Sea–to–Air CO_2 flux from 1948 to 2003 - a model study

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I. ABSTRACT

A biogeochemical model embedded in a state-of-the-art ocean general circulation and sea ice model has been applied to quantify the important mechanisms of the interannual and decadal sea-to-air CO_2 flux variability and the variations in the uptake of anthropogenic CO_2. The model is forced by daily NCEP/NCAR reanalysis data over a 56 year period of time, showing trends and variability on interannual and decadal scales. The total interannual variability of the model is ±0.50 Pg C yr^{-1} (2σ) and is largely dominated by ocean dynamics in the equatorial Pacific. In 1975-1976 the modeled interannual variability of the equatorial Pacific changes from ±0.32 Pg C yr^{-1} to ±0.23 Pg C yr^{-1}. A large trend in the modeled CO_2 fluxes during the 56 year period is caused by the increasing wind speed forcing over the Southern Ocean. We estimate an average CO_2 flux into the ocean of -1.74 Pg C yr^{-1} in the 1990-2000, with extremes of -1.20 Pg C yr^{-1} at the La Niña in 1996 and -2.10 Pg C yr^{-1} flux during the El Niños in 1993 and 1998. The 1993 and 1998 El Niños reduce the uptake of anthropogenic CO_2 in 1990-2000, that is already slowing down due to the rising buffer factor. Overall about 124.3 Pg of anthropogenic carbon have accumulated in the model ocean.

II. BACKGROUND

The ocean absorbs carbon dioxide and other trace gases and exchanges them with the atmosphere. These exchanges might interact with the ocean circulation and climate variability (e.g. El Nino/Southern Oscillation (ENSO), Pacific Decadal Oscillation (PDO), North Atlantic Oscillation (NAO), or Antarctic Circum Polar Wave) and climate change. Estimates of chlorophyll, primary production and temperature on the sea surface from satellite and in situ observations have documented a high variability of the marine carbon cycle in the tropics, the northern high latitudes, and the Southern Ocean. Natural variability and trend of the carbon fluxes in the marine ecosystem are determined by the variability of the circulation, diffusive processes, freshwater and carbon fluxes at the air-sea interface and biogeochemical processes. Estimates of the interannual variability of the sea-to-air CO_2 flux differ considerably:

1. Studies based on variations of the sea surface temperatures and CO_2 partial pressure (Feely et al., 1999) indicate a low variability (below ±0.5 Pg C yr^{-1}). This estimate is generally supported by ocean model simulations (Winguth et al., 1994; Le Quere et al., 2000; Obata and Kitamura, 2003; McKinley et al., 2004).

2. The $\delta^{13}C$ signal and terrestrial studies (Knorr, 2000) clearly indicate a dominant role of the terrestrial biosphere for the variability. However, Keeling et al. (1995) suggest that a considerable sea-air gas exchange, mostly anticorrelated to the terrestrial flux, is needed to explain the atmospheric CO_2 signal. Recent atmospheric inversion estimates (Rödenbeck et al., 2003) show an oceanic interannual variability that is more in line with the ocean model studies.

Here, we reevaluate the prediction of the CO_2 fluxes at the air-sea interface and estimate the oceanic uptake of anthropogenic CO_2 from fossil fuel and land-use change with a state-of-the-art carbon cycle model coupled to an ocean general circulation model (Box III) and compare the results with previous studies.

III. MODEL AND EXPERIMENT SETUP

1. OCEAN CIRCULATION MODEL

To investigate the variability in the marine carbon cycle, we are using the OM OGCM (Marseland et al., 2002) newly developed at the MPI in Hamburg. OM is a z-coordinate global general circulation model based on primitive equations for a Boussinesq-fluid on a rotating sphere.

Model features:

- Curvilinear coordinate system (Figure 1)
- 20 model levels (layer thicknesses of 20 m to 1400 m)
- Timestep 2,4 hours
- Isopycnal diffusion of the thermohaline fields
- Eddy-induced tracer transport (Gent et al., 1995)
- Bottom boundary layer slope convection scheme
- Sea ice model with viscous-plastic rheology (Hibler, 1979)

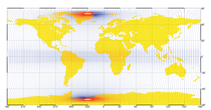

Figure 1. Configuration of the model grid.

2. CARBON CYCLE MODEL

The HAMOCC5 is online coupled to the MPI OM, running the same spatial and temporal resolution. Features include:

- Carbon chemistry (Maier-Reimer, 1993; OCMIP and NOCES)
- Air-sea gas exchange (Wanninkhof, 1992; OCMIP and NOCES)
- NPZD ecosystem model (Six and Maier-Reimer, 1996; Figure 2)
- Co-limitation of Fe, Si, N, and P
- Particle size class model
- 10-layer sediment model with pore-water chemistry

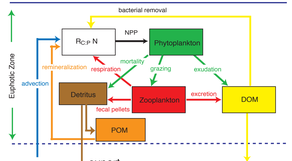

Figure 2. Schematic diagram of major processes in the euphotic zone simulated in HAMOCC5.

3. NCEP EXPERIMENT SETUP

The daily forcing used in the simulation has been derived from the NCEP reanalysis data (Kalnay et al. 1996) of near surface air and dew point temperature, 10 m wind speed, downward shortwave radiation, precipitation, cloudiness and wind stresses. The heat fluxes are calculated from the atmospheric forcing data and the actual model distribution of SST and sea ice using bulk formula. For freshwater a mass flux boundary condition is implemented, where the actual flux is calculated from prescribed precipitation and climatological river runoff and evaporation calculated from the latent heat fluxes. Additionally a weak restoring of the surface salinity towards the Levitus climatology is used with a time constant of 386 days. No surface salinity restoring is applied under sea ice.

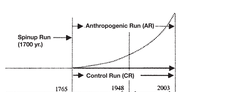

Figure 3. Schematic setup of the control run (CR) and the anthropogenic run (AR).

The model is spun up for 500 years using climatological forcing (from OMIP) after starting from Levitus. Thereafter, the forcing is switched to NCEP data for the period 1948 to 2000 and applied several times subsequently for total integration of 1700 years. The biogeochemical model started with a uniform tracer distribution and tracer adjusted to the circulation after about 1,000 model years with a preindustrial CO_2 concentration of 280 ppm. Two experiments where carried out: A control run from 1765 to 2003 without anthropogenic forcing (CR) and an anthropogenic run (AR) with prescribed atmospheric concentrations from ice cores and from Mauna Loa. No detrended NCEP forcing fields are used from 1948 to 2003 (Figure 3).

IV. AIR-SEA CO_2 FLUX AND ANTHROPOGENIC CO_2 UPTAKE

The CO_2 fluxes and the CO_2 partial pressure difference between the ocean and the atmosphere (ΔpCO_2) are tightly connected. In Figure 4, the mean spatial pattern of ΔpCO_2 is shown for the reference year 1995 of the "climatological" data compilation from Takahashi et al. The modeled pattern agrees reasonably well with the observations, but there are local differences. For example, small areas such as the Greenland Sea, Iceland Sea, Norway Sea and Labrador Sea are not well resolved in the course grid of Takahashi et al. [2002].

The effective flux of CO_2 represents the sum of the natural CO_2 fluxes and the uptake of anthropogenic CO_2. Because of the trend of the fluxes of the CR experiment, the total flux of CO_2 into the ocean between 1980 and 2000 is about 0.18 PgC yr^{-1} smaller than the computed uptake of anthropogenic CO_2. The average flux of -1.49 PgC yr^{-1} for 1980-89 and -1.74 PgC yr^{-1} for 1990-99 agrees reasonably well with the estimates from atmospheric inversions [Rödenbeck et al., 2003; Gurney et al., 2002] (Table 1).

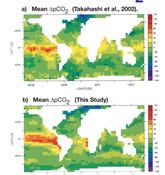

Figure 4. A) Mean ΔpCO_2 values from Takahashi et al. [2002], computed for the reference year 1995 in ppm. B) Mean ΔpCO_2 of the year 1995 of the anthropogenic run in ppm; interpolated to the 4° x 5° grid of Takahashi et al. [2002].

Table 1. Sea-to-air flux of CO_2 into the northern hemisphere, tropics and southern hemisphere in PgC yr^{-1}

	Time span	South/20 PgC yr^{-1}	Tropic PgC yr^{-1}	North/ 20N PgC yr^{-1}	Total PgC yr^{-1}
This Study (CR control)	1980-1999	-0.11	-1.18	-0.88	-2.18
This Study (AR anthropogenic)	1980-1989	-0.9	-0.85	-1.28	-3.5
	1990-1996	-1	-0.54	-1.32	-3.78
	1990-1999	-1.03	-0.6	-1.29	-3.72
	1995	-1.05	-0.64	-1.24	-3.75
	1980-1999			-1.3	-3.7±0.3
	1980-1996	-1.0±0.1	-0.6±0.2	-1.6±0.1	-3.7±0.3
	1996-1999	-1.2±0.2	-1.1±0.2	-1.7±0.1	-3.7±0.4
	1992-1996	-0.9±0.2	-0.3±0.4	-1.1±0.4	-3.5±0.4
Takahashi et al. [2002]	1995	-1.51	0.9	-1.03	-1.64
Roughton et al. [2001]	1980-1989				-1.6±0.8
	1990-1999				-3.7±0.5

The inventory of anthropogenic carbon is computed as the difference between the dissolved inorganic carbon (DIC) inventory of the AR and the CR experiment (Figure 5). Storage of anthropogenic CO_2 is high in areas with a low buffer factor (or Revelle factor). Most of the anthropogenic carbon that is taken up in the high latitudes and the upwelling regions is transported to the subtropics, and accumulated mostly in the upper few hundred meters of the water-column.

The modeled global spatial distribution and concentrations of anthropogenic DIC are in good agreement with the estimates from other studies (Table 2). In the Pacific and Indian Oceans the simulated inventory almost matches the calculations of Sabine et al. [2002, 1999], however our estimate for the Atlantic is about 25% lower than the calculation by Lee et al. [2003]. The difference may be related to the different approaches of Sabine et al. [2002, 1999) and Lee et al. [2003] to estimate the air-sea CO_2 disequilibrium term for shallow surfaces.

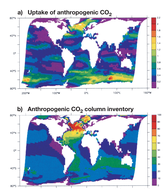

Figure 5. A) Estimated mean anthropogenic CO_2 uptake for 1990-99 in PgC yr^{-1}.
B) Estimated mean column inventory of anthropogenic CO_2 of the year 1995 in mol C m^{-1}.

Table 2. Anthropogenic carbon inventory in PgC.

Atlantic Ocean (1994)	South of equator	North of equator	Total
Lee et al. [2003]	18.5 ±3.9	28.4±4.7	46.9±8.6
This Study (1994)	13.3	23.1	36.4
Pacific Ocean (1994)	South of equator	North of equator	Total
Sabine et al. [2002]	28	16.5	44.5±5.0
This Study (1994)	27	17.5	44.5
Indian Ocean (1995)	South of 35S	North of 35S	Total
Sabine et al. [1999]	13.6±2.0	6.7±1.0	20.3±3.3
This Study (1995)	13.6	7.4	21
Total Ocean (1994)			
Lee & Sabine			112±17
This Study	South of equator	North of equator	Total
All of Above Regions			101.9
Total Ocean (1994)	57.6	46.7	104.3
Total Ocean (1995)	58.6	47.5	106.2

V. VARIABILITY OF CO_2 FLUXES IN THE TROPICAL AND NORTHERN PACIFIC

The global interannual CO_2 flux variability is governed by the equatorial Pacific (Figure 6). This result is in agreement with other ocean carbon cycle model studies [Winguth et al., 1994; Le Quere et al., 2000; Obata and Kitamura, 2003; McKinley et al, 2004]. In the control run (CR) experiment, the equatorial Pacific from 10°N to 10°S accounts for ±0.33 PgC yr^{-1}, which is about 65% of the global interannual CO_2 flux variability. The regime shift in 1975-77 is inherent in the NCEP/NCAR reanalysis (Figure 7). Most pronounced is the change in the equatorial Pacific, but it is evident in the Atlantic and the Southern Ocean, too. The interannual flux variability in the equatorial Pacific changes from ±0.33 PgC yr^{-1} (1948 to 1976) to ±0.27 PgC yr^{-1} (1977 to 2003), the overturning of both equatorial cells changes from 100±11 Sv to 77±5 Sv. The mean outgasing is reduced from 0.70 PgC yr^{-1} to 0.58 PgC yr^{-1}. The transition can also be seen in the Pacific Decadal Oscillation.

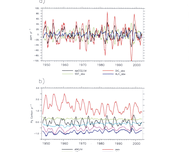

Figure 6. A) Component analysis for the terms of equation (5) in the surface box of the equatorial Pacific from 10°S to 10°N and 80°W to 135°E. B) Components of equation (4) for the upper 42 m of the same area. All fluxes are the control run and smoothed with a 12 month runing mean.

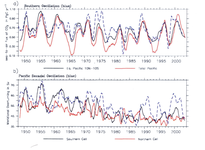

Figure 7. A) Sea-to-air CO_2 fluxes of the control run (smoothed with a 12 month running mean) of the total Pacific and of equatorial Pacific from 10°N to 10°S and 80°W to 135°E. The Southern Oscillation Index is shown in blue. B) Overturning of the southern and northern equatorial cell in the Pacific. The Pacific Decadal Oscillation Index is shown in blue.

VI. VARIABILITY OF CO_2 FLUXES IN THE NORTHERN ATLANTIC

It is generally accepted that the North Atlantic is a strong sink for CO_2. The modeled CO_2 flux and variability of the North Atlantic north of 50°N is -0.31 ±0.04 PgC yr^{-1} in the CR and -0.41±0.05 PgC yr^{-1} for 1990-99 in the AR experiment. The model produces a deep penetration of anthropogenic CO_2 in the high northern latitudes of the Atlantic, which is in agreement with estimates by Lee et al. [2003], Gruber [1998] and McNeil et al. [2003]. In areas of North Atlantic Deep Water formation, e.g. GIN Sea and Labrador Sea, intense surface cooling and deep winter convection carry the anthropogenic CO_2 signal down to the bottom of the ocean. Accumulation of anthropogenic CO_2 in the GIN Sea is lower than the uptake of anthropogenic CO_2 by air-sea gas exchange. Most of the water masses transported into the GIN sea originate in the North Atlantic Current and are not fully equilibrated with the atmospheric CO_2 concentrations, and a significant fraction of the anthropogenic CO_2 taken up by air-sea gas exchange is transported out of the GIN sea with the East Greenland Current and the Denmark Strait overflow. In the Labrador Sea and the North Atlantic south of the GIN Sea and Labrador Sea the in- and out-flows of anthropogenic CO_2 are roughly in balance. Highest rates of anthropogenic CO_2 uptake are simulated in deep convection areas near Greenland. This uptake is reduced by a rising buffer factor, causing only a small increase from 1980-89 to 1990-99.

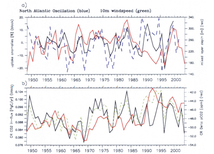

Figure 8. Yearly means for Greenland, Iceland and Norwegian Sea. In blue is the Arctic Oscillation Index and in green is the 10 m wind speed from the NCEP reanalysis. A) Anomaly in the uptake of anthropogenic CO_2 (AR experiment) and the average mixed layer depth. B) CO_2 in-flux and ΔpCO_2 from the control run (CR).

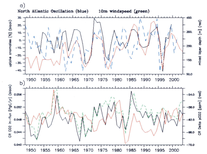

Figure 9. Yearly means for Labrador Sea. In blue the Arctic Oscillation Index and in green is the 10 m wind speed from NCEP reanalysis. A) Anomaly in the uptake of anthropogenic CO_2 (AR Experiment) an the average mixed layer depth. B) CO_2 in-flux and ΔpCO_2 from the control run (CR).

VII. CONCLUSIONS AND REFERENCES

We have used a fully prognostic biogeochemical global ocean circulation model, forced with surface fluxes computed from NCEP/NCAR reanalysis data for the period 1948-2003. The natural variability and the trends are analyzed in a control run with preindustrial atmospheric concentrations. In addition, the response of the system to anthropogenic atmospheric CO_2 concentrations has been tested. The total interannual variability of the model is ±0.50 PgC yr^{-1} (2σ). This is within the range of previous ocean model studies [Le Quere et al., 2000; Obata and Kitamura, 2003; McKinley et al, 2004] and recent atmospheric inversions [Rödenbeck et al., 2003]. The CO_2 flux is -1.49 PgC yr^{-1} for 1980-89 and -1.74 PgC yr^{-1} for 1990-99. Our simulated fluxes agree well with flux estimates from atmospheric inversions [Rödenbeck et al., 2003; Gurney et al., 2002] (Table 1).

We define the uptake of anthropogenic CO_2 as the difference between the CO_2 fluxes of the anthropogenic run and the control run. The uptake of anthropogenic CO_2 is 1.65 PgC yr^{-1} for 1980-89 and 1.91 PgC yr^{-1} for 1990-1999, with an accumulation of about 105 Pg of anthropogenic carbon by 1995. The inventory estimate is compatible with results from chlorofluorocarbon [McNeil et al., 2003] and from ΔC^* technique estimates [Lee et al., 2003; Sabine et al., 2002 and 1999]. A shift in 1975-76 reduces the outgasing of CO_2 in the equatorial Pacific in the control run from 0.70 to 0.58 PgC yr^{-1}. Nevertheless the total sea-to-air CO_2 flux increases by 0.006 PgC per year on average. This trend mainly originates in the Southern Ocean and is caused by increasing wind stress. This trend is the reason why the total flux of CO_2 is about 0.18 PgC yr^{-1} smaller than the computed uptake of anthropogenic CO_2 in the periods 1980-89 and 1990-99.

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