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The importance of ocean transport in the fate of anthropogenic CO_2

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Abstract

We assess uncertainties in projected oceanic uptake of anthropogenic CO_2 associated with uncertainties in model ocean transport using a suite of climate/carbon-cycle models. In response to a CO_2 pulse emission of 590 Pg C (corresponding to an instantaneous doubling of atmospheric CO_2 from 278 to 556 ppm), the fraction of CO_2 emitted absorbed by the ocean (model mean $\pm 2\sigma$) is 37±8%, 56±10%, and 81±4% in year 30, 100, and 1000 after the emission pulse, respectively. Modeled oceanic uptake of excess CO_2 on timescales from decades to about a century is strongly correlated with simulated present-day uptake of chlorofluorocarbons (CFCs) and anthropogenic CO_2, while the amount of excess CO_2 absorbed by the ocean from a century to a millennium is strongly correlated with modeled radiocarbon in the deep Southern and Pacific Ocean. The rates of surface-to-deep ocean transport are determined for individual models from the instantaneous doubling CO_2 experiments, and they are used to calculate oceanic uptake of CO_2 in response to emission pulses of 1000 and 5000 Pg C. These results are compared with simulated oceanic uptake of CO_2 from a number of model simulations with the coupling of climate-ocean carbon cycle and without it. This comparison demonstrates that the impact of different ocean transport rate across models on the oceanic uptake of anthropogenic CO_2 is of similar magnitude as that of climate-carbon cycle feedbacks in a single model associated with changes in temperature, circulation, and marine biology, emphasizing the importance of ocean transport in the fate of anthropogenic CO_2.

1 Introduction

Atmospheric CO_2 is expected to increase in the near future due to continued emissions from fossil fuel burning and land use changes. A major uncertainty in projecting future climate change is how much this emitted CO_2 will remain in the atmosphere. Different processes acting on different timescales are responsible for the removal of excess CO_2

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from the atmosphere. For example, the present ocean is, and the terrestrial biosphere appears to be, a net sink for anthropogenic carbon (Denman et al., 2007). Over the coming decades to centuries, the ocean is expected to continue acting as a CO_2 sink while the land could change from a net carbon sink to source (e.g. Cox et al., 2000; Bala et al., 2005). On timescales of a millennium and beyond, the reaction of dissolved CO_2 with calcium carbonate ($CaCO_3$) in deep ocean sediments will start to play an important role in buffering the human carbon perturbation (Broecker and Takahashi, 1978; Archer, 1997). On timescales of several hundred thousands of years the still airborne anthropogenic CO_2 will be removed from the atmosphere by the weathering of silicate rocks (Walker and Kasting, 1992; Zeebe and Caldeira, 2008).

An accurate projection of the oceanic uptake of anthropogenic CO_2 is important. On one hand, the amount of anthropogenic CO_2 absorbed by the ocean affects atmospheric CO_2 concentrations. The airborne anthropogenic CO_2 on millennial timescale, which is primarily determined by oceanic uptake of human-emitted carbon, has great implications for future sea level rise and ice sheet extent (Archer, 2005). On the other hand, oceanic uptake of anthropogenic CO_2 modifies ocean chemistry by making it more acidic, an urgent environmental problem independent of global warming (Caldeira and Wickett, 2003; Orr et al., 2005; Royal Society, 2005; Cao et al., 2007; Cao and Caldeira, 2008; Steinacher et al., 2008).

Global carbon cycle models are used to project the uptake of anthropogenic CO_2 by the ocean and terrestrial biosphere, but projections differ widely between models and on different timescales. Simulated carbon uptake in the 1990s by models participating in phase II of the Ocean Carbon Model Intercomparison Project (OCMIP-2) varies between 1.98 and 3.04 Pg C (1 Pg C=10^{15} g carbon) when atmospheric CO_2 was prescribed according to the IPCC S650 CO_2 stabilization scenario (Orr et al., 2002). Accumulated oceanic carbon uptake at the time of doubling CO_2 varies by a factor of two across eleven 3-D coupled carbon cycle/climate models participating in the Coupled Climate-Carbon Cycle Intercomparison Project (C4MIP) and forced with IPCC SRES A2 emission scenario (Friedlingstein et al., 2006). The fraction of CO_2 absorbed

by the ocean ranges from 24 to 34% in year 2100 and 49 to 62% in year 3000 for eight Earth system models forced by a scenario in which total CO_2 emission reaches about 1600 Pg C by year 2100 and is kept constant thereafter (Plattner et al., 2008). Regarding the long-term fate of anthropogenic CO_2, model-projected airborne fraction ranges from 35 to 58% and 23 to 47% 1000 and 5000 years from now in response to a CO_2 emission pulse of about 5000 Pg C (Archer, 2005; Lenton and Britton, 2006; Ridgwell and Hargreaves, 2007; Montenegro et al., 2007). A recent model intercomparison study shows that in response to a CO_2 emission pulse of 5000 Pg C, model-projected airborne CO_2 ranges between 20 and 30% 10 000 years after the emission pulse (Archer et al., 2008).

The discrepancy in projected atmospheric CO_2 and/or anthropogenic CO_2 uptake by the ocean across models can be attributed to differences in model representations of various processes, including ocean transport, biological uptake by both the ocean and terrestrial biosphere, sedimentation of calcium carbonate, and their interactions with climate change. Of these processes, ocean transport is a key player. First, the rate of ocean transport determines the rate by which anthropogenic CO_2 is transferred from the surface to the deep ocean. Second, on timescales over a millennium, the rate of ocean transport determines the rate by which anthropogenic CO_2 reaches ocean sediments and carbonate ions released from dissolving $CaCO_3$ returns to the surface and further neutralize fossil fuel CO_2. Therefore, ocean transport also affects the timescale of "$CaCO_3$ neutralization" (e.g. Archer et al., 1997; Ridgwell and Hargreaves, 2007). Third, ocean transport affects biological CO_2 uptake by controlling the availability of nutrients at ocean surface and the export of organic matter from surface waters to the deep ocean.

The purpose of this paper is to assess the effect of ocean transport on the uptake of anthropogenic CO_2 by comparing simulation results from a number of models. The models used in this study and simulation protocols are introduced in the next section. Model responses to different CO_2 emission pulses are presented in Sect. 3. We first investigate modeled ocean responses to a pulse release of 2 times of pre-industrial

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CO_2 and discuss how they are related to simulated inventories of chemical tracers such as radiocarbon and Chlorofluorocarbons (CFCs). We then present surface ocean response functions that characterize the rate of ocean transport for individual models, and use them to determine CO_2 uptake in response to emission pulses of 1000 and 5000 Pg C. The impact of ocean transport on oceanic CO_2 uptake is compared to that of climate change feedbacks. Discussion and conclusions follow in Sect. 4.

2 Models and simulation protocols

A suite of climate/carbon-cycle models of different complexities are used in this study. These include three models derived from the Grid ENabled Integrated Earth system model (GENIE-1, Edwards and Marsh, 2005): GENIE8 (8 ocean levels, Ridgwell et al., 2007a); GENIE16 (16 ocean levels, Singarayer et al., 2008); and MESMO (16 ocean levels, Matsumoto et al., 2008) (In addition to vertical resolution, these three versions of GENIE-1 differ in other aspects as detailed in Appendix A), the University of Victoria Earth System Climate Model (UVic, Weaver et al., 2001), Bern3D ocean model (Müller et al., 2006) with its physical core modified from Edwards et al. (1998) and Edwards and Marsch (2005), MPI-UW Earth system model (Mikolajewicz et al., 2007), high-latitude exchange/interior diffusion-advection (HILDA) model (Siegenthaler and Joos, 1992), and a modified HILDA model, LTCM (stands for the Long-term Carbon Cycle Model). In addition, archived results from five ocean carbon cycle models (AWI, Bern2.5D (previously known as PIUB), IGCR, SOC, UL) participating in phase II of the Ocean Carbon-Cycle Model Intercomaprison Project OCMIP-2 and performing CO_2 pulse emission simulations (http://www.ipsl.jussieu.fr/OCMIP/) are investigated. The ocean component of these models are all coarse-resolution, non-eddy-resolving models, but they differ considerably in their configurations including the grid resolution, sub-grid scale mixing parameterizations, and surface forcing. The main characteristics of each model are listed in Table 1, and details of these models are given in Appendix A.

Carbon uptake simulations in response to an instantaneous CO_2 emission pulse

were performed following the OCMIP-2 protocol (http://www.ipsl.jussieu.fr/OCMIP/phase2/simulations/Abiotic/HOWTO-Abiotic.html). Starting from the model pre-industrial state a CO_2 emission pulse of 590.2 Pg C (corresponding to an instantaneously doubling of atmospheric CO_2 concentration from 278 to 556 ppm by applying the conversion factor of 1 ppm=2.123 Pg C as used in OCMIP) is added to each model, and then the response of atmospheric CO_2 is calculated by air-sea exchange. The entire integration lasted for 1000 years. To have a direct comparison with OCMIP-2 simulations, processes other than the ocean carbon cycle, including CO_2 uptake by the terrestrial biosphere, interaction with $CaCO_3$ sediment, and climate change feedbacks are disabled in the CO_2 pulse emission simulations. To evaluate modeled oceanic uptake of CO_2 against their skills in simulating chemical tracers, simulations of natural radiocarbon (in terms of $\Delta^{14}C$) and historical uptake of anthropogenic CO_2 and CFCs were also performed.

3 Results

3.1 Double CO_2 experiments

Time series of modeled oceanic uptake in response to an instantaneous CO_2 emission of 590 Pg C are shown in Fig. 1. Among the models shown here, UL has the largest oceanic uptake, while UVic and GENIE16 have the lowest. The fraction of the total CO_2 emission absorbed by the ocean varies from 34 to 45%, 50 to 65%, and 77 to 84%, with a cross model mean (±1 standard deviation, 1σ) of 37±4%, 56±5%, and 81±2% in year 30, 100, and 1000 after the emission pulse, respectively. Many models have not reached steady state 1000 years after the emission pulse (in the absence of sediment $CaCO_3$ neutralization). For example, the fraction of oceanic uptake of excess CO_2 by Bern3D and LTCM is 80.7% and 82.2% in year 1000, which increases to 82.6% and 83.3% in year 2000 when the models reach steady state.

Many factors could contribute to the difference in oceanic uptake of CO_2 across

models, such as parameterization schemes of ocean mixing and surface boundary forcing (see Table 1). An extensive exploration of the role for each factor is beyond the scope of this study. Nonetheless, sensitivity experiments using GENIE16 show that differences in the intensity of vertical mixing, model vertical resolutions, and representation of the seasonal cycle all contribute to the discrepancies in modeled oceanic CO_2 uptake (Fig. S1) http://www.biogeosciences-discuss.net/5/4521/2008/bgd-5-4521-2008-supplement.pdf. One caveat is that the OCMIP model results presented here were from abiotic runs, while other model simulations include a component of marine biology. However, as long as the strength of biological carbon transport remains unchanged, as in the double CO_2 simulations where no feedbacks from changes in climate and biology are included, marine biology plays a minor role in the uptake of anthropogenic CO_2, as found by our sensitivity experiments (Fig. S2) and previous studies (Maier-Reimer, 1993; Murnane et al., 1999).

Positive correlations are observed between modeled CO_2 uptake and the uptake/inventories of different tracers that characterize the rate of ocean transport on different timescales (Figs. 2, 3 and 4). On the decadal timescale, modeled oceanic uptake of CO_2 is strongly correlated with present-day uptake of both CFC11 and anthropogenic CO_2. Beyond a century, the correlation with the uptake of CFC11 becomes weaker, while the strong correlation with the uptake of anthropogenic CO_2 extends to a few centuries (with r greater than 0.7). These observations are consistent with the fact that the uptake of anthropogenic CO_2 during the past is characterized by an ocean ventilation timescale of a few centuries, while the uptake of CFCs is characterized by an ocean ventilation timescale of several decades. On timescales from a century to a millennium, the amount of CO_2 absorbed by the ocean is strongly correlated with the content of natural radiocarbon in the deep ocean, which is governed by ocean ventilation over hundreds to thousands of years. This correlation is particularly strong with radiocarbon in the deep Southern (with r greater than 0.8) and Pacific Ocean (with r greater than 0.7), indicating that the processes controlling ventilation rate of the deep Southern and Pacific Ocean have a strong control on the long-term efficiency of

oceanic uptake for anthropogenic CO_2.

3.2 Surface ocean response functions

One key factor in the oceanic uptake of anthropogenic CO_2 is the rate of surface-to-deep ocean transport. However, the role of ocean transport is obscured by the influences from other factors, such as buffering capacity of the carbonate system and the rate of air-sea gas exchange. To separate the effect of ocean transport from other factors, we adopt the method of Joos et al. (1996) to determine surface ocean pulse response functions that characterize the rate of surface-to-deep ocean transport. The theoretical justification of the ocean pulse response functions is that the dynamics of a linear system can be fully characterized by its pulse (or Green's) function, and the transport of tracers in the ocean is described by a set of linear equations under steady state (constant circulation). Atmospheric and/or surface ocean pulse response functions have therefore been used to compare the uptake characteristics of anthropogenic carbon by ocean transport models (Maier-Reimer and Hasselmann, 1987; Sarmiento et al., 1992; Joos et al., 1996) and to build cost-efficient substitutes of more complex models for the uptake of carbon, heat and other tracers (Joos and Bruno, 1996). Compared to the atmospheric pulse response functions, the use of surface ocean pulse response functions avoids the problem arising from nonlinearities of the carbon chemistry and gives therefore more accurate results.

The use of surface ocean response functions is based on the reasoning that surface concentration of dissolved inorganic carbon (DIC_s) at a certain time t can be represented by the convolution integral of earlier carbon input, i.e. the air-sea carbon flux (f_{as}) at time t', multiplied by the fraction of the flux that is still found in the surface layer after time $t-t'$ (ocean surface response, r_s). This can be represented by the following equation (from Eq. 2 of Joos et al., 1996)

$$DIC_s(t) = \frac{1}{h}\int_{t0}^{t} f_{as}(t')r_s(t-t')dt' + DIC_s(t_0) \quad (1)$$

where h is model top layer thickness and t_0 is the time at which surface ocean is in equilibrium with the deep ocean. Given surface carbon concentration (DIC_s) and air-sea carbon flux (f_{as}), the ocean surface response (r_s) can be solved from the above equation.

Surface ocean response functions were derived for a subset of models using the above equation and globally averaged output of surface DIC and air-sea flux from 590 Pg C CO_2 pulse emission simulations. The results are shown in Fig. 5a. These responses represent the fraction of excess carbon added to the surface ocean that is still found in the ocean surface after a certain time, and therefore is a measure of the rate by which tracers (CO_2 here) are transported from the surface to the deep ocean. A validation of the derived surface ocean response functions is given in Appendix B.

It is not appropriate to compare surface ocean response functions as shown in Fig. 5a directly with each other because different models have different surface layer depths (Table 1), which would lead to different response functions (Joo et al., 1996). To compare the dynamical behavior of each model, we normalize the derived ocean surface responses to a uniform surface ocean depth of 50 m, and the differences in the normalized ocean surface response functions represent primarily differences in the rate of surface-to-deep transport between models (Fig. 5b). The comparison of Fig. 5b with Fig. 1 indicates that models with faster transport from the surface to the deep ocean (lower values of ocean surface response) generally have larger CO_2 uptake by the ocean, suggesting that differences in the rate of ocean transport are mainly responsible for differences in simulated carbon uptake across models.

3.3 Effect of ocean transport and climate change on anthropogenic CO_2 uptake

We investigate to what extent differences in ocean transport across models affect modeled anthropogenic CO_2 uptake by the ocean. Emission scenarios considered here include CO_2 emission pulses of 1000 and 5000 Pg C. A total CO_2 pulse size of 1000 Pg C corresponds to the cumulative CO_2 emissions by the end of the century from some of the comparably modest IPCC scenarios (For example, IPCC SRES A1T scenario has a

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cumulative CO_2 emission of 1038 Pg C from 1990 to 2100), while the 5000 Pg C release is roughly equivalent to the amount of available conventional fossil fuel resource (IPCC, 2001). To examine the effect of ocean transport on the uptake of anthropogenic CO_2, we constructed a surface ocean response model following Joos et al. (1996). Input to the surface ocean response model are: a surface ocean depth of 50 m, an ocean area of 3.61×10^{14} m^2, a global mean air-sea exchange rate of 0.061 mol m^{-2} yr^{-1} ppm^{-1} (Broecker et al., 1986), a cubic fit between surface DIC concentrations and ocean surface pCO_2 (to represent buffering capacity of the carbonate system) derived from results of GENIE16 simulations, and normalized surface response functions for each model as shown in Fig. 5b. In this way, differences in modeled response to pulse CO_2 emissions are caused only by different rates of ocean transport across models.

To compare the effect of ocean transport on CO_2 uptake with that of feedbacks from climate change, simulations in response to 1000 and 5000 Pg C CO_2 emission pulses were performed by a suite of climate/carbon-cycle models, including UVic, GENIE8, GENIE16, MESMO, HILDA, and MPI-UW used in the 590 Pg C emission pulse simulations and two additional models, CC_SED (Archer, 2005) and CLIMBER-2 (Brovkin et al., 2007). Results of pulse emission simulations from these models were also reported in a recent model intercomparison study for long-term fate of fossil fuel CO_2 (Archer et al., 2008). For each pulse emission simulation, each model was run twice: one with the coupling between climate change and the carbon cycle and the other without it; the difference between these two simulations represents the effect of climate change. Since our emphasis in this study is on oceanic uptake of anthropogenic CO_2, processes other than ocean uptake, including uptake by the terrestrial biosphere and deep sea $CaCO_3$ sediment, were disabled in the simulations presented here.

The rate of ocean transport affects physical uptake of anthropogenic CO_2 from the ocean surface to the deep ocean, while climate change affects the physical, chemical, and biological uptake of anthropogenic CO_2 through changes in temperature, circulation, and marine biology. As shown in Fig. 6, the effect of climate change in all models is to decrease oceanic uptake of anthropogenic CO_2 (increase atmospheric CO_2 con-

centrations by assuming a neutral terrestrial biosphere), but the magnitude of climate change effect varies widely between models. This discrepancy could be attributed to modeled differences in changes to temperature, circulation, and marine biology, and their interactions with the ocean carbon cycle, which merits further investigation.

It is noted that the absolute values of atmospheric CO_2 concentrations calculated from surface ocean response model runs depend on the choices of parameters used in the calculations (e.g. ocean area, air-sea exchange rate, buffering capacity of the carbonate system), but differences between model runs are much less sensitive to input parameters. What we are interested here is not the absolute values of projected atmospheric CO_2, but the difference in projected CO_2 concentrations as a result of different ocean transport across models, compared to that as a result of climate feedback on the ocean carbon cycle in a single model. Figure 6 shows that these two differences are of similar magnitudes, suggesting that the effect of different ocean transport across models on projected atmospheric CO_2 concentrations is comparable to that of climate change in a single model (by assuming a neutral terrestrial biosphere). For example, 100 years after CO_2 emission pulse of 5000 Pg C the range of differences in projected CO_2 concentration caused by different ocean transport is 231 ppm, compared with a maximum difference of 165 ppm as a result of climate change effect simulated by MPI-UW. At the same time, the spread of projected CO_2 concentrations due to differences in ocean transport across models is 88 (one standard deviation, 1σ) and 176 (2σ) ppm, compared with the difference of 108±51 ppm (mean $\pm 1\sigma$) associated with climate change feedbacks in a single model. 1000 years after CO_2 emission pulse of 5000 Pg C, the range of difference in projected CO_2 concentration as a result of differences in the rate of ocean transport is 351 ppm, compared with the maximum climate change effect of 404 ppm simulated by UVic. Meanwhile, the spread of projected CO_2 concentrations due to differences in ocean transport across models is 119 (1σ) and 238 (2σ) ppm, compared with the difference of 228±93 (mean $\pm 1\sigma$) associated with climate change feedbacks in a single model.

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4 Discussion and conclusions

In the study of oceanic uptake of anthropogenic CO_2, there has been a history of investigation in the effect of climate change on the ocean carbon cycle (e.g. Maier-Reimer et al., 1996; Sarmiento et al., 1998; Joos et al., 1999; Plattner et al., 2001; Chuck et al., 2005; Friedlingstein et al., 2006; Zickfeld, 2007; Plattner et al., 2008), and recently on the potential effects of ocean acidification (e.g. Heinze, 2004; Ridgwell et al., 2007a; Riebesell et al., 2007). It is found here that in the projection of anthropogenic CO_2 uptake by the ocean, the effect of differences in steady state ocean transport across models is of similar magnitude as that of climate feedbacks associated with changes in temperature, circulation, and marine biology (Fig. 6). Our study demonstrates that in the efforts aiming to achieve a more reliable projection of anthropogenic CO_2 uptake by the ocean, to reduce the uncertainty in the simulation of ocean transport is as important as to reduce the uncertainty in the projection of feedback effects on the ocean carbon cycle associated with changes in climate and marine biology. The importance of ocean transport in oceanic CO_2 uptake, as compared with climate change feedbacks, was also found through sensitivity experiments by varying the values of vertical diffusivity and climate sensitivity in a single model (Joos et al., 1999; Plattner et al., 2001).

Here we looked at oceanic uptake of anthropogenic CO_2 up to timescales of a millennium and did not include the buffering effect from deep ocean calcium carbonate sediment. On longer timescales, interactions between anthropogenic CO_2 and deep ocean sediment become more important. The rate of ocean transport affects the timescale of $CaCO_3$ neutralization by determining how long it will take the anthropogenic CO_2 absorbed at the ocean surface to reach the sea floor and how long it will take the released carbonate ions from dissolving sedimentary $CaCO_3$ to return to the ocean surface and further neutralize fossil fuel CO_2. Therefore, differences in the rate of ocean transport might explain a substantial part of the discrepancies between simulated long-term evolutions of anthropogenic CO_2 (e.g. Archer, 2005; Lenton and Britton, 2006; Ridgwell and Hargreaves, 2007; Montenegro et al., 2007; Archer et al., 2008).

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The high sensitivity of modeled oceanic uptake of anthropogenic CO_2 to the simulation of circulation metrics such as radiocarbon suggests that the simulation of these tracers can be used as metrics for modeled oceanic CO_2 uptake in the future. For example, when model-simulated natural radiocarbon in the deep Southern Ocean is evaluated against observational-based estimates (Fig. 3), OCMIP models presented here and GENIE8 would appear to overestimate the amount of CO_2 taken up by the ocean on timescales from a few centuries to a millennium.

In summary, this study emphasizes the importance of a realistic simulation for ocean transport in the projection of anthropogenic CO_2 uptake by the ocean. In addition to uptake of anthropogenic CO_2, a realistic ocean transport is also important in determining extra heat absorbed by the ocean that is particularly important for the long-term commitment of climate change. Previous studies emphasized the importance of underlying ocean transport and dynamics in the modeling of present-day ocean carbon cycle and associated biological processes (Doney et al., 2004; Najjar et al., 2007). This study further demonstrates that to have a reliable projection of oceanic uptake of anthropogenic CO_2, it is important to better evaluate and improve model's representation of ocean dynamics. This can be achieved by the simulation of a variety of physical and biogeochemical tracers that hold complementary information about the relevant ocean transport processes on a range of timescales (Maier-Reimer, 1993; Marchal et al., 1998; Doney, 1999; Matsumoto et al., 2004; Müller et al., 2006; Najjar et al., 2007; Cao and Jain, 2008).

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Appendix A

Model description

A1 OCMIP Models

A detailed description of models participating in the OCMIP-2 CO_2 pulse emission experiments (AWI, Bern2.5D, IGCR, SOC, UL) can be found in Orr et al. (2002). A brief description of each OCMIP model presented in this study is given here.

A2 AWI

The AWI model used in this study follows the approach of ocean circulation model of Schlitzer (1995). It has recently been extended to include biogeochemical nutrients and carbon cycles (Schlitzer, 2002). Unlike dynamical models that use approximations to the momentum equation and external forcing at the sea-surface to calculate the time-varying ocean circulation by applying a time-stepping procedure, the AWI model has a steady 3-D flow field representing the steady-state, annual mean circulation of the ocean.

A3 Bern2.5D

Bern2.5D is a physical-biogeochemical climate model that consists of a zonally averaged ocean model (Wright and Stocker, 1992, 1998), coupled to an atmospheric energy balance model (Stocker et al., 1992). The model includes a basic representations of the carbon cycle, both marine (Marchal et al., 1998) and terrestrial (Siegenthaler and Oeschger, 1987) components. The marine biological model is based on the classical Redfield approach and phosphate is used as a limiting nutrient for biological production.

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A4 IGCR

The IGCR model was developed based on the ocean physical/biogeochemical model used in Yamanaka and Tajika (1996) for the study on the vertical fluxes of particulate organic matter and calcite. The physical variables are given by the general circulation model with the same finite differential scheme as the GFDL model.

A5 SOC

The model used by the SOC group is the ocean component of the coupled ocean-atmosphere model developed by the Hadley Centre for Climate Research and Prediction, part of the UK Meteorological Office. The version of the Hadley Centre model used for the GOSAC simulations is HadCM3L, a coarse resolution form of the HadCM3 model (Gordon et al., 2000).

A6 UL

The UL model results from the CLIO (Coupled Large-scale model, Goosse, 1998) coupled with a comprehensive and prognostic ocean carbon model LOCH (Mouchet and Francois, 1996).

A7 Bern3D

The Bern3D model (Müller et al., 2006) is a cost-efficient, seasonally forced three-dimensional frictional geostrophic balance ocean model. Its physical core is based on the work by Edwards et al. (1998) and Edwards and Marsh (2005) and has been modified to feature distinct coefficients for isopycnal diffusion and Gent-McWilliams transport parameterizations, 32 depth layers, and an implicit numerical scheme for vertical diffusion. The transport parameters have been tuned toward observed chlorofluorocarbon inventories and deep ocean radiocarbon signatures. Sea surface temperatures are constrained by restoring and sea surface salinities by flux boundary conditions.

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An additional anomalous uniform freshwater surface flux of 0.15 Sv from the Atlantic to the Pacific basin is applied in order to intensify and deepen the Atlantic meridional overturning circulation. Forcing fields for wind stress are derived from the NCEP data. The implementation of biogeochemical cycling in the Bern3D model closely follows the OCMIP-2 protocols. However, prognostic formulations are applied to compute the production of organic matter, $CaCO_3$, and opal shells (Parekh et al., 2008; Tschumi et al., 2008).

A8 CC_SED

CC_SED was described by Archer (2005). It uses the HAMOCC2 stationary annual mean flow to transport geochemical tracers. The temperature of the ocean is offset uniformly with a 1000-year response time, relaxing to a target temperature determined by a deep-ocean climate sensitivity of 3°C. It is coupled to a sediment model (Archer, 1996) and weathering feedbacks are also included (Berner and Kothavala, 2001).

A9 CLIMBR-2

CLIMBER-2 consists of a two-dimensional atmosphere and a two-dimensional multi-basin dynamic ocean. The climate model is coupled to a terrestrial biosphere model (VECODE) and a phosphate-limited ocean biogeochemical cycle model (Brovkin et al., 2002; Brovkin et al., 2007; Ganopolski et al., 1998).

A10 The GENIE-1 model

The three versions of the Grid ENabled Integrated Earth system model (GENIE-1) employed in this study (GENIE8, GENIE16, MESMO) are all based on the same fast climate model of Edwards and Marsh (2005), which features a reduced physics (frictional geostrophic) 3-D ocean circulation model coupled to a 2-D energy-moisture balance model (EMBM) of the atmosphere and a dynamic-thermodynamic sea-ice model. The

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ocean model includes a representation of marine carbon cycling parameterizing biogenically induced geochemical fluxes based on a phosphate control of biological productivity, and calibrated against observational datasets of ocean geochemistry (Ridgwell et al., 2007a). The primary differences between the three versions of GENIE-1 (GENIE8, GENIE16, MESMO) concern the vertical resolution, means of parameter value calibration, and parameter values as described below and listed in Table S1 http://www.biogeosciences-discuss.net/5/4521/2008/bgd-5-4521-2008-supplement.pdf.

A11 GENIE8

"GENIE8" divides the model ocean into 8 vertical levels and has non-seasonal climatology identical to that described in Ridgwell et al. (2007a). Parameter values controlling climate were obtained by means of an ensemble Kalman filter (EnKF) methodology described in Hargreaves et al. (2004), with annual mean climatological observations of ocean salinity and temperature together with surface air temperature and humidity assimilated.

The marine carbon cycle was also calibrated by means of EnKF as described in Ridgwell et al. (2007a), but in addition to assimilating information concerning modern observations of ocean phosphate and alkalinity distributions, experimental observations of pH impacts on plankton calcification inform the prior uncertainties for calcification rate power (η) (Ridgwell et al., 2007b).

A12 GENIE16

"GENIE16" employs a 16 vertical level version of the ocean circulation component, and is forced by seasonal insolation (but annual average wind stress). The climatology of this configuration of GENIE-1 has been calibrated by means of a multi-objective tuning process as described in Matsumoto et al. (2008), using exactly the same observational climatological data as for the EnKF calibration of GENIE8 (Hargreaves et al., 2004) (except at increased vertical resolution in the ocean). Temperature diffusion around

Antarctica (90–60° S) is additionally reduced by 75% in the 2-D atmospheric energy balance module to capture some of the relative (seasonal) isolation of the atmosphere in this region. The resulting configuration of the climate model and resulting climatology is identical to that described in Singarayer et al. (2008).

The biogeochemical parameters are calibrated by the same multi-objective tuning process described in Matsumoto et al. (2008) and against the same 3-D ocean phosphate and alkalinity data-sets as for GENIE8, but without additional observational constraints on plankton calcification sensitivity (i.e. as per Ridgwell et al., 2007a). In addition, to ensure numerical stability of the calculation of atmosphere-ocean surface gas equilibrium, the time-stepping between ocean biogeochemistry and circulation is reduced to 1:2, compared to the 1:5 ratio used in GENIE8 (Ridgwell et al., 2007a).

A13 MESMO

Derived from GENIE-1 and like GENIE16, MESMO has 16 vertical levels and is forced by seasonal insolation. An important distinguishing feature of MESMO is the use of depth-dependent vertical diffusivity in the ocean. This improves significantly the ventilation of the interior ocean such that the deep ocean $\Delta^{14}C$ as well as the inventories of anthropogenic carbon and CFCs are consistent with data-based estimates. In addition, biological production occurs in the top two layers above the compensation depth of 100 m and is modified by additional parameters, such as diagnosed mixed layer depth and temperature. In the steady state control run, the annual export production of POC is 10.6 Pg C and of $CaCO_3$ is 1.0 Pg C. For the historical run where atmospheric pCO_2 is prescribed to follow the observation, $CaCO_3$ export is reduced to 0.9 Pg C/yr as a result of anthropogenic carbon lowering the carbonate ion concentration. A detailed description of the MESMO model is given in Matsumoto et al. (2008).

A14 HILDA

The High-Latitude Exchange-Interior Diffusion/Advection (HILDA) model is a box advection/diffusion model with transport parameters calibrated to match the ocean distribution of natural and bomb-produced radiocarbon (Siegenthaler and Joos, 1992). Here, the model has been applied in its mixed-layer impulse response form (Joos et al., 1996). The model, in combination with representations of the terrestrial biosphere, has been used for CO_2 projections in the IPCC Second and Third Assessment Report (Joos et al., 2001), in IPCC technical papers, and to calculate Global Warming Potentials for the Kyoto Protocol. The model includes an energy balance formulation and the equilibrium climate sensitivity has been set here to 3.2 K for a nominal CO_2 doubling.

A15 LTCM

The Long-term Carbon Cycle Model (LTCM) is a modified and extended ocean carbon cycle model based on the HILDA box advection/diffusion model of Siegenthaler and Joos (1992). The structure of the physical ocean model is built based upon the HIDAL model, but with some modifications. First, the advection of water from the deep high latitude ocean into low latitude ocean occurs at all depths instead of only at the bottom ocean as in HILDA. Second, unlike the original HILDA model in which vertical diffusivity decreases with ocean depth, vertical diffusivity in LTCM increases with depth following Bryan and Lewis (1979). The values of vertical diffusivity and other ocean transport parameters are calibrated against the recent data-based observations of natural radiocarbon (Key et al., 2004). The implementation of biogeochemical cycling closely follows the OCMIP-2 protocols, but biological carbon uptake is parameterized by the Michaelis-Menton type uptake kinetics instead of by restoring surface phosphate to observations as in OCMIP-2. A 1-D sediment column lies at the bottom of each ocean layer following ocean hypsometry and each column is divided into 10 vertical levels with a total depth of 10 cm. The solid component of sediment includes $CaCO_3$ and refractory materials. Dissolved inorganic carbon and alkalinity in the pore water ex-

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change with those of ocean water through diffusion. A parameterization of carbonate and silicate weathering as a function of temperature and CO_2 concentrations are included based on the GEOCARB model of Berner and Kothavala (2001). In addition, an energy balance atmosphere is coupled to the ocean model.

A16 MPI-UW

MPI-UW (Mikolajewicz et al., 2007) consists of a coupled coarse-resolution atmospheric general circulation model ECHAM3 (Roeckner et al., 1992) and an updated version of the Large Scale Geostrophic ocean model (LSG) (Maier-Reimer et al., 1993). The ocean carbon cycle is represented by HAMOCC3 ocean biogeochemistry (Winguth et al., 1994). The land biosphere is simulated using the dynamic vegetation model LPJ (Sitch et al., 2003).

A17 UVic

The University of Victoria Earth System Climate Model (UVic 2.8) model consists of a vertically integrated, energy/moisture balance, atmospheric model with dynamic feedbacks, coupled to a modified version of the MOSES2 land surface model, the MOM2 ocean general circulation model, and a dynamic/thermodynamic sea-ice model (Weaver et al., 2001; Meissner et al., 2003). Ocean carbon is simulated by means of an OCMIP-type inorganic carbon-cycle model and a marine ecosystem model, solving prognostic equations for nutrients, phytoplankton, zooplankton, and detritus (Schmittner et al., 2008). Isopycnal mixing and flux corrected transport were used in the ocean model with diapycnal diffusion specified as a horizontally constant, Bryan-Lewis profile. The only three parameters that have been changed from the default 2.8 configuration are the ocean biology fixed production ratio of carbonate to carbon (changed from 0.02 to 0.018), the e-folding depth for carbonate remineralization (changed from 4500 m to 6500 m) and the scale height for carbon in the atmosphere (changed from 7900 m to 8049 m).

Appendix B

Validation of surface ocean response functions

To test how well ocean response functions derived from 590 Pg C emission pulse experiments represent the rate of ocean transport for individual models, we constructed a surface ocean response model following Joos et al. (1996) to simulate historical CO_2 uptake by the ocean. Input to the surface ocean response model are: the prescribed CO_2 concentrations, the relationship between modeled surface DIC and $p\,CO_2$ derived from each model's 590 Pg C emission pulse simulation, the thickness of top model layer, the rate of air-sea gas exchange, and surface ocean response functions for each model. Oceanic CO_2 uptake simulated by full model runs and the corresponding surface ocean response model runs are compared in Table B1. Close agreement in oceanic carbon uptake is observed between full and response model calculations with the largest difference less than 5%, suggesting that surface ocean response functions essentially capture the overall strength of surface-to-deep ocean transport for the corresponding full models. The discrepancy is mainly due to the fact that the response model does not take into account natural variability of ocean transport and the spatial variability of carbon uptake.

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Table 1. Key features of models used in this study.

	Horizontal resolution (Lon×Lat)	Vertical levels	Top layer thickness (m)	Surface forcing	Seasonality	Lateral mixing	Vertical diffusivity ($cm^{-2}s^{-1}$)[c]	Mixed layer scheme	Sea ice
AWI	5°×4° to 2.5°×2°	26	61	adjusted	no	ISOP	0.1	–	no
Bern2.5D[b]	10°–15°×basin average	14	50	EMBM	no	HOR	0.4	–	yes
Bern3D	10°×3.2° to 19.2°	32	38.9	flux, restoring	yes	ISOP, GM	0.1	–	no
GENIE8	10°×3.2° to 19.2°	8	174.8	EMBM	no	ISOP,GM	0.27	–	yes
GENIE16	10°×3.2° to 19.2°	16	80.8	EMBM	yes	ISOP,GM	0.25	–	yes
HILDA	high and low latitude boxes	69	75	EMBM	no	–	0.15–2.4	–	no
IGCR[a]	4°×4°	66	50	restoring	no	HOR	0.3	–	no
LTCM	high and low latitude boxes	37	75	EMBM	no	–	1.3–9.7	–	no
MESMO	10°×3.2° to 19.2°	16	45	EMBM	yes	ISOP, GM	0.1–1.2	–	yes
MPI-UW	5.6°×5.6°	22	50	AGCM	yes	ISOP, GM	0.1–V^{d}_{max}	–	yes
SOC	2.5°×3.75°	20	10	flux, restoring	yes	ISOP, GM	0.1–1.5	KT	no
UL	3°×3°	20	10	bulk formula	yes	HOR	0.1–1.1	TKE	yes
UVic	3.6°×1.8°	19	50	EMBM	yes	ISOP, GM	0.3–1.3	–	yes

Abbreviations are as follows: EMBM: Energy and moisture Balance Model; HOR: Horizontal mixing parameterization; ISOP: Isopycnal mixing parameterization; GM: Gent and McWilliams (1990) mixing parameterization; KT: Kraus and Turner (1967) parameterization; TKE: Turbulent Kinetic Energy closure; AGCM: atmosphere general circulation model.
[a] It is now recognized as FRCGC (Frontier Research Center for Global Change).
[b] Previously known as PIUB. [c] Vertical diffusivity decreases with depth in HILDA, while increase with depth for other models with a depth-dependent profile. [d] A single maximum vertical diffusivity for MPI-UW (V_{max}) is not available, which depends on wind speed and stratification. Key references for each model are: AWI, Schiltzer (2002); IGCR, Yamanaka and Tajika (1996); Bern2.5D, Stocker et al. (1992); Bern- 3D, Müller et al. (2006); SOC, Gordon et al. (2000); UL, Goosse and Fichefet (1999); UVic, Weaver et al. (2001); GENIE8: Ridgwell et al. (2007a), GENIE16; Singarayer et al. (2008); MESMO, Matsumoto et al. (2008); MPI-UW, Mikolajewicz et al. (2007); HILDA, Siegenthaler and Joos (1992).

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Table B1. Historical CO_2 uptake (Pg C) simulated by full model runs and corresponding surface ocean response model runs. A 3% downward correction is applied to the 1990s CO_2 uptake for AWI, Bern2.5D, and IGCR (Orr et al., 2002), which are from simulations using the IPCC S650 scenario with 1990s atmospheric CO_2 concentrations slightly higher than the observed.

	1980–1999		1765–2000	
	full model	response model	full model	response model
AWI	46.4	44.7	160.0	159.0
IGCR	44.5	43.6	149.1	151.2
Bern2.5D	46.3	45.5	155.5	155.1
Bern3D	36.2	35.8	123.5	120.0
UVic	39.2	37.1	135.3	130.3
GENIE8	56.5	56.1	187.9	184.0
GENIE16	40.1	38.6	134.1	132.9
LTCM	37.2	37.5	121.1	122.2

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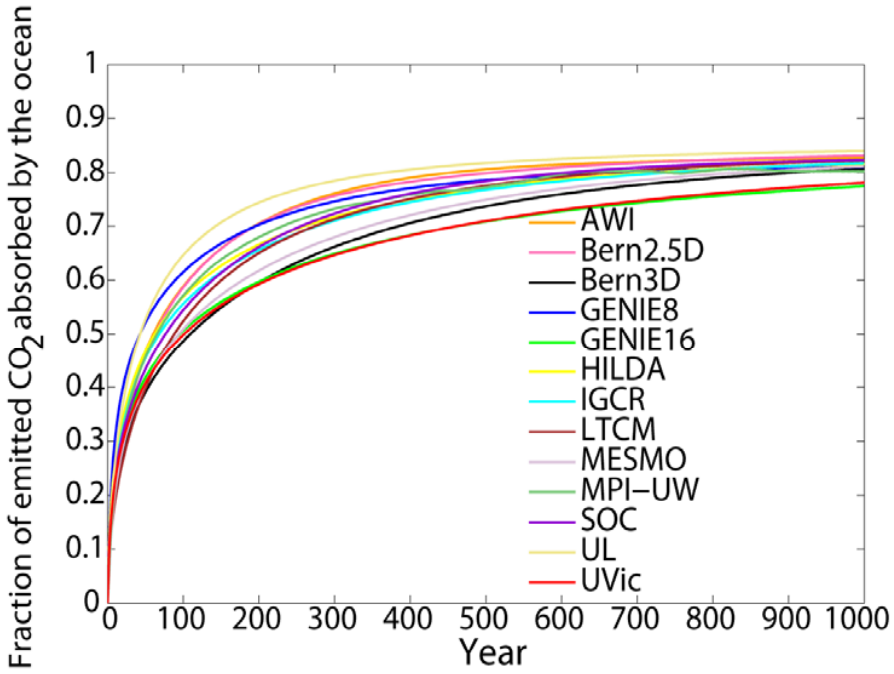

Fig. 1. Model-simulated oceanic uptake of CO_2 in response to a CO_2 pulse emission of 590.2 Pg C (corresponding to an instantaneous doubling of atmospheric CO_2 from 278 to 556 ppm).

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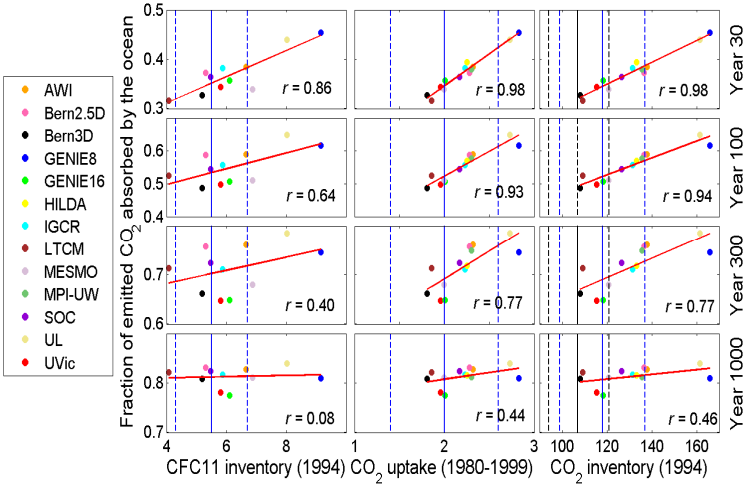

Fig. 2. Correlation of the oceanic uptake for anthropogenic CO_2 in response to an emission pulse of 590.2 Pg C with model-simulated CFC11 inventories (10^8 mole) in year 1994, mean anthropogenic CO_2 uptake (Pg C/yr) between year 1980 and 1999, and anthropogenic CO_2 inventories (Pg C) between year 1800 and 1994 (A 3% downward correction is applied to the 1990s CO_2 results for AWI, Bern2.5D, IGCR, PIUB, SOC, and UL (Orr et al., 2002), which are from simulations using the IPCC S650 scenario with 1990s atmospheric CO_2 concentrations slightly higher than the observed). The results are shown for years 30, 100, 300, and 1000 (following logarithmic distributions) after emission pulse. Vertical lines in each panel represent observational data (solid lines) and associated uncertainties (dashed lines). Observed CFC11 inventory is from Willey et al. (2004), CO_2 uptake is from Denman et al. (2007), and CO_2 inventory is from Sabine et al. (2004) (blue lines) and Waugh et al. (2006) (black lines). Also shown in each panel is the trend line and correlation coefficient. Model results shown here did not include climate feedbacks. If climate feedbacks are included, uptake and inventories are slightly lower. Simulations of CFCs were not performed by MPI-UW and HILDA.

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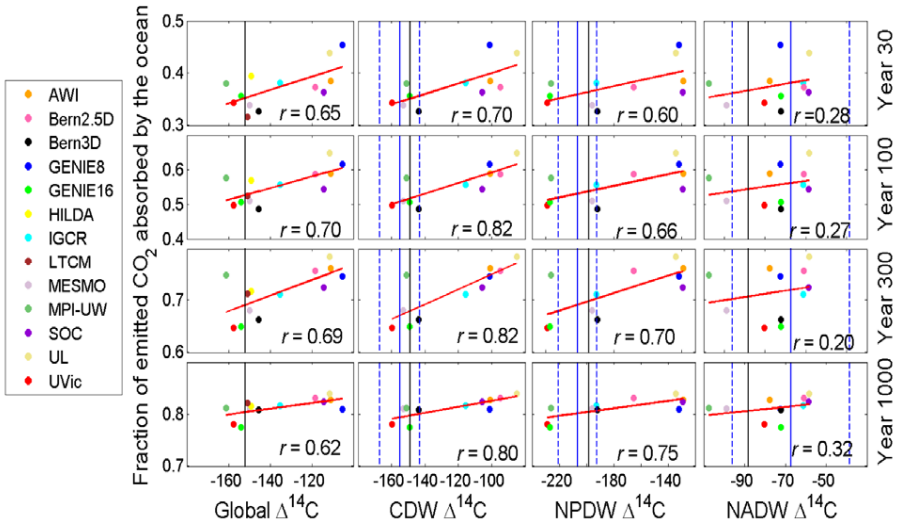

Fig. 3. Correlation of the oceanic uptake for anthropogenic CO_2 in response to an emission pulse of 590.2 Pg C with natural radiocarbon (permil) of the global ocean, Circumpolar Deep Water (CDW, 90–45° S, 1500–5000 m), North Pacific Deep Water (NPDW, Equator-60° N, 1500–5000 m), and North Atlantic Deep Water (NADW, Equator-60° N, 1000–3500 m). The results are shown for years 30, 100, 300, and 1000 (following logarithmic distributions) after emission pulse. Vertical lines in each panel represent observational data (solid lines) from Global Data Analysis Project (GLODAP) (Key et al., 2004) and associated uncertainties (one standard deviation, dashed lines). Analysis of Matsumoto et al. (2004) using the GLODAP bottle data is represented by blue lines, and our analysis using regridded GLODAP data are represented by black lines. Also shown in each panel is the trend line and correlation coefficient *r*.

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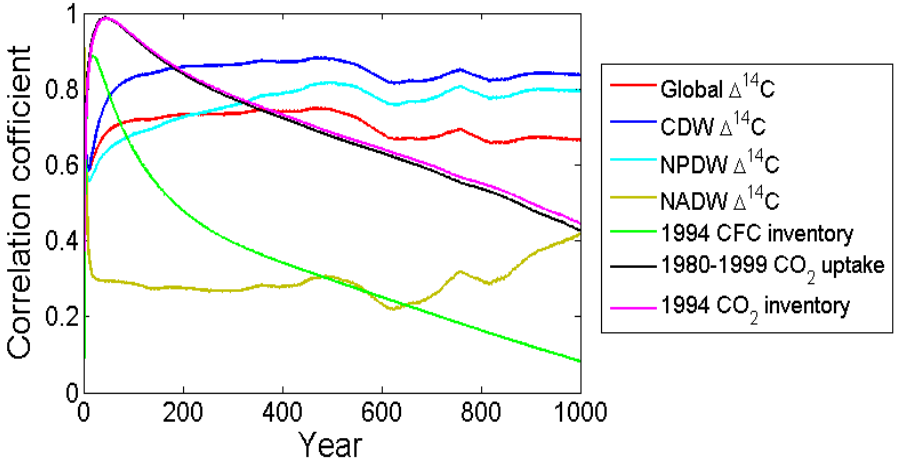

Fig. 4. Correlation of the oceanic uptake for anthropogenic CO_2 in response to an emission pulse of 590.2 Pg C with simulated natural $\Delta^{14}C$, CFC inventory (10^8 mole), CO_2 inventory (Pg C), and CO_2 uptake (Pg C/yr). On timescales from decades to a few centuries, modeled oceanic absorption of CO_2 emitted is strongly correlated with present-day uptake and inventory of anthropogenic CO_2. On timescales from a century to a millennium, the amount of CO_2 released absorbed by the ocean is strongly correlated with the content of natural radiocarbon in the deep Southern and Pacific ocean. CDW: Circumpolar Deep Water (90–45° S, 1500–5000 m); NPDW: North Pacific Deep Water (Equator-60° N, 1500–5000 m); NADW: North Atlantic Deep Water (Equator-60° N, 1000–3500 m).

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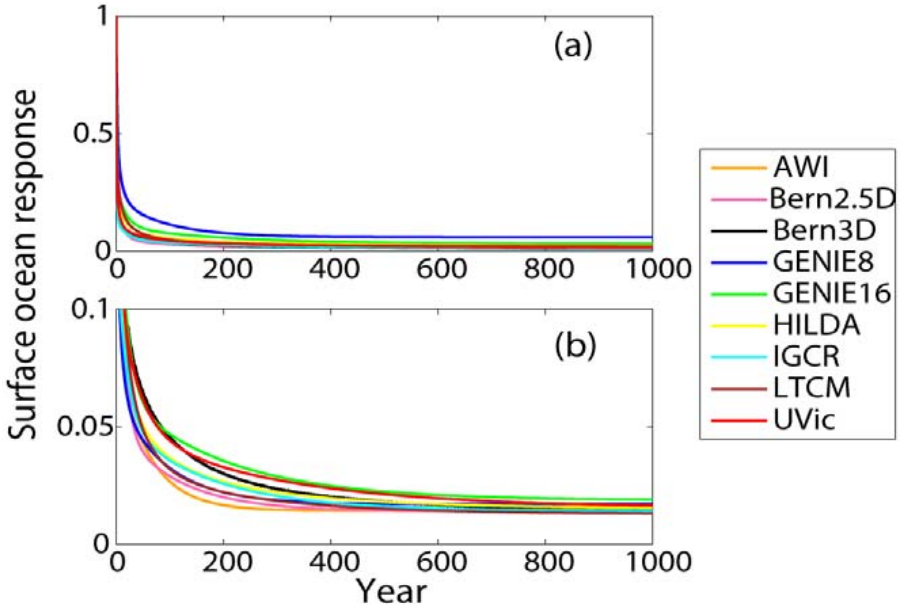

Fig. 5. Ocean surface responses that represent the fraction of an initially added amount of tracer to the surface ocean that remains in the surface after a certain time **(a)** ocean surface responses determined from the 590.2 Pg C CO_2 emission pulse simulations for individual models; **(b)** The same responses as (a), but normalized by a uniform surface depth of 50 m by multiplying each response by 50 m and divided by the top layer thickness of each model. Note that different scales are used in (a) and (b).

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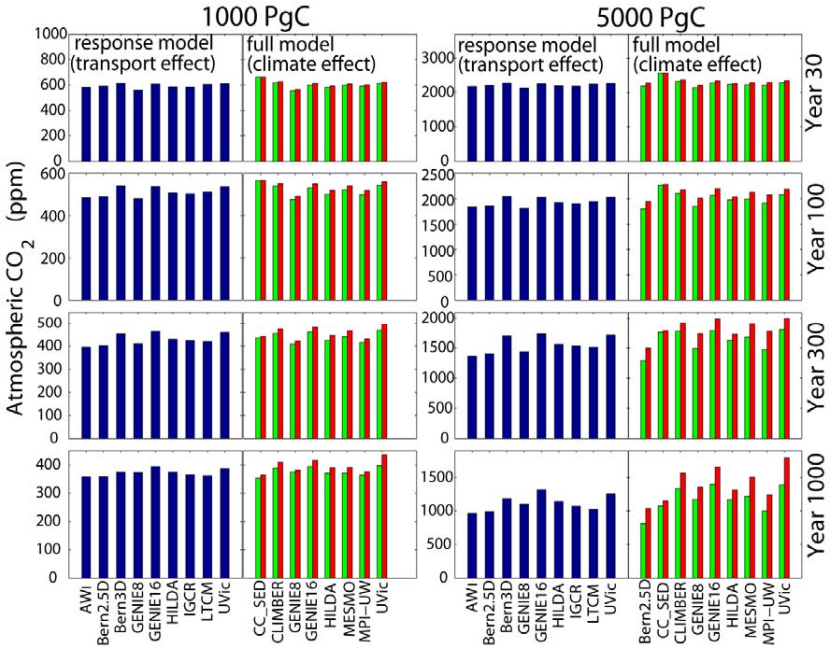

Fig. 6. Projected atmospheric CO_2 concentrations (by assuming a neutral terrestrial biosphere) in response to 1000 and 5000 Pg C emission pulses using surface ocean response model (dark blue bars) and full model runs with the inclusion of climate feedbacks on the ocean carbon cycle (red bars) and without it (green bars). The differences in CO_2 concentrations calculated by ocean response model runs are a result of differences in the rate of surface-to-deep ocean transport across models, while the differences in CO_2 concentrations calculated by full model runs are a result of climate feedbacks on the ocean carbon cycle in a single model associated with changes in temperature, circulation, and marine biology. It is shown that the effect of different ocean transport across models on projected atmospheric CO_2 concentrations is comparable to that of climate change in a single model (by assuming a neutral terrestrial biosphere).

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