

# Uncertainties of Predictions of Future Atmospheric CO<sub>2</sub> Concentrations

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Linear carbon cycle models, tuned to reproduce the CO<sub>2</sub> increase observed at Mauna Loa, independently of their individual assumptions, predict almost identical CO<sub>2</sub> concentration trends for fossil energy scenarios assuming a slightly increasing production in the next few decades. The basic information for such prognoses therefore is the airborne fraction observed over the last 20 years. Uncertainties in this quantity are due to possible errors in the estimate of fossil fuel consumption and the corresponding CO<sub>2</sub> emission, possible natural fluctuations in the baseline CO<sub>2</sub> level, and uncertainties regarding the biospheric CO<sub>2</sub> input and uptake as a result of deforestation and reforestation and land management. Depending on different assumptions the effective airborne fraction, defined as the ratio of CO<sub>2</sub> increase due to fossil fuel CO<sub>2</sub> alone to the integrated CO<sub>2</sub> production, might be as low as 0.38 or as high as 0.72, compared to the apparent airborne fraction of 0.55. The effective airborne fraction derived from carbon cycle models, considering only the CO<sub>2</sub> uptake by the ocean, lies in the range 0.60-0.70. A value as low as 0.40 seems therefore highly improbable. A high biospheric anthropogenic CO<sub>2</sub> input therefore must have been accompanied by a high CO<sub>2</sub> fertilization effect. Model considerations, however, are not in contradiction with a high biospheric input with the maximum production before 1958, which also would imply low preindustrial CO<sub>2</sub> concentrations in the range 270-280 ppm as reported recently.

## INTRODUCTION

Predictions of future atmospheric CO<sub>2</sub> concentrations are based on CO<sub>2</sub> input functions derived from assumed global energy consumption scenarios. Carbon cycle models of different degrees of complexity are used to calculate the airborne fraction of the integrated input for an assumed CO<sub>2</sub> input function. In this paper we address the questions: How accurately can we predict future atmospheric CO<sub>2</sub> concentrations for assumed CO<sub>2</sub> input functions, and what are the prime factors for the uncertainties of the prognoses?

If we restrict the discussion to the not too distant future, for example, the next 30-50 years, the following two observations are important:

1. The CO<sub>2</sub> input from fossil fuel combustion in the past has risen nearly exponentially after 1945 with a time constant of about 25 years [Keeling, 1973a; Rotty, 1977]. The exponential trend probably will continue for the next decades, maybe with a smaller growth rate [Rotty, 1980].

2. As long as small disturbances of the CO<sub>2</sub> concentrations in the different reservoirs are considered, it is likely that the carbon cycle will behave as a linear system. This is assumed in all carbon cycle models known to us.

Most carbon cycle models are 'tuned' to reproduce the observed atmospheric CO<sub>2</sub> increase. This is in general accomplished by adjustment of one or several model parameters, so that the model matches (using, for example, a least squares criterion) the smoothed global annual mean CO<sub>2</sub> concentrations between 1959 and 1978, as represented, for example, by the average of the Mauna Loa and the south pole data. It then follows that any tuned carbon cycle model will, for the near future, predict the same atmospheric CO<sub>2</sub> concentration trend.

This leads to the following consequences:

1. Uncertainties in CO<sub>2</sub> prognoses are largely dependent on the way the observed CO<sub>2</sub> record is interpreted, that is, which part of the atmospheric increase is attributed to the fossil fuel CO<sub>2</sub> input.

2. Short-term CO<sub>2</sub> prognoses are essentially model independent. Even if models with different characteristics predict the same atmospheric CO<sub>2</sub> concentration, they may differ, however, in the way they partition the nonairborne excess CO<sub>2</sub> between the oceanic and the biospheric reservoirs.

3. However, if the CO<sub>2</sub> input function ceases to increase exponentially and/or when over longer periods the CO<sub>2</sub> concentrations in the different reservoirs will significantly deviate from the equilibrium state, the detailed model characteristics will become important and affect the prognoses.

The foregoing considerations are illustrated by the model predictions depicted in Figure 1. These model runs have been performed with the box diffusion model developed in Bern [Oeschger *et al.*, 1975], and the CO<sub>2</sub> production estimate for the future originates from a recent study for the Umweltbundesamt of the Federal Republic of Germany [Oeschger and Heimann, 1981]. Curve 1 shows the prognosis using standard values of the model parameters. After changing the value for the eddy diffusion constant *K* from 4000 m<sup>2</sup>/yr to 10,000 m<sup>2</sup>/yr we obtain curve 2, which differs only slightly from the standard case. The larger capacity of the ocean for uptake of excess CO<sub>2</sub> is balanced by a 50% smaller biospheric uptake in order to reproduce the observed atmospheric CO<sub>2</sub> increase. Curves 3 and 4 bracket an estimated uncertainty in the airborne fraction (see below) of 10%. We notice how this uncertainty completely overshadows the rather drastic change in model dynamics as exemplified in cases 1 and 2.

Figure 2 shows the observed global annual mean atmospheric CO<sub>2</sub> level (the squares mark annual averages from the Mauna Loa and south pole records [Bacastow and Keeling, 1981a]) together with the CO<sub>2</sub> production rate as compiled by Rotty [this issue]. The dashed line that passes through the atmospheric data points represents the response of a 'tuned' model to the fossil fuel CO<sub>2</sub> input. As can be seen, short-term changes in the increase of the production rate (e.g., in 1974-1976) are smoothed out to a large extent.

## THE AIRBORNE FRACTION

Ideally, one would like to base forecasts of future atmospheric CO<sub>2</sub> concentrations on an airborne fraction of the anthropogenically released CO<sub>2</sub> defined as the ratio of the observed

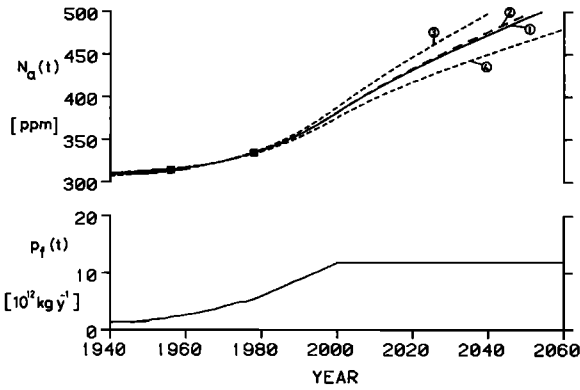


Fig. 1. (Top) Model prognoses for the atmospheric CO<sub>2</sub> concentration: curve 1, standard values of the model parameters; curve 2, eddy diffusion constant  $K = 10,000 \text{ m}^2/\text{yr}$ ; curves 3 and 4, effective airborne fraction 10% higher or lower than apparent airborne fraction, respectively. The solid squares mark the limits of the Mauna Loa record. (Bottom) Assumed CO<sub>2</sub> production function [from Oeschger and Heimann, 1981].

global average CO<sub>2</sub> increase since the beginning of industrialization to the entire CO<sub>2</sub> input due to fossil fuel combustion, deforestation, and changes in land management. Unfortunately, the preindustrial CO<sub>2</sub> concentration is poorly known, as well as the history of the CO<sub>2</sub> input due to human interaction with the biosphere. The airborne fraction is therefore generally defined as the ratio of two quantities which are known with some accuracy: the atmospheric CO<sub>2</sub> increase observed at Mauna Loa and the CO<sub>2</sub> input from fossil fuel combustion over the period of observation. We will call this quantity the 'apparent' airborne fraction. In the following we attempt to discuss the possible errors we make if we use this quantity to calibrate a carbon cycle model.

We assume that we know the atmospheric response function to a CO<sub>2</sub> pulse input into the atmosphere. We call this function  $R(t)$ .  $R(0)$  equals 1 and expresses the fact that at  $t = 0$  the CO<sub>2</sub> pulse is injected into the atmosphere.  $R(t)$  decreases with time and gives the percentage of the input, which at time  $t$  is still in the atmosphere.

From the box diffusion CO<sub>2</sub> cycle model we can obtain an approximation to the real  $R(t)$ , which is depicted in Figure 3. This  $R(t)$  only considers uptake of CO<sub>2</sub> by the ocean, which is quite well known from isotope studies. Any CO<sub>2</sub> uptake or release by the biosphere in the following is expressed by  $p_{\text{bio}}(t)$ ,

defined as the net biospheric CO<sub>2</sub> input. Thus a positive  $p_{\text{bio}}(t)$  corresponds to a net release, and a negative  $p_{\text{bio}}(t)$  corresponds to a net uptake of CO<sub>2</sub> by the biosphere.

Since the carbon cycle can be regarded as a linear system (assuming small disturbances), we may express the CO<sub>2</sub> content  $N_a(t)$  of the atmosphere at the time  $t$  as

$$N_a(t) = N_{a0} + a(t) + \int_{-\infty}^t p_f(\tau)R(t-\tau) d\tau + \int_{-\infty}^t p_{\text{bio}}(\tau)R(t-\tau) d\tau \quad (1)$$

where  $N_{a0}$  is the equilibrium CO<sub>2</sub> level and  $a(t)$  is the deviation from  $N_{a0}$  at time  $t$  due to natural fluctuations. The integrals involving  $p_f$  and  $p_{\text{bio}}$  represent response at time  $t$  to CO<sub>2</sub> from fossil fuel and to net changes in global biomass, respectively. Also,  $p_f(t)$  represents the production function for fossil fuel CO<sub>2</sub>. The apparent airborne fraction  $r_{af}$ , as defined earlier, thus becomes

$$r_{af} = \frac{N_a(t_2) - N_a(t_1)}{\int_{t_1}^{t_2} p_f(\tau) d\tau} = \frac{\Delta a + P_p - P_h + B_p - B_h}{\Delta Q_f} \quad (2)$$

where we have used the following abbreviations:

$$\Delta a = a(t_2) - a(t_1)$$

$$\Delta Q_f = \int_{t_1}^{t_2} p_f(\tau) d\tau$$

$$P_p = \int_{t_1}^{t_2} p_f(\tau)R(t_2 - \tau) d\tau$$

$$P_h = \int_{-\infty}^{t_1} p_f(\tau)\{R(t_1 - \tau) - R(t_2 - \tau)\} d\tau$$

$$B_p = \int_{t_1}^{t_2} p_{\text{bio}}(\tau)R(t_2 - \tau) d\tau$$

$$B_h = \int_{-\infty}^{t_1} p_{\text{bio}}(\tau)\{R(t_1 - \tau) - R(t_2 - \tau)\} d\tau$$

The convolution integrals for  $p_f$  and  $p_{\text{bio}}$  have been split into two parts in order to distinguish between the contribution of the production functions from the time period under study ( $t_1$  to  $t_2$ ) and that from the time period before ( $-\infty$  to  $t_1$ ), that is, from their history.

Figure 4 illustrates the terms  $P_p$  and  $P_h$  that appear in

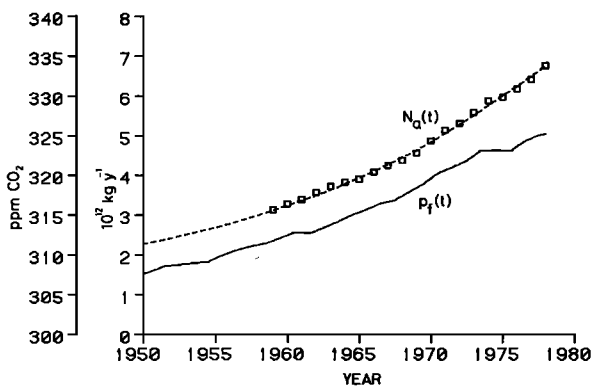


Fig. 2. Lower curve: Fossil fuel CO<sub>2</sub> production rate (in  $10^{12} \text{ kg C per year}$  [from Rotty, this issue]). The model has been 'tuned' to reproduce the observed data as closely as possible.

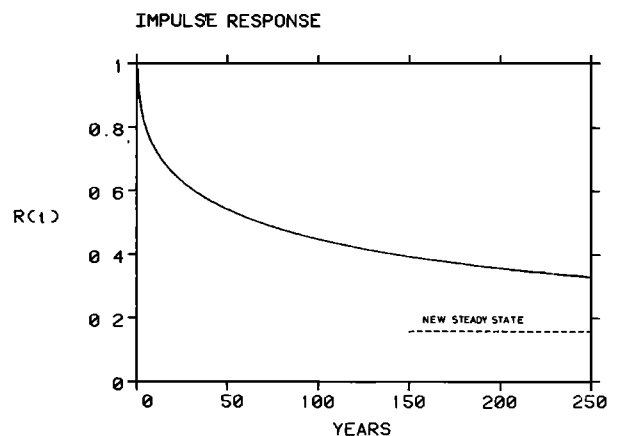


Fig. 3. Atmospheric CO<sub>2</sub> excess after a pulse input.

equation (2). The lower (declining) curve shows the response of the system if the production rate had dropped to zero in 1959. The corresponding decrease in atmospheric CO<sub>2</sub> concentration represents the 'history' term  $P_h$ . If the production rate is not stopped in 1959, we obtain the upper curve. The difference between the two functions corresponds to the response of the system to the CO<sub>2</sub> input during the time interval from  $t_1 = 1959$  to  $t_2 = 1978$ ; that is, this difference represents the term  $P_p$ .

For forecasting purposes it follows from the discussion in the introduction that one should know the magnitude of

$$r_{af}^* = (P_p - P_h) / \Delta Q_f \quad (3)$$

which might be termed 'effective' airborne fraction. It is this quantity that describes the response of the carbon system to an exponentially increasing input.

The effective airborne fraction  $r_{af}^*$  and the apparent airborne fraction  $r_{af}$  are related through

$$r_{af}^* = r_{af} - \frac{\Delta a + B_p - B_h}{\Delta Q_f} \quad (4)$$

Thus the term on the right of (4) describes possible corrections that have to be made if the effective airborne fraction is to be determined from the observed apparent airborne fraction.

DISCUSSION

We discuss now each of the terms in equation (2) that contribute to the apparent airborne fraction. First, let us consider the importance of the accuracy with which the fossil fuel CO<sub>2</sub> production is known. A recent reevaluation of the available data by Rotty [this issue] revealed a CO<sub>2</sub> production that is about 2-3% lower than what has been assumed before. According to this study, the total CO<sub>2</sub> emission from fossil fuel between 1959 and 1978 amounts to  $\Delta Q_f = 70 \times 10^{12}$  kg of carbon. This quantity, if uniformly mixed in the atmosphere, corresponds to a globally averaged change in CO<sub>2</sub> concentration by 32.9 ppm (parts per million by volume of dry air). Second, taking  $R(t)$  from the box diffusion model, we calculate estimates for the terms  $P_p$  and  $P_h$  and get  $P_p \approx 25.3$  ppm and  $P_h \approx 3.4$  ppm (see Figure 4). The difference  $P_p - P_h \approx 21.9$  ppm can be compared with the observed CO<sub>2</sub> increase of 18.2 ppm.

Neglecting all other terms in the apparent airborne fraction, we realize that the uptake of CO<sub>2</sub> by the ocean, as expressed by  $R(t)$ , could not account for all the nonairborne fossil CO<sub>2</sub>; that

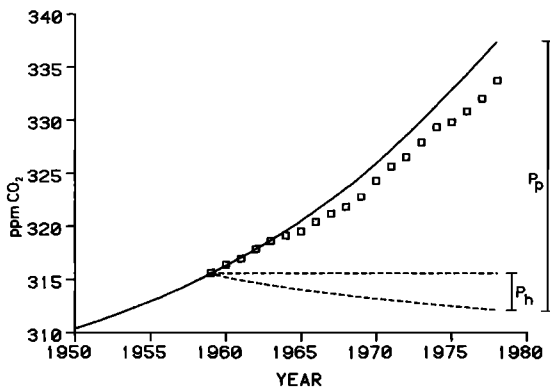


Fig. 4. Graphical representation of the terms  $P_p$  and  $P_h$  in the definition of the effective airborne fraction. These curves have been obtained with the box diffusion model without a biosphere, that is, considering only uptake of fossil fuel CO<sub>2</sub> by the ocean. The observed atmospheric CO<sub>2</sub> levels (squares) are shown for comparison.

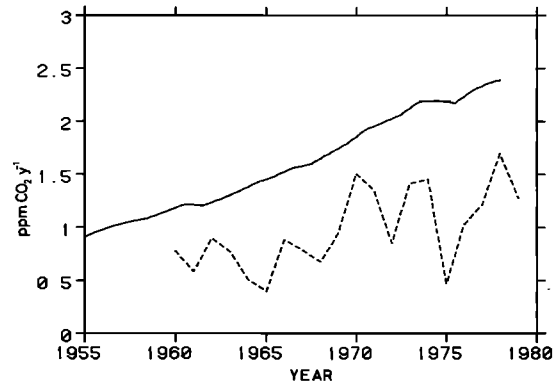


Fig. 5. Upper curve: Annual input of fossil fuel CO<sub>2</sub>. Lower curve: Annual increase of atmospheric CO<sub>2</sub> based on the average of the secular trends from Mauna Loa and the south pole.

is, in our carbon cycle model, in order to fit the observed CO<sub>2</sub> increase, we have to introduce a net CO<sub>2</sub> uptake by the biosphere of 3.7 ppm (see Figure 2). Of interest then is the comparison of the relative sizes of  $P_p$  and  $P_h$ . We observe that the history term  $P_h$  is only about 13% of the term describing the airborne part of the CO<sub>2</sub> released during the observation period  $P_p$ . This shows that the relatively small deviations of the fossil CO<sub>2</sub> production curve from its exponential increase in the past (that occurred, for example, during the two world wars) have a negligible effect upon  $r_{af}$ .

If we choose a shorter time interval, the relative size of the history term becomes important. In the limit of a 1-year interval,  $P_h$  is about one third of  $P_p$ .

Figure 5 shows the annual increases in atmospheric CO<sub>2</sub> concentrations together with the corresponding CO<sub>2</sub> production function. The strong fluctuations in the annual increases are attributed to natural variations of the atmospheric CO<sub>2</sub> level. This explanation is plausible, since the gross CO<sub>2</sub> fluxes between atmosphere and ocean and between atmosphere and biosphere amount to about 40 ppm/yr and 10 ppm/yr, respectively. These fluxes do not necessarily have to cancel exactly each year. For example, short-term fluctuations in sea surface temperature, perhaps related to the southern oscillation, and climatic effects on plant growth and decomposition could account for such imbalances.

On the basis of analyses by Bacastow [1976, 1979] and others we conclude that the atmospheric CO<sub>2</sub> level may vary as much as 1-1.5 ppm over 5 years. The term  $\Delta a$  in equation (2), for a time period of 18 years, will therefore be smaller than about 2 ppm in absolute magnitude.

Additionally, these short-term fluctuations of  $a(t)$  are superimposed over longer-term variations. Sea surface temperatures in the northern hemisphere have been dropping by about 0.5°C between the late 1950's and the mid-1970's [Namias and Cayan, 1981; Kukla et al., 1977]. If a similar trend had taken place also in the southern hemisphere, a corresponding atmospheric CO<sub>2</sub> decrease of the order of 1 ppm between 1959 and 1978 would have resulted.

Complications arise if we include the biospheric CO<sub>2</sub> input (or uptake) in the discussion, since the production function  $P_{bio}(t)$  is poorly known.

Let us first approximately estimate the total integrated biospheric CO<sub>2</sub> input. Carbon cycle models treating only  $p_f(t)$  lead to estimates of the preindustrial atmospheric CO<sub>2</sub> content of approximately 290-300 ppm, whereas other estimates based on

TABLE 1. Summary of Estimates for the Different Terms Appearing in Equations (2), (3), and (4) for the Apparent Airborne Fraction

Parameter	Value	Description
$N_a(t_2) - N_a(t_1)$	18.2 ppm	observed increase in the atmosphere [Bacastow and Keeling, 1981a]
$\Delta Q_f$	32.9 ± 2 ppm	fossil fuel CO <sub>2</sub> input ( $70 \times 10^{12}$ kg C) [Rotty, this issue]
$r_{af}$	0.55	apparent airborne fraction
$P_p$	25.3 ppm	calculated with box diffusion model
$P_h$	3.4 ppm	[Oeschger et al., 1975]
$r_{af}^*$	0.67	effective airborne fraction calculated with box diffusion model
$B_p$	8 ppm	constant biospheric source 0.5 ppm/yr
	17.6 ppm	biospheric release scenario of Moore [1982]
$B_h$	2 ppm	pioneer effect of 40 ppm CO <sub>2</sub> released around 1890
	4 ppm	constant biospheric source of 0.5 ppm/yr
	5.3 ppm	biospheric release scenario of Moore [1982]
$\Delta a$	-2 to +2 ppm	southern oscillation effect, sea surface temperature fluctuations
	-1 ppm	drop in sea surface temperature by 0.5°C

The time period considered is  $t_1 = 1959$ ,  $t_2 = 1978$ .

$\delta^{13}\text{C}$  records from tree rings and CO<sub>2</sub> concentration studies on ice cores indicate the possibility of values between 270 and 280 ppm. Therefore 20 ppm of the increased CO<sub>2</sub> concentration may be the result of the biospheric CO<sub>2</sub> input.

To estimate the effect of such a biospheric source upon the apparent airborne fraction, we consider three different time histories for  $p_{\text{bio}}(t)$ .

First, we assume that the whole biospheric input had been centered around 1890 ('pioneer effect') and calculate from  $R$  (60 years)  $\approx 0.5$  a total biospheric release of 40 ppm. The term  $B_h$  amounts then to about 2 ppm, and  $B_p = 0$ , which consequently would lead to a higher  $r_{af}^*$ . Similar estimates have been reported by Bacastow and Keeling [1981b] for various sizes and time characteristics of the pioneer effect.

Second, we assume a constant net biospheric source since 1860 of 0.5 ppm/yr (half the estimate of Moore et al. [1981]) and get  $B_p = 8$  ppm and  $B_h = 4$  ppm. In this case the effective airborne fraction  $r_{af}^*$  was smaller than the apparent airborne fraction by about 0.13, that is, 0.42. It is interesting to notice that if the production function is constant and not exponentially increasing, the history term  $B_h$  amounts to 50% of the term relating to the production from the interval under study.

Third, we consider a biospheric input function  $p_{\text{bio}}(t)$  increasing with time throughout the last 100 years and of a size comparable to the fossil fuel input  $p_f(t)$ . In this case,  $B_p$  would dominate  $B_h$ , and the effective airborne fraction  $r_{af}^*$  would be considerably lower than the apparent airborne fraction  $r_{af}$ . For example, the carbon input flux due to perturbations of the biota as compiled by Moore [1982], which amounts to about  $2.5 \times 10^{12}$  kg C per year in 1950, results in  $B_p = 17.6$  ppm and

$B_h = 5.3$  ppm. If this flux represented the global net biosphere-atmosphere flux, then  $r_{af}^*$  would be merely 0.18 compared to  $r_{af} = 0.55$ . Such a low value would seriously contradict our best estimate of  $r_{af}^*$  (0.67) based on a carbon cycle model that has been calibrated and tested with the radioisotope <sup>14</sup>C. Such a big discrepancy would reveal a serious lack of knowledge on carbon cycle dynamics, which we consider improbable.

We therefore believe that the biospheric CO<sub>2</sub> production values from Moore [1982] do not represent the net global change in biomass that enters equation (1). It is, for example, conceivable that a significant amount of CO<sub>2</sub> could at the same time have been taken up by the biosphere due to the fertilizing effect [Keeling, 1973b; Pearman and Hyson, 1981].

We would like to emphasize that only the first scenario for the biospheric input discussed here would correspond to a low preindustrial CO<sub>2</sub> concentration in the range 270–280 ppm. A biospheric input increasing with time as in the third scenario would imply a low value of the effective airborne fraction, permitting the uptake of the large integrated biospheric input by the system without a correspondingly high integrated atmospheric CO<sub>2</sub> increase. The preindustrial CO<sub>2</sub> concentration therefore would be only slightly lower than that estimated without biospheric input.

Table 1 gives a summary of estimates for the different terms that appear in equations (2)–(4).

In the following discussion we estimate how much the theoretical airborne fraction, as defined above, could differ from the apparent one.

#### Upper range

$$\Delta Q_f = 30.9 \text{ ppm}$$

$$P_p - P_h = \underset{\substack{\text{observed} \\ \text{increase}}}{18.2} + \underset{\Delta a}{2} + \underset{\substack{\text{pioneer} \\ \text{effect}}}{2} = 22.2 \text{ ppm}$$

$$r_{af}^* = 0.72$$

#### Lower range

$$\Delta Q_f = 34.9 \text{ ppm}$$

$$P_p - P_h = \underset{\Delta a}{18.2} - \underset{\substack{\text{constant} \\ \text{biospheric} \\ \text{source of} \\ 0.5 \text{ ppm/yr}}}{1} - 8 + 4 = 13.2 \text{ ppm}$$

$$r_{af}^* = 0.38$$

From these estimates we conclude that the theoretical airborne fraction should lie in the range 0.38–0.72. Without more knowledge on the biospheric CO<sub>2</sub> input function and the atmospheric CO<sub>2</sub> concentrations prior to 1956 it is difficult even to find out if the apparent airborne fraction underestimates or overestimates the effective airborne fraction.

#### CONCLUSIONS

Regarding predictions of future atmospheric CO<sub>2</sub> concentrations for the next few decades, the interpretation of atmospheric data constitutes the basic uncertainty, since tuned linear models, in spite of different properties, give almost identical results. For long-term predictions, however, the individual model properties become significant.

Depending on assumptions of natural CO<sub>2</sub> level variations and the history of the biospheric net input, the effective airborne fraction might be as low as 0.38 or as high as 0.72, compared to the apparent airborne fraction of 0.55. However,

we do not think that predictions based on the observed airborne fraction in the near future will deviate considerably from the actual increase, since the tuning of the model to reproduce the Mauna Loa record to a certain degree implicitly accounts for unknown properties of the carbon cycle and uncertainties regarding the biospheric input.

If the effective airborne fraction lies at the upper limit of the estimates (i.e., ~0.65), there is no significant disagreement with present carbon cycle models. A theoretical airborne fraction of 0.40 or less, however, would imply strong deficiencies of the models which are difficult to account for without violating the constraints imposed by the observed <sup>14</sup>C distribution in the ocean and the natural atmospheric <sup>14</sup>C variation time series.

If a linear response of the system is assumed, only a high net biospheric CO<sub>2</sub> input with its production maximum before the Mauna Loa observation period would be compatible with low preindustrial atmospheric CO<sub>2</sub> concentrations of 270–280 ppm as reported recently.

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