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Reply to Idso

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1. Starting points and setting the stage

We agree whith Idso that CO_2 fertilization of terrestrial ecosystems is of great importance in the understanding of the behaviour of the amplitude of the seasonal cycle of atmospheric CO_2 as analyzed in our paper (Kohlmaier et al., 1989, henceforth called II).

In a previous paper (Kohlmaier et al., 1987, henceforth called I), we were able to show that if CO_2 fertilization of global land biota was already real at present time (with a β factor between 0.25 and 0.50), then indeed one should expect an annual carbon sequestering of 0.5–1.0 Gt C a^{-1} for living biota (I, 1987) and 0.7 ± 0.4 Gt a^{-1} for the increase in litter and soil organic matter (Kohlmaier et al., 1988), both for the year 1982, while Keeling et al. (1989) estimated ≈ 2 Gt C for the year 1980.

We have, however, reasons to believe that the amplitude of the seasonal cycle, as measured at Mauna Loa Observatory (MLO) is influenced significantly by factors other than the rising levels of atmospheric CO_2 which is clearly demonstrated by the near constancy of the amplitude beyond the year 1982, as shown in Fig. 1. This could be explained by the fact that CO_2 fertilization in natural ecosystems is indeed lower or at most equal to the experiments in enclosed and monitored environments of relatively short periods or that there are other strong compensating factors which hide the CO_2 fertilization.

From the strong fluctuations of the seasonal amplitude (Fig. 1) we suspect that the year to year climatic variabilities (including the extreme El Niño events) have a strong influence on the seasonal amplitude. It is therefore not unlikely that also trends in the climatic variables (with running means equal to or larger than 3 to 5 years) like the mean annual surface temperature or precipitation will alter the annual amplitude.

Next to the external variation of parameters, influencing the net primary production (NPP) and ecosystem respiration (RES) and thus the amplitude, we certainly need to consider the changes internal to the biome systems. Any seasonal cycle analysis weighs the changes in the biomes with respect to their seasonal amplitude contributing to the signal at the point of observation. Thus for MLO, which essentially integrates the signal of all biota of the northern hemisphere, we expect that changes in the tropical zones (with small seasonality) are noticed less clearly than those in higher latitudes. When analyzing the changes we must keep in mind that not only the present land use changes need to be considered but that also the long term dynamics of ecosystems, not in a steady state, may be of significance.

2. The amplitude analysis of the seasonal cycle in atmospheric CO_2, and its relation to a CO_2 fertilization effect

In our previous analysis of the seasonal cycle in II, which referred to the Mauna Loa measuring period from 1958 to 1982, we concluded that we could explain only approximately 25% of the observed increase, considering a CO_2-fertilization factor β of 0.375. It is suggestive that a β-factor in the neighbourhood of 2, which most ecologists are not willing to accept, could explain the observed

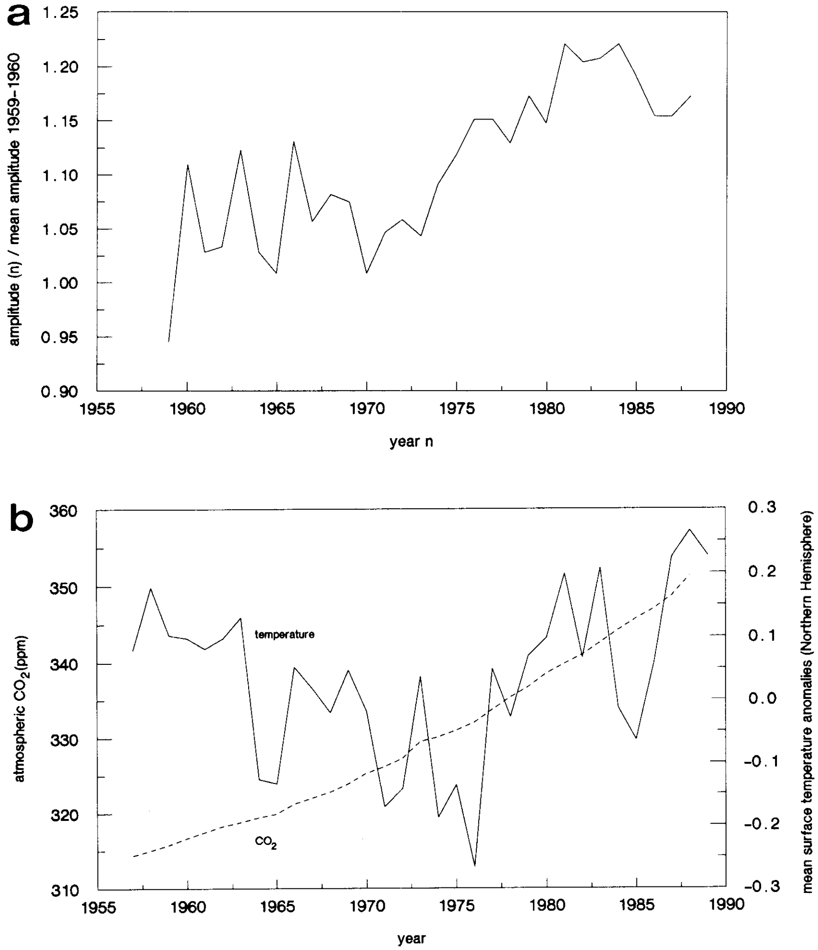

Fig. 1. (a) Relative peak to peak amplitude of the seasonal cycle of atmospheric CO_2 as measured at Mauna Loa Observatory. (b) Seasonally adjusted atmospheric CO_2-concentration (after Keeling et al., 1989), and mean annual surface temperature anomalies for the northern hemisphere (after Schönwiese et al., 1990).

amplitude increase until 1982. However, a qualitative inspection of Fig. 1 seems to indicate that such a monocausal relationship cannot hold any longer, if we consider the period beyond 1982, where the amplitude fluctuated strongly but with a practically constant longer term trend, while atmospheric CO_2 still increased monotonously.

In eq. (9) of II, we showed that the mean peak to peak amplitude $A(n)$ of the Mauna Loa seasonal cycle can be related to the net primary production, NPP, of the northern hemisphere and the heterotrophic respiration, RES, and their corresponding contributions to the seasonal rise of atmospheric CO_2 (winter season of length $m_W \approx 7.5/12$) and the corresponding fall of atmospheric CO_2 (summer season of length $m_s \approx 4.5/12$).

$$A(n) = m_s[\mathrm{RES}_w(n) - \mathrm{NPP}_w(n)] + m_w[\mathrm{NPP}_s(n) - \mathrm{RES}_s(n)] + b(n), \qquad \text{(II.9)}$$

where $b(n)$ contains all contributions outside the biosphere. We suggested in II that appropriate values for NPP and RES in the reference year 0 (1958) could be represented by the values:

$$\mathrm{NPP_s}(0) = 23\ \mathrm{Gt\ C\ a^{-1}},$$

$$\mathrm{NPP_w}(0) = 12\ \mathrm{Gt\ C\ a^{-1}},$$

with

$$\mathrm{NPP}(0) = \mathrm{NPP_s}(0) + \mathrm{NPP_w}(0) = 35\ \mathrm{Gt\ C\ a^{-1}};$$

$$\mathrm{RES_s}(0) = 16\ \mathrm{Gt\ C\ a^{-1}},$$

$$\mathrm{RES_w}(0) = 19\ \mathrm{Gt\ C\ a^{-1}},$$

with

$$\mathrm{RES}(0) = \mathrm{RES_s}(0) + \mathrm{RES_w}(0) = 35\ \mathrm{Gt\ C\ a^{-1}}.$$

From eq. (II.9), we can derive the simple relation for the amplitude change, neglecting external factors, i.e., $b(n) = 0$:

$$\frac{A(n)}{A(0)} = \frac{p(n)\cdot \mathrm{NPP}(n) - r(n)\cdot \mathrm{RES}(n)}{p(0)\cdot \mathrm{NPP}(0) - r(0)\cdot \mathrm{RES}(0)} \tag{1a}$$

where

$$p(n) = m_{\mathrm{w}}(n)\frac{\mathrm{NPP_s}(n)}{\mathrm{NPP}(n)} - m_{\mathrm{s}}(n)\frac{\mathrm{NPP_w}(n)}{\mathrm{NPP}(n)}, \tag{1b}$$

and similarly

$$r(n) = m_{\mathrm{w}}(n)\frac{\mathrm{RES_s}(n)}{\mathrm{RES}(n)} - m_{\mathrm{s}}(n)\frac{\mathrm{RES_w}(n)}{\mathrm{RES}(n)}, \tag{1c}$$

where $p(0) = 0.282$ and $r(0) = 0.082$.

In the reference year 0, $A(0)$ as derived from the seasonality of the biota alone is given by 7 Gt C, or approximately by little less than 7 ppmv (1 ppmv = 1.06 Gt C for northern hemisphere); this signal is alternated by the north/south exchange and the troposphere/stratosphere exchange which are not included in the simple model.

In a first consideration we set $p(n) = p(0)$ and $r(n) = r(0)$, implying that the distribution of NPP and RES over the summer and winter season is approximately maintained during the Mauna Loa period. In principle, NPP(n) and RES(n) of eq. (1a) can be calculated in a dynamic model of the biota and soils which respond to a change in CO_2 (CO_2 fertilization effect) as well as to a change in temperature, precipitation or in land use, or a combined effect. We should expect that for CO_2 fertilization alone $\mathrm{NPP}(n) \geqslant \mathrm{RES}(n)$ (compared to II.10 and II.11) where the inequality sign would imply carbon sequestering, as only increased production and litter formation leads to additional heterotrophic respiration which is delayed in time. On the other hand we expect for enhanced surface temperatures that $\mathrm{NPP}(n) < \mathrm{RES}(n)$ as the temperature response of litter and soils is characterized by much larger Q_{10}-values than are observed for NPP.

It is easily seen from eq. (1a) that a 20% increase of both NPP and RES in 30 years ($n = 30$) could lead to an increase of 20% of the amplitude. If on the other hand only RES is increased by 20% while NPP remains constant, we would expect a decrease in the amplitude by 8.2%, while an increase of 20% of NPP alone would increase the amplitude by 28.2%. One of the factors responsible for the amplitude "constancy" after 1982 could be indeed due to the observed rising temperatures, although we need some more detailed information on the response of vegetation to climate and climate changes for a quantitative estimate.

In a second consideration, we can postulate that the distribution of NPP(n) and RES(n) over summer and winter has been altered relative to the original distribution of NPP(0) and RES(0).

We find in a sensitivity analysis that an increase of $\mathrm{RES_s}$ by $1\ \mathrm{Gt\ C\ a^{-1}}$ and corresponding decrease of $\mathrm{RES_w}$ by $1\ \mathrm{Gt\ C\ a^{-1}}$ leads to a value: $r(n) = 0.111$, and similarly an increase/decrease of $\mathrm{NPP_s}/\mathrm{NPP_w}$ by $1\ \mathrm{Gt\ C\ a^{-1}}$ to a value: $p(n) = 0.311$.

If this shift takes place simultaneously for NPP and RES in the same way, the amplitude increase will not be altered. If, however, NPP(n) remains constant, while RES(n) is increased by 20%, for example, the amplitude will be decreased by 11.1%, somewhat more than if the distribution had remained constant.

3. Conclusions. Towards a multifactorial approach in the understanding of a changing biosphere and the seasonal cycle

Our simplified amplitude of the Mauna Loa seasonal cycle does not agree with CO_2 as the monocausal agent. If β values larger than our suggested range of $\beta = 0.15$ to 0.60 are used then large compensating factors have to be found to explain the amplitude behaviour beyond 1982.

In the previous section we showed that we need to consider both NPP(n) and RES(n) and their distributions over the summer and winter season, to understand the mean amplitude. All factors which change these quantities could be responsible for the biotic contribution to the amplitude change. Other factors (designated by $b(n)$) could be responsible as well.

If RES(n) is enhanced more than NPP(n), then the amplitude may decrease, a situation which could be caused by a large temperature increase.

In a preliminary analysis (Kohlmaier et al., 1988), we found that airborne nitrogen compounds, both from combustion processes and from fertilized fields, could enhance NPP on a global basis in a comparable magnitude as enhanced CO_2 levels.

Internal ecosystem dynamics may contribute to the seasonal cycle in as much as they have a significant seasonal component. The tropical forests exhibit small seasonality and their productivity is decreasing, thus we conclude that they may be producing a small decrease in the MLO seasonal amplitude over time. The standing timber estimates of Armentano and Hett (1980), the flux analysis by Enting and Mansbridge (1989), using the direct inversion of atmospheric CO_2 concentration data, and the north-south CO_2 gradient analysis by Tans et al. (1990) indicate that the temperate and part of the boreal forests may be a sink for atmospheric CO_2 which imply a growth of the standing stock along with an increase of the seasonal component of these ecosystems, leading to an amplitude increase. D'Arrigo et al. (1987) come to similar conclusions by analyzing the NDVI data over these areas and measuring at the same time the tree rings at the northern tree line.

Increases in agricultural productivity have been obtained in the first part of the Mauna Loa period mainly through extensive methods, having only a small influence on the amplitude change, while in the second part intensive measures have been used mainly through input of industrial fertilizers and pesticides, bringing about a higher productivity and along with it an increase in the amplitude.

Increased anthropogenic nitrogen and phorosphorus discharge of rivers influence the coastal production of the marine food chain. Although the effect on a regional scale may be very spectacular, Kohlmaier (1988) estimated that the global contribution, especially with respect to the amplitude change, still should be very small.

We mentioned above that there is a barrier for interhemispheric exchange of atmospheric CO_2. Depending on the wind fields used, Heimann et al. (1986) estimated that the release of fossil fuel carbon and its atmospheric transport contribute to the seasonal atmospheric CO_2 cycle. Fossil fuel use is somewhat greater in winter than in summer and atmospheric transport varies seasonally.

In summary, we conclude that certainly more than one factor may be responsible for the observed variations in the seasonal CO_2 amplitude, with vegetation and soils being the most likely candidates for such a behaviour.

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