorem" – that is, as a proof, or, at least, as an evidence that it is possible to develop a realistic global carbon cycle model reproducing the seasonal cycle of the globally averaged monthly atmospheric concentration of CO_2.

This conclusion is not trivial. The discrepancy between simulated and observed seasonal variations in the globally averaged atmospheric concentration of CO_2 could be attributed to the "representation error" of the current observation network. For example, Chen (2011) compared GEOS-Chem CO_2 (Nassar et al., 2010) with GLOBALVIEW-CO_2, found significant discrepancy, and wrote, "The apparent discrepancy between modeling results and observations results from the "representation error" of observation stations" (Chen, 2011). Shall we improve observation network to bring observations in agreement with simulations, or shall we improve models? The "existence

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theorem" suggests that it is possible to bring modeling results closer to observations by improving models. However, there is no evidence that improvement of observation network may bring observations closer to modeling results.

4 Conclusions

The more comprehensive the model, the less people understand how it works. The model which is used in this study omits many important details in sake of conceptual clarity. This allows us to reveal the structural components which are essential for the realistic simulation of seasonal variations in the carbon exchange between the atmosphere and the terrestrial part of the biosphere. They are as follows: (1) the share of quickly decaying fractions in the litterfall; (2) the seasonal cycle of the storage of quickly decaying fractions in the litter; (3) the seasonal pattern of the input into the pool of quickly decaying fractions of litter.

Since the share of quickly decaying fractions is high in the leaf and fine root litter, some efforts should be done to improve the components of comprehensive global carbon cycle models that describe seasonal variations in the storage of leaf and fine root litter, the share of leaves and fine roots in the litterfall, and the seasonal pattern of the input into the pool of leaf and fine root litter. All this is essential to understanding where the discrepancy between simulated and observed globally averaged monthly atmospheric concentrations of carbon dioxide comes from.

Acknowledgements. The research received financial support from the Russian Foundation for Basic Research, grant No 13-05-00781. The author also acknowledges intellectual support received from Alexey Eliseev, Nikolay Zavalishin, Maxim Arzhanov and Kirill Muryshev and highly appreciates the comments made by Ning Zeng and Ralph Keeling on earlier versions of this paper.

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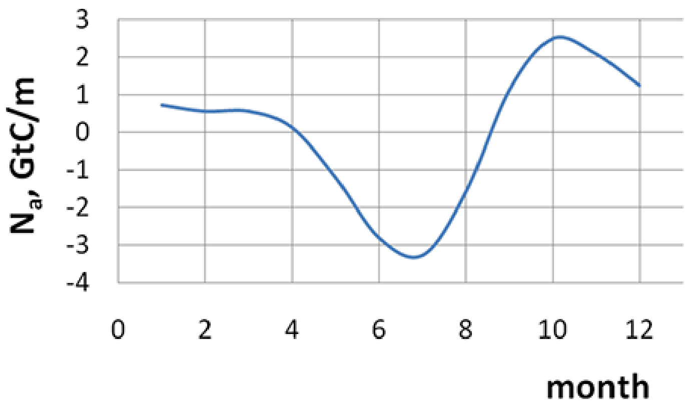

Fig. 1. Seasonal cycle of the de-trended net carbon exchange between the atmosphere and other pools (N_a) in 1995–2005.

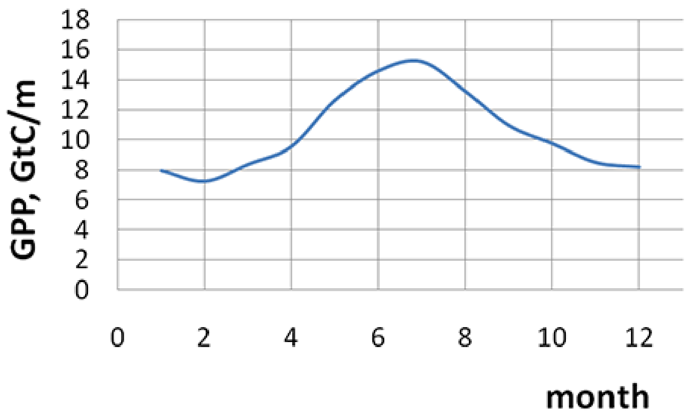

Fig. 2. Seasonal cycle of the Gross Primary Production (GPP) as calculated using Eqs. (4)–(7).

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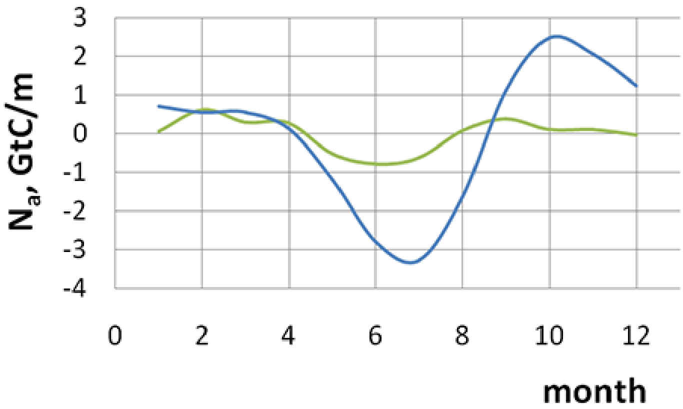

Fig. 3. The seasonal cycle of the in the net exchange between the atmosphere and the terrestrial part of the biosphere (green) in the lack of quickly decaying litter fraction, $-\mathrm{GPP}(m) + R_\mathrm{a}(m) + R_{\mathrm{h,s}}(m)$, as compared to N_a (blue).

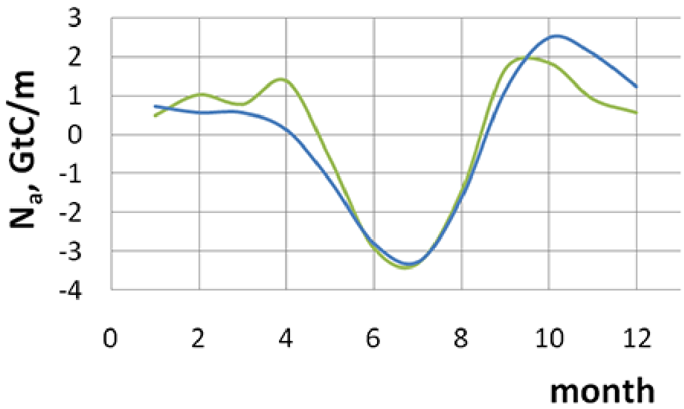

Fig. 4. The seasonal cycle of the in the net exchange between the atmosphere and the terrestrial part of the biosphere (green) if quickly decaying litter fractions form 70 % of litterfall, $-\mathrm{GPP}(m) + R_a(m) + 0.3R_{h,s}(m) + 0.7R_{h,q}(m)$, as compared to N_a (blue).

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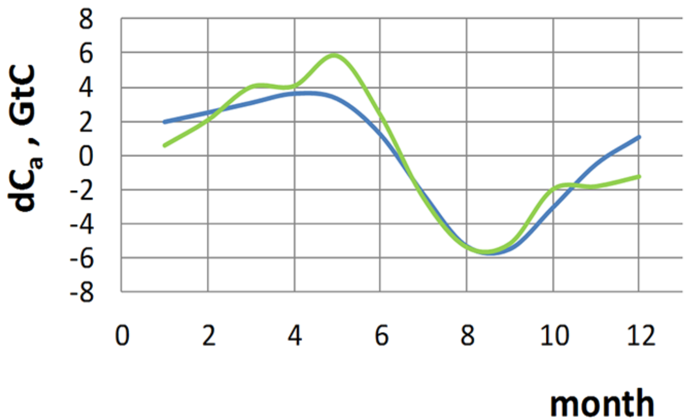

Fig. 5. The part of the seasonal cycle of the de-trended atmospheric carbon storage that could be attributed to the net exchange between the atmosphere and the terrestrial part of the biosphere (green) as compared to the total (blue).

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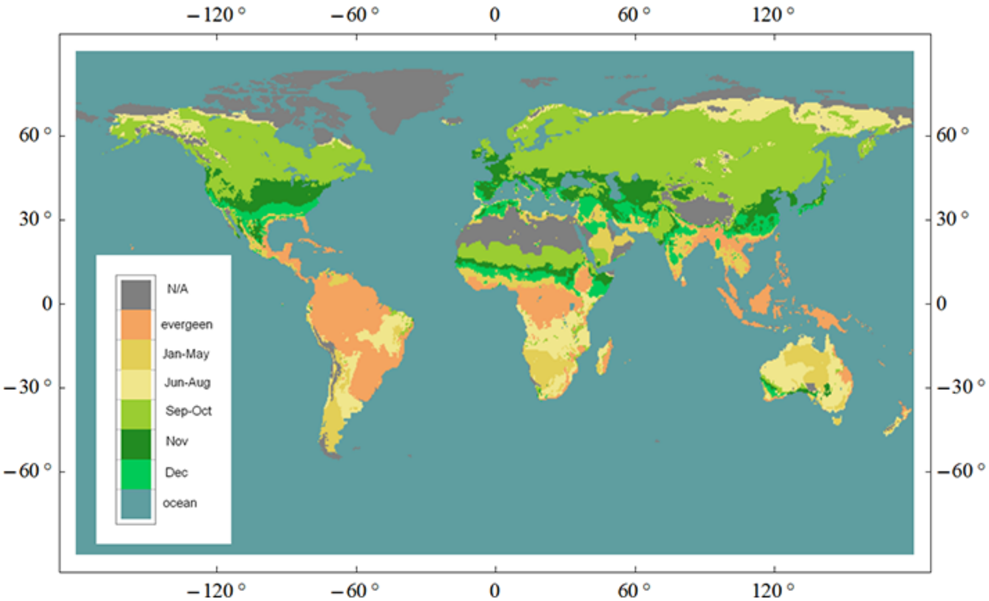

Fig. 6. The month at which deciduous trees supposedly shed leaves due to the end of growing season.

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