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

Results from a RECCAP synthesis

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Biogeosciences, 10, 1983-2000 (2013) doi:10.5194/bg-10-1983-2013

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Results from a RECCAP synthesis

<u>Outline</u>

-What we (should) know about anthropogenic carbon uptake by the ocean.
-Why should we care about anthropogenic CO_2 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 CO_2 is dissolved in the sea then has been estimated through the use of existing models"
2. The static capacity of CO_2 uptake by the ocean is huge (≈ 90 % of excess CO_2)
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

*1979: Atm CO_2 = 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 (CO_2) (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.

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 CO_2 concentration with sufficient accuracy to permit a quantitative assessment of the buildup of CO_2 in this reservoir (see Fig. 1) (9, 10). We have good records over this time period of the amount of CO_2 released through the combustion of fossil fuels, that is, coal, oil, and gas (see Fig. 2) (11, 12). These inventories show that the CO_2 content of the atmosphere has risen by about one-half as much as would be the case if all the CO_2 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 CO_2 increase, the actual value for the airborne fraction of CO_2 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).

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The problem is then to account for the missing CO_2. Three possibilities exist. This CO_2 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 CO_2 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 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 CO_2 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 CO_2 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 CO_2) + (forest cutback CO_2) − (CO_2 taken up by the ocean) − (CO_2 taken up in organic residues)] then lies in the range from one-quarter to the total amount of fossil fuel CO_2 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 CO_2 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 CO_2 by the ocean. Our conclusion will be that current estimates of ocean uptake are sufficiently firm to exclude the possibility that appreciably more excess CO_2 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 CO_2 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 CO_2 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 mea-

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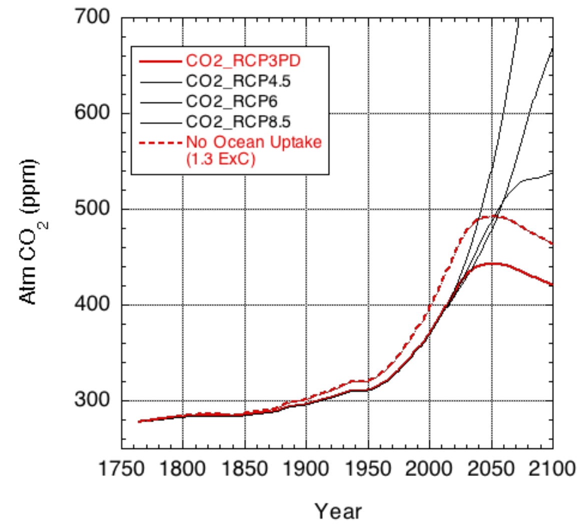
Why we care about Anthropogenic CO_2 Uptake by the Ocean?

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)



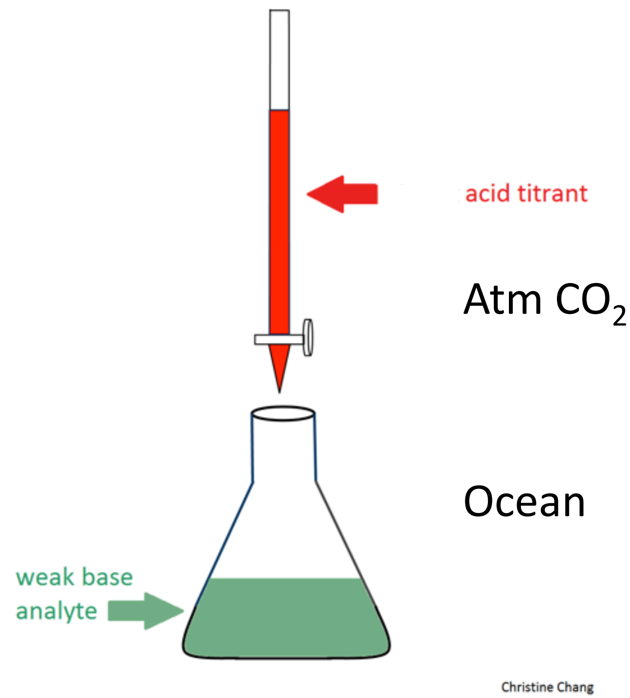
2. Ocean Acidification (the global ocean titration)

$$CO_2 + H_2O \rightleftarrows H_2CO_3$$
$$H_2CO_3 \rightleftarrows H^+ + HCO_3^-$$
$$CO_3^{2-} + H^+ \rightleftarrows HCO_3^-$$

$$CO_2 + CO_3^{2-} + H_2O \rightleftarrows HCO_3^-$$

A. Detrimental to (calcifying) organisms

B. Decreases ocean CO_2 uptake capacity



Regional Carbon Cycle Assessment and Processes (RECCAP)

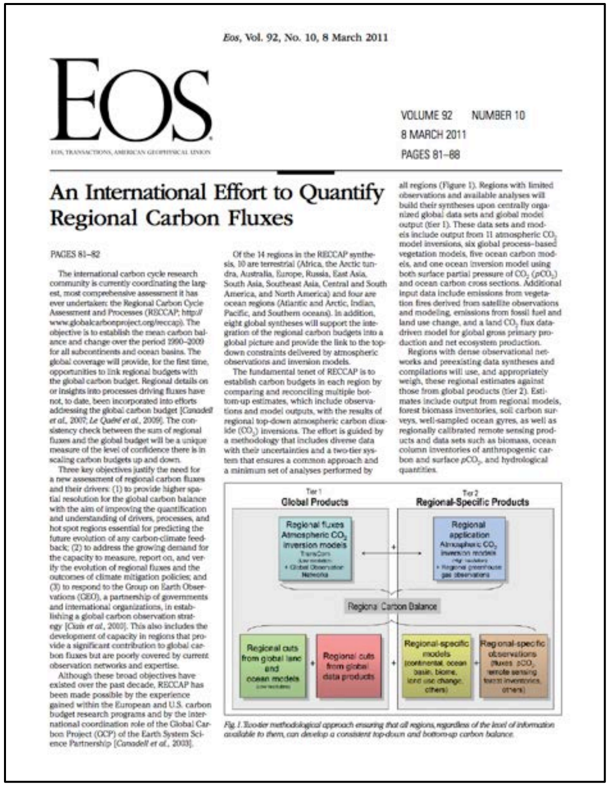
(http:// www.globalcarbonproject.org/reccap)

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


Eos, Vol. 92, No. 10, 8 March 2011

EOS

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An International Effort to Quantify Regional Carbon Fluxes

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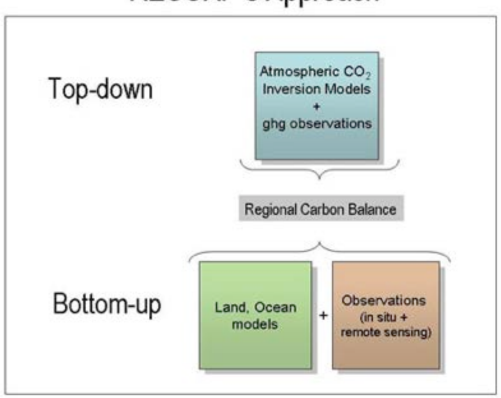
Fig. 1. Two-tier methodological approach ensuring that all regions, regardless of the level of information available to them, can develop a consistent top-down and bottom-up carbon balance.

A. Provide syntheses that can be cited in international assessments

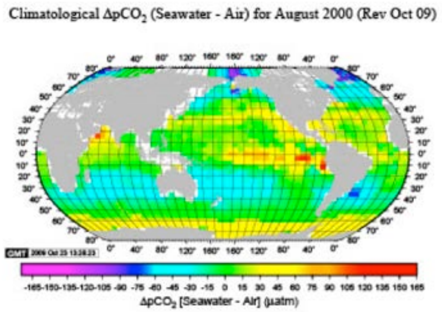
B. Place close attention to observational (global) constraints and methodologies

RECCAP's Approach



Global Ocean Carbon Uptake: Tools

$F = k\ s\ \Delta pCO2$, $F = a \langle u^2 \rangle \Delta pCO2$



1. pCO_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

2. **Ocean biogeochemistry ocean general circulation models (OBGCMs)**

Abbreviation	Name	Key Reference	Years used
BER	MICOM-HAMOCCv1	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^{b}_{k15}	$CCSM\text{-}ETH_{k15}$	Graven et al. (2012)	1990 to 2007
ETH^{c}_{k19}	$CCSM\text{-}ETH_{k19}$	–	1990 to 2007
LSC	NEMO-PISCES	Aumont and Bopp (2006)	1990 to 2009
UEA^{d}_{NCEP}	$NEMO\text{-}PlankTOM5_{NCEP}$	Buitenhuis et al. (2010)	1990 to 2009
UEA^{e}_{ECMWF}	$NEMO\text{-}PlankTOM5_{ECMWF}$	–	1990 to 2009
UEA^{f}_{CCMP}	$NEMO\text{-}PlankTOM5_{CCMP}$	–	1990 to 2009

(9 model runs, 4 lineages)

3. **ΔpCO_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 CO_2 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]	−2.5	±0.7			

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 CO_2 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

[a]For the period of 1990-2007

[b]The 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

[c]Using the areas as provided in the OIP with a total surface area of 34.00 × 10^{13} m^2 (35.87 total-1.87 (ice cover) × 10^{13} m^2) (see Table A2)

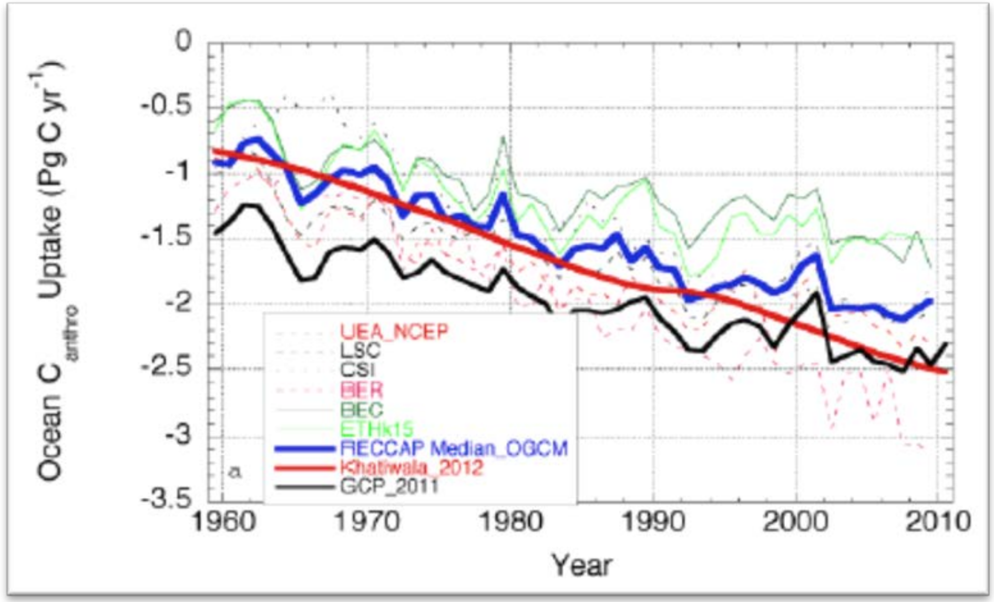
[d]Using UEA_{NCEP}, LSC,CSI, BER, BEC, and ETH_{k15}

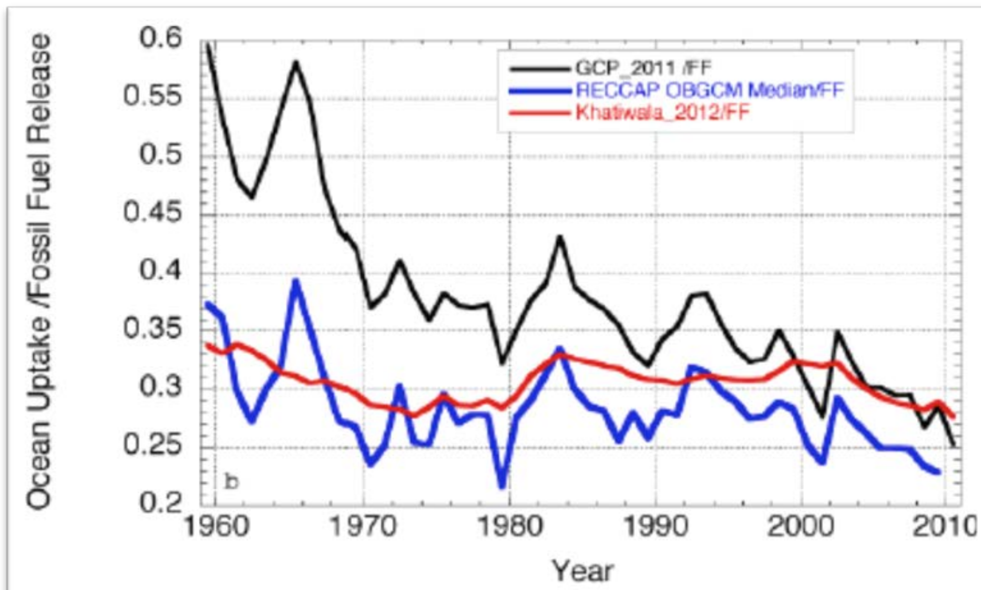
Global Ocean Carbon Uptake: Magnitude, Variability and **Trends**

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 CO_2 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

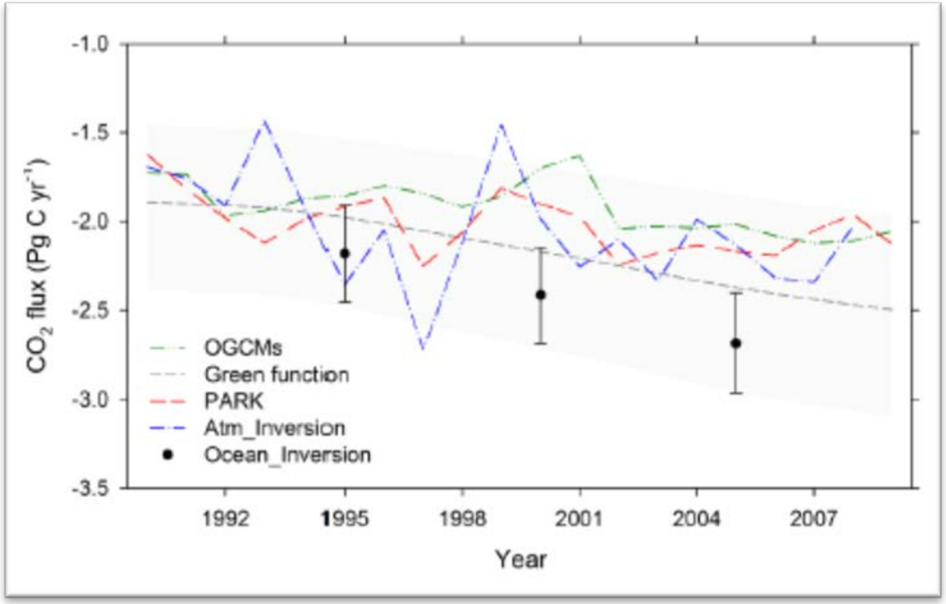
20-year RECCAP interval

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 CO_2 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
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O_2/N_2[i]	−2.5	±0.7			

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^{-}	"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

Median sea–air anthropogenic CO_2 fluxes for the different approaches centered on year 2000.

Approach	Anthr. CO_2 flux	Uncertainty	IAV[e]	SAV[f]	Trend
	$\mathrm{Pg\,C\,yr^{-1}}$	$\mathrm{Pg\,C\,yr^{-1}}$	$\mathrm{Pg\,C\,yr^{-1}}$		$(\mathrm{Pg\,C\,yr^{-1}})$ $\mathrm{decade^{-1}}$
Empirical	−2.0	±0.6[a]	0.20	0.61	−0.15
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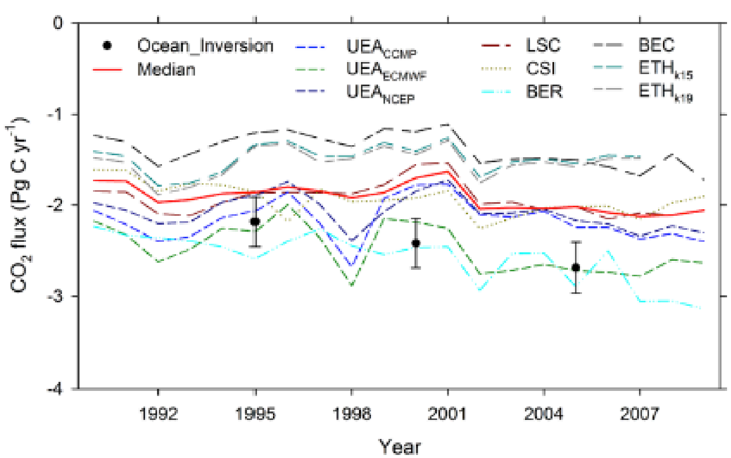

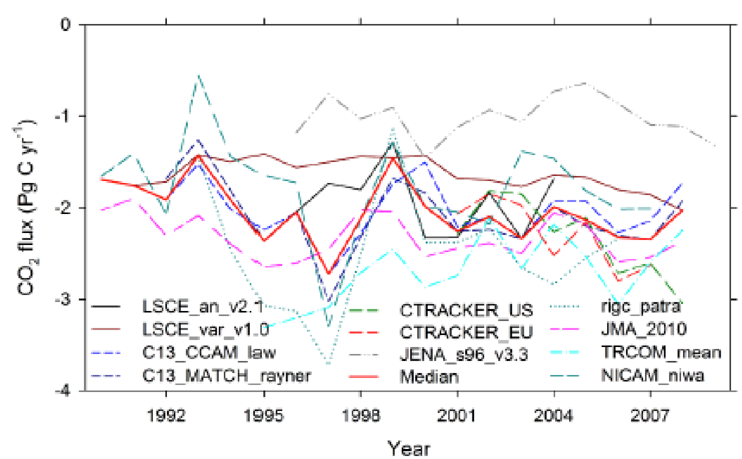

Global Ocean Carbon Uptake: Magnitude, **Variability** and Trends

Sub-annual (seasonal) variability

Median sea–air anthropogenic CO_2 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
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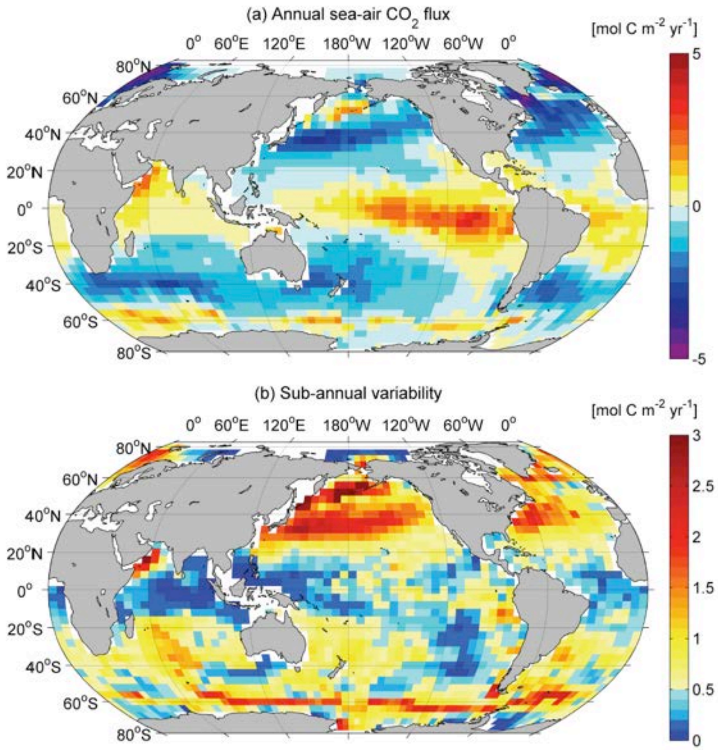
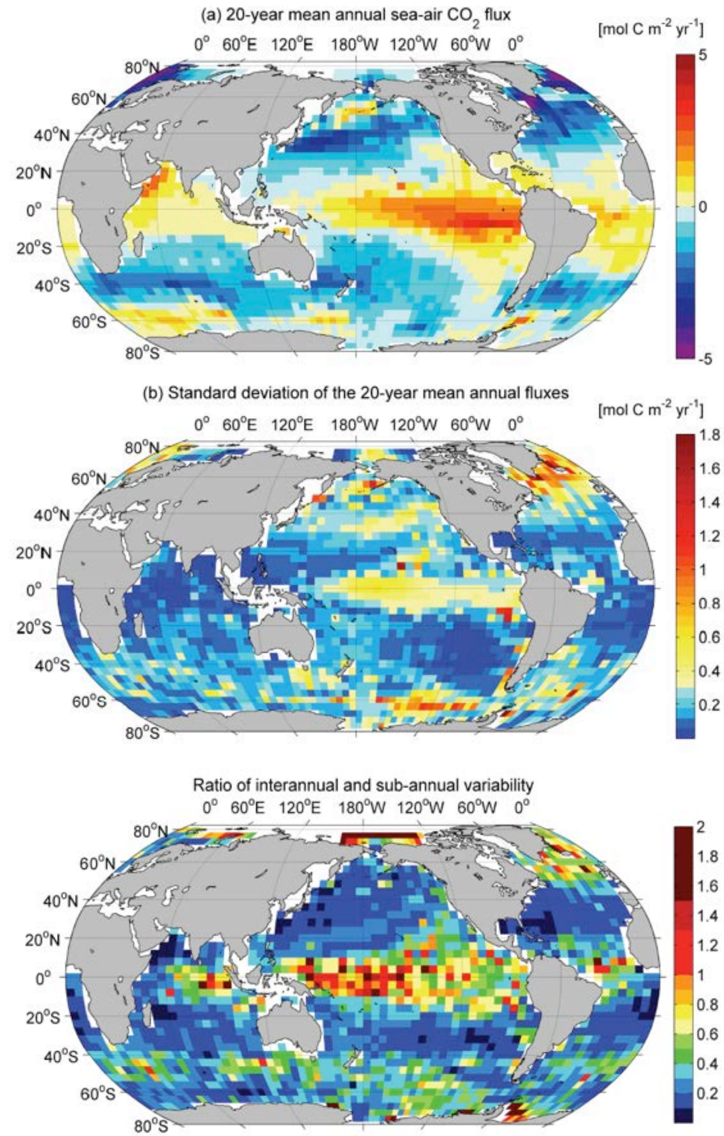
Ocean Inversion	−2.4	±0.3[d]			−0.5[j]
Interior (Green function)[g]	−2.2	±0.5	–	–	−0.35
O_2/N_2^h	−2.2	±0.6			
O_2/N_2^i	−2.5	±0.7			

Global Ocean Carbon Uptake: Magnitude, Variability and Trends

Seasonal



Interannual



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

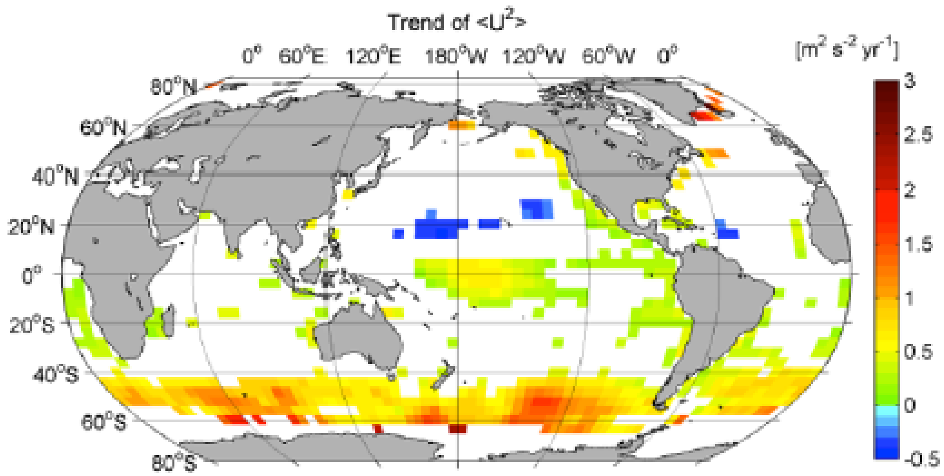
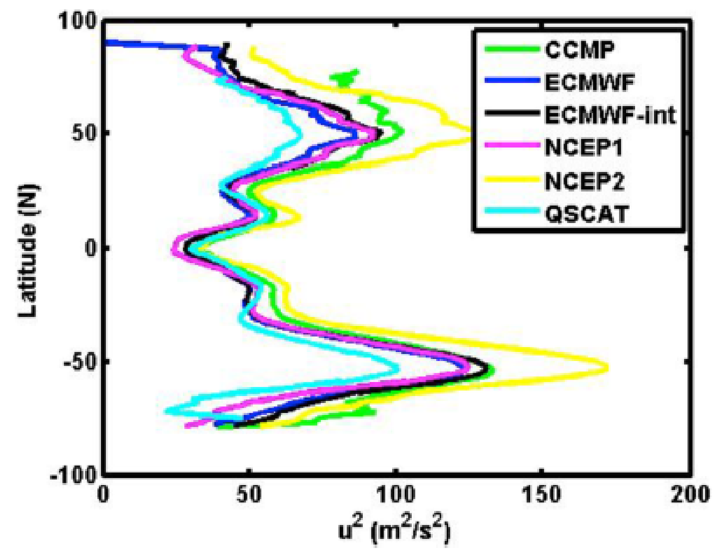


Fig. 4. Global pattern of the temporal trend of the second moment of surface wind speed $< U^2 >$ for the 20 yr CCMP wind product (1990–2009). Regions where trends are at less than 90 % confidence level are masked.



Part of the SOCAT effort