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Dynamics of global atmospheric CO_2 concentration from 1850 to 2010: a linear approximation

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Abstract

The increase in anthropogenic CO_2 emissions largely followed an exponential path between 1850 and 2010, and the corresponding increases in atmospheric CO_2 concentration were almost constantly proportional to the emissions by the so-called "airborne fraction". These observations suggest that the dynamics of atmospheric CO_2 concentration through this time period may be properly approximated as a linear system. We demonstrate this hypothesis by deriving a linear box-model to describe carbon exchanges between the atmosphere and the surface reservoirs under the influence of disturbances such as anthropogenic CO_2 emissions and global temperature changes. We show that the box model accurately simulates the observed atmospheric CO_2 concentrations and growth rates across interannual to multi-decadal time scales. The model also allows us to analytically examine the dynamics of such changes/variations, linking its characteristic disturbance-response functions to bio-geophysically meaningful parameters. In particular, our results suggest that the elevated atmospheric CO_2 concentrations have significantly promoted the gross carbon uptake by the terrestrial biosphere. However, such "fertilization" effects are partially offset by enhanced carbon release from surface reservoirs promoted by warmer temperatures. The result of these interactions appears to be a decline in net efficiency in sequestering atmospheric CO_2 by $\sim 30\,\%$ since 1960s. We believe that the linear modeling framework outlined in this paper provides a convenient tool to diagnose the observed atmospheric CO_2 dynamics and monitor their future changes.

1 Introduction

Anthropogenic CO_2 emissions from fossil-fuel usage and land-use changes have been almost exponentially increasing since the Industrial Revolution (Fig. 1). Their accumulation in the atmosphere appears to be changing Earth's climate (IPCC, 2007). The full potential of anthropogenic CO_2 emissions for changing the climate has not yet

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reached because only 41–45 % of the CO_2 emitted between 1850 and 2010 remained in the atmosphere while the rest was sequestered by lands and oceans (Jones and Cox, 2005; Canadell et al., 2007; Raupach et al., 2008; Knorr, 2009) (Fig. 1). This largely constant ratio, generally referred to as the "airborne fraction" (denoted as "γ" in this paper), was conventionally used to evaluate the efficiency of global carbon sinks (carbon sequestered by lands and oceans) in assimilating the extra CO_2 from the atmosphere (Jones and Cox, 2005; Canadell et al., 2007). A few recent studies found that the airborne fraction can also be influenced by trends and variations in anthropogenic emissions and other extrinsic forcing events (e.g., volcanic eruptions), and thus may not be an ideal indicator for monitoring changes in the carbon sink efficiency (Knorr, 2009; Gloor et al., 2010; Frölicher et al., 2013). Although these previous studies mainly focused on explaining the constancy of the airborne fraction from the perspective of global carbon-cycle dynamics, we can look at the problem from a different perspective. For instance, we can use the stable airborne fraction to examine the dynamic characteristics of the carbon cycle. This paper is dedicated to address the latter question. In particular, we propose that the responses of atmospheric CO_2 concentration to the disturbances of anthropogenic CO_2 emissions since 1850s can be properly approximated by a linear dynamic system with largely constant parameters.

Our hypothesis is based on two important observations. First, it is a basic feature of a stable linear system that its responses to an exponentially increasing forcing [e.g., $\exp(\alpha t)$, $\alpha > 0$, $t \geq 0$] will approach the input signal with a constant ratio. Indeed, because exponential functions are invariant (to the extent of a constant factor) to differential operators, the effects of a linear system on an exponential input are simply to delay the signal or/and to regulate its magnitude (Naylor and Sell, 1982). Because the intrinsic responses of a stable linear system must be decaying with time, the output from the system will be increasingly dominated by an exponential signal proportional to the input [i.e., $\propto \exp(\alpha t)$].

Second, a nonlinear dynamic system can be linearly approximated around a steady point within a neighborhood in its state space (Khalil, 2001). In the case of the global

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carbon cycle, the existence of such a (quasi) steady state is evident in that the atmospheric CO_2 concentration (and the corresponding global climatology) had been stable for thousands of years before the industrial era (IPCC 2007). Therefore, the observed simple proportional relationship between the atmospheric CO_2 concentrations and the increasing CO_2 emissions suggest that recent changes of the global carbon cycle may be still within the linear neighborhood of the system's last steady state.

Another disturbance that this study intends to examine is the impact of climate changes on the atmospheric CO_2 dynamics. Global surface temperature has increased by $\sim 1\,^{\circ}C$ since the beginning of the 20th century (Hansen et al., 1999; Brohan et al., 2006). Given the tight coupling between temperature and the carbon cycle (Keeling et al., 1995; Joos et al., 1999, 2001; Lenton, 2000; Rafelski et al., 2009), the warming alone may release a large amount of CO_2 from the land and the oceans into the atmosphere, redistributing carbon among these reservoirs. The impacts of temperature changes on the carbon system have different dynamic characteristics than those of CO_2 emissions and need to be analyzed separately (see below).

We demonstrate our analytical framework by developing a simple two-box model that represents carbon exchanges between the atmosphere and the surface (i.e. land and ocean) reservoirs. Although such a "toy" model only represents a first-order approximation of the global carbon cycle, important characteristics of the atmospheric CO_2 dynamics can still be learned from it. Throughout the analysis we compare the results obtained from the two-box model to those from the more advanced Bern model (Siegenthaler and Joos, 1992; Enting et al., 1994; IPCC 1996, 2001), which is slightly revised and recalibrated in this study (see the Appendix). The Bern model couples the atmosphere with a process-based ocean biogeochemical scheme (Siegenthaler and Joos, 1992; Shaffer and Sarmiento, 1995; Joos et al., 1999) and a multi-component terrestrial biosphere module (Siegenthaler and Oeschger, 1987). The global carbon-cycle processes described in the Bern model help us diagnose the biogeophysical mechanisms underlying the characteristics of the atmospheric CO_2 dynamics identified with our simple linear model.

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2 Datasets

Annual atmospheric CO_2 concentration data from 1850 to 1960 are based on the ice core CO_2 records from Law Dome, Antarctica (Etheridge et al., 1996) and those between 1960 and 2010 are compiled from NOAA Earth System Research Laboratory (ESRL) (Keeling et al., 1995; Conway et al., 1994). We merged the data following the approach described in Le Quéré et al. (2009) and calculated annual CO_2 growth rate as the first-order difference of the yearly CO_2 concentrations. Long-term records of anthropogenic CO_2 emissions from fossil fuel burning and cement production are compiled by Boden et al. (2011) and those of land-use changes are from Houghton (2003), both downloaded from the Carbon Dioxide Information Analysis Center at Oak Ridge National Laboratory, TN, USA (http://cdiac.ornl.gov). Two sets of monthly surface temperature data are used, including GISTEMP from NASA Goddard Institute for Space Studies (Hansen et al., 1999) and the CRU-NCEP climate dataset (Sitch et al., 2008; Le Quéré et al., 2009), available from 1901 to the present with spatial resolutions of 0.5×0.5 (CRU-NCEP) or 1×1 (GISTEMP) degrees. Monthly time series of temperature are aggregated globally and over the tropics (24° N–24° S), and smoothed with a 12 month running window to convert the monthly data to annual values. We calculated temperature anomalies relative to their 1901 to 1920 annual mean and assumed the 20-years mean temperature to be representative of temperature climatologies between 1850 and 1900. This assumption is reasonable as suggested by analysis of other long-term coarse-resolution temperature datasets (Jones et al., 2003; Brohan et al., 2006).

3 Derivation of the two-box model

This study considers only the "fast" carbon flows between the atmosphere and the (combined land and oceans) surface at time scales within hundreds of years (IPCC 2001). When human disturbances are absent, carbon outflows from the atmosphere

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are inflows to the surface (e.g., through photosynthesis in green vegetation and the dissolution of CO_2 in the surface water) while carbon outflows from the surface (e.g., through respiration and the outgassing of the dissolved CO_2) are the inflows to the atmosphere. Human emissions of CO_2, on the other hand, represent an "external" source of CO_2 to the system by rapidly releasing carbon (e.g., fossil fuel burning) from reservoirs that were formed over millions of years and by permanently altering the structure of land surface carbon pools (e.g., land-cover/land-use changes).

Following our linearization proposition, we describe the dynamics of such a two-box carbon system using the following equations:

$$\dot{A}' = -\alpha_A \cdot A' + \alpha_S \cdot S' + \beta_T \cdot T' + \dot{E}' \quad (1a)$$

$$\dot{S}' = +\alpha_A \cdot A' - \alpha_S \cdot S' - \beta_T \cdot T' \quad (1b)$$

where A and S denote carbon storages in the atmosphere and the surface reservoirs, respectively, and E is the accumulated anthropogenic CO_2 emissions since the industrial era. The three variables can be measured by the same unit of parts per million by volume ($1\,\text{ppm} =\sim 2.13 \times 10^9$ metric-ton carbon or GtC). The prime symbol (e.g., "E'") indicates that changes in a variable relative to its preindustrial steady-state level. The preindustrial emissions are assumed negligible so that $E' = E$. The dot accent (e.g., "$\dot{E}'$") indicates the first-order derivative with regard to time, such that $\dot{E}'$ represents the annual rate of CO_2 emissions ($\text{ppm}\,\text{yr}^{-1}$). The positive constant parameters α_A and α_S (yr^{-1}) describe the decaying rates of corresponding carbon anomalies. Their reciprocals (i.e., $\tau_A = 1/\alpha_A$, $\tau_S = 1/\alpha_S$) are often referred to as the response time (or e-folding time) of the carbon reservoirs (IPCC 2001). T (°C) denotes indices of global (or large-scale) surface temperatures and the coefficient β_T ($\text{ppm}\,\text{yr}^{-1}\,^\circ\text{C}^{-1}$) represents the sensitivity of atmospheric CO_2 growth rate to temperature changes. The term $\beta_T T'$ thus indicates the impacts of temperature increases on the global carbon cycle, which release CO_2 from the surface reservoirs to the atmosphere.

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Because mass (carbon) is conserved in the two-box model, Eq. (1a) and (1b) are not independent. Adding the two equations together leads to

$$\dot{A}' + \dot{S}' = \dot{E}'$$

or

$$A' + S' = E'. \tag{1c}$$

Equation (1c) has a clear physical meaning that the anthropogenically emitted CO_2 either resides in the atmosphere or in the surface reservoirs (i.e., the land and the oceans). Substituting this relationship into Eq. (1a) to replace S', we obtain

$$\dot{A}' + (\alpha_A + \alpha_S) \cdot A' = \beta_T \cdot T' + \alpha_S \cdot E' + \dot{E}'. \tag{2a}$$

Therefore, the dynamics of atmospheric CO_2 represented by the two-box model is determined by an ordinary differential equation of A' under the disturbances of anthropogenic emissions (E' and $\dot{E}'$) and the changing climate (T').

4 Model determination and evaluation

We want to determine the parameters of Eq. (2a) with observational records of A', T', and E', and evaluate how well the model captures the observed atmospheric CO_2 dynamics. In order to construct a regression model from Eq. (2a), we rearrange the equation as follows:

$$\dot{E}' - \dot{A}' = (\alpha_A + \alpha_S) \cdot A' - \alpha_S \cdot E' - \beta_T \cdot T', \tag{2b}$$

where $\dot{E}' - \dot{A}'$ represents the strength of annual carbon sinks. However, because $A' \approx \gamma \cdot E'$ (Fig. 1), where γ is the airborne fraction, the "collinearity" between the two regressors prevents us from determining the coefficients associated with them separately

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(Chatterjee and Hadi, 2006). Indeed, substituting the airborne-fraction relationship into Eq. (2b) leads to

$$\dot{E}' - \dot{A}' = [\alpha_A - (1/\gamma - 1)\alpha_S] \cdot A' - \beta_T \cdot T', \quad (2c)$$

which implies that only β_T and a combination of α_A and α_S can be estimated from the observations.

We may reach the above argument from another perspective. Figure 1 shows that the anthropogenic CO_2 emissions (E' and $\dot{E}'$) can be approximated by exponential functions. Let $E' = \exp(\alpha_E t)$, and it follows that $\dot{E}' = \alpha_E \cdot \exp(\alpha_E t)$. By applying the airborne fraction relationship ($A' \approx \gamma \cdot E'$ and $\dot{A}' \approx \gamma \cdot \dot{E}'$) and neglecting the influence of temperature ($\beta_T T'$) for now, we obtain

$$\gamma \cdot [\alpha_E + (\alpha_A + \alpha_S)] \cdot \exp(\alpha_E \cdot t) \approx (\alpha_S + \alpha_E) \cdot \exp(\alpha_E \cdot t),$$

or

$$\alpha_A - (1/\gamma - 1) \cdot \alpha_S \approx (1/\gamma - 1) \cdot \alpha_E. \quad (2d)$$

The term on the left-hand side of Eq. (2d) is the same as the (regression) coefficient associated with the A' in Eq. (2c). Equation (2d) suggests that this coefficient is closely related to the exponential disturbances (α_E) to the system. Because $\alpha_E > 0$ and γ is about 0.41–0.45 (Fig. 1), it is follows that $(1/\gamma - 1) > 1$ and $\alpha_A > \alpha_S$ (or $\tau_A < \tau_S$). Given that the response time of atmospheric CO_2 is at the order of 10 years (Revelle and Suess, 1957), we choose τ_A to be 12 years ($\alpha_A \approx 0.083\,\mathrm{yr}^{-1}$) and subsequently estimate τ_S to be ~ 34 years ($\alpha_S \approx 0.029\,\mathrm{yr}^{-1}$).

The estimation of the β_T parameter in Eq. (2a) requires the choice of a large-scale temperature index that is representative of climate change and closely related with global carbon cycle. Previous studies showed that the land surface air temperature in the tropics (24S-24N) are most strongly coupled with interannual variations in the

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growth rate of atmospheric CO_2 by a sensitivity (β_T) of $\sim 1.64\,\mathrm{ppm\,yr^{-1}\,°C^{-1}}$ (Adams and Piovesan, 2005; Wang et al., 2013). Here we found that the same temperature-CO_2 coupling may also operate at longer time scales. Indeed, because the system is linear, variations in A', T', E', and their derivatives over different time scales must satisfy Eq. (2a) separately. Because the interannual variations ("IAV") in the emissions (both $\dot{E}'$ and E') and the atmospheric CO_2 concentration (A') are relatively small (Fig. 1), neglecting them in Eq. (2a) leads to

$$\dot{A}'_{\mathrm{IAV}} \approx \beta_T \cdot T'_{\mathrm{IAV}}, \tag{2e}$$

which is the same linear relationship as previous reported (Wang et al., 2013).

With the model parameters determined, we use the two-box model to simulate the changes of atmospheric CO_2 concentration between 1850 and 2010 from historical records of temperature and CO_2 emissions (Fig. 2). The simulated results follow the evolution of the observed atmospheric CO_2 concentration to a high degree of accuracy, capturing more than 96 % of the variability (i.e., $r^2 > 0.96$) of the latter (Fig. 2). The standard deviations (σ) of the differences between simulated values and those measured accurately since 1960 are ~ 0.9 ppm for the atmospheric CO_2 concentration and ~ 0.4 ppm for its growth rate, respectively (Fig. 2). These results are highly comparable to those simulated with the Bern model (Fig. 2) or the more sophisticated climate-carbon models reported in the literature (e.g., Joos et al., 1999; Lenton, 2000; Friedlinstein et al., 2006), strongly supporting our hypothesis that the atmospheric CO_2 dynamics in the past one and half centuries can be properly approximated with linear models.

5 Disturbance-response functions

A question of importance to the carbon-cycle and the climate science is how fast (and how much of) the anthropogenically emitted CO_2 will be absorbed by the land and

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the oceans. We address this question by analyzing the responses of the box model to some idealized disturbances (Fig. 3). For the simplicity of the analysis, we assume that changes in temperature are independent from the disturbances of anthropogenic CO_2 emissions.

We first check the model's responses to an impulse disturbance of anthropogenic CO_2 emissions. Shown in Fig. 3, the initial atmospheric CO_2 anomaly decays relatively fast, as 60–70 % of the emitted CO_2 is absorbed by the surface reservoirs within 20 years of the disturbance. However, the rate of carbon assimilation by the land and the oceans significantly slows down in the following decades and eventually becomes neutral as the system approaches steady-state. In the end, 15–25 % of the simulated CO_2 anomaly will likely stay in the atmosphere for thousands of years (Fig. 3). These results are generally consistent with the findings from fully coupled climate-carbon models (Cao et al., 2009; Archer et al., 2009; Joos et al., 2013).

The impulse-response functions of the linear box models can be analytically characterized. For the two-box model of Eq. (2a), when the system approaches a (new) steady state after the disturbance, all the time derivatives ($\dot{E}'$ and $\dot{A}'$) will be zero. Assuming that temperature does not change during the process, we easily obtain the steady state of A' as

$$A' = \frac{\alpha_S}{\alpha_A + \alpha_S} \cdot E' = \frac{\tau_A}{\tau_A + \tau_S} \cdot E', \tag{3a}$$

or more generally

$$\frac{A'}{\tau_A} = \frac{S'}{\tau_S}, \tag{3b}$$

where the mass-conservation relationship represented by Eq. (1c) is used in the derivation. Therefore, the extra CO_2 added to the "fast" carbon cycle by anthropogenic emissions will be partitioned between the atmosphere and the surface corresponding to the response times (τ) of the reservoirs, respectively. Because $\tau_S > \tau_A$ (see Eq. 2d and

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the related discussions), a majority of the emitted CO_2 will eventually be absorbed by the surface carbon reservoirs (Fig. 3). In other words, the long-term fate of the CO_2 emitted into the atmosphere is largely determined by the response times of the surface reservoirs (Revelle and Suess, 1957).

The rates at which the atmospheric CO_2 anomaly decays are determined by the solutions (i.e., eigenvalues) to the characteristic equation of the system. For a two-box system like Eq. (2a), the problem is particularly simple because the only eigenvalue (λ) is

$$\lambda = \alpha_A + \alpha_S, \tag{4}$$

and the solution of Eq. (2a) is therefore

$$A' = \frac{\alpha_A}{\alpha_A + \alpha_S} \exp[-(\alpha_A + \alpha_S) \cdot t] + \frac{\alpha_S}{\alpha_A + \alpha_S}. \tag{5a}$$

A helpful observation of Eq. (5a) is that, when $t \ll 1/(\alpha_A + \alpha_S)$, the solution can be approximated by

$$A' \approx \frac{\alpha_A}{\alpha_A + \alpha_S}[1 - (\alpha_A + \alpha_S) \cdot t] + \frac{\alpha_S}{\alpha_A + \alpha_S} = 1 - \alpha_A \cdot t \approx \exp(-\alpha_A \cdot t). \tag{5b}$$

That is, A' initially decays at a maximum rate of α_A as if the capacity of the surface carbon reservoir were unlimited (i.e., $\alpha_S = 0$).

Next we consider the system's responses to disturbances induced by changes in surface temperatures. Unlike anthropogenic CO_2 emissions, changes in temperature do not add additional CO_2 to the "fast" carbon cycle but only re-distribute carbon between the atmosphere and the surface (Eq. 1a and b), and so the system will recover to its initial steady state once the temperature anomaly is removed. However, increases in temperature are persistent under climate-change scenarios. Therefore, we examine

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the responses of atmospheric CO_2 to a step change in temperature, which is determined from Eq. (2a) as:

$$A' = \beta_T/(\alpha_A + \alpha_S)\cdot T'. \quad (6a)$$

Because $\alpha_A > \alpha_S$, for rough estimates we can also use

$$A' \approx \beta_T/\alpha_A \cdot T'. \quad (6b)$$

Based on the estimated model parameters, therefore, atmospheric CO_2 may rise by ~ 15 ppm for an increase of 1 °C in temperature within a few decades (Fig. 3).

The relationships represented by Eqs. (3b), (5b), and (6b) can be easily generalized to higher-order systems, providing a convenient way to characterize the models' disturbance-response functions without fully solving the system equations. However, the uncertainties associated with these results – especially the long-term responses of atmospheric CO_2 – need to be emphasized. One key source of the uncertainties is that model's parameters are not fully determined by the observations of the global climate-carbon system. As discussed in Sect. 4, the estimation of the model parameter α_S depends on the choice of α_A, which is only loosely constrained by the prior knowledge. It is possible for us to choose another pair of α_A and α_S so that the box model's disturbance response functions better approximate those of the Bern model. However, tuning the model in this fashion has only cosmetic effects to the results and does not reduce the associated uncertainties. In addition, in reality the climate system and the global carbon cycle are not independent but tightly coupled. Therefore, a comprehensive assessment of the long-term fate of anthropogenic CO_2 emissions in the atmosphere must account for the effects of the associated changes in global temperature, which is beyond the scope of this study and demands dedicated investigations in the future.

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6 Biogeophysical implications

The biogeophysical implications of the above modeling results need additional discussions. To illustrate, we further rearrange Eq. (2c) to obtain

$$\dot{E}' - \dot{A}' + \beta_T \cdot T' = [\alpha_A - (1/\gamma - 1)\alpha_S] \cdot A'. \quad (7)$$

On the left-hand side of the equation, the term "$\dot{E}' - \dot{A}'$" is usually used to measure the *net* strength of annual global carbon sinks. However, because the warming temperature also releases carbon on from the surface into the atmosphere ($\beta_T \cdot T'$), this extra source of CO_2 has to be absorbed by the global carbon sinks. By accounting for the effects of temperature changes, the term "$\dot{E}' - \dot{A}' + \beta_T \cdot T'$" thus define a *gross* global carbon sinks. Examining Eq. (7) with the observational data shows that both the net and the gross carbon sinks have been steadily increasing in response to the rising atmospheric CO_2 concentration in the past 160 years, reaching ~ 2.5 and ~ 4.0 ppm yr^{-1} respectively in 2010 (Fig. 4).

Because the efficiency of sea–air carbon exchanges is constrained by the buffering effects of the surface biogeochemistry (Revelle and Suess, 1957), ocean carbon uptakes simulated by the Bern model account for ~ 50 % of the *net* global sinks, while the other 50 % is contributed by land processes, consistent with the literature (Canadell et al., 2007; Le Quéré et al., 2009). Therefore, Fig. 4 suggests that the increasing atmospheric CO_2 concentration must have promoted carbon assimilation by the terrestrial biosphere (Ballantyne et al., 2012), most likely through the CO_2 fertilization effect (Körner and Arnone, 1992; Oechel et al., 1994; Long et al., 1991, 2004) and the associated ecological changes (Keenan et al., 2013; Graven et al., 2013). Indeed, the gross CO_2 fertilization effects of terrestrial vegetation may be higher than previously thought: because the surface warming rapidly releases a proportion of the assimilated carbon back to the atmosphere (Fig. 4) (Piao et al., 2008; Wang et al., 2013), the increased turnover rate may have obscured the evaluation of the magnitude of the CO_2 fertilization effects, which we found in calibrating the Bern model (see the Appendix).

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Shown in Fig. 4, the gross carbon sinks have a nearly direct linear relationship (with a constant slope $\sim 0.04\,yr^{-1}$; $r = 0.98$) with the atmospheric CO_2 concentrations throughout the entire data period. In comparison, the relationship between the apparent carbon sinks and the CO_2 concentrations is slightly nonlinear, with its slope decreasing from $\sim 0.03\,yr^{-1}$ in 1960 to $\sim 0.02\,yr^{-1}$ in 2010. Note that the slope of these linear relationships can be largely interpreted as the efficiency of surface carbon reservoirs in sequestering annual CO_2 emissions. As such, although the *gross* carbon-sequestration rates of the surface reservoirs changed little, the *net* efficiency of the system may have been slowed by $\sim 30\,\%$ in the past five decades (Raupach et al., 2013). These results highlight the significant impacts of climate changes on the global carbon cycle.

7 Conclusions

Inspired by the fact that airborne fraction of anthropogenic CO_2 emissions has been remarkably stable in the observational records, we propose and demonstrate in this paper that the observed dynamics of the global atmospheric CO_2 concentration from 1850 to 2010 can be properly approximated as a linear system. In particular, we derived a simple box model to describe carbon exchanges between the atmosphere and the surface carbon reservoirs under the disturbances of anthropogenic CO_2 emissions as well as global temperature changes. We show that, with a few appropriately retrieved parameters, the model can successfully simulate the observed changes and variations of the atmospheric CO_2 concentration and its first-order derivative (i.e., CO_2 growth rate) across interannual to multi-decadal time scales. The results are highly comparable to those obtained with more sophisticated models in the literature, confirming that the simple linear model is capable in capturing the main features of atmospheric CO_2 dynamics in the past one and half centuries.

A distinct advantage of our linear modeling framework is that it allows us to analytically, and thus most directly, examine the dynamic characteristics of the (modeled) carbon-cycle system. Our analyses indicate that many of such characteristics

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are closely associated with the response times of the atmosphere and surface carbon reservoirs. For instance, the initial decaying rate of an impulse of CO_2 emitted into the atmosphere is mainly influenced by the response time of the atmosphere, but the proportion of the extra CO_2 that stays in the atmosphere at long-term time scales is determined by the ratio between the response times of the atmosphere and the surface reservoirs. Unfortunately, the collinearity exhibited by the observed time series of CO_2 emissions and atmospheric CO_2 concentrations has obscured the determination of the response times for individual surface reservoirs, inducing uncertainties of the estimated long-term responses of the global carbon system. In other words, although the steady CO_2 airborne fraction allows us to represent the carbon-system dynamics with a simple model, it prevents us to resolve further details of the surface carbon reservoirs.

Our model results also have important biogeophysical implications. They highlight that the responses of the global carbon cycle to recent anthropogenic and climatic disturbances are still within the resilience zone of the system, such that annual (gross) terrestrial and ocean carbon sinks linearly increases with the atmospheric CO_2 levels. On one hand, the elevated atmospheric CO_2 concentration must have enhanced land carbon uptakes through the "fertilization" effects and the associated ecological changes. On the other hand, however, the enhanced gross carbon uptakes are partially offset by the increases in global surface temperatures, which accelerate the release of carbon from the surface reservoirs into the atmosphere. As a result, the "net" efficiency of global land and oceans in sequestering atmospheric CO_2 may have slowed by $\sim 30\,\%$ since 1960s, although the airborne fraction of CO_2 emissions remains largely constant.

Finally and importantly, we emphasize that the linear approximation of the global carbon cycle discussed in this paper is conditioned on the pre-industrial (quasi) steady state of the system. The global climate-carbon system is clearly nonlinear beyond this scope (Archer et al., 2009), which can establish different steady states over glacial/interglacial time scales (Sigman and Boyle, 2000). A major concern stemming from climate change is that, because the post-industrial anthropogenic disturbances on the global carbon cycle are so strong and rapid, they may abruptly alter the pace

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at which the natural climate-carbon system evolves and drive the system into a different state at a drastically accelerated rate (IPCC 2001). Our results clearly indicate that the rising atmospheric CO_2 concentrations and the associated increases in global temperature have significantly intensified the global carbon cycle in the past one and half centuries. Although such intensification of the carbon system seems to be within the linear zone as of now, its resilience may be weakened, or lost, in the future. As the anthropogenic CO_2 emissions continue to increase and the global temperature continues to warm, scientists generally expect surface – in particular, terrestrial – carbon reservoirs to saturate and their CO_2 sequestration efficiency to decrease, such that the responses of the global carbon cycle to the anthropogenic disturbances will eventually deviate from their original path. With this concern regarded, the simple linear model developed in this study may serve as a convenient tool to monitor the early signs when the natural carbon system is pushed away (by anthropogenic emissions) from its linear zone.

Appendix A: Calibrations of the Bern carbon-cycle model

The Bern model is a coupled global carbon-cycle box model (Siegenthaler and Joos, 1992; Enting et al., 1994) that was used in previous IPCC Assessment Reports to study changes in atmospheric CO_2 concentration under different emission scenarios (IPCC 1996, 2001). It couples the High-Latitude Exchange/Interior Diffusion–Advection (HILDA) ocean biogeochemical model (Siegenthaler and Joos, 1992; Shaffer and Sarmiento, 1995; Joos et al., 1999) with an atmosphere layer and a multi-component terrestrial biosphere model (Siegenthaler and Oeschger, 1987). The HILDA model describes ocean biogeochemical cycling through two well-mixed surface layers in low and high latitudes, a well-mixed deep ocean in the high latitude and a dissipative interior ocean in the low latitude. Ocean tracer transport is represented by four processes: (1) eddy diffusion within the interior ocean (k, $3.2 \times 10^{-5}\,m^2\,s^{-1}$), (2) deep upwelling in the interior ocean (w, $2.0 \times 10^{-8}\,m\,s^{-1}$), which is balanced by lateral trans-

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port between the two surface layers as well as the down-welling in the polar deep ocean, (3) lateral exchange between the interior ocean and the well-mixed polar deep ocean (q, $7.5 \times 10^{-11}\,s^{-1}$); and (4) vertical exchange between the high-latitude surface layer and the deep polar ocean (u, $1.9 \times 10^{-6}\,m\,s^{-1}$) (Shaffer and Sarmiento, 1995). The effective exchange velocity between surface ocean layers and the atmosphere in both low and high latitudes is assumed to be the same ($2.32 \times 10^{-5}\,m\,s^{-1}$) (Shaffer and Sarmiento, 1995). Ocean carbonate chemistry (e.g., the Revelle buffer factor) is based on the formulation given by Sarmiento et al. (1992). In addition, we implemented the influence of sea surface temperature on the partial pressure of dissolved CO_2 in seawater with a sensitivity of$\sim 4.3\,\%\,^{\circ}C^{-1}$ (Gordon and Jones, 1973; Takahashi et al., 1993; Joos et al., 2001). The changes in global mean sea-surface temperature (SST) is approximately 0.8–1.0 °C from 1850s to 2000s (Rayner et al., 2003; Brohan et al., 2006) slightly lower than that of the tropical land-based air temperature ($\sim 1.0\,^{\circ}C$) but with a trend resembling the latter (Rayner et al., 2003; Jones et al., 2003; Hansen et al., 2006). For simplicity, therefore, we used the long-term trend of the tropical land air as a proxy for the corresponding trend in global SST.

The terrestrial biosphere in the Bern model is represented by four carbon compartments (ground vegetation, wood, detritus, and soil) with prescribed turnover rates and allocation ratios. The global net primary production (NPP), the influx to the biosphere, is assumed to be $60\,GtC\,yr^{-1}$ at the pre-industrial level; and the effect of CO_2 fertilization on NPP (i.e., the β effect) is described with a logarithmic function with a β parameter of 0.38 (Enting et al., 1994). The original Bern model does not consider the effects of changing global temperatures on terrestrial ecosystem respiration, which have been suggested to play an important role in regulating the variability of the global carbon cycle at interannual to multi-decadal time scales (Wang et al., 2013; Rafelski et al., 2009). Therefore, we implemented temperature's effects on terrestrial ecosystem respiration in the Bern model with an overall sensitivity (Q_{10}) of ~ 1.5 (Lenton, 2000; Davidson and Janssens, 2006; Wang et al., 2013). We also changed the pre-industrial CO_2 concen-

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tration to 285 ppm in the Bern model to reflect the findings obtained from the observations (Fig. 4 of the main text).

We calibrated the Bern model so that the model outputs fit the observed atmospheric CO_2 data most favorably. Because no major revisions were made to the ocean carbon cycle module (HILDA), we focused mainly on calibrating the biosphere module. With the original biosphere model parameters, the simulated atmospheric CO_2 concentrations were found to be distinctly higher than observations, reaching ~ 411 ppm in 2010. These results are induced because rising temperatures enhance respiration in the model, reducing the net land carbon sinks to an unrealistic $\sim 0.5\,\mathrm{ppm\,yr^{-1}}$ in 2010. To balance the temperature-enhanced respiration, we need to increase the β parameter from 0.38 to 0.64 to incorporate a higher rate of gross biosphere carbon uptake as enhanced by CO_2 fertilization (Long et al., 2004) and the associated ecological changes (Keenan et al., 2013). With the β parameter set at 0.64, the simulated global terrestrial NPP increased by 14 % from its pre-industrial level and reached $\sim 69\,\mathrm{GtC\,yr^{-1}}$ in 2010, which qualitatively agrees with recent estimates inferred from the isotope measurements (Welp et al., 2011). As such, the re-calibrated Bern model is able to simulate accurately the observed changes/variations in atmospheric CO_2 concentration and growth rate in the past 150 years (Fig. 2 of the main text). The simulated ocean and land components of global carbon sinks are also consistent with estimates found in previous studies (e.g., Canadell et al., 2007; Le Quéré et al., 2009).

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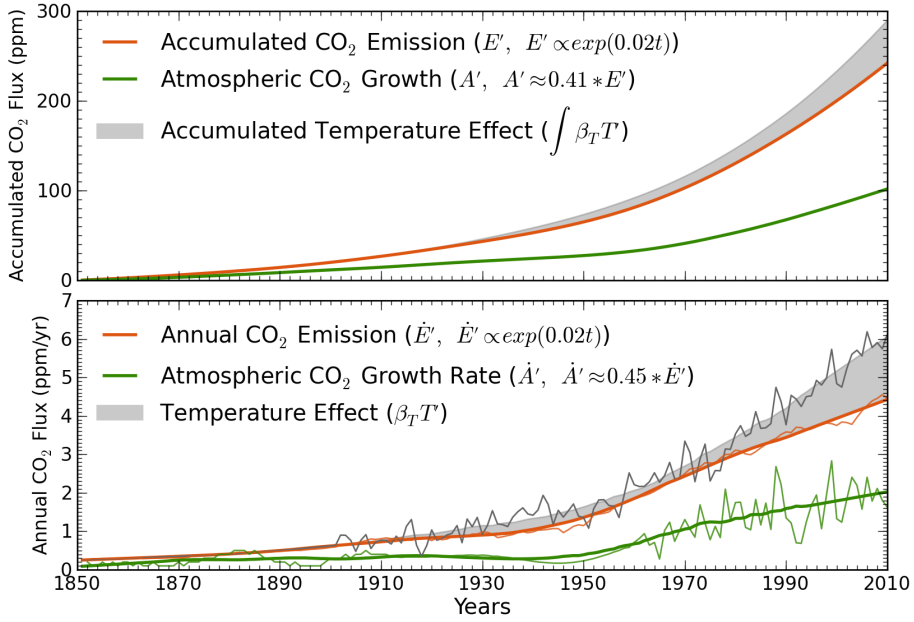

Figure 1. Time series of global anthropogenic CO_2 emissions (red line), atmospheric CO_2 concentrations (green line), and the anomalous CO_2 fluxes induced by warming surface temperatures (gray shade) between 1850 and 2010. The Top panel indicates the accumulated CO_2 fluxes or the total concentration changes while the Bottom panel shows them at annual steps. The thick and the thin lines indicate long-term and interannual variations of the time series, respectively. The mathematical symbols are the same as in Eq. (1) and explained in the text. In both annual and accumulative cases, CO_2 emissions largely increase as an exponential function of time, while changes in the atmospheric CO_2 concentrations are proportional to the corresponding emissions by a factor about 0.41–0.45.

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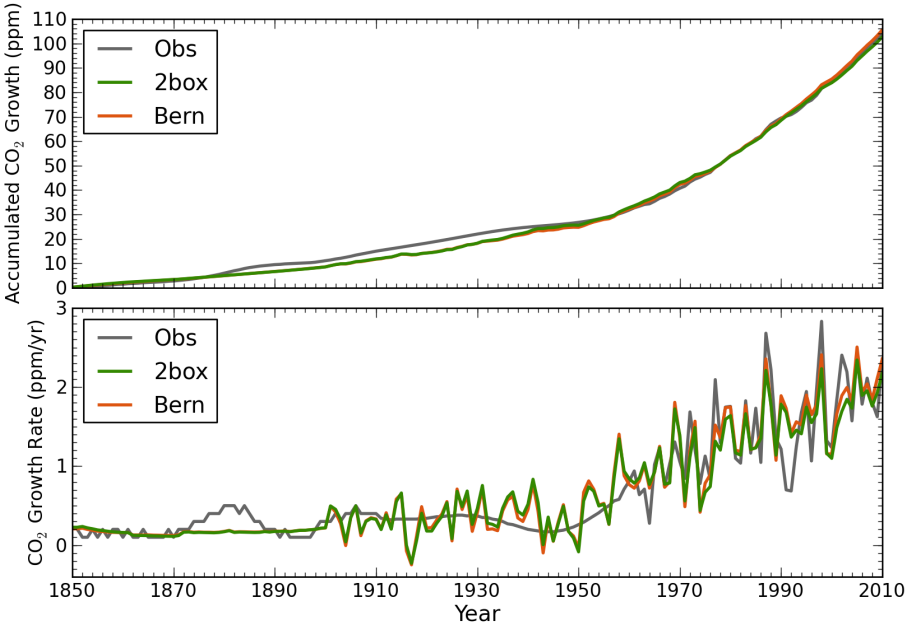

Figure 2. Simulations of the observed atmospheric CO_2 concentrations (Top Panel) and growth rates (Bottom Panel) from anthropogenic CO_2 emissions and land-surface air-temperature data using the two-box model ("2box") and the Bern model ("Bern"). The atmospheric CO_2 concentration in 1850 (i.e., 284.7 ppm) is used as the initial condition for the model integration. Long-term mean temperature before 1901 is assumed to be stable and represented by the 1901–1920 mean. Other model parameters used in these simulations are explained in the main text (the two-box model) or the Appendix (the Bern model).

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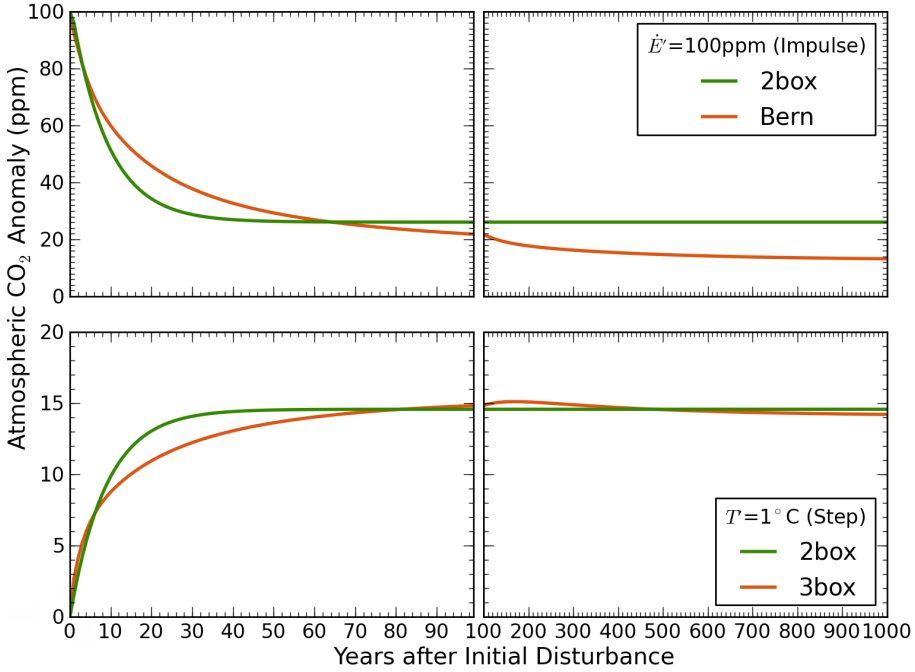

Figure 3. Disturbance-response functions of the atmospheric CO_2 concentration simulated by the two-box model ("2box") and the Bern model ("Bern"). The Top panel shows the responses of atmospheric CO_2 concentration to an impulse increase (of 100 ppm) in anthropogenic CO_2 emissions and the Bottom panel shows the corresponding responses to a step increase (of 1 °C) in surface temperatures.

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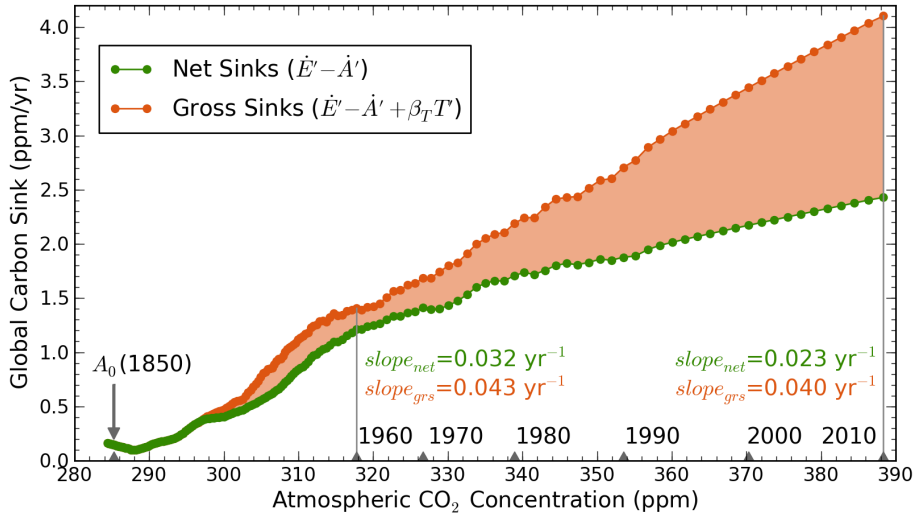

Figure 4. Global annual carbon sinks (ppm/yr) as a function of atmospheric CO_2 concentration from 1850 to 2010. The green dots indicate the observed "net" carbon sinks and the red dots indicate the "gross" carbon sinks that accounted for the effects of temperature changes (Eq. 7). The differences between the gross and the net carbon sinks (the shaded area) indicate the extra carbon fluxes released into the atmosphere as a result of warming temperatures (Fig. 1). The gray arrow ("*A*") indicates the estimated atmospheric CO_2 level (284.7 ppm) that was stable at pre-industrial CO_2 emission rates and climate conditions. The slopes between the global annual carbon sinks and corresponding changes in atmospheric CO_2 concentration (relative to *A*) generally reflect carbon-sequestration efficiencies of global land and ocean reservoirs.

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