

Global Ocean Carbon Uptake: Magnitude, ~~Variability~~ and Trends

Results from a RECCAP synthesis

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Global Ocean Carbon Uptake: Magnitude, ~~Variability~~ and Trends

Results from a RECCAP synthesis

Outline

- What we (should) know about anthropogenic carbon uptake by the ocean.
- Why should we care about anthropogenic CO₂ uptake by the ocean.
- The goals of RECCAP.
- The magnitude and trends carbon uptake by the ocean for the last 20 years based on observations and models.



What is known about Anthropogenic Carbon Uptake by the Ocean

1. “Current estimates of ocean uptake are sufficiently firm to exclude the possibility that appreciably more excess CO₂ is dissolved in the sea than has been estimated through the use of existing models”
2. The static capacity of CO₂ uptake by the ocean is huge (≈ 90 % of excess CO₂)
3. The uptake rate is controlled by ocean ventilation and to lesser extent air-sea gas exchange limiting the current uptake to ≈ 25 % (2 Pg C) of fossil fuel release.

While on 1st order ocean uptake is well-established, absolute magnitude and (changing) trends must be quantified.

26 October 1979, Volume 206, Number 4417

SCIENCE

carbon cycle

*1979: Atm CO₂ = 337 ppm

Fate of Fossil Fuel Carbon Dioxide and the Global Carbon Budget

W. S. Broecker, T. Takahashi, H. J. Simpson, T.-H. Peng

Claims have recently been made that the cutting and burning of forests is currently a major source of carbon dioxide (CO₂) (1-4). These claims come as a shock to those of us engaged in global carbon budgeting, as we have been calling for a modest increase in the size of the terrestrial biosphere (5-8) in order to achieve a balance in the carbon budget.

the atmosphere has risen by about one-half as much as would be the case if all the CO₂ released from fossil fuel combustion had remained in the air (assuming no significant change in the terrestrial biomass). In view of the uncertainties in estimates of both the fuel consumed and the atmospheric CO₂ increase, the actual value for the airborne fraction of CO₂

0.89 ± 0.06. As we explain below, the reaction of carbon atoms with anthropogenic phosphorus atoms to form organic residues accounts for about 0.02 of the amount of fossil fuel CO₂ released since 1958. Adding this contribution to the ocean and atmosphere inventories, we achieve a total of 0.91 ± 0.07.

Estimates of forest cutting and burning suggest that the amount of CO₂ released by these processes since 1958 ranges from 20 to 100 percent of that released by the burning of fossil fuels (1-4). If true, the unaccounted for residual [that is, (fossil fuel CO₂) + (forest cut-back CO₂) - (CO₂ taken up by the ocean) - (CO₂ taken up in organic residues)] then lies in the range from one-quarter to the total amount of fossil fuel CO₂ released (see Table 1). Thus, if the forests are decreasing in biomass at anywhere near the rates claimed, there must be a major error in our budgeting.

We examine below the assumptions associated with estimates of the transfer of excess CO₂ from the atmosphere to other reservoirs. We do not review the fuel consumption or atmospheric increase estimates, as they have been discussed and reevaluated by several investigators (9-12). Rather, we will start with a discussion of uptake of CO₂ by the ocean. Our conclusion will be that current estimates of ocean uptake are sufficiently firm to exclude the possibility that appreciably more excess CO₂ is dissolved in the sea than has been estimated through the use of existing models (5-8).

This being the case, we will look to the biosphere (living and dead) for resolution of the budgetary contradiction. We conclude that the regrowth of previously cut forests and the enhancement of forest growth resulting from the excess CO₂ in the atmosphere have probably roughly balanced the rate of forest destruction during the past few decades.

Seawater Uptake of Carbon Dioxide

Existing estimates of the amount of fossil fuel CO₂ that has thus far been taken up by the ocean are based entirely on modeling. The secular increase in the dissolved inorganic carbon content of seawater is as yet too small to be measured.

Summary: The fate of fossil fuel carbon dioxide released into the atmosphere depends on the exchange rates of carbon between the atmosphere and three major carbon reservoirs, namely, the oceans, shallow-water sediments, and the terrestrial biosphere. Various assumptions and models used to estimate the global carbon budget for the last 20 years are reviewed and evaluated. Several versions of recent atmosphere-ocean models appear to give reliable and mutually consistent estimates for carbon dioxide uptake by the oceans. On the other hand, there is no compelling evidence which establishes that the terrestrial biomass has decreased at a rate comparable to that of fossil fuel combustion over the last two decades, as has been recently claimed.

In this article we review the elements of the carbon budget and attempt to reconcile these seemingly conflicting views.

The carbon budgeting strategy is as follows. Since 1958, it has been possible to measure the secular trends in the atmospheric CO₂ concentration with sufficient accuracy to permit a quantitative assessment of the buildup of CO₂ in this reservoir (see Fig. 1) (9, 10). We have good records over this time period of the amount of CO₂ released through the combustion of fossil fuels, that is, coal, oil, and gas (see Fig. 2) (11, 12). These inventories show that the CO₂ content of

could lie anywhere in the range from 0.48 to 0.56. We will use the value of 0.52 ± 0.04 adopted by Oeschger *et al.* (8).

The problem is then to account for the missing CO₂. Three possibilities exist. This CO₂ could be stored in the terrestrial biosphere (mainly as wood and soil humus), in the sea (mainly as dissolved inorganic carbon), or in shallow-water sediments (mainly as organic residues). Of these, seawater storage must dominate. The results of ocean uptake modeling (to be described below) indicate that 0.37 ± 0.04 of the fossil fuel CO₂ generated between 1958 and the present has been taken up by the sea. Adding this value to the airborne fraction (0.52 ± 0.04), we obtain a total of

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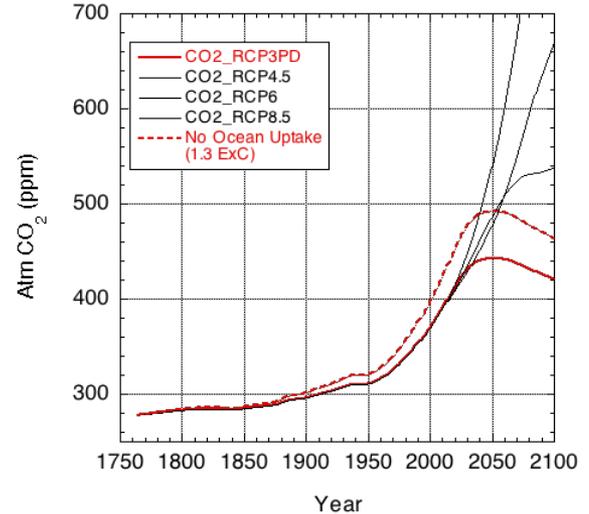
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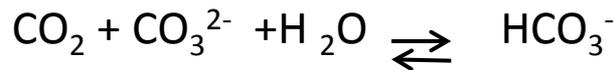
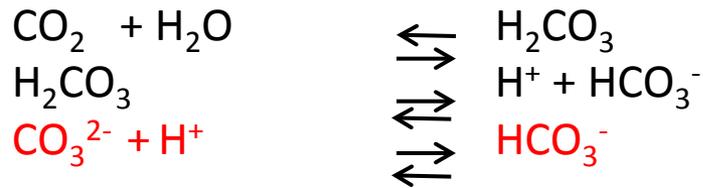
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Why we care about Anthropogenic CO₂ Uptake by the Ocean?

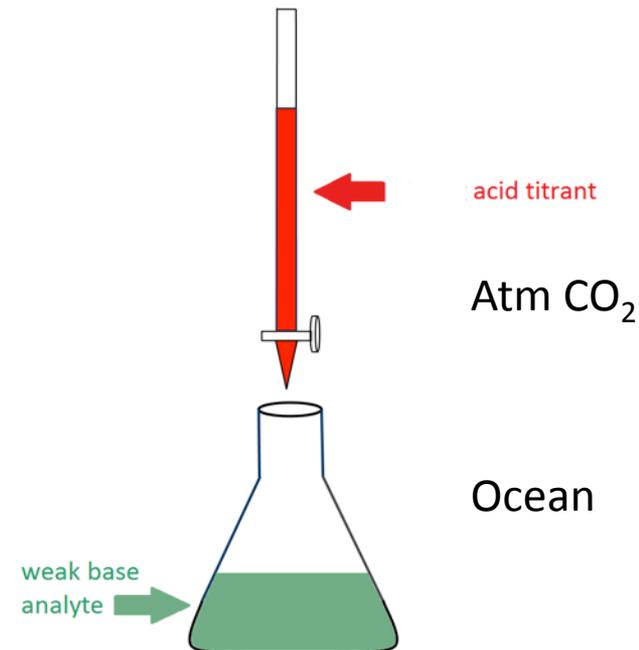
1. What is in the ocean is not in the atmosphere
 25-30 % sequestered by the ocean
 (This ecosystem service has already
 “bought us” 10-15 years)



2. Ocean Acidification (the global ocean titration)



- A. Detrimental to (calcifying) organisms
- B. Decreases ocean CO₂ uptake capacity



Regional Carbon Cycle Assessment and Processes (RECCAP)

([http:// www.globalcarbonproject.org/reccap](http://www.globalcarbonproject.org/reccap))

Three key objectives justify the need for a new assessment of **regional carbon fluxes and their drivers**:

- (1) to provide higher spatial resolution for the global carbon balance with the aim of improving the quantification and understanding of drivers, processes, and hot spot regions essential for predicting the future evolution of any carbon-climate feed-back;
- (2) to address the growing demand for the capacity to measure, report on, and verify the evolution of regional fluxes and the outcomes of climate mitigation policies;
- (3) to respond to the Group on Earth Observations (GEO), a partnership of governments and international organizations, in establishing a global carbon observation strategy

A. Provide syntheses that can be cited in international assessments

B. Place close attention to observational (global) constraints and methodologies

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An International Effort to Quantify Regional Carbon Fluxes

PAGES 81–82

The international carbon cycle research community is currently coordinating the largest, most comprehensive assessment it has ever undertaken: the Regional Carbon Cycle Assessment and Processes (RECCAP; <http://www.globalcarbonproject.org/reccap>). The objective is to establish the mean carbon balance and change over the period 2000–2030 for all subcontinents and ocean basins. The global coverage will provide, for the first time, opportunities to link regional budgets with the global carbon budget. Regional details on or insights into processes driving fluxes have not, to date, been incorporated into efforts addressing the global carbon budget (Canadell et al., 2007; Le Quesle et al., 2009). The consistency check between the sum of regional fluxes and the global budget will be a unique measure of the level of confidence there is in scaling carbon budgets up and down.

Three key objectives justify the need for a new assessment of regional carbon fluxes and their drivers: (1) to provide higher spatial resolution for the global carbon balance with the aim of improving the quantification and understanding of drivers, processes, and hot spot regions essential for predicting the future evolution of any carbon-climate feed-back; (2) to address the growing demand for the capacity to measure, report on, and verify the evolution of regional fluxes and the outcomes of climate mitigation policies; and (3) to respond to the Group on Earth Observations (GEO), a partnership of governments and international organizations, in establishing a global carbon observation strategy (Kinn et al., 2009). This also includes the development of capacity in regions that provide a significant contribution to global carbon fluxes but are poorly covered by current observation networks and expertise.

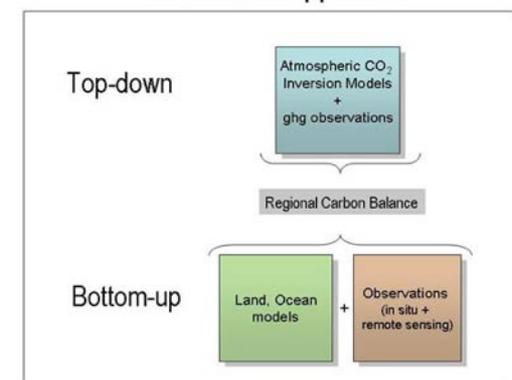
Although these broad objectives have existed over the past decade, RECCAP has been made possible by the experience gained within the European and U.S. carbon budget research programs and by the international coordination role of the Global Carbon Project (GCP) of the Earth System Science Partnership (Canadell et al., 2009).

Of the 14 regions in the RECCAP synthesis, 10 are terrestrial (Africa, the Arctic tundra, Australia, Europe, Russia, East Asia, South Asia, Southeast Asia, Central and South America, and North America) and four are ocean regions (Atlantic and Arctic, Indian, Pacific, and Southern oceans). In addition, eight global syntheses will support the integration of the regional carbon budgets into a global picture and provide the link to the top-down constraints delivered by atmospheric observations and inversion models.

The fundamental test of RECCAP is to establish carbon budgets in each region by comparing and reconciling multiple bottom-up estimates, which include observations and model outputs, with the results of regional top-down atmospheric carbon dioxide (CO₂) inversions. The effort is guided by a methodology that includes diverse data with their uncertainties and a two-tier system that ensures a common approach and a minimum set of analyses performed by all regions (Figure 1). Regions with limited observations and available analyses will build their syntheses upon centrally organized global data sets and global model output (tier 1). These data sets and models include output from 11 atmospheric CO₂ model inversions, six global process-based vegetation models, five ocean carbon models, and one ocean inversion model using both surface partial pressure of CO₂ (pCO₂) and ocean carbon cross sections. Additional input data include emissions from vegetation fires derived from satellite observations and modeling, emissions from fossil fuel and land use change, and a land CO₂ flux data-driven model for global gross primary production and net ecosystem production.

Regions with dense observational networks and preexisting data syntheses and compilations will use, and appropriately weigh, these regional estimates against those from global products (tier 2). Estimates include output from regional models, forest biomass inventories, soil carbon surveys, well-sampled ocean gyres, as well as regionally calibrated remote sensing products and data sets such as biomass, ocean column inventories of anthropogenic carbon and surface pCO₂, and hydrological quantities.

RECCAP's Approach



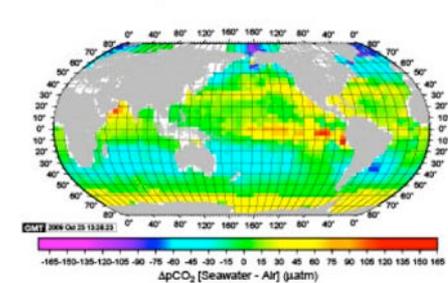
Global Ocean Carbon Uptake: Tools

$$F = k_s \Delta p\text{CO}_2, F = a \langle u^2 \rangle \Delta p\text{CO}_2$$

1. $p\text{CO}_2$ climatology

“If this cross check is ever to be effectively carried out, a decade of preparation and measurement will be required. It is a complex task” Broecker et al. Science 1979

Climatological $\Delta p\text{CO}_2$ (Seawater - Air) for August 2000 (Rev Oct 09)



2. Ocean biogeochemistry ocean general circulation models (OBGCMs)

Abbreviation	Name	Key Reference	Years used
BER	MICOM-HAMOCv1	Assmann et al. (2010)	1990 to 2009
CSI	CSIRO-BOBGCM	Matear and Lenton (2008)	1990 to 2009
BEC	CCSM-BEC	Doney et al. (2009a, b)	1990 to 2009
ETH _{k15} ^b	CCSM-ETH _{k15}	Graven et al. (2012)	1990 to 2007
ETH _{k19} ^c	CCSM-ETH _{k19}	–	1990 to 2007
LSC	NEMO-PISCES	Aumont and Bopp (2006)	1990 to 2009
UEA _{NCEP} ^d	NEMO-PlankTOM5 _{NCEP}	Buitenhuis et al. (2010)	1990 to 2009
UEA _{ECMWF} ^e	NEMO-PlankTOM5 _{ECMWF}	–	1990 to 2009
UEA _{CCMP} ^f	NEMO-PlankTOM5 _{CCMP}	–	1990 to 2009

(9 model runs, 4 lineages)

3. $\Delta p\text{CO}_2$ empirical (interannual variability directly or indirectly controlled by temperature, Park, Lee, Wanninkhof et al.)

4. Ocean inverse models

5. Atmospheric inverse models

6. Atm constraints O_2/N_2

8. Interior transient tracer based

Global Ocean Carbon Uptake: Magnitude, Variability and Trends

- A. Look at time period 1990-2009 (consistent global forcing)
- B. With consistent approaches the global flux for 2000 is:

Median sea-air anthropogenic CO₂ fluxes for the different approaches centered on year 2000.

Approach	Anthr. CO ₂ flux	Uncertainty	IAV ^e	SAV ^f	Trend
	Pg C yr ⁻¹	Pg C yr ⁻¹	Pg C yr ⁻¹		(Pg C yr ⁻¹) decade ⁻¹
Empirical	-2.0	±0.6 ^a	0.20	0.61	-0.15
OBGCM	-1.9	±0.3 ^b	0.16	0.38	-0.14
Atm. Inversion	-2.1	±0.3 ^c	0.40	0.41	-0.13
Ocean Inversion	-2.4	±0.3 ^d			-0.5 ^j
Interior (Green function) ^g	-2.2	±0.5	-	-	-0.35
O ₂ /N ₂ ^h	-2.2	±0.6			
O ₂ /N ₂ ⁱ	-2.2	±0.7			
	-2.5				

Best estimate 2000 = 2.0 ± 0.4 Pg C yr⁻¹

Global Ocean Carbon Uptake: Magnitude, Variability and Trends

Appreciable differences within approaches, in part, due to differing inputs as mundane as surface area of the ocean

Table A1. Twenty-year mean sea-air anthropogenic CO₂ fluxes from the OGCM and the adjusted flux normalizing for area (Pg C yr⁻¹).

Abbreviation	OGCM	Area (10 ¹³ m ²) ^b	Provided flux	Adjusted flux ^c
UEA _{NCEP}	NEMO-PlankTOM5 _{NCEP}	35.0	-2.08	-2.03
UEA _{ECMWF}	NEMO-PlankTOM5 _{ECMWF}	35.0	-2.48	-2.46
UEA _{CCMP}	NEMO-PlankTOM5 _{CCMP}	35.0	-2.16	-2.12
LSC	NEMO-PISCES	31.9	-1.93	-2.03
CSI	CSIRO-BOGCM	34.3	-1.93	-2.00
BER	MICOM-HAMOCCv1	36.1	-2.58	-2.54
BEC	CCSM-BEC	30.6	-1.39	-1.71
ETH _{k15}	CCSM-ETH _{k15} ^a	33.0	-1.49	-1.67
ETH _{k19}	CCSM-ETH _{k19} ^a	33.0	-1.53	-1.73
Median (6-model runs) ^d			-1.93	-2.01
Average			-1.90	-1.99
St. dev. (6-model runs) ^d			0.43	0.31

^aFor the period of 1990-2007

^bThe areas used in the models. They differ slightly from those described in the model documentation due to the transposition of the original grid area to 1° × 1° grid area

^cUsing the areas as provided in the OIP with a total surface area of 34.00 × 10¹³ m² (35.87 total-1.87 (ice cover) × 10¹³ m²) (see Table A2)

^dUsing UEA_{NCEP}, LSC, CSI, BER, BEC, and ETH_{k15}

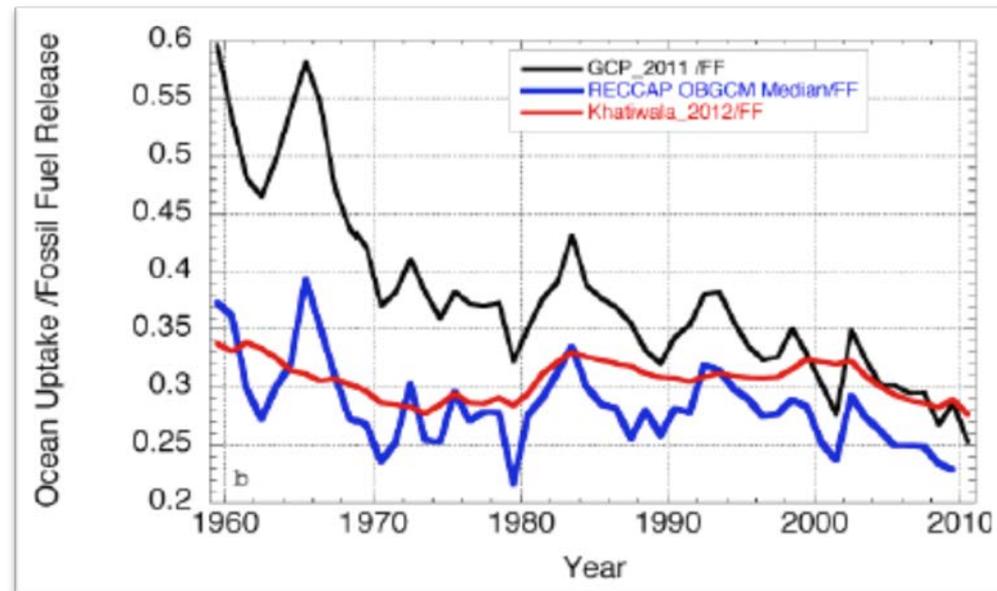
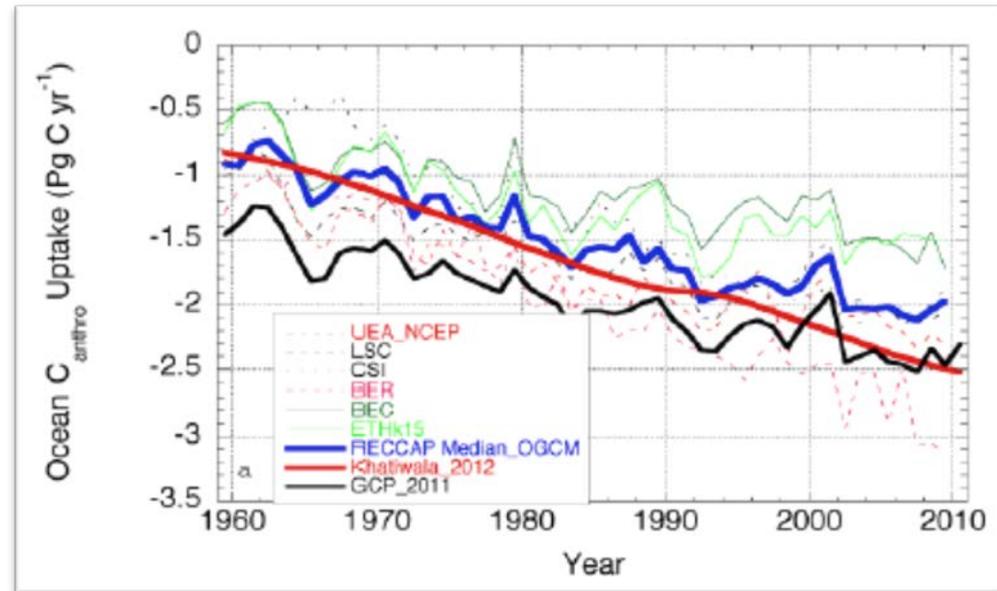
Global Ocean Carbon Uptake: Magnitude, Variability and Trends

50-year model runs using different types of models show increases in uptake. Models based on ocean interior measurements show appreciably greater trends in uptake

“Is the ocean sink saturating?”

Fraction of FF CO₂ taken up by ocean differs dramatically between methods with interior approaches showing less change (ie. The fraction of FF taken up by the ocean is nearly unchanged)

50-year records of environmental forcing used for OBGCM are not reliable

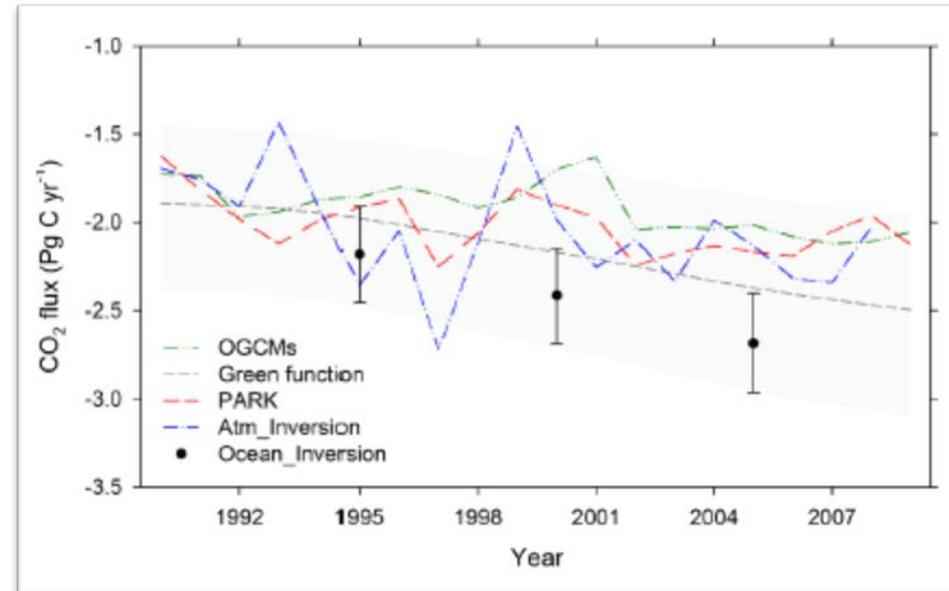


Global Ocean Carbon Uptake: Magnitude, Variability and Trends

20-year RECCAP interval

Methods relying on surface flux information show:

- A. Smaller trend in absolute uptake
- B. Significant variability that will affect trends over short time periods
- C. Differences between approaches is the same as for 50-year record



Median sea-air anthropogenic CO₂ fluxes for the different approaches centered on year 2000.

Approach	Anthr. CO ₂ flux Pg C yr ⁻¹	Uncertainty Pg C yr ⁻¹	IAV ^e Pg C yr ⁻¹	SAV ^f Pg C yr ⁻¹	Trend (Pg C yr ⁻¹) decade ⁻¹
Empirical	-2.0	±0.6 ^a	0.20	0.61	-0.15
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O ₂ /N ₂ ^h	-2.2	±0.6			
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Global Ocean Carbon Uptake: Magnitude, Variability and Trends

Concluding remarks:

Global ocean uptake (2000) :	2.0 ± 0.4	Pg C yr ⁻¹	“best estimate”
Global subannual variability :	0.5 ± 0.2	Pg C yr ⁻¹	“Av. OBGCM, Emp., Atm Inverse”
Global interannual variability:	0.2	Pg C yr ⁻¹	“best estimate”
Global trends:	0.15	Pg C yr ⁻¹	“best estimate”

Uptake decreasing (as % of total ff release) but magnitude uncertain:

- The ocean cannot keep up with rate of fossil fuel release
- The buffer capacity of the ocean is decreasing

Rate of uptake decreasing much faster in OBGCMs and empirical approaches compared to inventory based estimates:

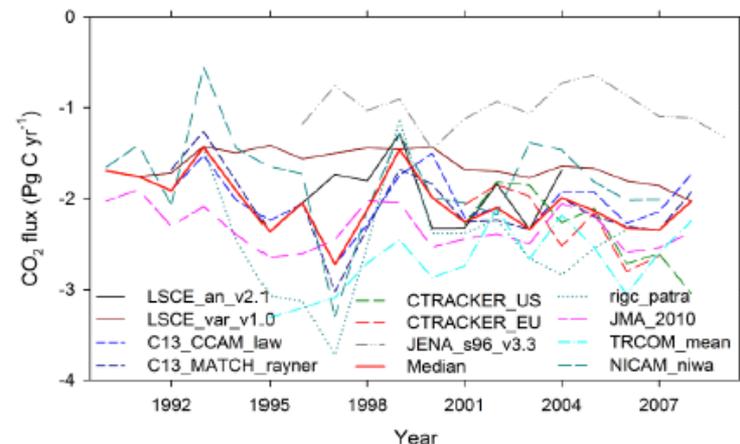
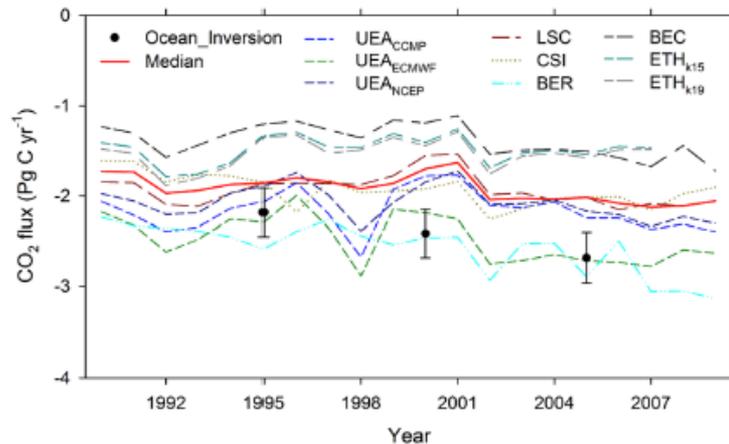
- In last two decades ocean circulation, biogeochemistry and wind patterns have changed decreasing rate of uptake

Global Ocean Carbon Uptake: Magnitude, Variability and Trends

Interannual variability

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Global Ocean Carbon Uptake: Magnitude, Variability and Trends

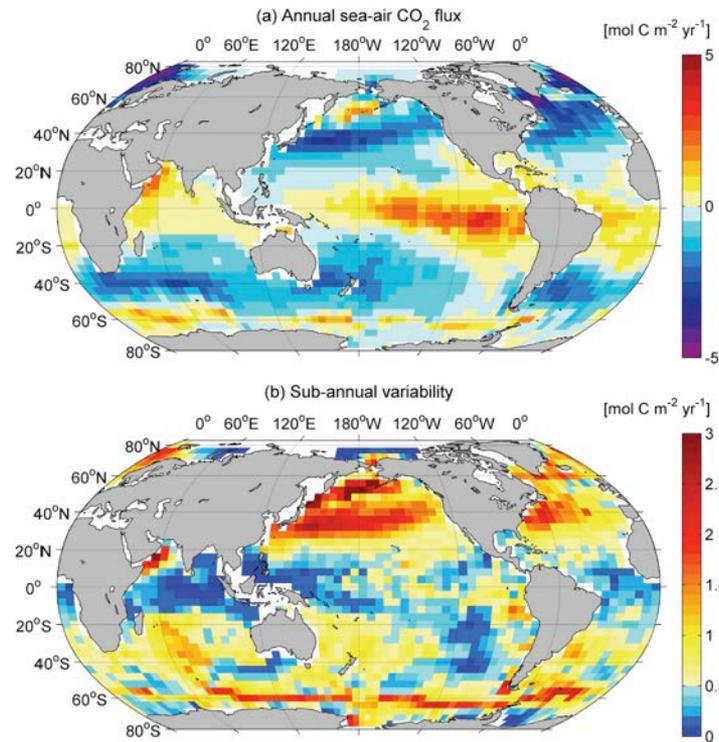
Sub-annual (seasonal) variability

Median sea–air anthropogenic CO₂ fluxes for the different approaches centered on year 2000.

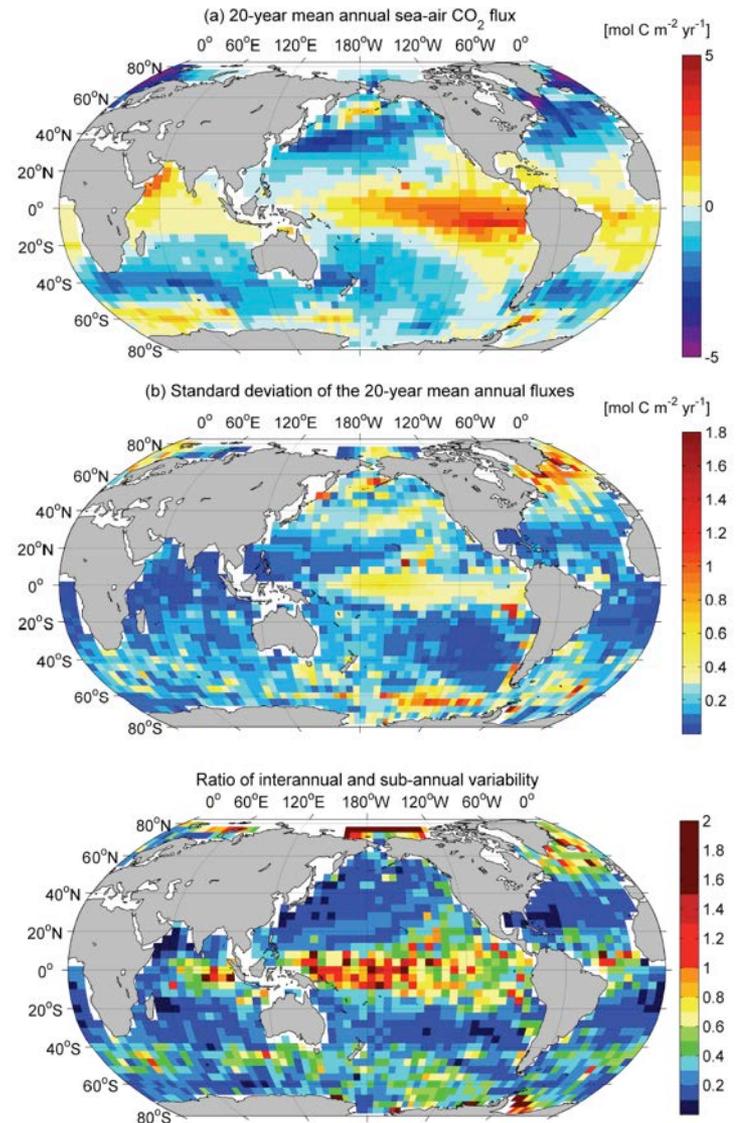
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Global Ocean Carbon Uptake: Magnitude, Variability and Trends

Seasonal



Interannual



Interannual variability controlled by large scale climate reorganizations (ENSO, NAI, SAM)

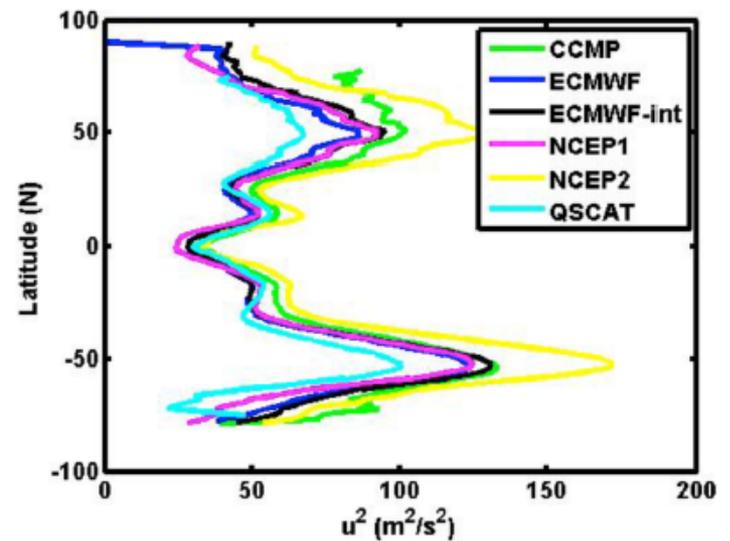
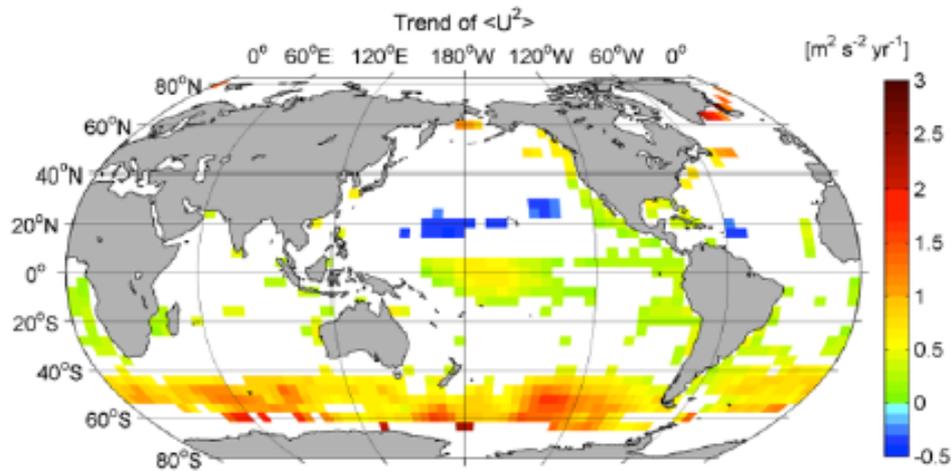


Fig. 4. Global pattern of the temporal trend of the second moment of surface wind speed $\langle U^2 \rangle$ for the 20 yr CCMP wind product (1990–2009). Regions where trends are at less than 90 % confidence level are masked.

Part of the SOCAT effort

