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Coupled climate-society modeling of a realistic scenario toward the sustainable earth

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Abstract

A conceptual model was developed to project the global warming for this century by retaining several components essential to the climate and the society systems. The climate system under the forcing of anthropogenic carbon dioxide is represented by global-mean surface air temperature (SAT) and carbon storage separated into the atmosphere, land and ocean. SAT rises due to the atmospheric carbon, which is partially absorbed by the terrestrial ecosystem and the ocean. These absorption rates are reduced by SAT rise. The anthropogenic carbon dioxide is emitted from the society system, which is described by global energy production (P) and the energy efficiency/carbon intensity (E), at a rate of P/E. P is composed of the production per capita (H) and the population (M) in the developed countries and regions, $P=H\times M$. These society components were set to grow on the historical basis in last 50 years, while incentive of the society was introduced to reduce a growth rate of H and to increase that of E in proportion to SAT rise. It is shown that a medium-level carbon emission among the basic scenarios in the Special Report on Emissions Scenarios (SRES) prediction for this century could be achieved when the growth rate of H is reduced by 30%, and that of E is doubled at 1°C warming. Until the end of this century, both terrestrial ecosystem and ocean work as sinks. Once the incentive of the society is eliminated, the carbon emission approaches the upper limit of the SRES scenarios, and the terrestrial ecosystem changes into a source of carbon dioxide. Since H and E are more closely related to

lifestyle and technology, respectively, the individuals are urged to change their lifestyle in the developed countries, and the institutions should develop low-carbon technologies and spread them to the developing countries. By extending the society system that achieves the medium-level carbon emission for a couple of centuries, the oceanic absorption was found to become more crucial than the land counterpart, and hence, behaviors of the ocean are supposed to be estimated more accurately.
Keywords: global warming, climate-society model, future projection, carbon cycle

1. Introduction

For making the sustainable earth realistic, we would have to solve various critical issues such as global warming, food supply, water resource and energy issues. These issues are major obstacles for human being to overcome for a century and more. Since they give effects to each other, we have to search an optimal solution among them. This is a main agenda following Kyoto Protocol. The representative method was to provide various scenarios, in which our world proceeds through global warming and the other problems: e.g., Nakicenovic and Swart (2000). This approach is useful for us to imagine hypothetical routes to approach the sustainable world. The modeling for the approach is based on a carbon dioxide emission, as schematically drawn in Fig.1a. On the other hand, we ought to realize the most likely route, which might be far from sustainability and described as ‘business as usual’, on the basis of our past behavior and socio-economy system, and then, show the way of improving them. Using a coupled model of climate and carbon-emission shown in Fig.1b, it is predictable how quickly we will be able to develop low-carbon society and to replace fossil fuel with carbon-free energy. The speed is not only dependent on technology but on society, in particular, our incentive to develop new technology, to construct a society system to support its usage, etc. This attempt should provide a basis for us to look for the optimal route beyond Kyoto Protocol.

The urgent issues interact with each other and worsen the others, as shown by an obvious example of deforestation enhancing global warming. Efforts have been devoted to figure out how significantly and quickly global warming will damage the forests (e.g., Oechel et al., 2000; Rustad et al., 2001). A more complicated interaction is that efforts of resolving one issue often create a bad impact on the others. One of the immediate examples is that an intention to reduce carbon dioxide emission yields innovation of efficient methods to produce ethanol from grains, resulting in a food cost rise and also the shortage. This consequence encourages more investors to open primeval forests, which definitely increases carbon dioxide emission. These social reactions are crucial to global warming but too detailed to include explicitly in the present coupled climate-society model. An initial approach for us is instead, by amalgamating sophisticated interactions, to take the historical trend in our society and to add modifications that may occur under global warming. For the same reason, greenhouse gases other than carbon dioxide are put aside in this study.

“Warming of the climate system is unequivocal, as is now evident from observations of increase in global average air and ocean temperatures”, Intergovernmental Panel on Climate Change (IPCC) stated in the latest assessment report, Summary for Policy Makers in Working Group I (IPCC, 2007a). The global average temperature has increased by 0.74°C for the last 100 years and a further warming trend is expected in the next 100 years. According to the projections by the IPCC report, the global average of warming by the end of the 21st century is 1.5–5.8°C. No matter which greenhouse gas emission scenarios come true in the future, it is very likely that an enormous impact of the global warming on our living environment is unavoidable. A half of the uncertainty is attributable to the climate models, whereas the other half arises from choice of the scenarios.

The key component to the modifications caused by global warming is the feedback between the natural system and human behavior, which is often affected by economical incentive and government policies. We should not forget about the fact that industrial and governmental decisions are in turn influenced by the nature itself (Fig.1b). The main objective in this study is to provide the right direction and actions to take or not to take for the present human toward the sustainable and enjoyable earth through the optimal route, rather than presenting various scenarios for the future.

In addition to the nature-society feedback, the natural system itself possesses feedback mechanisms between climate and carbon cycles. The terrestrial ecosystem absorbs carbon dioxide more effectively under higher carbon dioxide in the atmosphere, as long as warming is moderate. However, the ecosystem will be damaged under the further warming toward the end of this century, and the carbon stock may reach its limit (Cramer et al., 2001). The ocean also will be influenced by the warming gradually (Friedlingstein et al., 2006), which is easily imagined from higher partial pressure of carbon dioxide and lower productivity in the warmer ocean (Sarmiento et al., 1995; Bopp et al., 2005).

In section 2, the conceptual climate model is constructed on the basis of the recent trend of climate change, and then, verified against the future predictions shown in various sophisticated models. In section 3, the society model is produced on the basis of the recent social history. In section 4 for presenting the results of the coupled model during this century, a main focus is given to the sensitivity to the feedback from the warming to carbon emission, which is related with incentive of the society under the global warming. The projection is extended for a couple of centuries in section 5, by examining the sensitivity to absorption of carbon by the terrestrial ecosystem and the ocean. The results are discussed in section 6.

2. Climate model

In the last few decades, great efforts have been devoted to developing models of the climate system by describing physical, geochemical and biological processes in the atmosphere, ocean, land and cryosphere. The trend is to use large computer resources (e.g., Sakamoto et al., 2005), while a conceptual model is also used on the basis of sophisticated models in comparison between the two types of models (Claussen et al., 2002; IPCC, 2007b). In this study, the conceptual model is chosen and used as a platform for estimating a temperature rise in response to carbon dioxide emission.

2.1 Governing equations of global warming and carbon emission

The global warming is represented by T (K) an increase in the global mean SAT, which is assumed to rise linearly with the carbon dioxide content C_{air} in the atmosphere exceeding the pre-industrial level. The warming is partly cancelled by a longwave radiation toward the space:

$$\frac{dT}{dt} = A_T C_{air} - B_T T \qquad (2.1)$$

where C_{air} is measured in ppmv. The coefficient of warming is chosen to be A_T=5×10^{-4} Ky^{-1}, by which warming proceeds at 0.05 degree per year due to a carbon dioxide excess of 100 ppmv. This warming rate corresponds to the increase in ocean temperature with a 300-m thick layer, which circulates quickly above the main thermocline, caused by a radiative forcing of 2 Wm^{-2} associated with this carbon dioxide excess. The radiation cooling coefficient is set to be B_T=0.05 y^{-1} or 0.05 degree cooling per year with temperature higher by 1 degree. Once the carbon dioxide content is given, these two coefficients produce results comparative with the predictions for the 21st century using various sophisticated models (IPCC, 2007b), while the present model responses to carbon dioxide slightly faster than some models (e.g., Hansen et al., 2000). The comparison can be examined using the results of the climate model in the latter part of this section.

The anthropogenic carbon dioxide is emitted to the atmosphere and partly absorbed into land and ocean. Thus, carbon is stocked in the three components: i.e., the atmosphere, land and ocean.

$$\frac{dC_{total}}{dt} = A_C \frac{P}{E} \qquad (2.2a)$$

$$\frac{dC_{land}}{dt} = A_{land} C_{air} - B_{land} \left| \frac{dT}{dt} \right|^2 \qquad (0 \le C_{land} \le C_{land\max}) \qquad (2.2b)$$

$$\frac{dC_{ocean}}{dt} = A_{ocean}(C_{air} - C_{oceanabs})(1 - B_{ocean}T) \qquad (dC_{ocean}/dt \ge 0) \qquad (2.2c)$$

$$C_{air} = C_{total} - C_{land} - C_{ocean} \qquad (2.2d)$$

The emission rate P/E is given by a society system in Gigaton (10^9 ton) of carbon per year (GtC/y) and accumulated within C_{total} at a conversion rate of A_C=0.47 (GtC)$^{-1}$, which increases C_{total} by 2.8 ppmv due to 6 GtC/y emission (Keeling and Whorf, 2005; Marland et al., 2005). Once all carbon dioxide is kept in the atmosphere, C_{air} increases by 2.8 ppmv. The components of carbon dioxide in land and ocean are converted to the values equivalent to the atmospheric one: i.e., they are measured in atmospheric ppmv, as if they stay in the atmosphere.

As shown in (2.2b) and (2.2c), the components in land and ocean primarily grow by absorbing the atmospheric component with absorption coefficients, A_{land} and A_{ocean}. The land coefficient A_{land} is chosen to be 1/120 y^{-1} under the estimation that the terrestrial ecosystem takes up the atmospheric amount in 120 years. This term represents higher primary production of the terrestrial ecosystem under the growing carbon dioxide content in the atmosphere and also moderately warmer climate. Following IPCC (2007b), the emission due to land use change is combined into the air-to-land flux. The oceanic counterpart is assumed to proceed twice faster: i.e., A_{ocean}=1/60 y^{-1}. Although it is well accepted that carbon dioxide gradually mixes downward to the main thermocline in the ocean and increases its partial pressure at the sea surface, such effects are considered all together in the estimation of A_{ocean}. These coefficients are validated with the partitions in the terrestrial ecosystem and the ocean among the current increase in carbon dioxide (IPCC, 2007b).

2.2 Feedback from climate to terrestrial ecosystem

The last term in (2.2b) accommodates the impacts of global warming on terrestrial ecosystem and carbon stock in soil, while the higher primary production under the moderate global warming is included in the first term on the right-hand-side. The principle is related to the fact that the terrestrial ecosystem cannot follow the shift of the favorable conditions toward higher latitudes during the global warming. As consequence of global warming, precipitation will decrease in some regions (IPCC, 2007b) and may give damage also on the terrestrial ecosystem. Soil respiration will increase, since organic carbon in soil is decomposed faster under higher temperature and less precipitation in the similar manner. High latitude and tropical peatlands, which have stored carbon for more than 10 thousand years, would emit carbon dioxide under warmer climate upto 100 GtC in next 100 years (Gruber et al., 2004).

The effects are parameterized by the time derivative of the warming. When the power of this term is chosen, we consider the interannual variabilities in temperature and precipitation at a several-year cycle and their standard deviations. As shown in Fig.2, it is natural that these parameters fluctuate and occasionally damage the terrestrial ecosystem. The probability of the damage is limited only to the extreme case. Once the long-term trend is superimposed on the variability, the probability increases rapidly at a rate larger than that proportional to a temperature increase and precipitation change. Therefore, the power is chosen to be 2 here, and hence, a drastic change may occur from a sink to a source in a qualitatively same way as sophisticated models show in Fig.3 (Cramer et al., 2001; Friedlingstein et al., 2006).

In Fig.3, the carbon fixation into the terrestrial ecosystem increases until 2050-2100 depending on models and then decreases afterward (Friedlingstein et al., 2006). The terrestrial ecosystem changes from sink to source in 2100-2170. In this paper, B_{land} is chosen to be 1×10^3 (ppmv)yK^{-2}, reducing the annual fixation at a rate of 0.1 ppmv due to warming of 0.01 degree per year. Although the pre-industrial carbon stock could be emitted to the atmosphere, we choose the conservative case in which the anthropogenic carbon only is emitted under the constraint on C_{land} to be non-negative. This constraint is consistent with the moderate sources in Cramer et al. (2001). The model behavior will be confirmed to be appropriate in the latter part of this section.

Even if the anthropogenic carbon stock is not emitted back from the terrestrial ecosystem to the atmosphere, all models tend to reduce carbon fixation rates beyond 2100 (Cramer et al., 2001). This behavior implies the limit of carbon stock $C_{landmax}$ in the terrestrial ecosystem, which is essentially produced in the nutrient-limited ecosystem at a time scale of 100 years (Comins and McMurtrie, 1993). In the present study, the limit has not been reached in this century (section 4), while the possible model behavior will be examined as the terrestrial carbon stock reaches the limit after 2100 (section 5). As an example, the stock limit is set to a third of the current stock (210 GtC), which is equivalent to $C_{landmax}$=100 ppmv. It is remarked that $C_{landmax}$ implicitly implies the nutrient limitation, although nitrogen fixation and deposition are still uncertain, and $C_{landmax}$ is not calculated from available nitrogen (Wang and Houlton, 2009).

2.3 Feedback from climate to ocean

The oceanic absorption is set in (2.2c) to be influenced by temperature rise and content of anthropogenic inorganic carbon in the intermediate-to-deep water responsible for carbon absorption: i.e., these two effects are represented by B_{ocean} for the temperature rise and $C_{oceanabs}$ for the carbon content. Solubility of carbon dioxide decreases in the ocean under global warming, and its partial pressure increases equivalently to 10 ppmv, as sea surface temperature (SST) becomes higher by 1 degree (Sarmiento et al, 1995). This is rather a small effect compared with the anthropogenic increase in the atmospheric content of carbon dioxide. As the other mechanism, the warmer surface layer is less mixed with intermediate water and deep water, which carry anthropogenic carbon to the subsurface ocean. As consequence of these physical changes, the warming is considered to reduce phytoplankton production and then carbon absorption in the subpolar regions. The productive subpolar regions shift toward higher latitudes with narrower oceans in the zonal direction.

Although model simulation provides useful information as carried out by Friedlingstein et al. (2006), we attempt to estimate effects of the individual components. Concerning the first component, a weaker atmospheric cooling generates a thinner mixed-layer in winter and reduces upward flux of nutrients and hence phytoplankton production in spring and summer (Bopp et al., 2005). Since SAT is at most lower by 10°C than the winter mixed-layer temperature in wide regions, SAT warmer by 1-degree is estimated to reduce a maximum mixed-layer depth and consequently phytoplankton production by about 10%. Deep water formation and the global conveyor belt must be weakened under global warming with some evidence in the Atlantic (Bryden et al., 2005) and the Pacific (Fukasawa et al., 2004), while its effects on the ocean productivity may take time longer than 100 y to appear. As for the third component, the subpolar regions that correspond to SST less than 10°C will reduce by 10% with 1-degree warming, which can be estimated from the oceanic responses to basin-scale climate variability (Takahashi et al., 2006). Hence, the air-to-sea carbon dioxide flux may be also reduced by 10%, which will lead to reduction in the global and annual mean flux by more than 10%. Therefore, the coefficient B_{ocean} is set 0.2 K^{-1} (20% reduction by 1-degree higher SAT), which is rather a conservative estimate. Once T exceeds $1/B_{ocean}$, the oceanic absorption is fixed to be zero, which makes sense because warm surface water tends to shut down vertical mixing and consequently absorption of carbon dioxide.

The additional effect is related to resurfacing anthropogenic carbon, which was contained at the sea surface certain years ago and comes again to the sea surface within intermediate and deep water, being indicated as change in Revelle factor. As the time from the previous contact to the present contact becomes longer, this effect becomes minor. Thus, we do not have to consider the effects for the North Atlantic Deep Water (NADW), but take 100 y or so for the Antarctic Intermediate Water (AAIW) and 50 y for the North Pacific Intermediate Water (NPIW). The AAIW is taken as a representative case, which is originated from the NADW along with isopycnal mixing toward the Southern Ocean (Hiraike and Ikeda, 2009). Thus, the length between the previous and present contact times is estimated to be 100 y. The surface water responsible for oceanic absorption is assumed as mixture between the deep water which is not affected by anthropogenic carbon dioxide and the intermediate water which was influence by the anthropogenic carbon dioxide at 100 y in prior. $C_{oceanabs}$ is taken as a half of C_{air} at 100 y in prior. Since this effect is minor during a rapid increase in atmospheric carbon, it is not included in this century simulation with $C_{oceanabs}$=0 (section4), but retained for the period beyond 2100 (section 5).

In addition to the feedback described above, a well-predicted trend is ice cover reduction in the Arctic Ocean and near Antarctica. The ice retreat will adopt the shift of high biological production to higher latitudes, while it will also expose under-ice carbon-rich water to the atmosphere. In addition, brine rejection, which now transports carbon dioxide downward, will weaken. However, the combination of these effects is still very uncertain (Bates and Mathis, 2009). The other possible trend is intensification of the positive Southern Annular Mode, which will enhance vertical circulation under Ekman divergence and increase dissolved inorganic carbon (DIC) near the sea surface (Lenton and Matear, 2007). Hence, sea-to-air carbon dioxide flux will increase. In this paper, these aspects were not explicitly estimated for B_{ocean} but only discussed in terms of uncertainty of a future projection. More additional aspects are discussed also in section 6.

2.4 Verification of the conceptual model

The climate model is now verified against the current state and the SRES scenario prediction. Our choice is to force the model by a carbon emission in the middle of the various scenarios. Although the anthropogenic carbon and warming are defined to be relative to the pre-industrial states, a more practical approach is taken in this study: i.e., the model is initialized in 1900 as the basis for the anthropogenic effects by excluding very minor anthropogenic effects and uncertainty related to natural variability before 1900.

The model results are shown in Fig.4 and 5. The carbon emission is set to be 6.0 GtC/y around 2000, accumulating to total of 114 ppmv above the 1900 value. The model yields the absorption by the terrestrial ecosystem at 15% of the carbon emission and by the oceanic absorption at 34% in 2000. The content is partitioned into 57% in the atmosphere, 14% in the terrestrial ecosystem and 29% in the ocean by 2000. The oceanic content is consistent with the observation results (e.g., Sabine et al., 2004). The land content may be deduced from the residual between the total emission and the content in the atmosphere and ocean, while the model result is supported also by the sum of the actual carbon fixation (Nowak et al., 2004) and the emission due to land use change (Houghton, 2003). The atmospheric component is about 64 ppmv above the 1900 value, reaching about 360 ppmv. SAT rises by 0.44 degree. All these values are comparable with the conditions around 2000, while it is remarked that these results are slightly conservative.

By the end of this century, the carbon emission is increased to 20 GtC/y. The atmospheric stock reaches 354 ppmv; i.e., the carbon dioxide content is about 650 ppmv in the atmosphere. SAT rises by 2.71 degree. This behavior is well included in the envelope of model ensemble prediction forced by the several basic scenarios in SRES (Nakicenovic and Swart, 2000). The accumulated carbon dioxide is partitioned into 52% in the atmosphere, 14% in the terrestrial ecosystem and 34% in the ocean. The terrestrial ecosystem still absorbs carbon at a rate of 2.6 GtC/y in 2100, while the absorption rate is reduced by 59% due to the feedback from the global warming represented by the last term in (2.2b). The oceanic uptake is also reduced to 5.8 GtC/y by 54% due to the last term in (2.2c). It is noted that their absorption rates are still larger than the current values, simply because the excess of the atmospheric content is 354 ppmv and almost five times of the current one (64 ppmv). Thus, the impact of the feedback from the global warming is similar between the ocean and the terrestrial ecosystem in the present case. However, it is emphasized that the terrestrial ecosystem would receive more feedback, as the warming proceeds faster.

For comparison, the additional case was carried out by excluding the last terms in (2.2b) and (2.2c). The difference from the reference case is very minor in 2000 and grows as time proceeds. The atmospheric component is 265 ppmv above the 1900 value, and SAT rise is 2.16 degree in 2100. Thus, they are smaller by 89 ppmv and 0.55 degree than those in the case with the feedback. The terrestrial ecosystem absorbs carbon at 4.7 GtC/y, and the ocean uptake is 9.4 GtC/y. They are larger by 2.1 GtC/y and 3.6 GtC/y than the rates in the feedback case, respectively. It is noted that the reductions are smaller than the last terms in (2.2b) and (2.2c) in the feedback case, since atmospheric carbon dioxide is higher in the feedback case than the no-feedback case. The additional remark is that the terrestrial carbon stock is 104 ppmv in 2100 (Fig.5) and is about to approach the limit, which is not applied yet in this case but would reduce the uptake even without the feedback.

Friedlingstein et al. (2006) examined various models through the Coupled Carbon Cycle-Climate Model Intercomparison Project (C4MIP). The differences between the coupled and uncoupled models showed a wide variety, while a consistent outcome was that the terrestrial ecosystem role grows nonlinearly as the global warming proceeds. Under SRES A2 scenario, majority of the models predicted the fixation reduction to be 2-to-3 GtC/y, which 2.1 GtC/y in the present model is comparable with. The oceanic role grows almost linearly but is more uncertain among the various models in C4MIP. The present model gives a high end of 3.6 GtC/y, whereas the oceanic absorption (5.8 GtC/y) itself is similar to most of the C4MIP models. This positive climate-carbon cycle feedback leads to an additional increase in atmospheric CO_2 concentration of 20 to 220 ppmv by 2100, within which the present model result lies. One remark is that the C4MIP isolated only the feedback from climate to ecosystems, whereas the present model included all possible feedbacks from climate to carbon cycles into the last terms of (2.2b) and (2.2c): e.g., a highly stabilized thermocline would shorten the adjustment time of carbon spread in the ocean. Our tentative conclusion is that the terrestrial ecosystem has a feedback more sensitive to global warming and hence is more crucial for the future prediction at least in this century.

3. Climate-society model

The society component is now formulated and coupled with the climate model, which was verified in section 2. The emission rate of anthropogenic carbon dioxide is determined by the society component. In the present study, a few variables are selected to represent the society component and formulated as functions of SAT. A small number of parameters are specified, on which sensitivity of the carbon dioxide emission is examined. This society model is discussed in relation to typical economic models later in this section.

The anthropogenic carbon dioxide is emitted at a rate of P/E, which is described by global energy production P and the energy efficiency/carbon intensity E. P is composed of the production per capita H and the population M in the developed countries and regions with active industries; i.e., $P=H\times M$. This population only is considered to be responsible for the global warming. The society components H, M and E are primarily set to grow at constant rates relatively to their values on the historical basis in last 50 years. In addition, incentive of the society may reduce H and increase E, as the global warming continues. The key mechanism in the feedback from the natural system to human behavior may include economical incentive and government policies. Industrial and governmental decisions are actually influenced by the nature itself through public opinions. No additional incentive or forcing is given to growth of M, as no one has right to prevent the others from joining the developed countries and regions.

The society component equations are

$$\frac{dH}{dt} = (A_H - D_H T)H \qquad (3.1a)$$

$$\frac{dM}{dt} = A_M\left(1 - \frac{M}{M_{\max}}\right)M \qquad (3.1b)$$

$$\frac{dE}{dt} = (A_E + D_E T)E \qquad (3.1c)$$

All industrial production and residential usage are compounded into (3.1a) with a constant growth rate A_H. The population in the developed countries and regions is formulated on the basis of a constant growth rate A_M in the last century, whereas the growth rate reduces as M approaches but never exceeds the maximum global population $M_{\max}$ (10 billion). Both coefficients are taken to be 0.015 y^{-1} so that they are nearly doubled in 50 years. Hence, the total energy production P grows by a factor of 4 in 50 years. These growth rates are comparable with those in last 50 years (IPCC, 2007c). The energy efficiency denotes energy production with a fixed carbon dioxide emission and is estimated to increase by 30% in 50 years (Nakicenovic et al., 2006): i.e., $A_E = 0.005$ y^{-1}. Many models produced various time sequences, while a majority showed continuous improvement. Here, E is measured relatively to the value in 2000, and hence, P and H are measured in the unit of a carbon dioxide emission. The initial conditions of these three variables are set so that the solution may reach H=6 ton per year, M=1 billion and E=1 in 2000. Thus, the anthropogenic carbon dioxide is emitted nearly at 6 GtC/y in 2000. It will be shown in section 4 that the feedback effects are minor until 2000.

The feedback from the natural system to the social system is all amalgamated into the anthropogenic carbon dioxide emission through the growth rates of H and E. The growth rate of H is reduced, and that of E is increased, in proportion to T. The feedback may arise from economical incentive, government policies, change in lifestyle, value in our mind, etc. It might be feasible to analyze the actual mechanisms included in the feedback, however we take a case study to examine the solutions under different sets of D_H and D_E. The case of D_H=D_E=0 is defined as 'business as usual'. D_H=0.005 $y^{-1}K^{-1}$ corresponds to one-third slowdown of the energy production growth per capita under the global warming of 1 degree. D_E=0.005 $y^{-1}K^{-1}$ describes a doubled speed of the energy efficiency growth under T=1 degree. For a simple categorization, the former incentive comes from individual efforts, and the latter incentive is related to technology development, which includes wider application of existing technology (Pacala and Socolow, 2004). However, it is noted that the complete separation is difficult: e.g., individual minds could guide governments toward more support for technology development, and governments' measures encourage individuals toward reduction of energy use.

In typical economic models (e.g., Nordhaus and Boyer, 2005; Fujino et al., 2006), the value of environment will increase due to the damage associated with global warming, and governments will decide to implement carbon tax and make investment in technology development. Individuals may support these measures by the governments and tend to purchase products with low carbon usage. Industrial and transportation sectors decide to reduce fossil fuel use. All these processes are evaluated in a particular society system under certain international treaties and formulated in the models. The present model implicitly retains these essential components, which are instead parameterized in a simpler manner.

4. Projection for this century

In this section, two parameters, D_H and D_E, are chosen to change so that four cases are examined. The climate model has a simple setting with $C_{landmax}$ infinitely large and $C_{oceanabs}$=0. As the warming is used as a realistic index, T is measured by °C, hereafter. The reference case is first presented for D_H=D_E=0 and can be defined as 'business as usual' or 'persistent trend'. The coupled model is first verified against the climate model presented in section 2.4 and also the current state only until 2000. The model results are shown in Fig.6a, 6b and 7a. The carbon emission grows up to 5.2 GtC/y by 2000 and accumulates to 94 ppmv above the pre-1900 value. The absorption by the terrestrial ecosystem is 14% of the carbon emission, and the oceanic absorption is 31% in 2000. The accumulated content is separated into 55% in the atmosphere, 14% in the terrestrial ecosystem and 31% in the ocean by 2000. The atmospheric component is about 53 ppmv above the pre-1900 value to be about 350 ppmv. SAT rises by 0.35°C. All the values of the growth are about 10% lower than the climate model (section 2.4), and are slower than the actual state by about 7 to 10 years. The partitions are very close to those in the climate model.

In 2100, this case emits carbon at 47.7 GtC/y (Fig.7b) and reaches warming of 5.00°C, which is equivalent to the threshold ($1/B_{ocean}$) between sink and no-sink (Fig.6a). This progression is near the highest emission scenario and well above the case for the model verification with 20 GtC/y emission and 2.71°C warming (Fig.4). The total carbon emission accumulates to 1025 ppmv. It is stored with 789 ppmv in the atmosphere and 236 ppmv in the ocean, while the terrestrial ecosystem switches from sink to source around 2065 and has emitted the entire anthropogenic stock by 2085 (Fig.6b). The carbon emission from the terrestrial ecosystem reaches a peak of nearly 16 GtC/y, 50% of the anthropogenic emission at 2085 and then returns zero after all stock is lost (Fig.6b). The oceanic stock reaches a maximum around 2100 and soon stops absorption. Thus, the feedback from climate to the terrestrial ecosystem seems the most crucial mechanism for this century.

Since the sensitivity to B_{land} becomes crucial under the rapid warming, it is examined here by halving the value to 500(ppmv)yK^{-2}. The anthropogenic emission is not modified in this sensitivity study, since no feedback occurs with D_H=D_E=0. The warming is 4.41°C at 2100, while the large differences are seen in carbon accumulation in the terrestrial ecosystem (positive 78ppmv) and the carbon emission from the terrestrial ecosystem to be 5.4 GtC/y only. However, the carbon emission will grow rapidly, and the carbon accumulation will be lost soon. Thus, B_{land} modifies the progression by 25 years or so, but does not change the fundamental trend. By considering the sensitivity to the terrestrial ecosystem revealed by these two cases, it is stated that the emission from terrestrial ecosystem will contribute to warming around 1°C at the end of this century.

As B_{land} is switched back to 1×10^3 (ppmv)yK^{-2}, the second case has D_H changed to 0.005 y^{-1}K^{-1}, corresponding to one-third slowdown of H, the energy production per capita under T=1°C. In 2100, carbon emission is 23.5 GtC/y, and warming is 3.16°C (Fig.6c). This warming reduces the growth rate of H so that H reaches a peak around 2100. However, the carbon emission is still growing due to increasing M, the population in the developed countries and regions. The atmospheric carbon is nearly a half of the reference case, and the oceanic carbon is comparable but growing much faster (Fig.7c). The terrestrial ecosystem is emitting carbon at 0.6 GtC/y to the atmosphere and will soon lose all carbon stored during the global warming. The third case has D_H changed back to zero and D_E changed to 0.005 y^{-1}K^{-1}. This case describes a doubled speed of the energy efficiency growth under T=1°C. The carbon and climate are exactly the same as those in the second case (Fig.6d). The efficiency E grows now about four times faster than the state in 2000, while H is equal to the reference case.

In the fourth case, both D_H and D_E are given to be 0.005 y^{-1}K^{-1} so that, under the global warming of 1°C, the energy production per capita may grow more slowly by one-third, and a speed of the energy efficiency may grow twice faster. In 2100, carbon is emitted at 14.3 GtC/y (Fig.7d) and warming reaches 2.24°C (Fig.6e). This progression belongs to a more rapid reduction in anthropogenic carbon emission than the case for the model verification with 20 GtC/y emission and 2.71°C warming (Fig.4). The total carbon emission accumulates to 580 ppmv and stored at 280 ppmv in the atmosphere, 206 ppmv in the ocean and 94 ppmv in the terrestrial ecosystem. Although a minor difference is seen in lower atmospheric carbon of 280 ppmv in the fourth case than 354 ppmv in the climate model, a remarkable difference is that the carbon emission peaks out at the end of this century. This difference is induced by both of the slower growth of carbon emission per capita and the faster growth of the energy efficiency in the fourth case. However, it is noted that air temperature is still increasing beyond 2100.

5. Sensitivity to carbon stock in the natural system beyond this century

It was shown in section 4 that, among the four cases, we can expect the sustainable world only with D_H and D_E set to be 0.005 $y^{-1}K^{-1}$. Here, the sustainable world is meant to be that carbon emission will be reduced, and the earth will return to the current state. Let us examine what projection would occur beyond 2100; in particular, sensitivity to the parameters of the feedbacks between climate and terrestrial ecosystem, and also between climate and ocean. It is clear that emission from the terrestrial ecosystem should be avoided, while its carbon stock may reach the limit as time proceeds. The other crucial point is that the warming is supposed to stop before oceanic carbon absorption stops. Therefore, $C_{landmax}$ and B_{ocean} are chosen as the parameters for a case study beyond 2100 until 2300. Since the simulation period becomes longer, the resurfacing sea water affected by anthropogenic carbon has to be included: i.e., differences are also mentioned between the case of $C_{oceanabs}$=0 and the case of $C_{oceanabs}$=0.5·C_{air}(t-100), where C_{air}(t-100) denotes the carbon concentration in the atmosphere 100 y in prior.

First of all, the progression is examined after 2100 with the values of $C_{landmax}$ and B_{ocean} set in section 4: i.e., $C_{landmax}$ has no limit. Once $d(P/E)/dt$ is written down in the form of $\alpha(P/E)$, (3.1) makes α fall between $(A_H-D_HT+A_M-A_E-D_ET)$ and $(A_H-D_HT-A_E-D_ET)$, depending on M well below M_{max} and close to M_{max}, respectively. Thus, air temperature approaches 2.5°C near 2100, and anthropogenic carbon emission peaks out: i.e., the society model turns into the carbon emission reduction phase. Then, carbon content in the atmosphere reaches a maximum, and finally air temperature comes to a peak. Actually in the fourth case with $C_{oceanabs}$=0, the peaks occur as follows: P/E=14.4 GtC/y in 2094, C_{air}=336 ppmv in 2142, and T=3.25°C in 2162. Once $C_{oceanabs}$ is changed to 0.5·C_{air}(t-100), they occur as P/E=14.3 GtC/y in 2092, C_{air}=347 ppmv in 2143, and T=3.37°C in 2165. Thus, the resurfacing sea water affected by anthropogenic carbon gives negligible impacts until the mid-22nd century. As the population in developed countries and regions approaches the limit, all these variables tend to reduce after the peaks. At the end of the 23rd century (2300), P/E=1.97 GtC/y, C_{air}=104 ppmv, and T=1.30°C for $C_{oceanabs}$=0, while P/E=1.18 GtC/y, C_{air}=168 ppmv, and T=2.29°C for $C_{oceanabs}$=0.5·C_{air}(t-100). Since the differences are significant, we should state that the resurfacing anthropogenic cargon should be considered in the case when atmospheric carbon saturates or reduces for a long period.

The further discussion is devoted to a limit in the terrestrial carbon stock, which is essentially consistent with the mechanistic models (e.g., Comins and McMurtrie, 1993). When no limit is given to $C_{landmax}$, C_{land} grows to 513 ppmv by 2300. If $C_{landmax}$ is set at 300 ppmv (640 GtC), C_{land} reaches this limit in 2184, and then, C_{air} increases again, but gradually reaches a maximum in 2234. It reduces after that consistently along with the anthropogenic carbon emission and air temperature, as P/E=0.51 GtC/y, C_{air}=314 ppmv, and T=3.25°C in 2300. Thus, the terrestrial ecosystem does not take carbon any more, resulting in higher carbon dioxide in the atmosphere and higher warming than the case of no limit. It is noted that this state requires continuation of a faster reduction in the anthropogenic carbon emission.

Let us examine the full case study of 16 cases with four choices of $C_{landmax}$, and also four choices of B_{ocean} (Table 1). Once $C_{landmax}$, is set lower with B_{ocean} fixed at 0.2 (K^{-1}), a new state appears. If it is set to be 100 ppmv (210 GtC), which is reached in 2104, before the carbon content in the atmosphere reaches a peak. Oceanic carbon reaches the saturation of 335 ppmv in 2204 with SAT rise of 5.00°C. Air temperature continues to increase until 2300: i.e., P/E=0.04 GtC/y, C_{air}=538 ppmv, and T=5.37°C in 2300. The ocean completely stops absorption, since warming is higher than the threshold $1/B_{ocean}$ =5°C. As time proceeds, carbon dioxide increases in the atmosphere, and air temperature goes up.

The climate-ocean feedback is now examined with B_{ocean} varied. The cases with B_{ocean} larger to be 0.25 (K^{-1}) exhibit continuous warming for $C_{landmax}$,=300 ppmv., where the threshold of air temperature is 4°C. For B_{ocean} reduced to 0.15 (K^{-1}), warming stops before 2300 even when $C_{landmax}$, is 100 ppmv. Once we take a pivot at (B_{ocean}, $C_{landmax}$,)=(0.2, 200), only 25% variation in B_{ocean} corresponds to variation more than 50% in $C_{landmax}$. The uncertain mechanisms that could produce these variations are discussed more extensively in section 6 with reference to the previous studies.

This case study gives us the following important message: the climate-ocean feedback and the terrestrial carbon stock limit are crucial to global warming. The primary player is the climate-ocean feedback: i.e., within the realistic range of the terrestrial carbon stock, the earth will restore the present climate with B_{ocean}=0.15, but the warming will continue with B_{ocean}=0.3 (Table 1). When B_{ocean} is between these two values, the projection is dependent on $C_{landmax}$. Once we fill up the stock too early, it is impossible to reestablish the atmosphere-ocean carbon cycle and restore the present climate, even though we reduce anthropogenic carbon emission to an infinitesimal level.

6. Summary and discussion

6.1 Summary

In summary, it is impossible to achieve the medium scenarios in the SRES by taking the historical trend of technological development. Many options are available for wider application of existing technology, while the historical trend shows that the speed has been too low. The achievement would become feasible within this century under the two following conditions to be satisfied: at 1°C warming, the energy efficiency/carbon intensity is doubled, and the growth rate of the production per capita is reduced by 30%. As suggested by Edmonds et al. (2004), even if the energy efficiency is improved, fossil fuel usage will continue to increase without governmental and international policies for atmospheric carbon dioxide stabilization. This suggestion is essentially consistent with the conclusion in the present study.

Value and lifestyle may have to be changed in the developed countries and regions. Technology should be transferred from the developed countries to the developing countries. Value and lifestyle changes are helpful for technology development also. Ordinary economic models provided high rates of energy efficiency improvement, as the value of environment increases under global warming. However, this idealized condition is subject to world-wide recognition of the value, for which governmental and international policies would be helpful. It is still too optimistic at this stage to expect that the energy efficiency would improve by following the economic models' suggestions.

6.2 Possible processes at time scales longer than 100 years

As far as we take the direction toward the sustainable world in this century by enhancing the energy efficiency and reducing the growth rate of the production per capita, it is meaningful and necessary to examine the sensitivity of the climate-carbon cycle feedback beyond 2100. As time scales increase, the projection becomes more sensitive to the climate-ocean feedback than the climate-terrestrial ecosystem feedback. From a comparison among various models for this century, Friedlingstein et al. (2006) suggested weaker climate-ocean feedback: i.e., a majority of the models possessed 10-to-20% reduction in air-to-sea carbon dioxide flux due to climate-marine ecosystem feedback for the range of 2-to-4°C warming. Two points are noted here: one is that some oceanic responses take time longer than 100 years, and the other point is that the present model could represent more than marine ecosystem roles.

The warming until 2300 in the present study is compared with the quasi-equilibrium warming at a time scale of 1000 years and longer. In section 5, the warming of 1°C is produced by an excess of carbon dioxide 80~90 ppmv in the atmosphere with B_{ocean}=0.2 (K^{-1}). Considering only radiation forcing of carbon dioxide and solubility dependence on temperature, Archer et al. (2004) suggested equilibrium sensitivity of atmospheric carbon dioxide to ocean temperature at 50 ppmv K^{-1}. The sensitivity of 10 ppmv K^{-1} is cited as another reference for the time scale of glacier-interglacier variability, 10-to-100 thousand years. This sensitivity implies additional mechanisms to those considered here. By comparing these references, the climate-ocean feedback used in the present study is a half of that for 1000 years and may be relevant to a few hundred years.

More processes could be important for the period longer than 100 years other than those considered in this study. The weakening of the global conveyor belt was mentioned in section 2.3 (Bryden et al., 2005; Fukasawa et al., 2004). There may be debate on which direction the weakening of deep water formation and the conveyor belt contribute to. Vertical water motion generally tends to carry deep water, which contains high inorganic carbon and other nutrients, to the sea surface. Thus, partial pressure of carbon dioxide increases, and biological productivity is enhanced. Under the situation that both effects work, the upper ocean has tended to approach the equilibrium state since the time before the ongoing global warming started. Hence, the weaker vertical motion retains a thinner upper layer and would basically shorten the response time of the ocean, which will speed up an increase in atmospheric carbon dioxide.

Retreat of Arctic Ocean sea ice is progressing even now and will modify carbon dioxide flux between the ocean and the atmosphere. The ice retreat will expose under-ice carbon-rich water to the atmosphere, and also reduce brine rejection, which now transports carbon dioxide downward. Bates and Mathis (2009) estimated an increase in carbon dioxide uptake by the ocean to be about 0.1 GtC/y, whereas they combined these effects with an increase in biological production. Since the latter process is considered within the shift of the high production to higher latitudes in the present study, we have to revise the estimate solely due to the Arctic ice retreat to an opposite sign. Thus, the sea ice retreat in the Arctic may reduce carbon dioxide uptake.

Bates and Mathis (2009) pointed out acidification also. Once the ocean absorbs anthropogenic CO_2, pCO_2 and DIC concentration increase, but pH decreases in the upper ocean. Acidification generally shows up at low temperature such as the Arctic Ocean. In the Arctic Ocean, major effects come from sea-ice melt, river runoff increase and higher biological production, and induce various impacts on $CaCO_3$ saturation states. Thus, these processes may give unpredictable consequences in the Arctic.

In this study, only the anthropogenic carbon dioxide will be emitted under damaged terrestrial ecosystem. Peatlands have stored carbon for more than 10 thousand years in high latitudes and tropical regions. They would emit carbon dioxide due to drier conditions and forest fires upto 100 GtC (Gruber et al., 2004). Another greenhouse gas, methane is also emitted. Thus, greenhouse gases might come out to the atmosphere more than the anthropogenic one as another additional mechanism of larger global warming.

6.3 Observation evidence

The final point is the difficulty in identifying observational evidence how ocean reacts to global warming. In addition to absorption of carbon dioxide by marine ecosystem, the large carbon storage in deep ocean seems to reduce contact with and emission to the atmosphere under global warming. The latter effect has been exhibited in interannual variability of carbon dioxide flux through the sea surface in the tropical and subtropical regions (e.g., Inoue et al., 2002; Gruber et al., 2002). Difficulty exists in an attempt to make use of this interannual variability for projection of global warming. Once climate indices (Southern Oscillation Index, North Atlantic Oscillation, etc.) are introduced, atmospheric circulation induces ocean circulation and modifies distribution of deep water mass, in addition to air temperature change. Thus, it is difficult to isolate the oceanic features which are expected to occur under global warming.

One example is introduced here, by citing a modeling study in Valsala and Maksyutov (2010) on the subpolar gyre in the North Pacific. The annual average of air-to-sea carbon flux was larger by 0.2 GtC/y in 2003-2004 than 1999-2001. Chhak et al. (2009) categorized these two periods into two opposite phases of Pacific Decadal Oscillation. The main part of the subpolar gyre was colder in 2003-2004 by 1°C than 1999-2001. This sensitivity provides 20% reduction of the carbon flux, based on the mean value of 1 GtC/y, in response to 1°C warming. However, the signal in sea surface temperature has clear spatial variability. In addition, atmospheric circulation varies between the two opposite phases. Thus, it is not straightforward to identify the carbon flux variability as a function of temperature.

The other example is taken from interannual variability in the Southern Ocean. Lenton and Matear (2007) used a coupled physical-biogeochemical model, and suggested reduction of carbon uptake by 0.1 GtC/y under the positive Southern Annular Mode (SAM) per unit change. Westerly winds enhance Ekman divergence and consequent vertical circulation, and hence, increase DIC near the sea surface. Therefore, sea-to-air carbon dioxide flux will increase, and the net air-to-sea flux will decrease in the entire Southern Ocean. Since the SAM is predicted to shift to positive under global warming, the consequence will be reduction in oceanic uptake of carbon dioxide. Even if this prediction is right, its effect is hard to estimate for future at this stage from the observation.

In order to separate the effects of temperature rise and atmospheric circulation, reliable data are necessary for a longer period. Combination of data and modeling is also a necessary approach toward a more accurate projection to realize a sustainable world.

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Figures

Fig.1 The schematic structures of (a) a climate model driven by prescribed carbon dioxide emission scenarios and (b) a climate model where carbon dioxide emission receives feedback from the climate system.

Fig.2 The increase in the probability of damage on terrestrial ecosystem due to high temperature as the mean temperature rises, for no rise (solid), slow rise (dashed) and fast rise (dotted).

Fig.3 Carbon dioxide fixation (GtC/y) by terrestrial ecosystem reproduced from C4MIP report (Friedlingstein et al., 2006).

Fig.4 Climate model results forced by a prescribed carbon emission within ensemble prediction in the SRES scenarios.

Fig.5 Carbon fluxes (GtC/y) and contents (ppmv) above the 1900 values in (a) year 2000 for the climate model experiment and (b) year 2100.

Fig.6 (a) Reference case of the coupled climate-society model, $D_H=0$ and $D_E=0$, (b) carbon absorptions by land and ocean in the reference case, (c) the case of more incentive for low-carbon lifestyle, $D_H=0.005$ and $D_E=0$, (d) the case of more incentive for efficiency improvement, $D_H=0$ and $D_E=0.005$ and (e) the case of more incentive for both lifestyle and efficiency, $D_H=0.005$ and $D_E=0.005$.

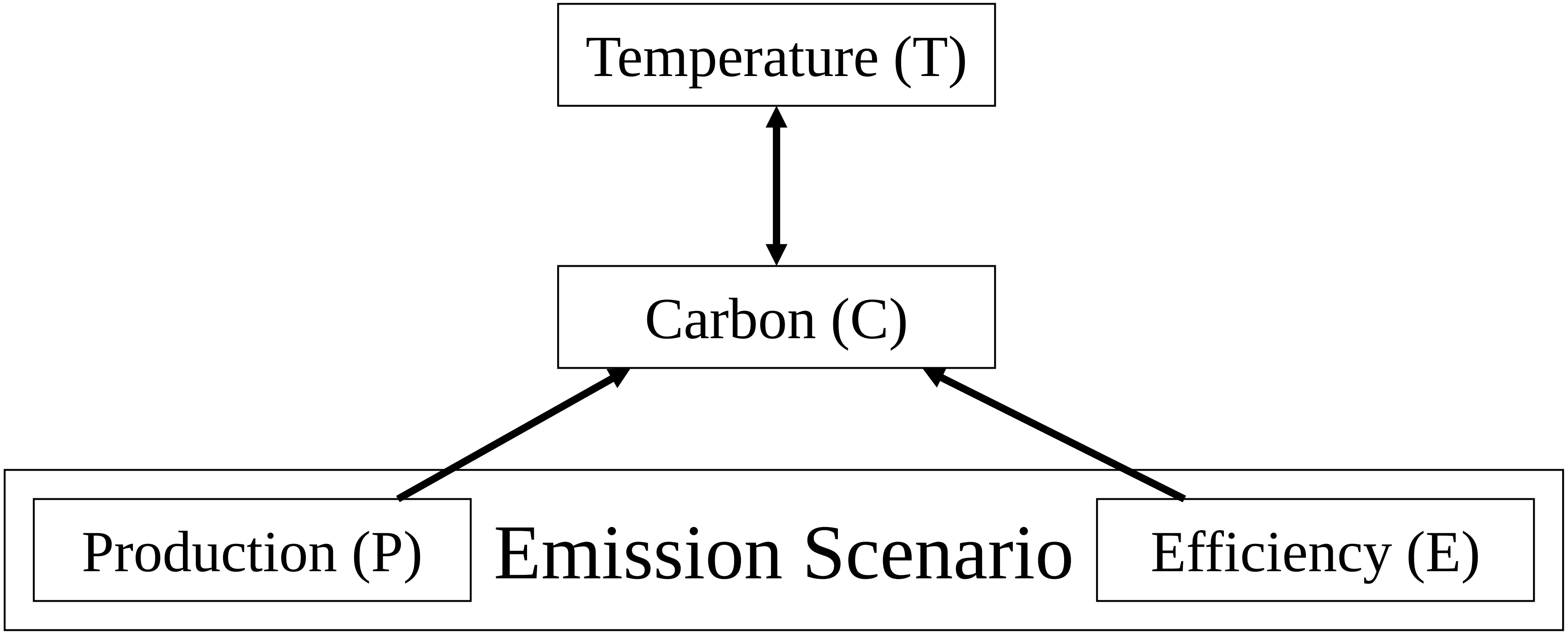
Fig.7 Carbon fluxes (GtC/y) and contents (ppmv) above the 1900 values in (a) year 2000 for the coupled-model experiment with $D_H=0$ and $D_E=0$. In year 2100 with (b) $D_H=0$ and $D_E=0$, (c) $D_H=0.005$ and $D_E=0$, and (d) $D_H=0.005$ and $D_E=0.005$.

Table 1 SAT rise (K) and anthropogenic carbon emission (GtC/y) at year 2300 in the sensitivity study with four cases for each of B_{ocean} and $C_{landmax}$.

		$C_{landmax}$ (ppmv)			
		100	200	300	400
B_{ocean} (K^{-1})	0.15	3.57/0.19	3.25/0.44	2.85/0.88	2.36/1.44
	0.2	5.37/0.04	4.15/0.18	3.25/0.51	2.57/0.95
	0.25	5.95/0.02	5.24/0.06	4.31/0.18	3.11/0.44
	0.3	6.12/0.01	5.42/0.03	4.56/0.10	3.63/0.22

Each column includes SAT rise/anthropogenic carbon emission. The threshold is $1/B_{ocean}$ between the continuous warming and restoring the equilibrium after 2300.

Scenario-Climate Modeling



Temperature (T)

Carbon (C)

Production (P)

Emission Scenario

Efficiency (E)

Fig.1a The schematic structures of a climate model driven by prescribed carbon dioxide emission scenarios.

Climate-Society Modeling

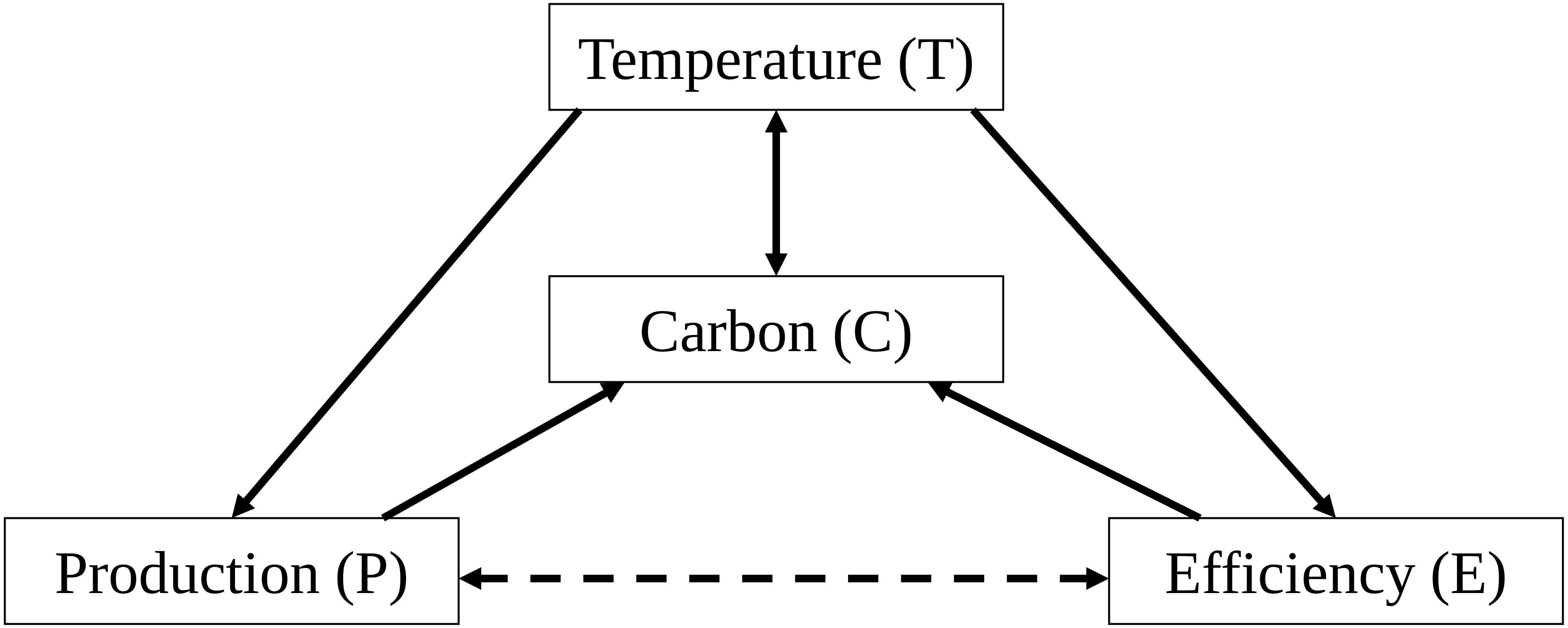


Fig.1b The schematic structures of a climate model where carbon dioxide emission receives feedback from the climate system.

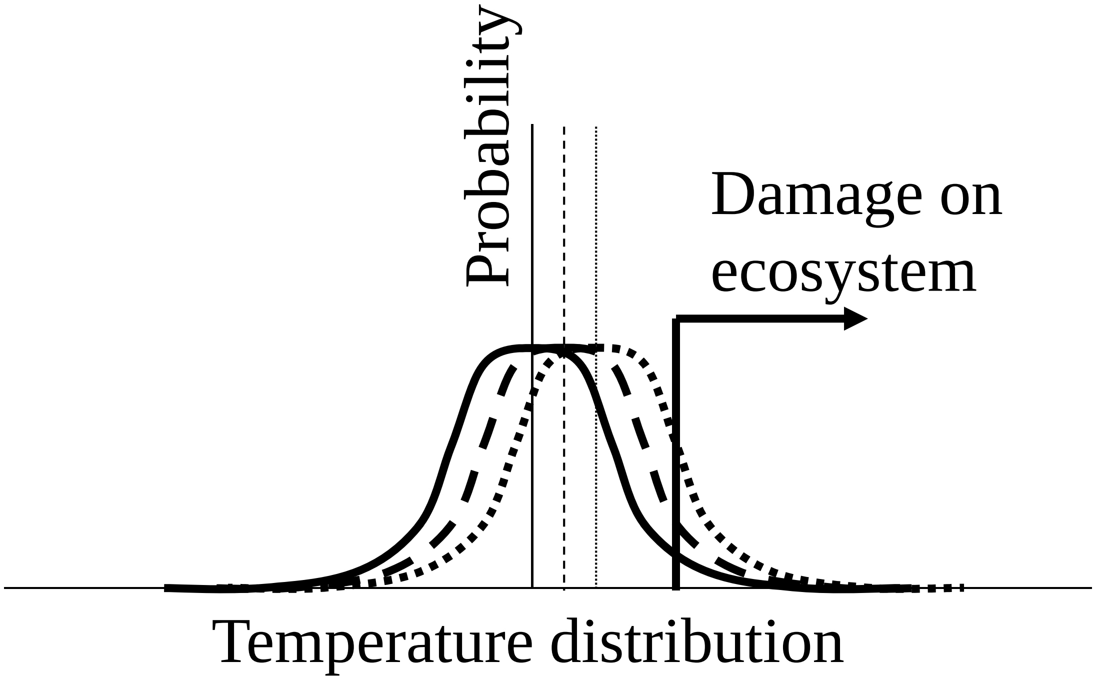


Fig.2 The increase in the probability of damage on terrestrial ecosystem due to high temperature as the mean temperature rises, for no rise (solid), slow rise (dashed) and fast rise (dotted).

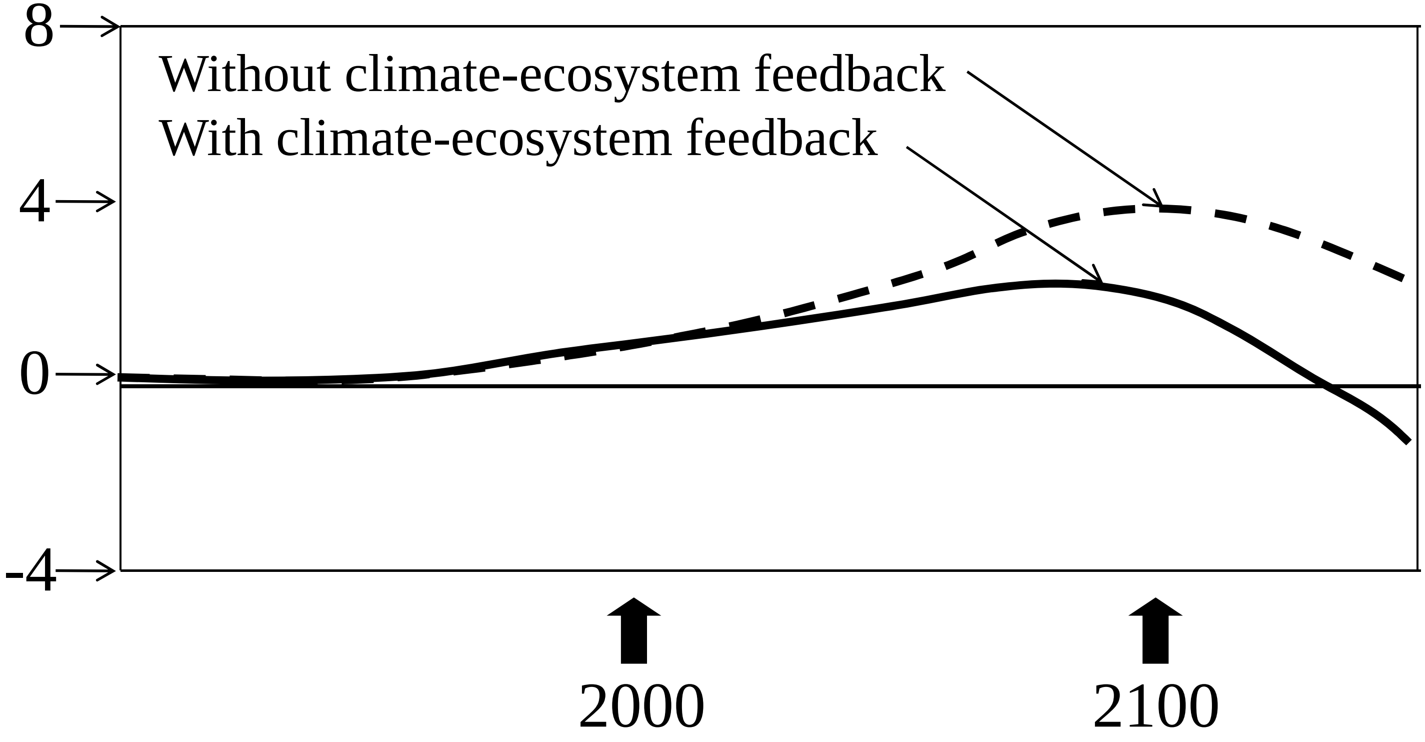
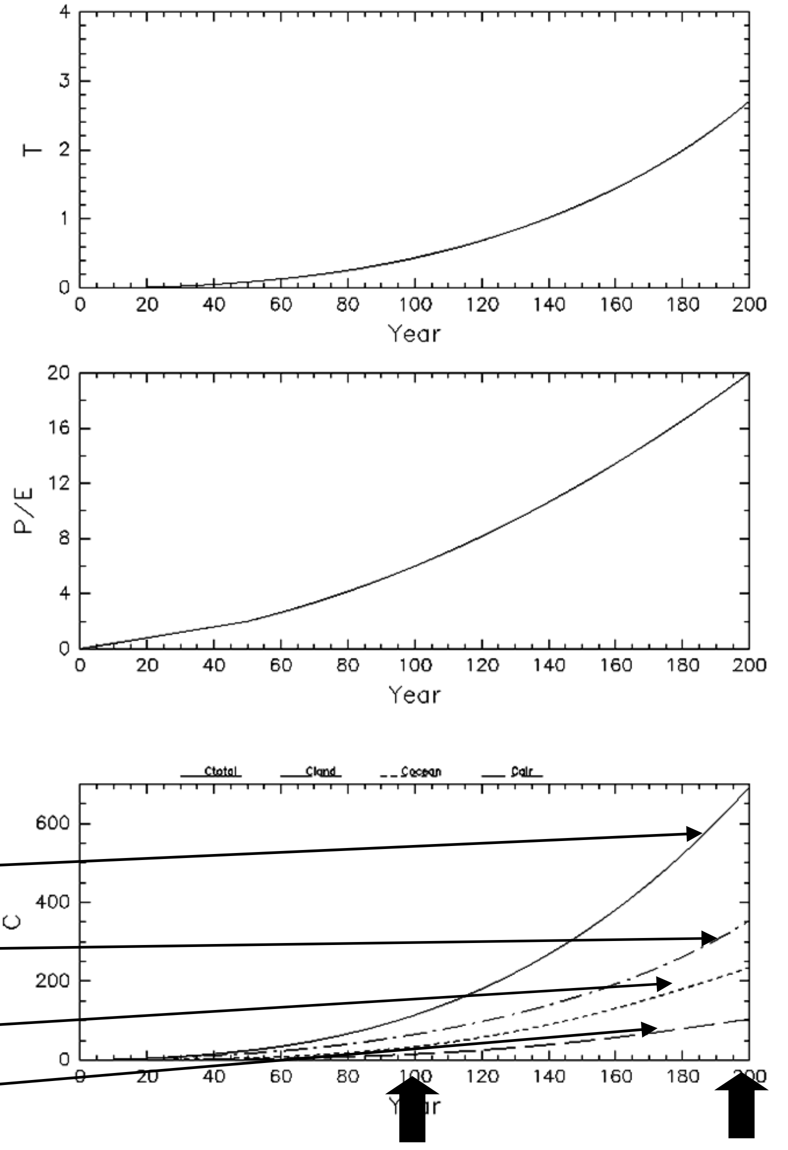


Fig.3 Carbon dioxide fixation (GtC/y) by terrestrial ecosystem reproduced from C4MIP report (Friedlingstein et al., 2006).

Fig.4
Climate model results forced by a prescribed carbon emission within ensemble prediction in the SRES scenarios



Temp. increase (ºC)

Carbon emission (GtC/y)

Carbon dioxide
Total
Atmos.
Ocean
Land
(ppmv)

2000

2100

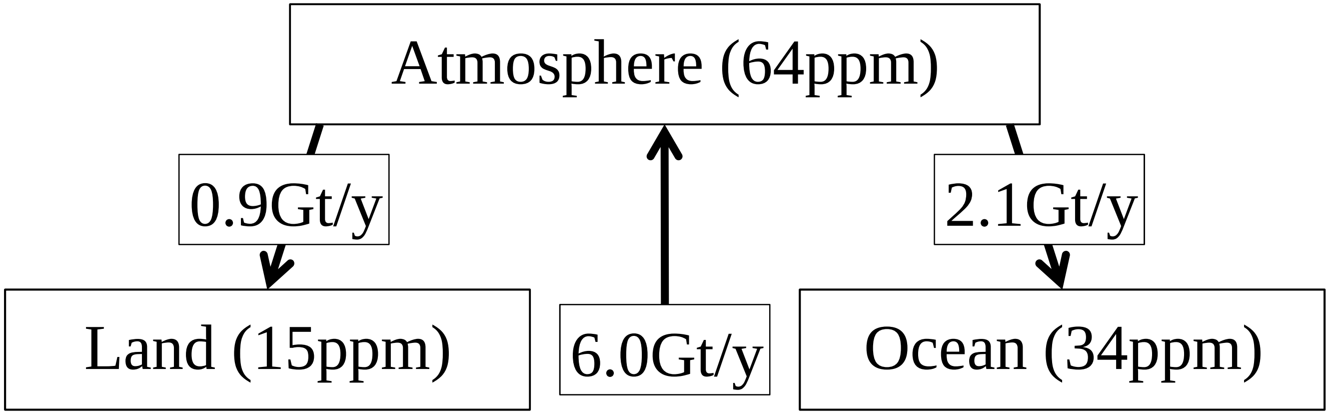


Fig.5a Carbon fluxes (GtC/y) and contents (ppmv) above the 1900 values in year 2000 for the climate model experiment

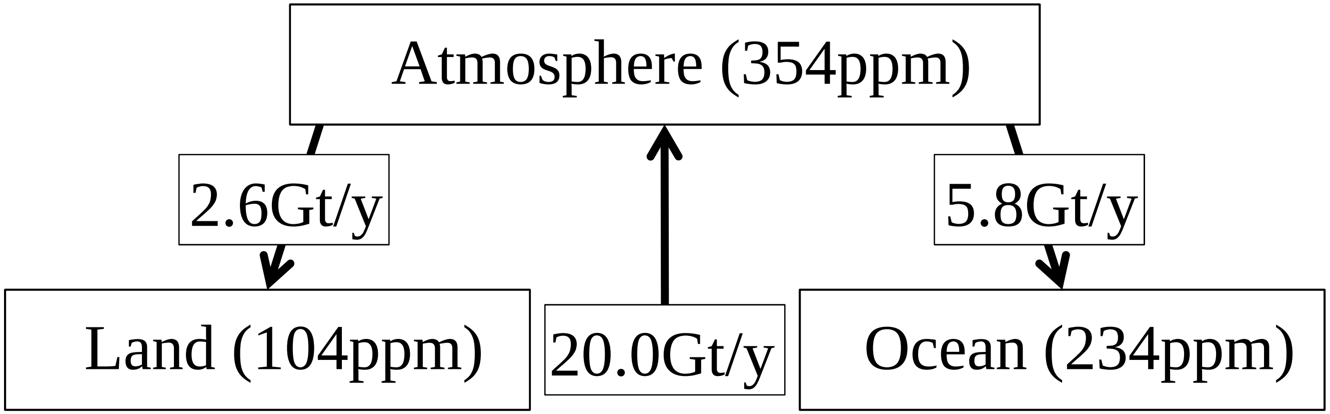
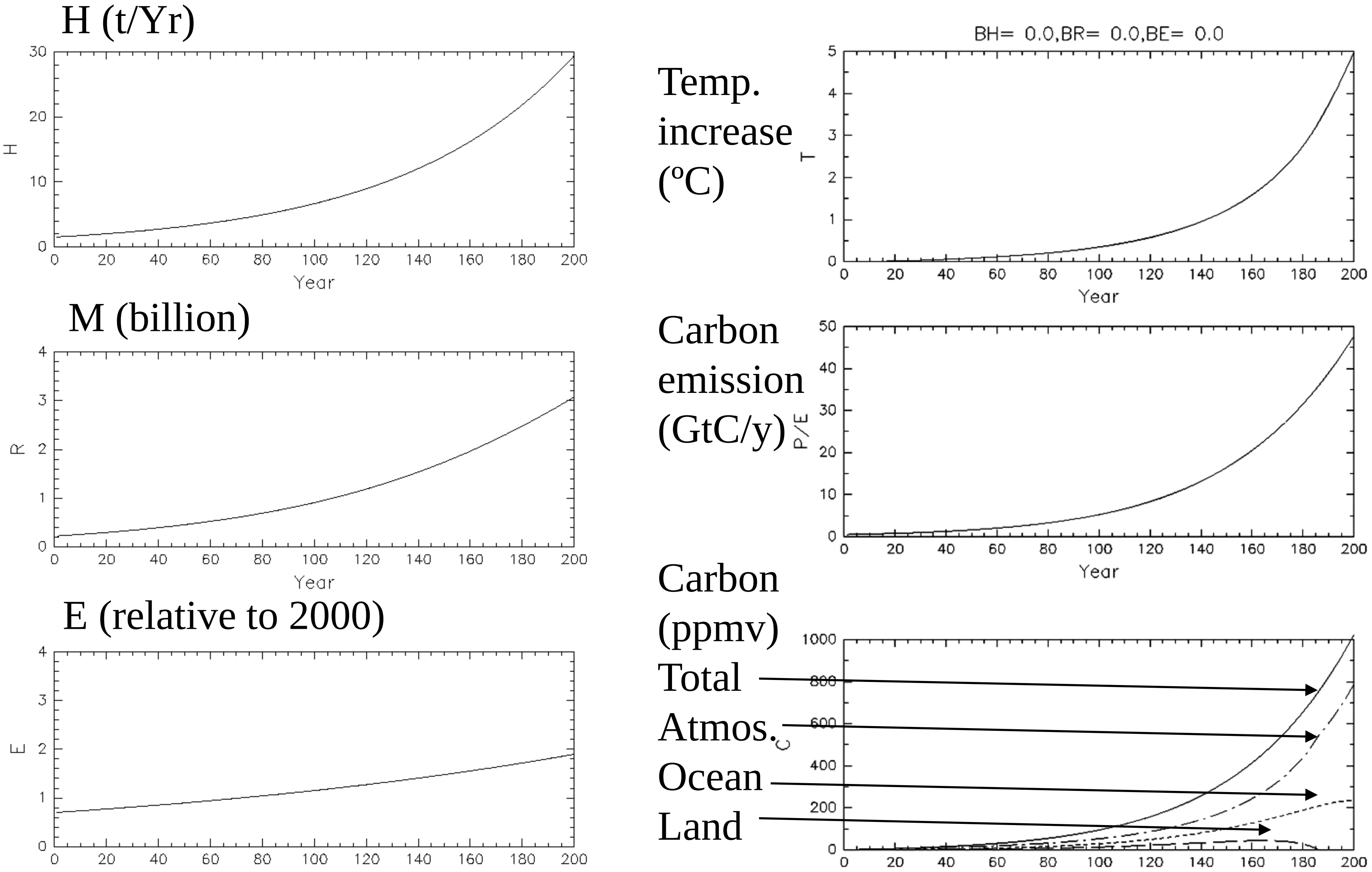


Fig.5b Same as Fig.5a but for year 2100



H (t/Yr)

M (billion)

E (relative to 2000)

Temp. increase (ºC)

Carbon emission (GtC/y)

Carbon (ppmv)

Total

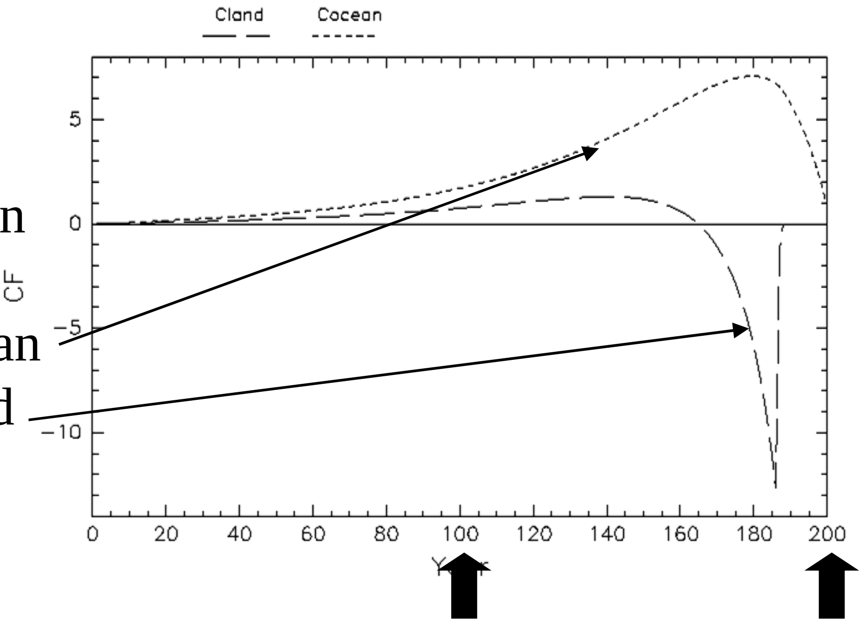
Atmos.

Ocean

Land

Fig.6a Reference case of the coupled climate-society model, D_H=0 and D_E=0.

Fig.6b Carbon absorptions by land and ocean in the reference case.



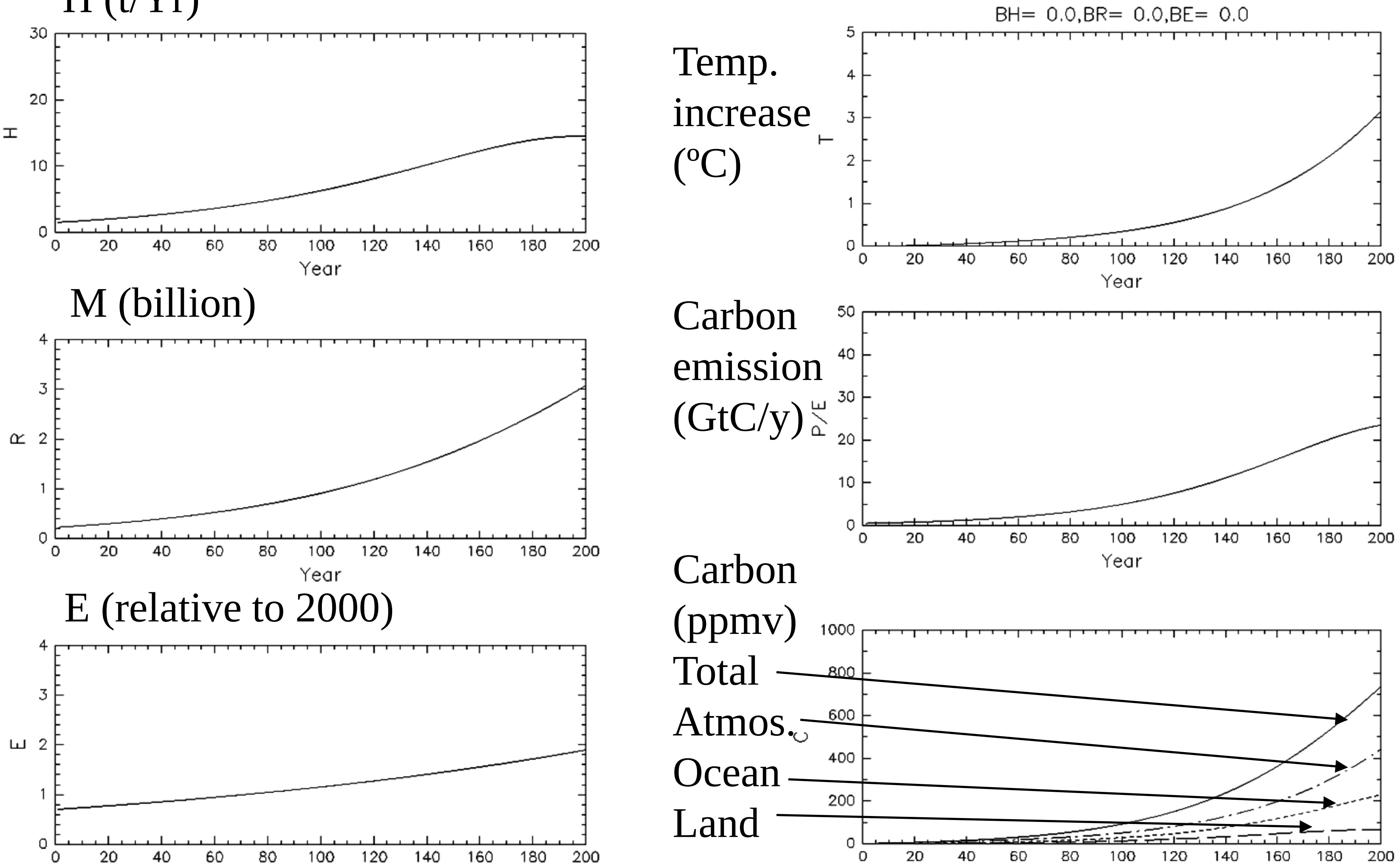
Carbon emission (GtC/y)

To Ocean

To Land

2000

2100



H (t/Yr)

M (billion)

E (relative to 2000)

Temp. increase (ºC)

Carbon emission (GtC/y)

Carbon (ppmv)

Total

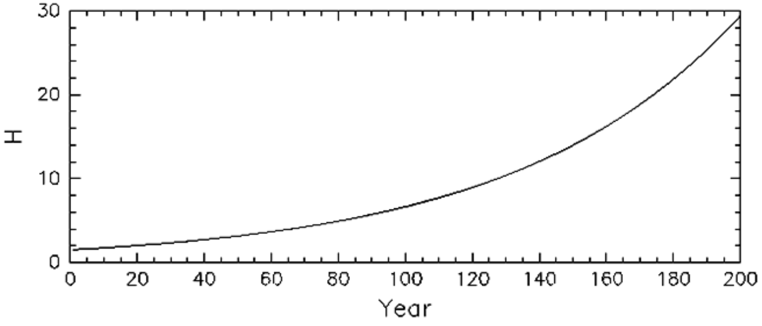
Atmos.

Ocean

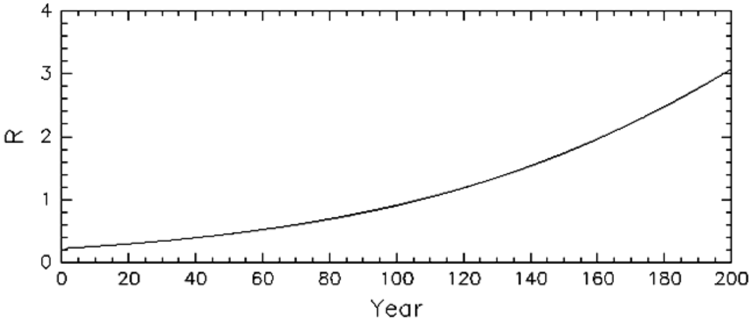
Land

Fig.6c Same as Fig.6a but for the case of more incentive for low-energy lifestyle, D_H=0.005 and D_E=0.

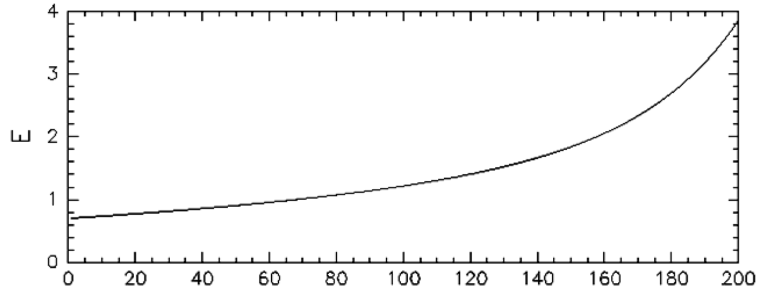
H (t/Yr)



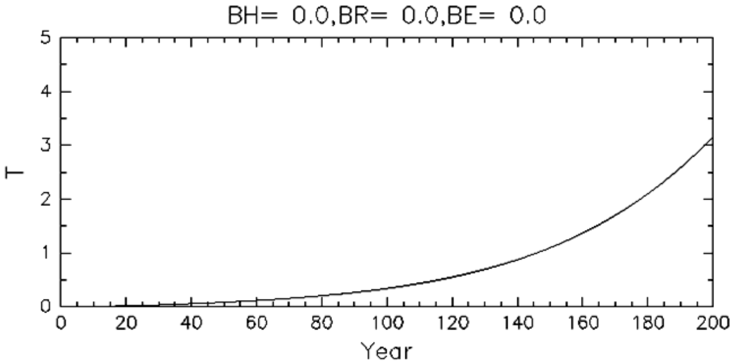
M (billion)



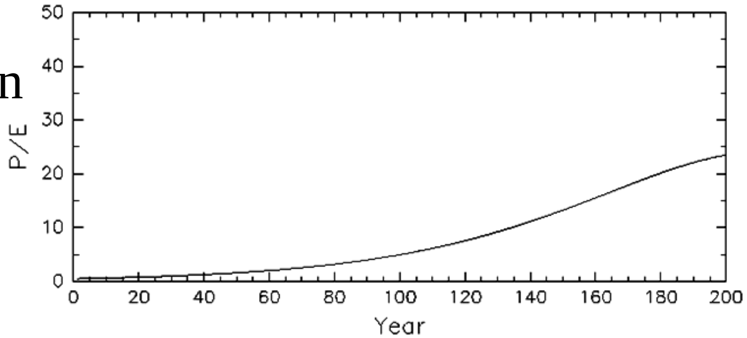
E (relative to 2000)



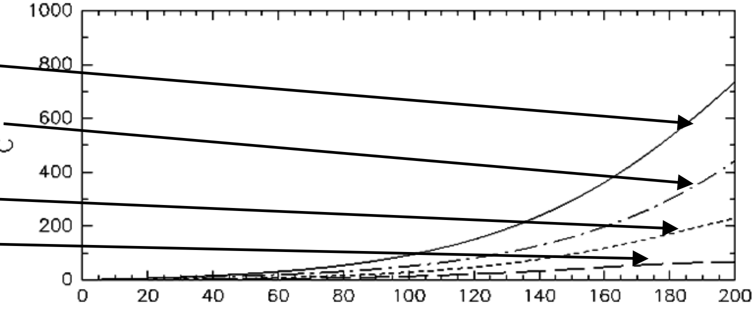
Temp. increase (ºC)



Carbon emission (GtC/y)



Carbon (ppmv)



Total

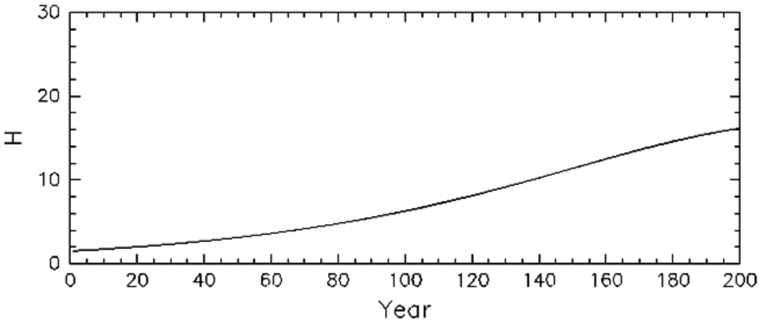
Atmos.

Ocean

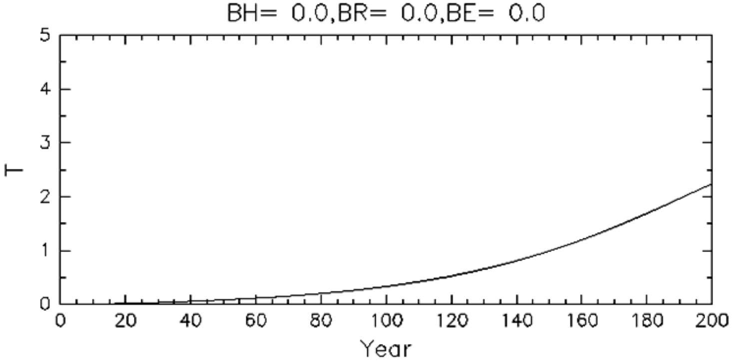
Land

Fig.6d Same as Fig.6a but for the case of more incentive for efficiency improvement, D_H=0 and D_E=0.005.

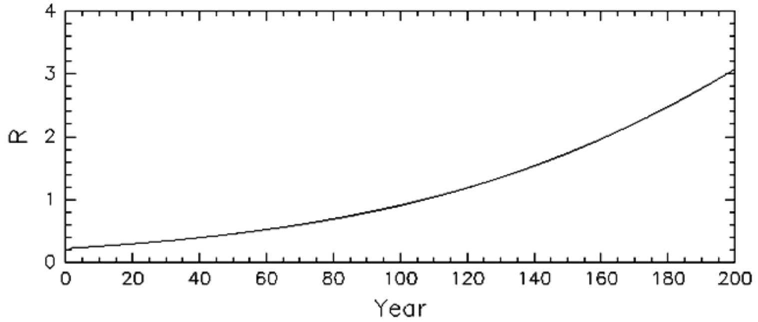
H (t/Yr)



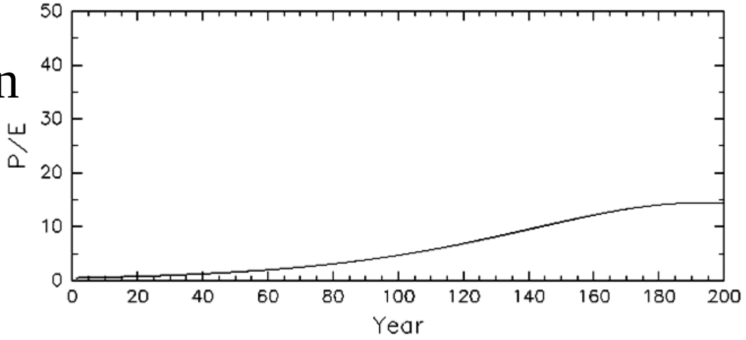
Temp. increase (ºC)



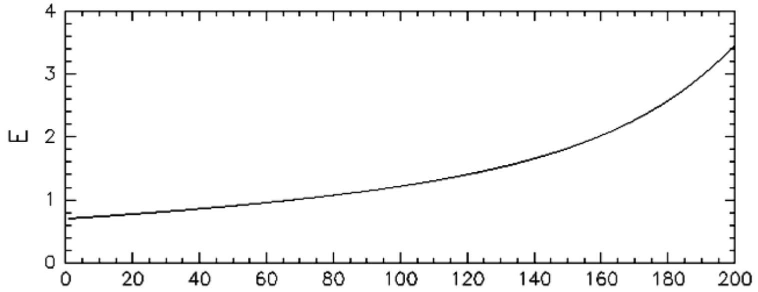
M (billion)



Carbon emission (GtC/y)



E (relative to 2000)



Carbon (ppmv)

Total

Atmos.

Ocean

Land

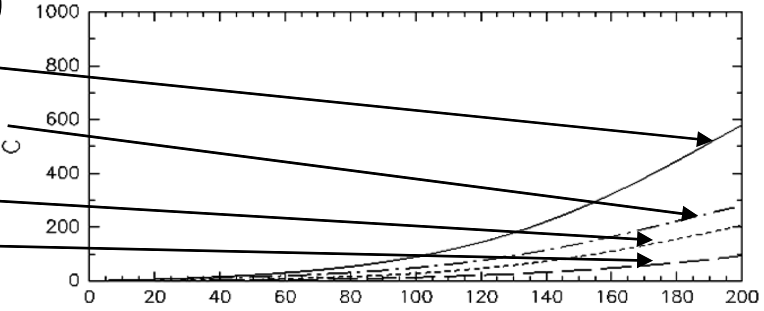


Fig.6e Same as Fig.6a but for the case of more incentive for both lifestyle and efficiency, D_H=0.005 and D_E=0.005.

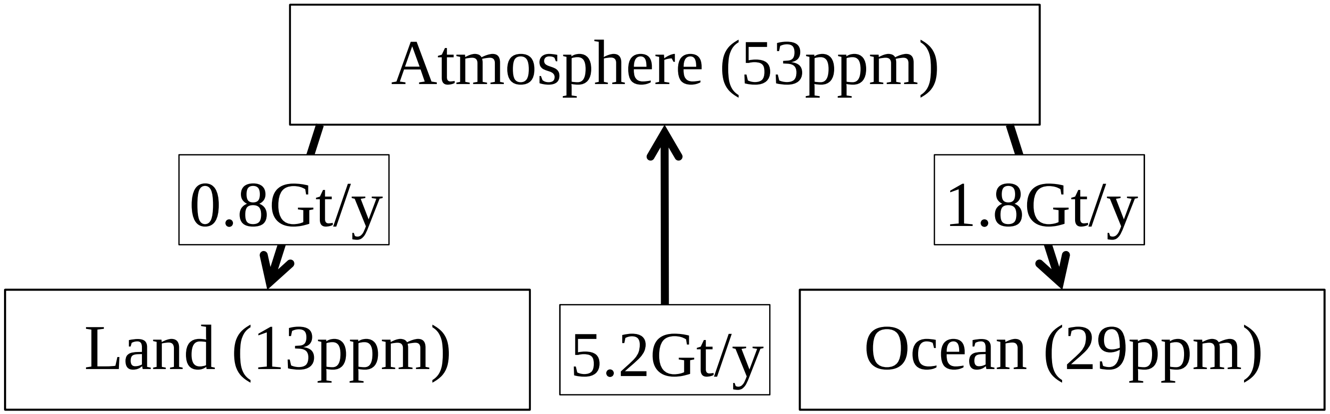


Fig.7a Carbon fluxes (GtC/y) and contents (ppmv) above the 1900 values in year 2000 for the coupled-model experiment

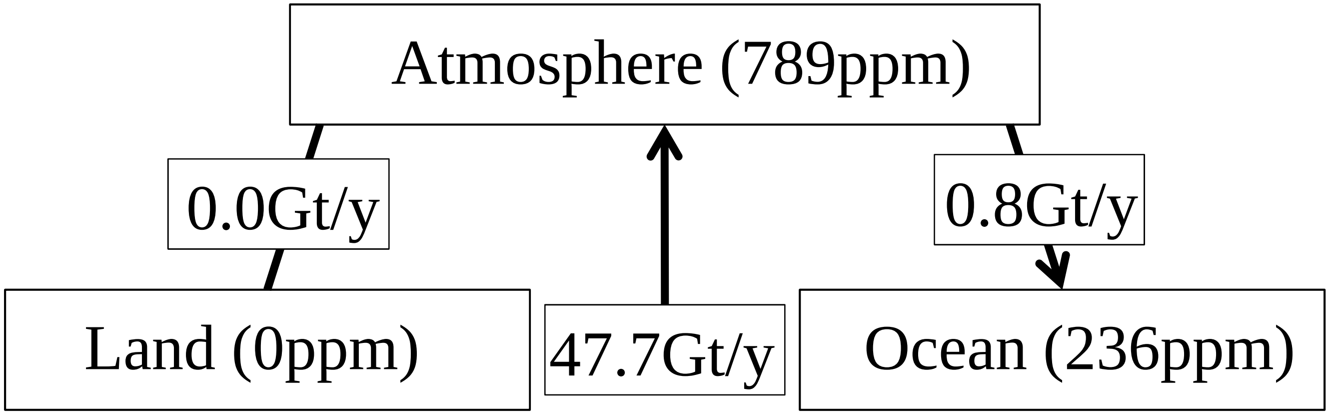


Fig.7b Same as Fig.7a but for year 2100 with $D_H=D_E=0$

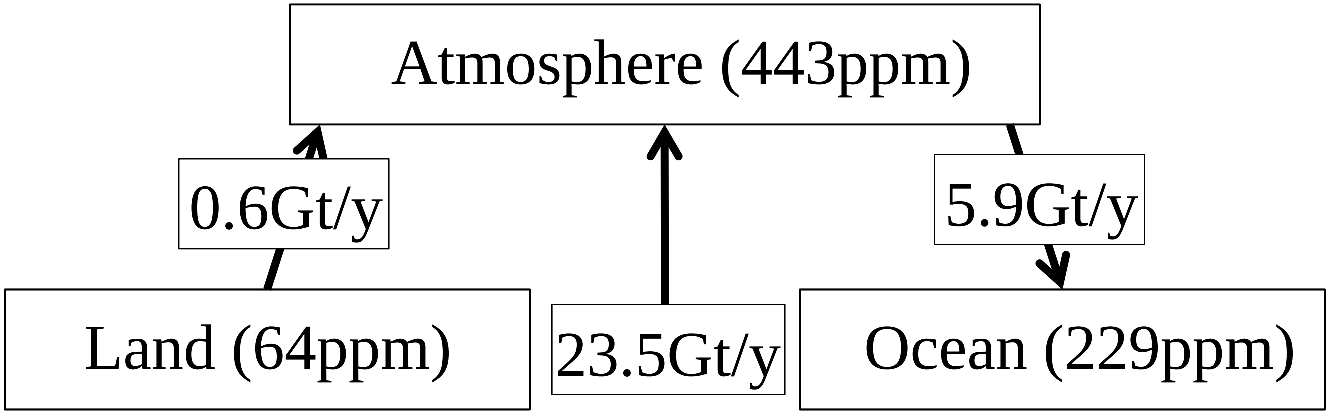


Fig.7c Same as Fig.7b but with D_H=0.005 and D_E=0

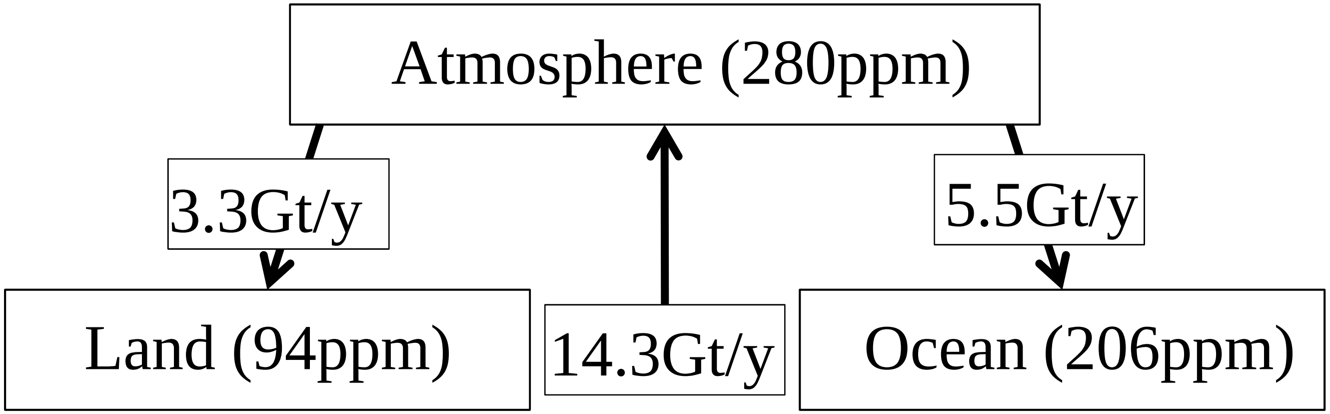


Fig.7d Same as Fig.7b but with D_H=D_E=0.005