

Metrics to assess the mitigation of global warming by carbon capture and storage in the ocean and in geological reservoirs

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[1] Different metrics to assess mitigation of global warming by carbon capture and storage are discussed. The climatic impact of capturing 30% of the anthropogenic carbon emission and its storage in the ocean or in geological reservoir are evaluated for different stabilization scenarios using a reduced-form carbon cycle-climate model. The accumulated Global Warming Avoided (GWA) remains, after a ramp-up during the first ~ 50 years, in the range of 15 to 30% over the next millennium for deep ocean injection and for geological storage with annual leakage rates of up to about 0.001. For longer time scales, the GWA may approach zero or become negative for storage in a reservoir with even small leakage rates, accounting for the CO₂ associated with the energy penalty for carbon capture. For an annual leakage rate of 0.01, surface air temperature becomes higher than in the absence of storage after three centuries only. **INDEX TERMS:** 1620 Global Change: Climate dynamics (3309); 1615 Global Change: Biogeochemical processes (4805); 1610 Global Change: Atmosphere (0315, 0325); 0322 Atmospheric Composition and Structure: Constituent sources and sinks. **Citation:** Haugan, P. M., and F. Joos (2004), Metrics to assess the mitigation of global warming by carbon capture and storage in the ocean and in geological reservoirs, *Geophys. Res. Lett.*, 31, L18202, doi:10.1029/2004GL020295.

1. Introduction

[2] Climate change primarily due to emissions of CO₂ is believed to be among the most serious environmental problems. Among many different political, economic and technological measures proposed to cope with this problem, capture and storage of CO₂ from point sources has received some attention [IPCC, 2002] (see <http://www.climatepolicy.info/ipcc/ipcc-ccs-2002/index.html>). If a storage option is perfect, i.e., with no possibility for leakage to the atmosphere, the effect on atmospheric CO₂ and climate will be the same as that of permanently avoided emissions by other means. However, if storage occurs in the ocean, communication with the atmosphere will ultimately affect atmospheric CO₂. Even for geological storage, leakage can not be excluded, and is likely to depend strongly on local characteristics of the reservoirs. In order to assess the usefulness of such sequestration options there is a need to quantitatively compare time trajectories of atmospheric CO₂ and climate state for each option in relation to a reference trajectory. Previous model

studies [e.g., Kheshgi *et al.*, 1994; Orr *et al.*, 2001; Caldeira *et al.*, 2002; Herzog *et al.*, 2003] have begun to address aspects of different options. In this paper we make a first step at systematic comparison over a time scale of a millennium, using a simple model that is first validated against more complex models. We introduce a simple metric called Global Warming Avoided (GWA), and briefly discuss how different the same results may appear when evaluated in different ways and over different time horizons.

2. Model Description and Experimental Setup

[3] A cost-efficient, reduced form model of the coupled carbon cycle-climate system is applied to study the millennium-scale climate impacts of carbon capture and storage for a range of CO₂ stabilization scenarios and generic storage options. Model results for atmospheric CO₂, global mean surface temperature change, and the oceanic injection efficiency are compatible to those of comprehensive general circulation models, albeit obtained at much less computational costs.

[4] The model consists of the High Latitude Diffusion-Advection (HILDA) model coupled to a 4-box biosphere model [Joos *et al.*, 1996], and an energy balance model [Joos and Bruno, 1996]. The ocean component has a vertical diffusivity for heat and tracers varying with the vertical coordinate. The climate sensitivity for a nominal doubling of atmospheric CO₂ is set to 2.5°C. The ocean component has previously been used in simulations of future atmospheric CO₂ for the second and third Assessment Report of the Intergovernmental Panel on Climate Change [Schimel *et al.*, 1996; Prentice *et al.*, 2001].

[5] First, we check the ability of the model to simulate the efficiency of sequestering CO₂ in the ocean. The study by Orr *et al.* [2001] included a comparison between seven different ocean carbon cycle models applied to ocean injection at three different depths and seven different geographical locations in the world ocean. They injected 0.7 PgC yr⁻¹ during years 2000–2100 and maintained atmospheric CO₂ at levels corresponding to IPCC scenario S650 which stabilizes at 650 ppm. Results were expressed in terms of an Injection Efficiency E_i (the additional mass of CO₂ in the ocean relative to a reference with no injection divided by the total injected since the start of injection). When running the present model with equivalent forcing and boundary conditions, we find that injection efficiencies are within the range of the comprehensive model results for injection at 800 and 3000 m (Figure 1).

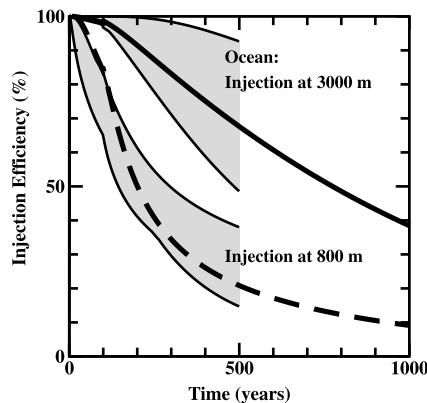


Figure 1. Injection efficiency for annual injection of 0.7 GtC at 800 m (dashed) and 3000 m (solid) for the HILDA ocean model. The range spanned by the results of seven ocean circulation models used in the Ocean Model Intercomparison Project (OCMIP [Orr *et al.*, 2001]) and run until year 2500 is shown in gray.

[6] Next, we perform case studies with different ocean and geological storage scenarios. As reference we use anthropogenic emissions (Figure 2) derived with our model from scenarios WRE450, WRE550, and WRE1000 which stabilize atmospheric CO_2 at 450, 550, and 1000 ppm, respectively, if no sequestration is applied. WRE1000 is included for illustration and is viewed as incompatible with the United Nations Framework Convention on Climate Change which calls for stabilization of greenhouse gas concentrations at a level that prevents dangerous anthropogenic interference with the climate system. In sequestration scenarios, 30% of the annual emissions are captured from year 2035 onward. In order to simulate build-up of sequestration capability, we assume no sequestration before 2010 and a linear increase in the percentage captured over the 25 years from 2010 to 2035. Since capture requires energy, we assume that for the captured CO_2 , there is more CO_2 produced. This energy penalty is set at 20% [IPCC, 2002], and the added CO_2 is also sequestered. So for example if the reference case annual emission is 10 PgC yr^{-1} , the sequestration scenarios would emit 7 PgC yr^{-1} and store 3.6 PgC yr^{-1} . Technical progress may lower the energy penalty and results for a 5% percent penalty are given in the auxiliary material¹; our main findings are not sensitive to this choice.

[7] For geological storage, we include a “perfect” storage case in which all the sequestered CO_2 is assumed to be isolated from the atmosphere indefinitely, and two cases where there is an annual leakage rate of 0.001 and 0.01, respectively, of the cumulative amount of CO_2 stored at any point in time. The inclusion of a high leakage rate scenario is deliberate to explore the impact of unfavourable storage conditions. Leakage from geological storage is assumed to be directly to the atmosphere. For ocean storage the two cases correspond to injection depths of 800 and 3000 m, and the effective delayed partial leakage

to the atmosphere is calculated as part of the model integration.

3. Results

[8] Figure 3 shows the resulting atmospheric CO_2 , global average surface air temperature and its rate of change for all 6 cases and 20% energy penalty for the WRE550 stabilization scenario (see auxiliary material for additional scenarios). In the case of perfect storage, the maximum atmospheric burden is reduced to 490 ppm, the temperature increase by the end of the century is reduced from 1.7 to 1.5°C and by the end of the millennium from 2.3 to 1.8°C, and the maximum rate of temperature change from 0.014 to 0.013°C per year. On the other extreme, atmospheric CO_2 approaches 600 ppm and temperatures are higher than in the reference case after three centuries for a leakage rate of 0.01 per year. Ocean injection at 800 m reduces atmospheric CO_2 for the first 600 to 700 years, but gives atmospheric CO_2 and temperatures close to those of the reference cases at the end of the millennium. For deep ocean and geological storage with annual leakage rate of 0.001, temperatures and CO_2 levels are still distinctly different from the reference cases at the end of the simulation period. Results for WRE450 and WRE1000 are qualitatively similar to those for WRE550. The temperature increase by the end of the millennium is reduced for perfect storage from 1.6 to 1.3°C and from 4.3 to 3.3°C for WRE450 and WRE1000, respectively. The difference in temperature perturbations relative to the reference scenario is at any time smaller than 33% for the range of scenarios (see Figure S3c in the auxiliary material).

[9] Another way to compare scenarios is by taking the time integral of the temperature difference between two scenarios, a quantity which may be denoted Global Warming Avoided (GWA) (Figure 3d). GWA in units of °C year is defined by
$$GWA(t) = \int_{t_0}^t (T_{ref} - T_s) dt,$$
 where T_s is the surface air temperature of any given (sequestration) scenario, T_{ref} is that of the reference scenario, t_0 is the starting time, here year 2010, and t is the time at which cumulative effects are compared.

[10] GWA increases almost linearly with time for the perfect storage cases to reach by the end of the millennium 234, 392, and 773°C year for the WRE450, WRE550, WRE1000 cases, respectively. For WRE550, GWA increases to 251°C year for deep ocean injection and

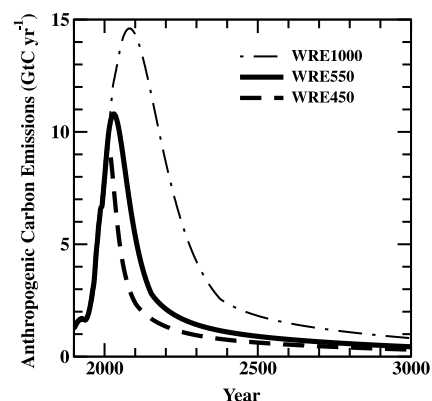


Figure 2. Anthropogenic carbon emissions for the WRE450, WRE550, and WRE1000 stabilization scenarios.

¹Auxiliary material is available at <ftp://ftp.agu.org/apend/gl/2004GL020295>.

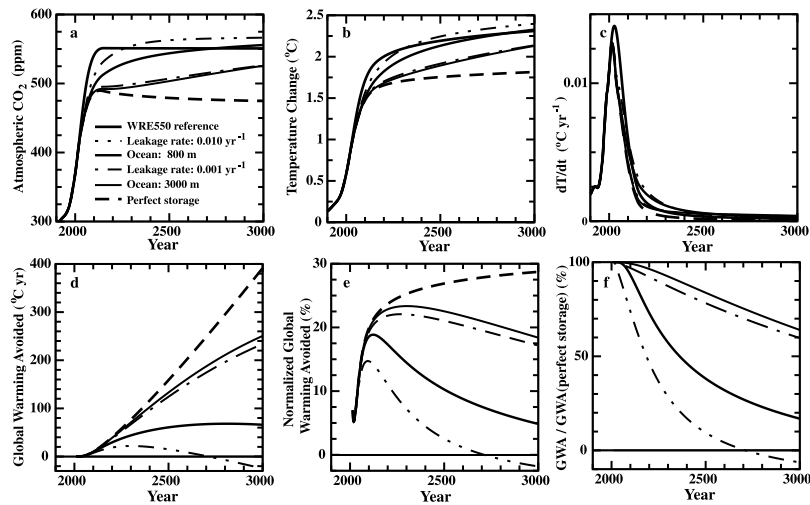


Figure 3. Projected (a) atmospheric CO₂, (b) global average surface temperature change, (c) rate of global average surface temperature change, and Global Warming Avoided (d) in °C year, (e) in percent of the cumulative warming of the reference case, and (f) relative to the perfect storage case for WRE550. 30% of the annual emissions are injected into the ocean at 800 m (thin solid), 3000 m (solid), or in a geological reservoir assuming no leakage (thick dash, perfect storage), a leakage rate of 0.001 (dash-dot) or 0.01 per year (dash-dot-dot). No carbon is captured and stored in the WRE550 reference case (thick solid).

233°C year for geological storage with an annual leakage rate of 0.001. It remains close to 140°C year during the second half of the millennium for shallow ocean injection and turns negative after year 2700 for an annual leakage rate of 0.01.

[11] Next, we evaluate how much of the future cumulative warming of the reference case is avoided by storage (Figure 3e). Normalized GWA is expressed as a percentage of the accumulated warming of the reference simulation:

$$GWA_{Norm}(t) = \left(\int_{t_0}^t (T_{ref} - T_s) dt \right) / \left(\int_{t_0}^t (T_{ref} - T_0) dt \right) 100\%,$$

where T_0 is the temperature at time t_0 . By the end of the millennium, 26% (WRE1000) to 30% (WRE450) of the reference accumulated warming are avoided for perfect storage, 17% to 19% for deep ocean injection, but only 5% for shallow ocean injection, and an additional 1% to 2% of warming is accumulated in the high leakage case.

[12] Finally, the effectiveness, EFF , of the different capture and storage schemes is compared relative to the ideal, perfect storage case: $EFF(t) = GWA(t) / GWA_{PS}(t)$, where $GWA_{PS}(t)$ is the GWA for perfect storage (Figure 3f). The effectiveness of the deep ocean injection and of geological storage with annual leakage of 0.001 is around 60% by year 3000, whereas it has fallen below 20% for shallow ocean injection and to negative values for the high leakage case.

4. Discussion

[13] Recently, *Caldeira et al.* [2003] constructed with a reduced-form model stabilization pathways leading to a 2°C warming after year 2150 for different climate sensitivities. They did not study ocean or geological storage with leakage, but concluded that climate stabilization requires a considerable fraction of the global energy production (between 20 and 80% during the first century for a 2°C climate sensitivity to CO₂ doubling) to be effectively

emission-free. *Harvey* [2004] interpreted the United Nations Framework Convention on Climate Change to imply a commitment to stabilize atmospheric CO₂ at 350–450 ppm. Carbon capture and storage as investigated here may be part of a portfolio of emission mitigation options that will be considered to avoid dangerous anthropogenic climate interference.

[14] The good match with injection efficiencies obtained by more complex models, leads us to conclude that our model has a credible performance for ocean storage at 800 m and 3000 m injection depth. Caveats should be made concerning limitations in our understanding of global carbon cycle mechanisms and possible future changes in ocean circulation [*Plattner et al.*, 2001]. The generic 3000 m and 800 m injection depth scenarios represent global average performances for these depths, while in reality geographical dependencies are to be expected. Our modelled temperature response depends on the climate sensitivity of the model, here set to 2.5°C for a nominal doubling of CO₂. Uncertainty about the real climate sensitivity is probably the major limitation in our ability to determine allowable CO₂ emissions over the next few centuries to achieve climate stabilization [*Caldeira et al.*, 2003].

[15] We have evaluated carbon capture and storage applying various metrics such as atmospheric CO₂, global average surface temperature warming and GWA for different times and periods over this millennium. Effectiveness is defined here as the GWA of a given sequestration scenario relative to the GWA of perfect storage. This effectiveness should not be confused with the injection efficiency (denoted sequestration efficiency by *Mignone et al.* [2004]). It is not appropriate in the present paper to suggest whether it is the GWA or the state at any given point in time which should be the recommended metric for assessing success or failure of any given sequestration action. We note, however, that the choice can make a big difference.

[16] The GWA metric could be useful, either in its basic definition (in units of degree-years), normalized to the accumulated warming of the reference trajectory, or normalized to the GWA of perfect storage. Other metrics such as injection efficiency or airborne fraction are simpler in that they only require carbon accounting. However, the climate impact of CO₂ released to the atmosphere from imperfect storage will vary with the time history of the release. Time-dependent coupled carbon-climate modelling is necessary to properly account for these processes affecting the GWA, but can be done with relatively simple models. Herzog *et al.* [2003] on the other hand calculate the net present value of the benefits of a sequestration strategy assuming that it is proper to discount future costs. This requires carbon price scenarios in addition to a carbon-climate model. Carbon prices would depend on how to account for climate costs of leaky reservoirs.

[17] The GWA over a 1000 year period is significantly positive for most cases considered. For longer time scales, beyond the integration period, it is conceivable that the GWA may approach zero or become negative for storage in a reservoir with even small leakage rates, accounting for the CO₂ associated with the energy penalty. In the case of shallow ocean injection (800 m) (or with annual leakage rates of more than a few permil), the surface air temperature becomes higher than for the corresponding emission scenarios before the end of the millennium. This illustrates the temporary character of storage in the near surface ocean and the effects of increased total CO₂ amount associated with energy penalty due to capture.

[18] Leakage and permanency are issues for storage in geological reservoirs. Our results indicate that global-average leakage rates should be less than 0.001 per year to avoid temperature and CO₂ concentrations to become higher than in scenarios without capture and geological storage over the next millennia. This implies that reservoirs are to be monitored over long time periods (centuries to millennia) for verification of the effectiveness in avoiding emissions of carbon capture and storage schemes.

[19] Ideally, 15 to 30% of the accumulated warming over the millennium may be avoided for capture and storage of 30% of the emissions leading to CO₂ stabilization. 30% of the CO₂ emissions, used as an example point of reference in this study, corresponds to almost the same mass as that of the total fossil fuel burned because a mole of CO₂ is about three times as heavy as a mole of fossil carbon. Capturing 30% of the global carbon emissions is not trivial and would require a massive investment in additional infrastructure, such as capture facilities and pipelines to transport captured CO₂ to storage areas, with potentially unwarranted social and economic impacts.

[20] This paper addresses only the effectiveness of ocean and geological storage. In particular for the ocean, there are

significant environmental impact issues which need to be addressed before rational decisions can be made whether to implement such options. This implies a need to obtain fundamental data on the behavior of CO₂ in the ocean, ocean ecosystem responses to CO₂, long-term leakage from geological reservoirs and the socio-economic consequences of various carbon capture and storage schemes.

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