The Ocean Carbon Cycle

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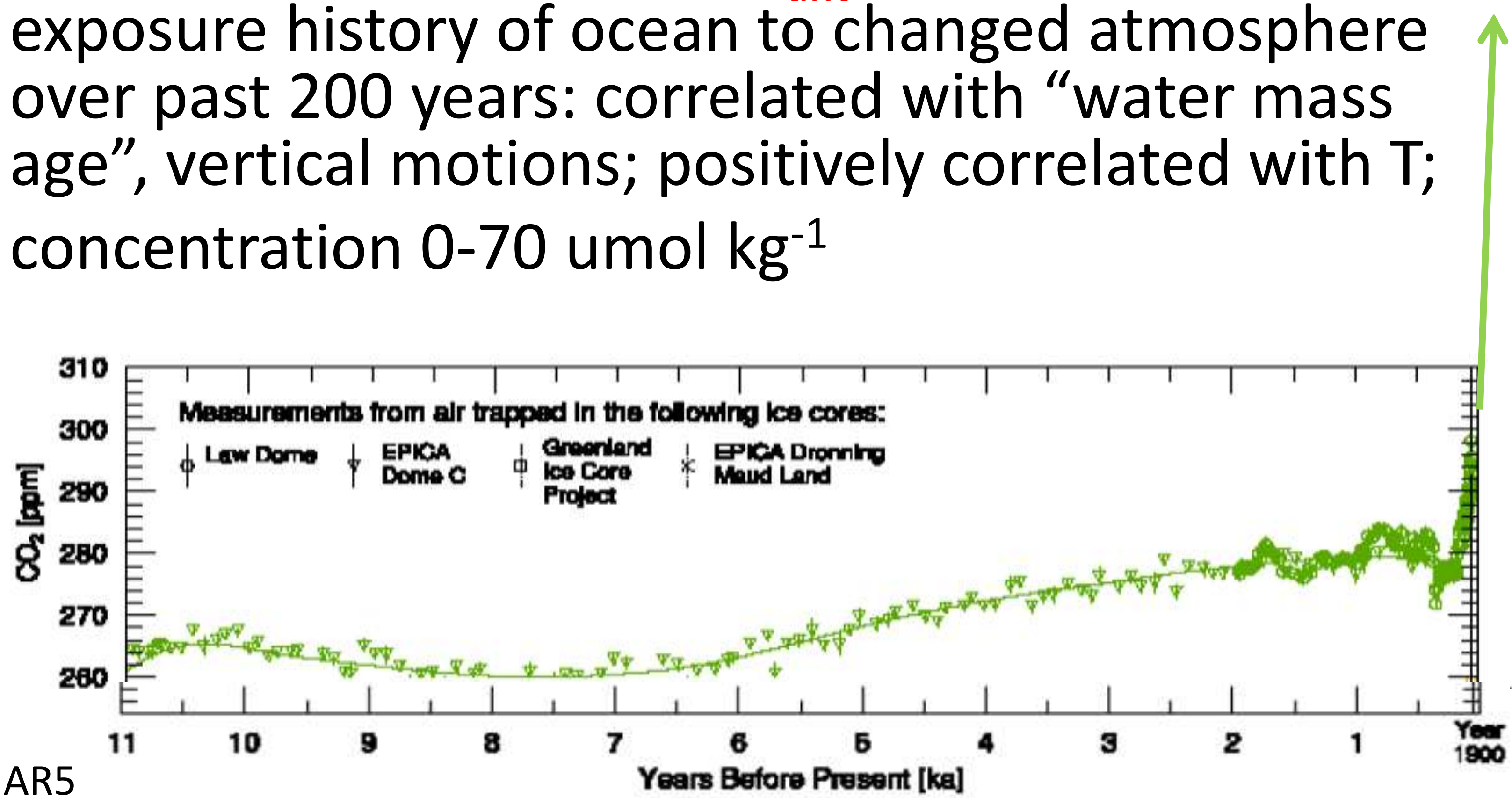
Premise: There are Two Flavours (or Colours) of Carbon

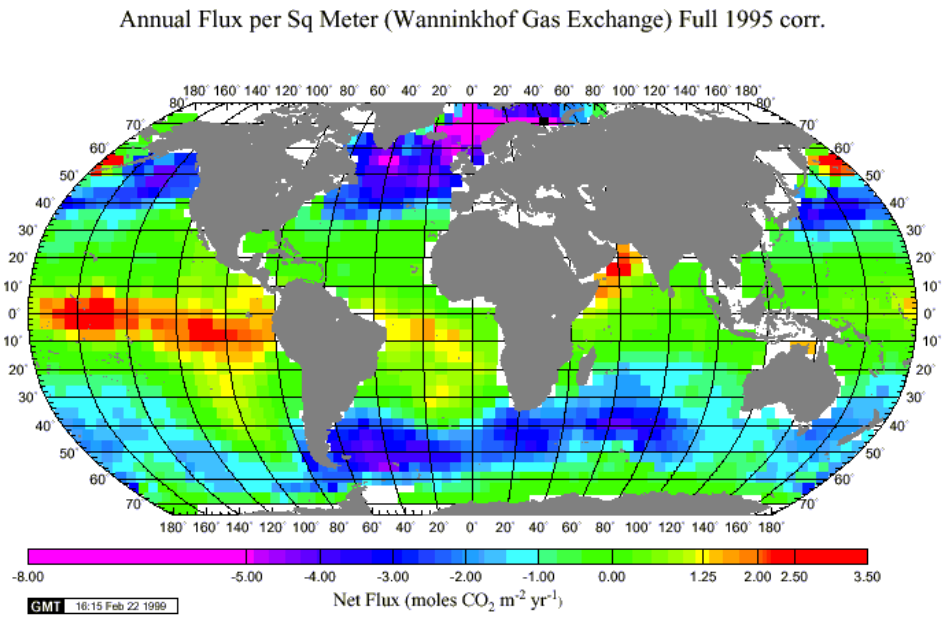
- **Natural carbon** (ocean variability inversely correlated with T; O_2)
  concentration c. 2000 umol kg^{-1}

- **Anthropogenic carbon or C_{ant}** (depends on exposure history of ocean to changed atmosphere over past 200 years: correlated with "water mass age", vertical motions; positively correlated with T;
  concentration 0-70 umol kg^{-1}



IPCC, AR5

Uptake of Anthropogenic or Excess CO_2 (C_{ant})



Takahashi et al.

The uptake of Excess CO_2 is a 'Perturbation' of the steady-state, preindustrial air-sea CO_2 flux (this was determined by physical and biogeochemical controls).

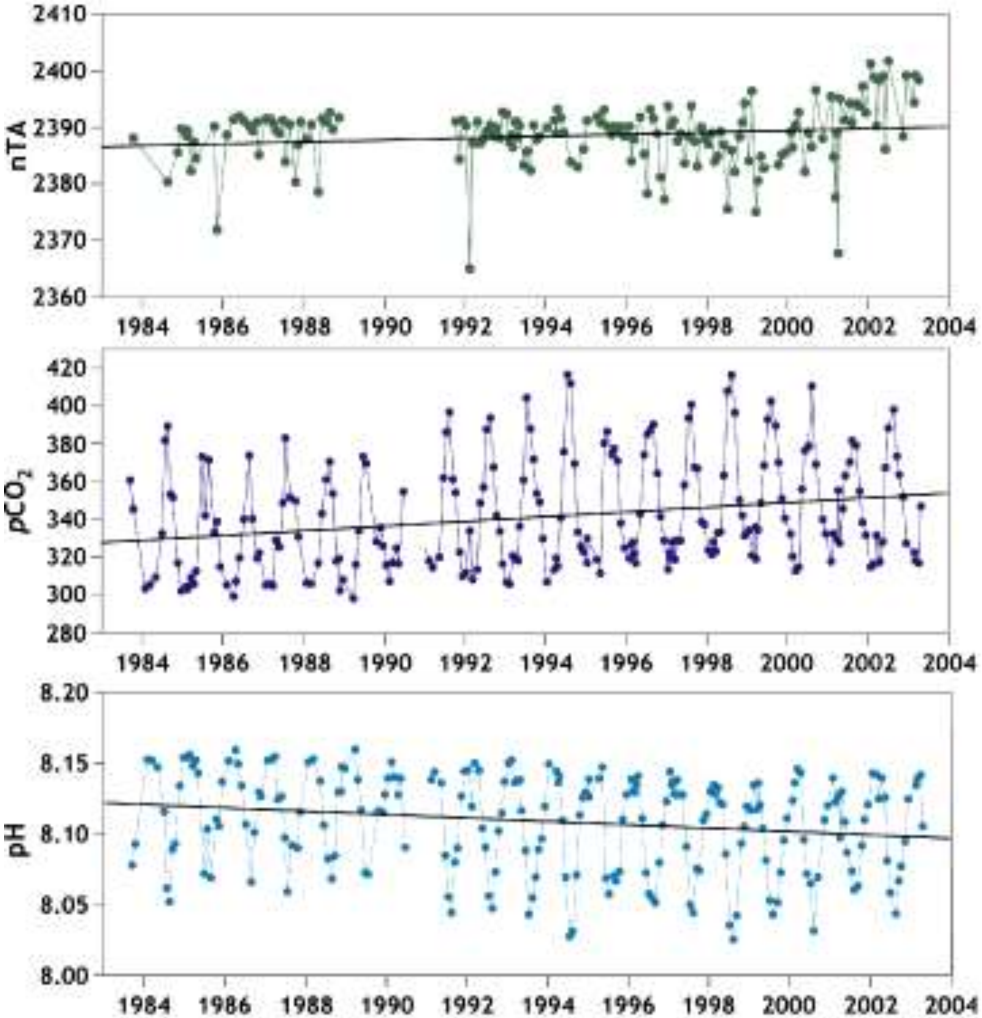
As pCO_2 (atmos) increases:

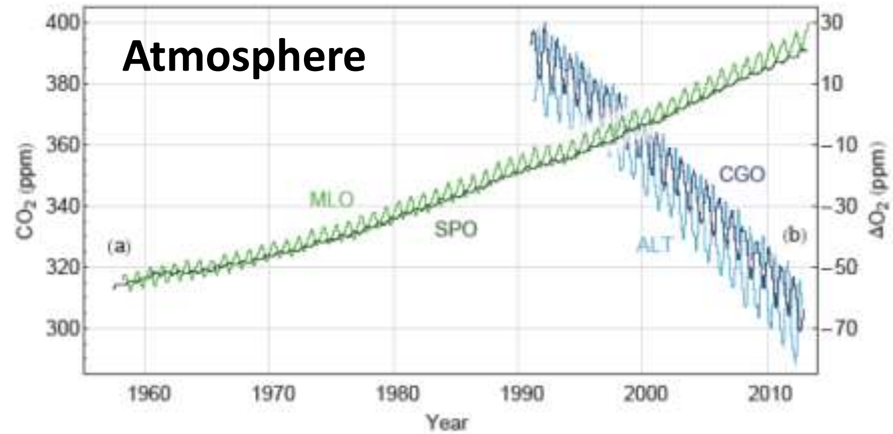
CO_2 SINK regions become stronger
CO_2 SOURCE regions become weaker

Both cause C_T to increase with time ('storage of Excess CO_2'

Note: Oceanic biological processes do not directly drive Excess CO_2 uptake by the ocean. In contrast to land, carbon is not a biolimiting element in the ocean. (But 'indirect' feedback effects may be very important)

A Detective Story….





IPCC, AR5

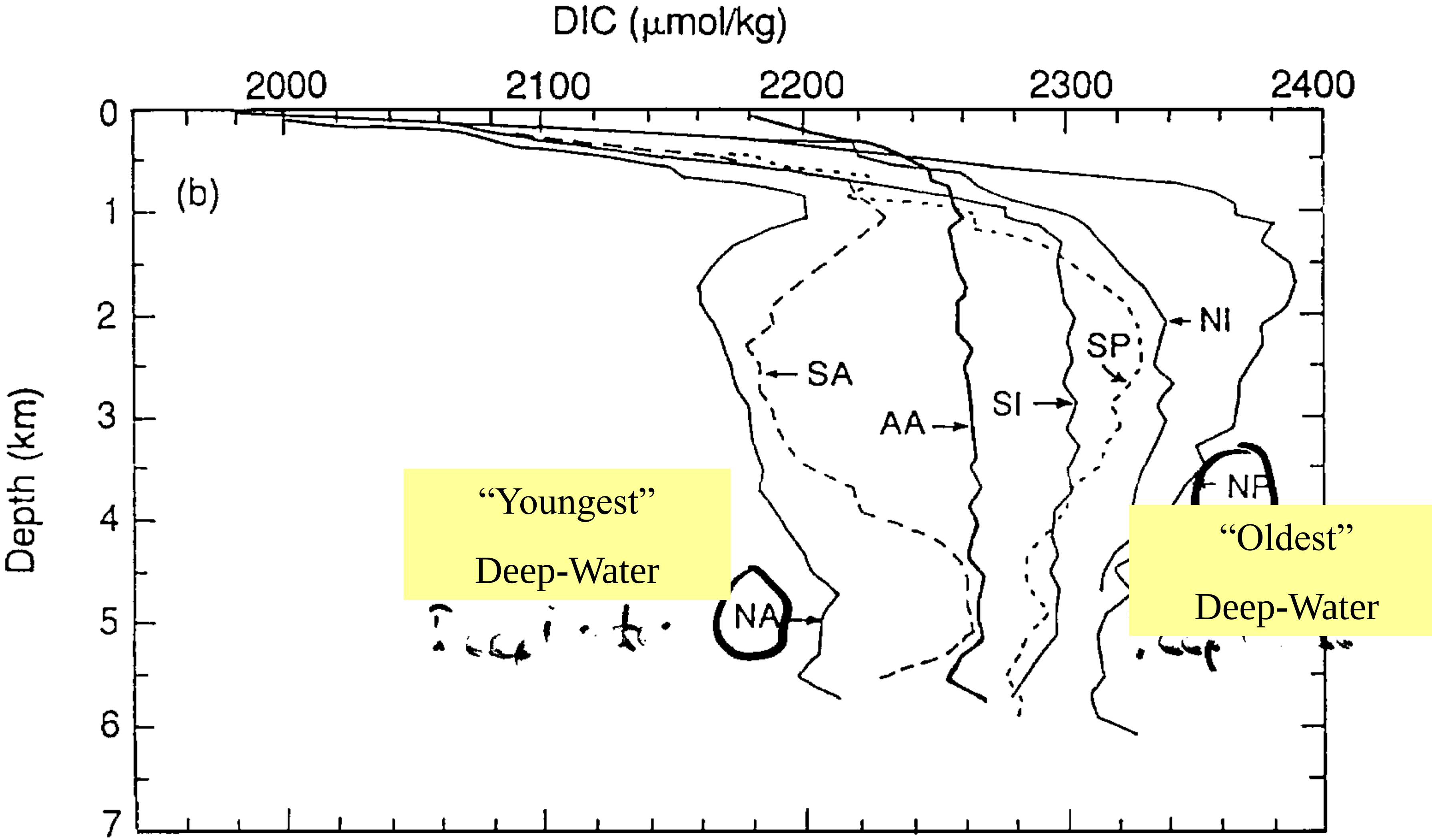
The Surface Ocean tends to track atmospheric pCO_2

Bermuda time-series:
a quiet, low productivity part of the ocean

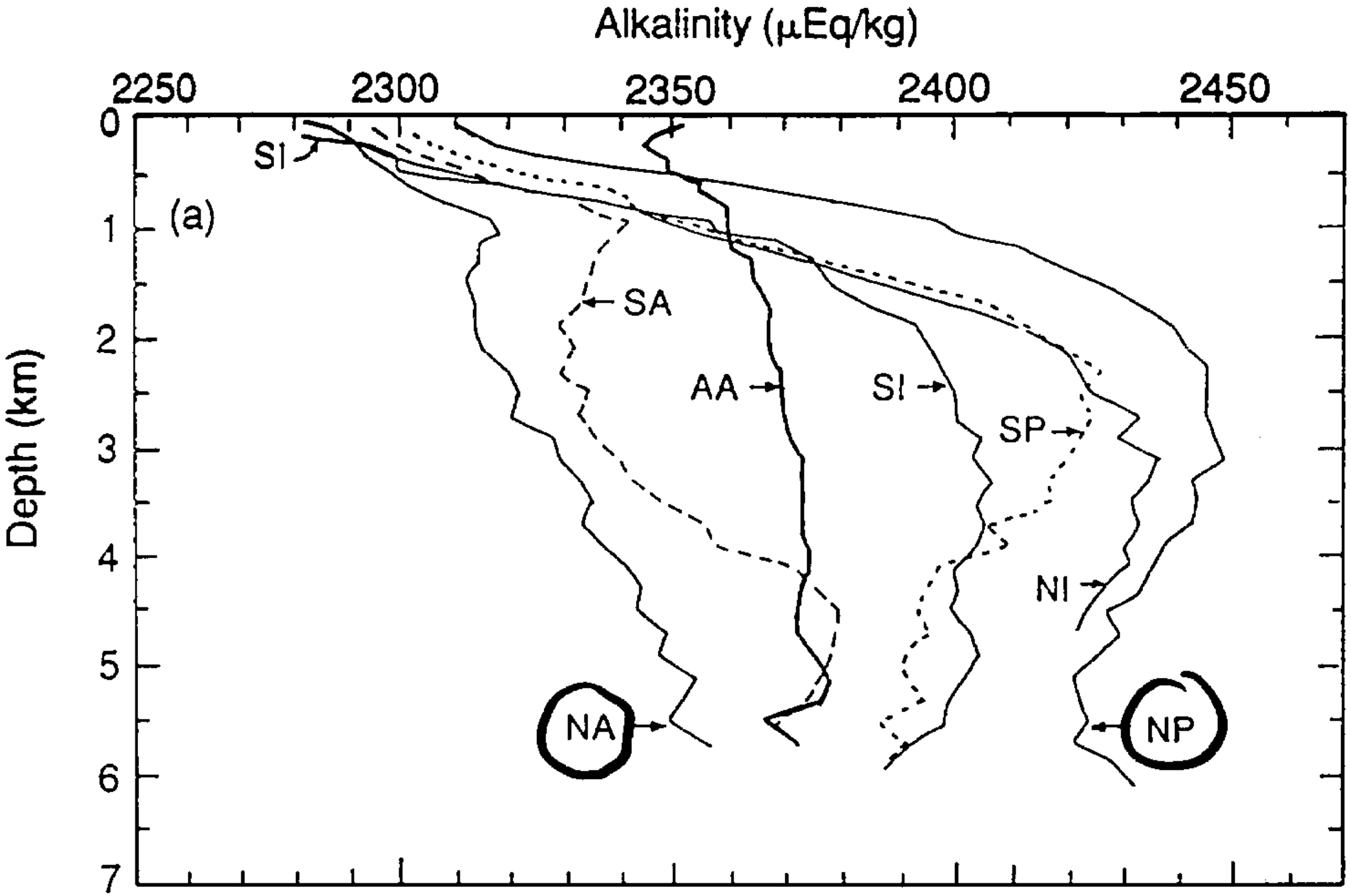
→detection should be easy?

Nick Bates, BBSR

The Deep Ocean….. Natural geographical variability

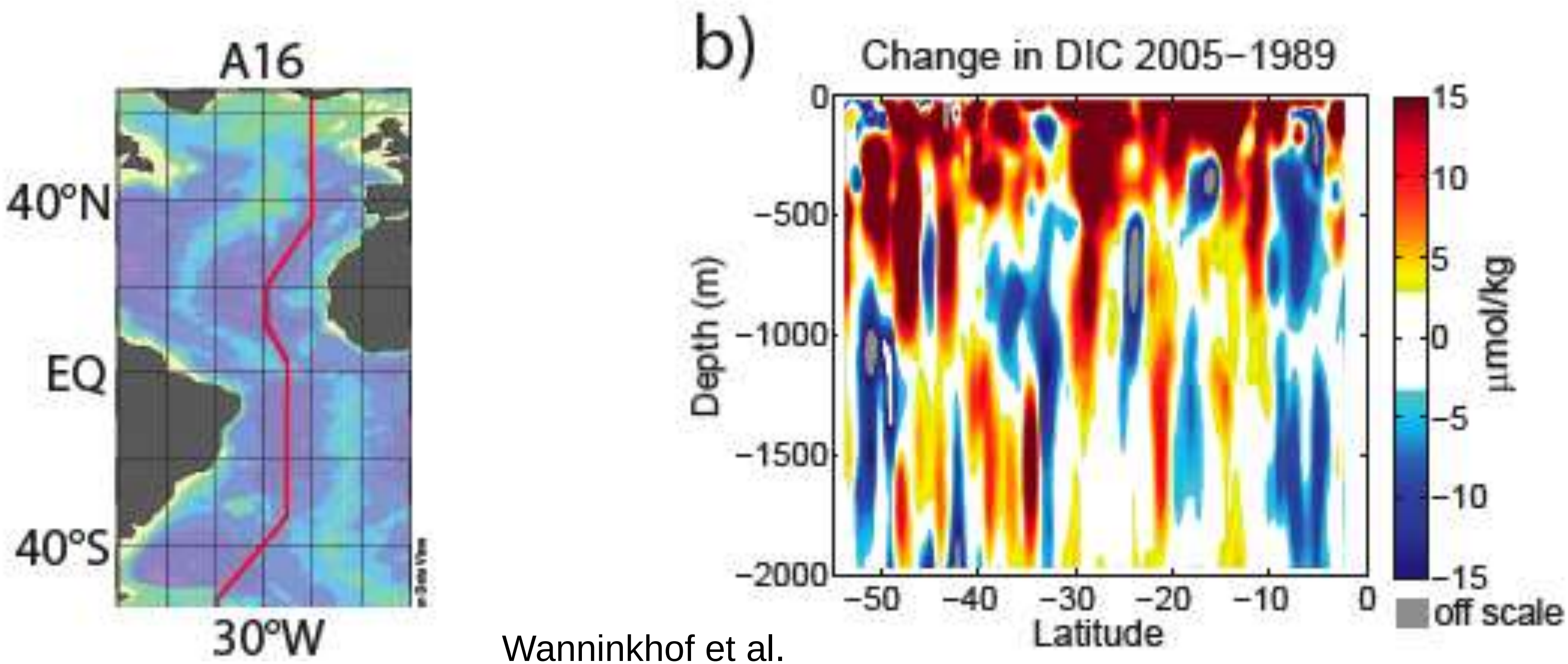


Alkalinity….. In steady-state???



Deep Ocean:
The C_{ant} increase is small
and masked by natural variability….

c.50% of the CO_2 that mankind has released is dissolved in the oceans (somewhere)
But it is hard to find....

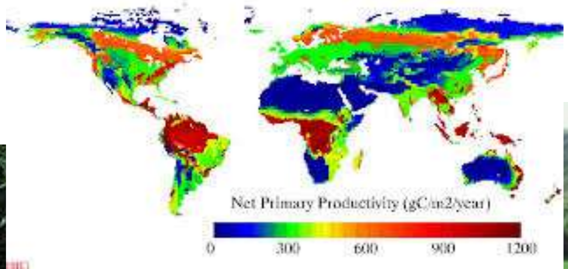


Wanninkhof et al.

Simple, direct comparison of CO_2 concentrations measured decades apart don‘t reveal a clear increase
(Anthropogenic change swamped by variability associated with biological processes coupled with circulation / eddy variability)

But we CAN do it....

(and it's easy compared to keeping track of carbon on land....)



Remember: the Two Flavours (or Colours) of Carbon

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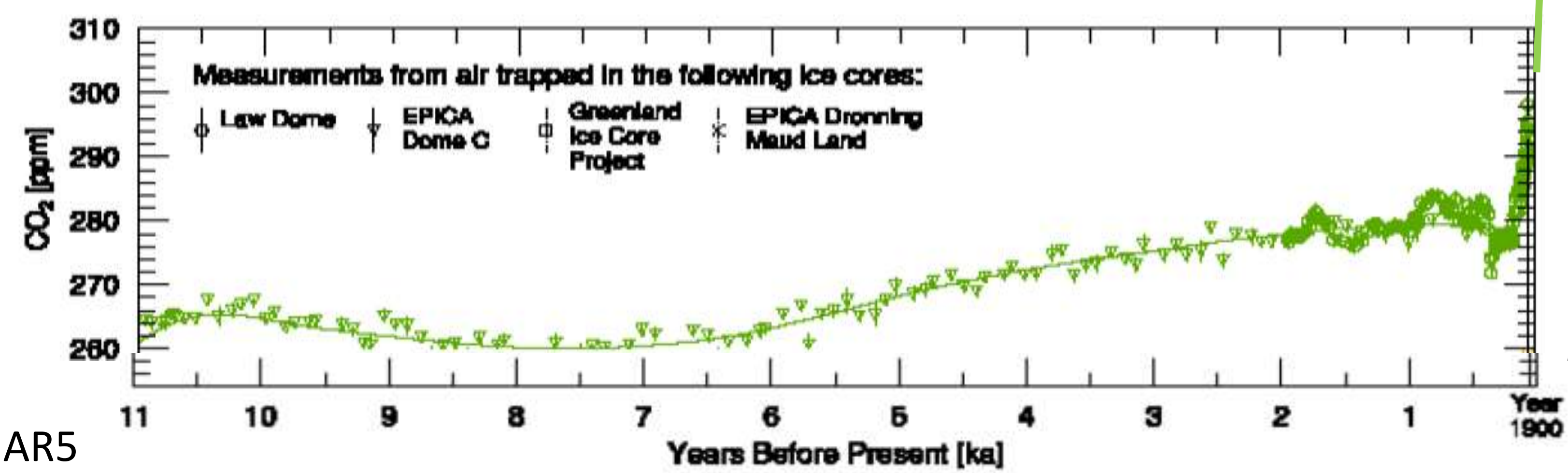
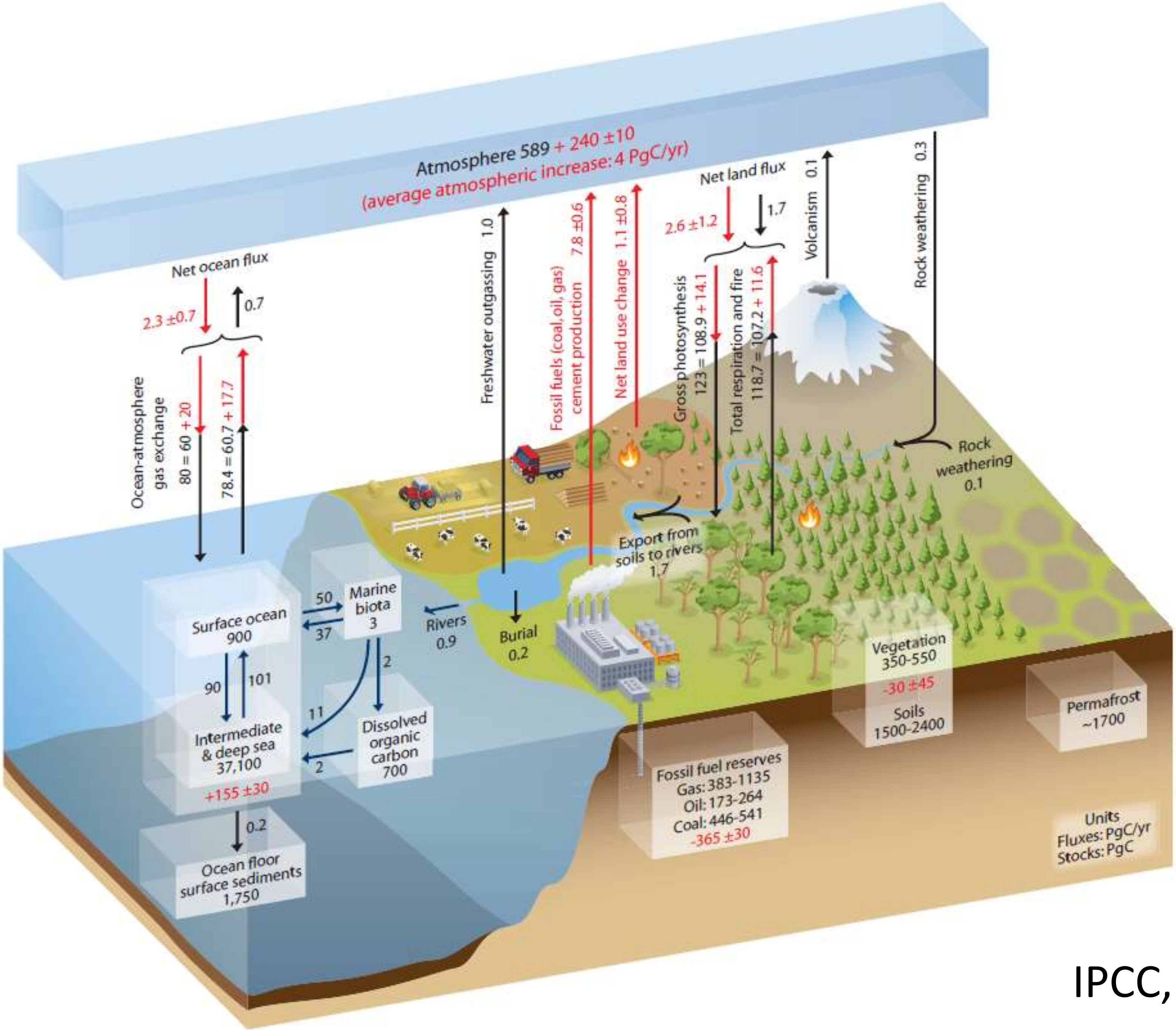


IPCC, AR5



Atmosphere 589 + 240 ±10
(average atmospheric increase: 4 PgC/yr)
Net ocean flux
2.3 ±0.7
0.7
Ocean-atmosphere gas exchange
80 = 60 + 20
78.4 = 60.7 + 17.7
Freshwater outgassing 1.0
Fossil fuels (coal, oil, gas) cement production 7.8 ±0.6
Net land use change 1.1 ±0.8
Net land flux
2.6 ±1.2
1.7
Gross photosynthesis 123 = 108.9 + 14.1
Total respiration and fire 118.7 = 107.2 + 11.6
Volcanism 0.1
Rock weathering 0.3
Rock weathering 0.1
Export from soils to rivers 1.7
Surface ocean 900
50
37
Marine biota 3
Rivers 0.9
Burial 0.2
90
101
2
11
Intermediate & deep sea 37,100
+155 ±30
Dissolved organic carbon 700
2
0.2
Ocean floor surface sediments 1,750
Fossil fuel reserves
Gas: 383-1135
Oil: 173-264
Coal: 446-541
-365 ±30
Vegetation 350-550
-30 ±45
Soils 1500-2400
Permafrost ~1700
Units
Fluxes: PgC/yr
Stocks: PgC

IPCC, AR5

We CAN observe the oceanic C_{ant} increase:
(or, more accurately, estimate it from observations)

„Observe“
Back-calculations (*introduced by Peter Brewer/Arthur Chen in 1978*):
based on measurements of ocean carbon;
correct for natural C variability
lots of assumptions.... not all justifiable
need 3-D preindustrial C concentration reference;
“snapshot“

„Estimate“
Proxy-approaches (*e.g. approach of Niki Gruber et al., Khatiwala, etc..*):
based on „transient tracers“ e.g. CFCs
need transfer function: tracer $\rightarrow C_{ant}$
(based on “difficult“ concept of water mass age)
Green function / TTD tracer approach looks v. promising
Gives time-history of C_{ant}
BUT *tracers are not perfect analogs of* CO_2
Assumes constant circulation over time
and “well-behaved” variation of $(pCO_2sw - pCO_2atm)$

Icon #1: The Global CO_2 Survey Result

(based on c. 8 years of ship-based sampling and a quasi-preformed CO_2 approach…)

1800-2004 (Sabine et al., 2004). Anthropogenic Carbon

Emissions: 244 ± 20 (Fossil fuel + Cement)

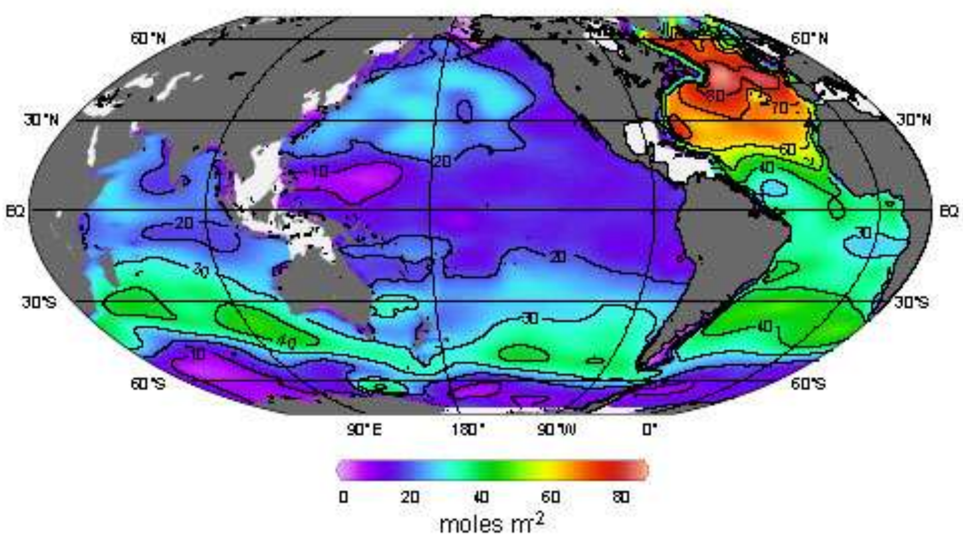
“Sinks“:

Ocean Inventory: 118 ± 19 (from Observations)

Atmosphere: 165 ± 4 (from Observations)

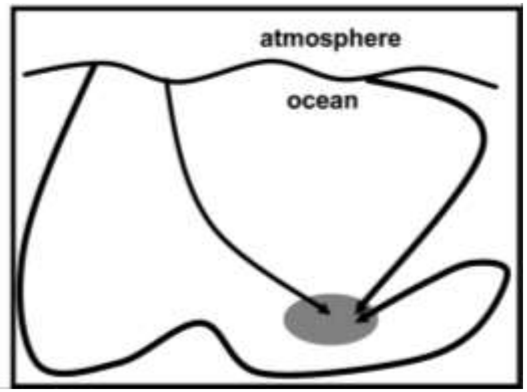
Terrestrial: -39 ± 28 (by difference) =small source

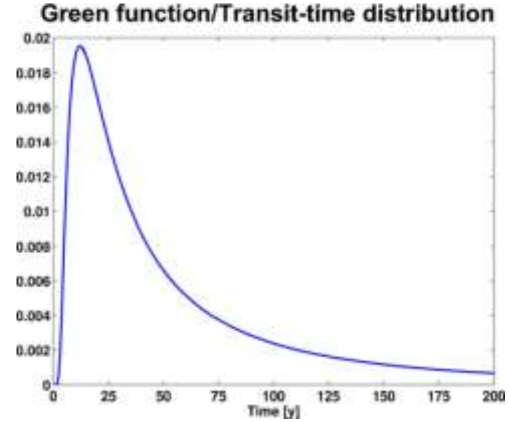
Units: PgC yr^{-1}



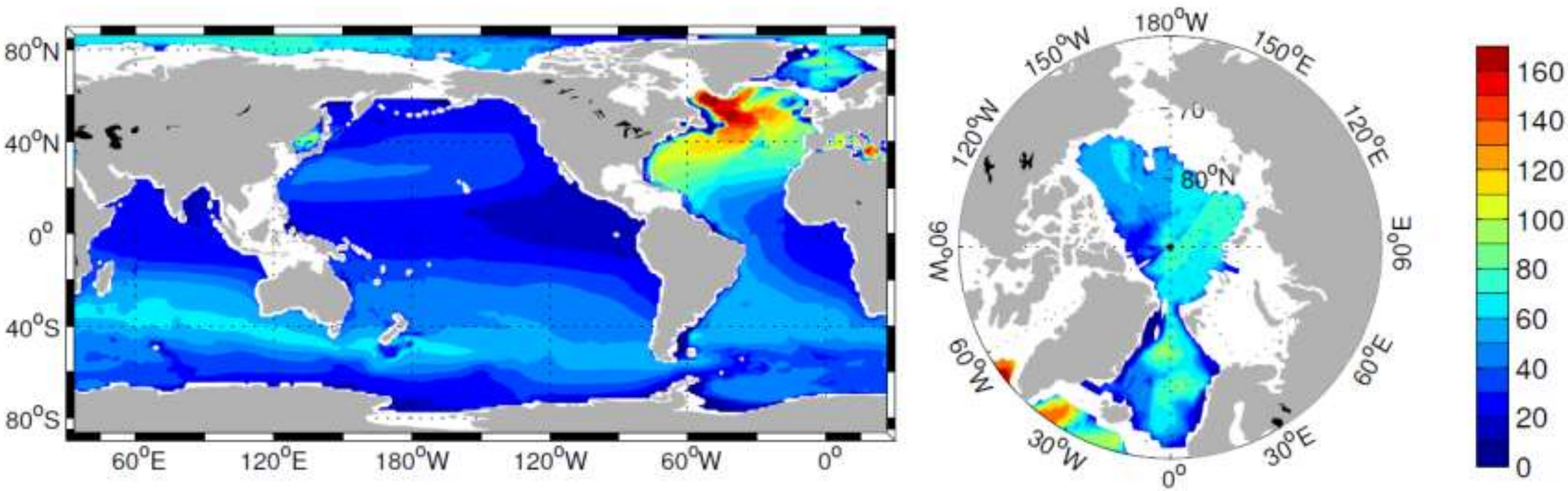
New estimates
Khatiwala et al., 2013

Ocean interior waters represent mixtures of water mass ages

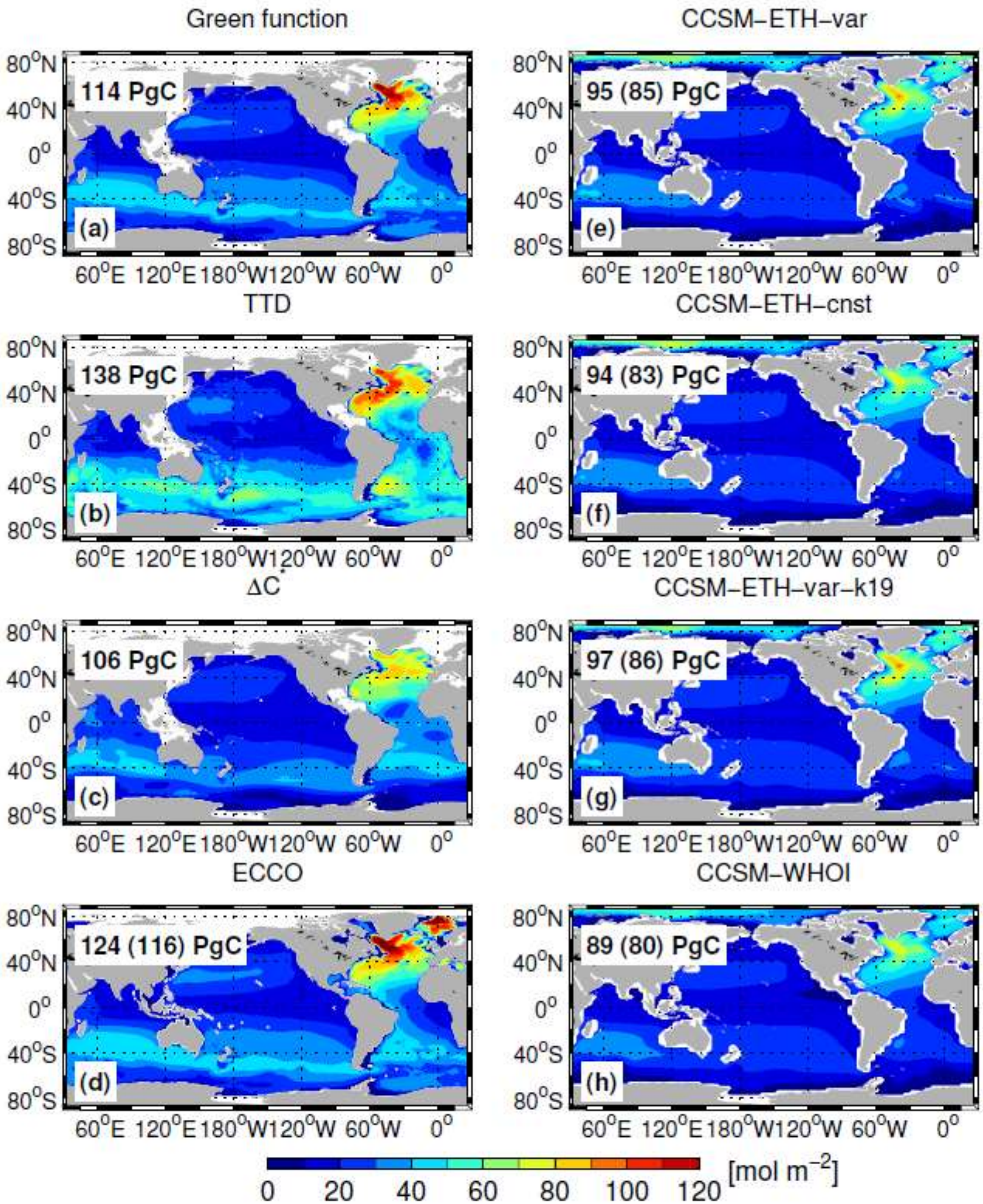




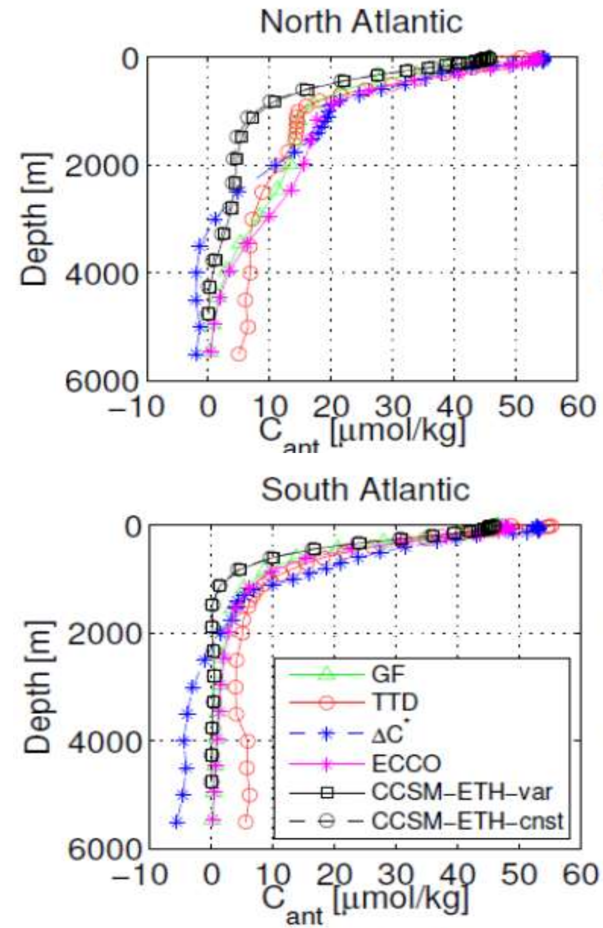
Green Function / TTD based.
Maximum entropy fit to multiple, gridded tracers: transient (e.g. CFCs) and steady-state)
Ocean circulation constant over time; "calibrated" at one time-point (WOCE era dataset)
Air-sea CO_2 disequilibrium scales linearly with pCO_2 increase in the atmosphere



C_{ant} inventory in 2010, mol m^{-2}



Basin-averaged profiles



Khatiwala et al., 2013

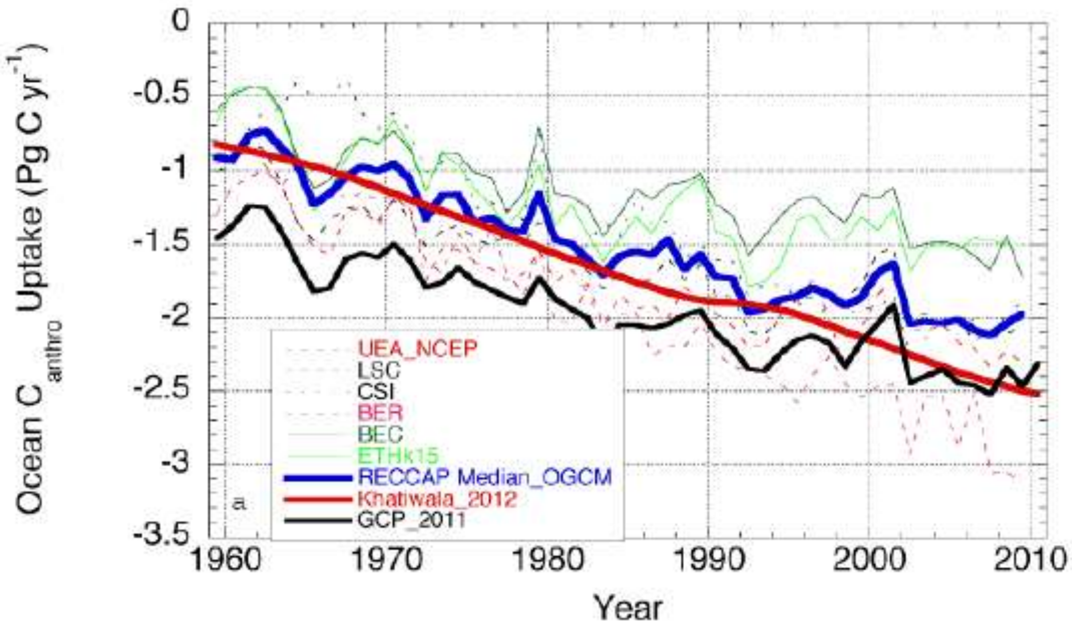
Meet the new IPCC Budget

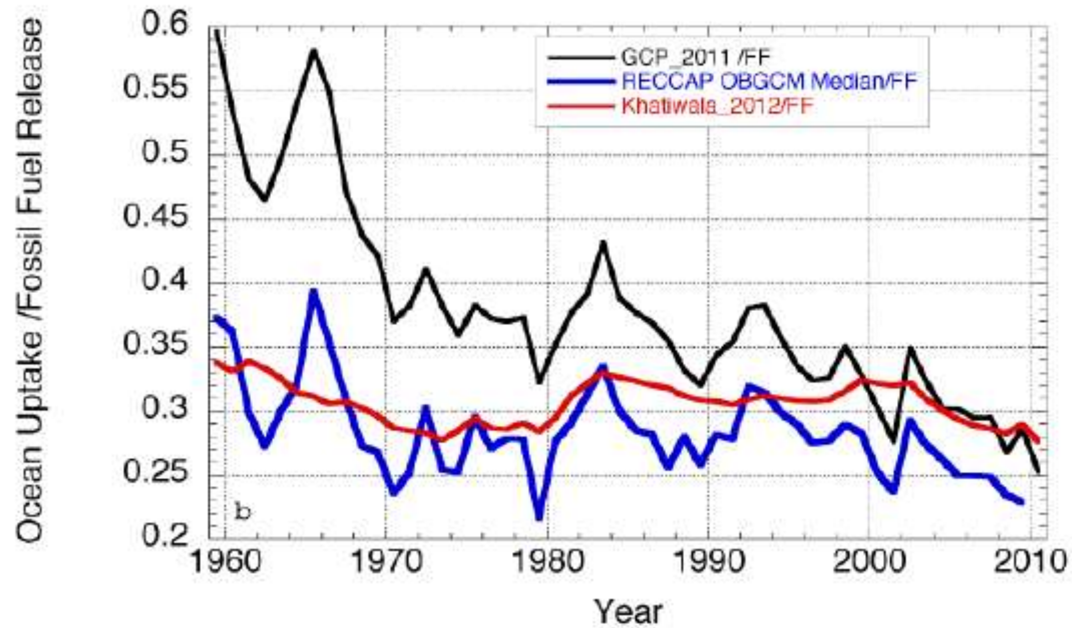
Table 6.1: Global anthropogenic CO_2 budget, accumulated since the Industrial Revolution (onset in 1750) and averaged over the 1980s, 1990s, 2000s, as well as the last ten years until 2011. By convention, a negative ocean or land to atmosphere CO_2 flux is equivalent to a gain of carbon by these reservoirs. The table does not include natural exchanges (e.g., rivers, weathering) between reservoirs. The uncertainty range of 90% confidence interval presented here differs from how uncertainties were reported in AR4 (68%).

	1750–2011 Cumulative	1980–1989	1990–1999	2000–2009	2002–2011
	PgC	PgC yr^{-1}	PgC yr^{-1}	PgC yr^{-1}	PgC yr^{-1}
Atmospheric increase[a]	240 ± 10[f]	3.4 ± 0.2	3.1 ± 0.2	4.0 ± 0.2	4.3 ± 0.2
Fossil fuel combustion and cement production[b]	365 ± 30[f]	5.5 ± 0.4	6.4 ± 0.5	7.8 ± 0.6	8.3 ± 0.7
Ocean-to-atmosphere flux[c]	–155 ± 30[f]	–2.0 ± 0.7	–2.2 ± 0.7	–2.3 ± 0.7	–2.4 ± 0.7
Land-to-atmosphere flux	30 ± 45[f]	–0.1 ± 0.8	–1.1 ± 0.9	–1.5 ± 0.9	–1.6 ± 1.0
Partitioned as follows					
Net land use change[d]	180 ± 80[f,g]	1.4 ± 0.8	1.6 ± 0.8	1.1 ± 0.8	0.9 ± 0.8
Residual terrestrial flux[e]	–150 ± 90[f]	–1.5 ± 1.1	–2.7 ± 1.2	–2.6 ± 1.2	–2.5 ± 1.3

Similar not so different from that of Sabine et al., 2004

IPCC AR5





Longer-term trends in C_{ant} uptake seem somewhat uncertain or at least variable between models

Can We Measure C_{ant} Storage "directly" from Repeated High-Quality Carbon Surveys?

1. Transient Tracers in the Ocean North Atlantic Survey 1981

2. Meteor 60; Leg 5 2004

Tanhua et al., 2007

A Quasi-statistical Approach to Estimating ΔC_{ant} between Two Surveys of Carbon

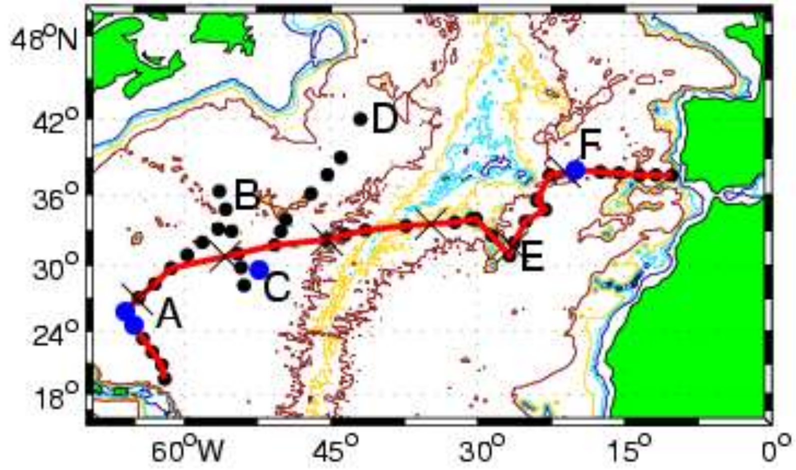
Extended Multiple Linear Regression (eMLR):
Multiple Regression method of Wallace (1995) as extended by Friis et al (2004):

1. Establish regression for TTO data of 1981
   $C_{1981} = a1.T + b1.S + c1.AOU + d1.ALK + e1.SiO_4$
2. Establish similar regression equation for Meteor 60/5 data of 2004
   $C_{2004} = a2.T + b2.S + c2.AOU + d2.ALK + e2.SiO_4$
3. Subtract coefficients of two regressions
4. $\Delta C_{ant} = (a_2-a_1).T + (b_2-b_1).S + (c_2-c_1).AOU + (d_2-d_1).ALK + (e_2-e_1).SiO_4$

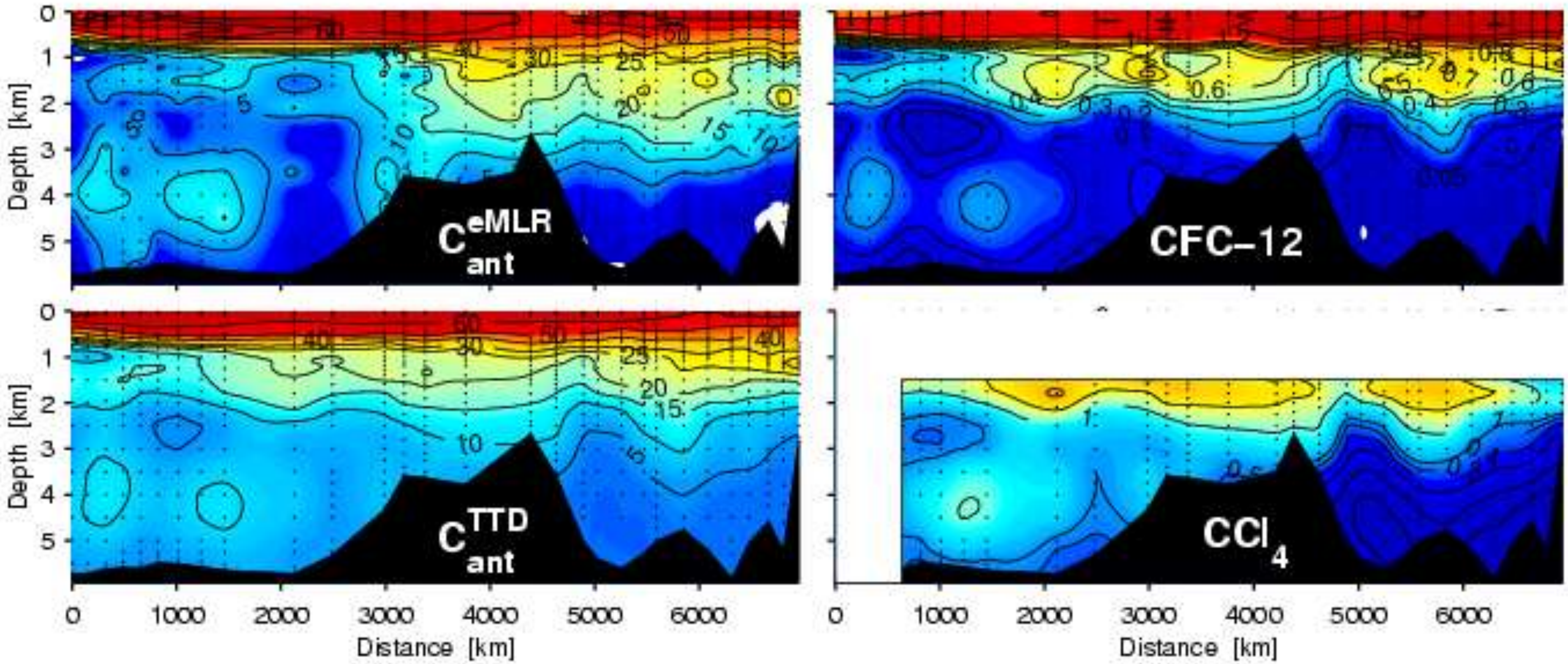
ΔC_{ant} converted to full C_{ant} signal (post 1750)

North Atlantic sub-tropical gyre

Qualitative comparison with tracers;
Quantitative comparison with proxy-based estimate using CFCs (TTD-approach)



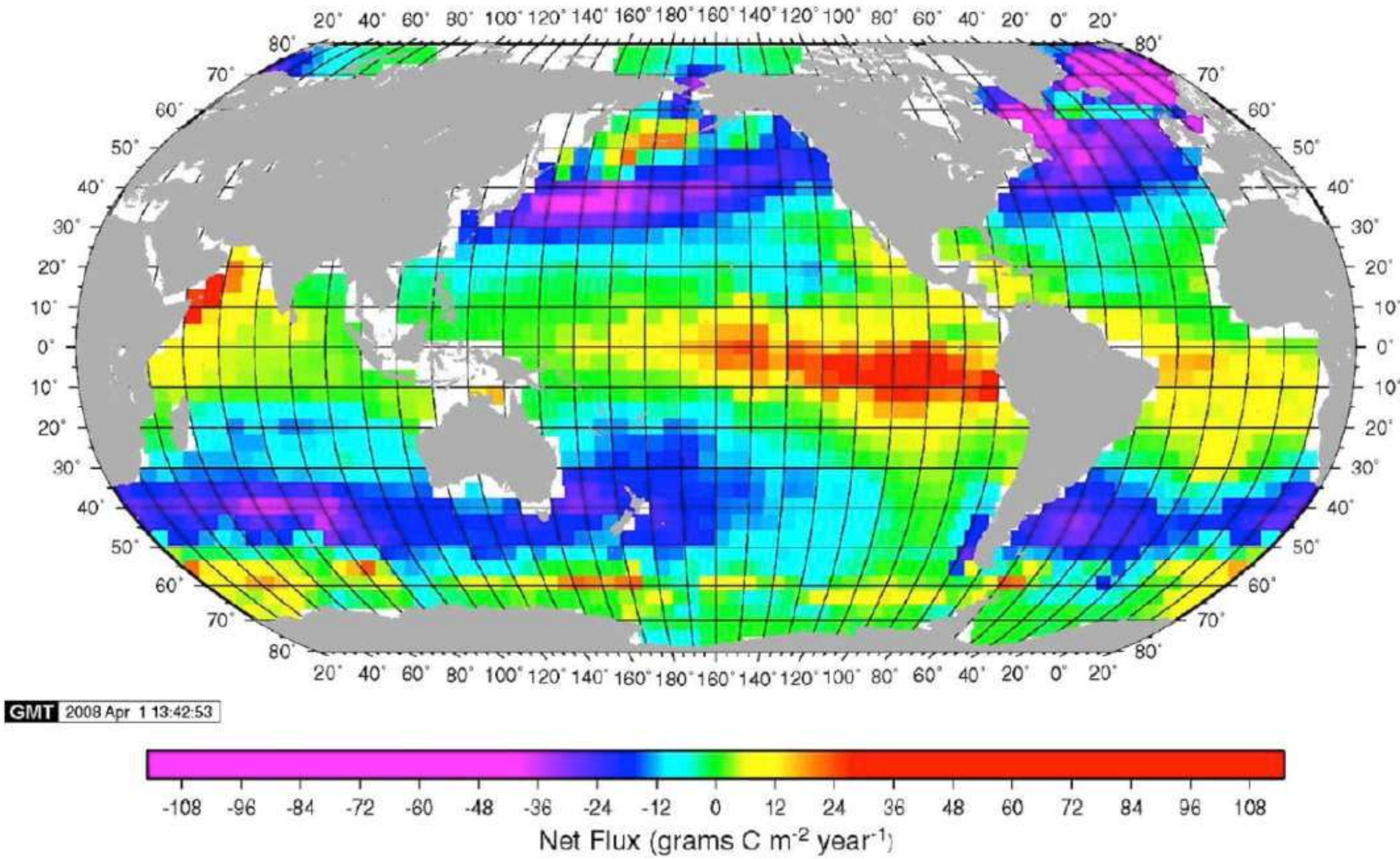
Tanhua et al., 2007



Icon #2: the Takahashi Climatological CO_2 Flux

Air-Sea Flux (C_{ant}) = Global Net Flux – (river-induced outgassing) - Burial

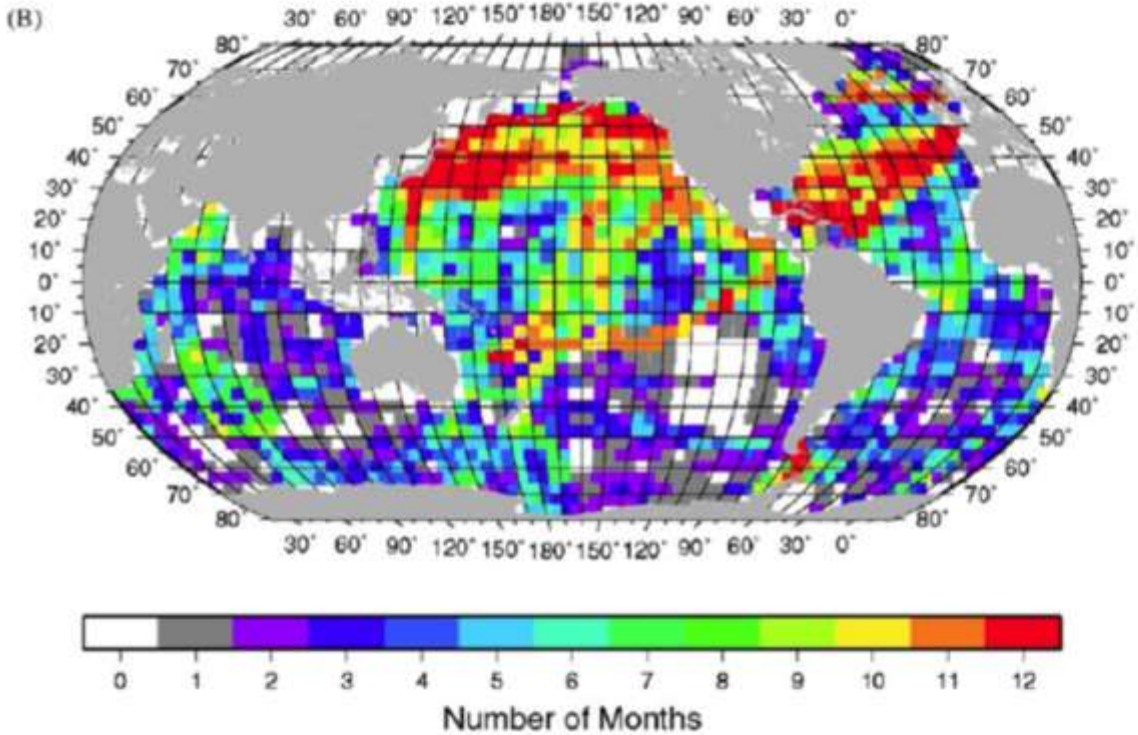
$$F = k \times K_0 \times (pCO_{2w} - pCO_{2a}) = k \times K_0 \times \Delta pCO_2$$



Updated estimated of air-sea C_{ant} flux for 2000: 2.0 Pg yr^{-1}

Wanninkhof et al. (2012)

Data Limitations



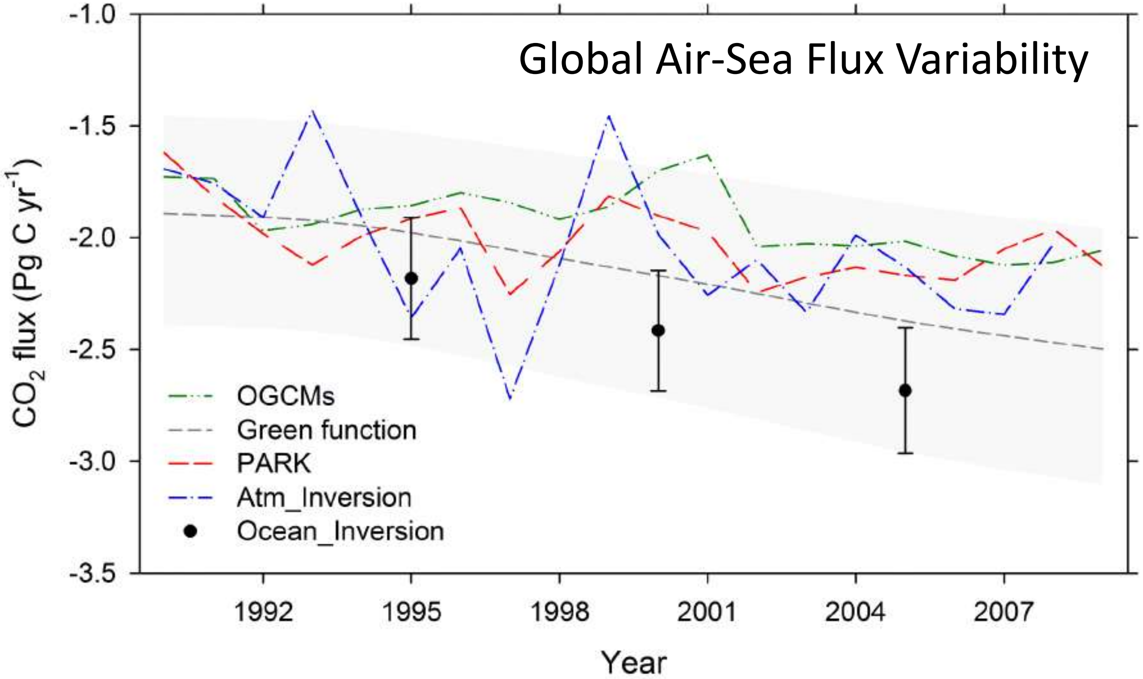
Takahashi et al. (2009). **(b)** Number of months in each 4° by 5° area where at least one surface water pCO_2 measurement has been made since the early 1970s. White areas are pixels that have no measurements. Reproduced from Fig. 1 in Takahashi et al. (2009).

Interannual variability and trends are poorly resolved by data

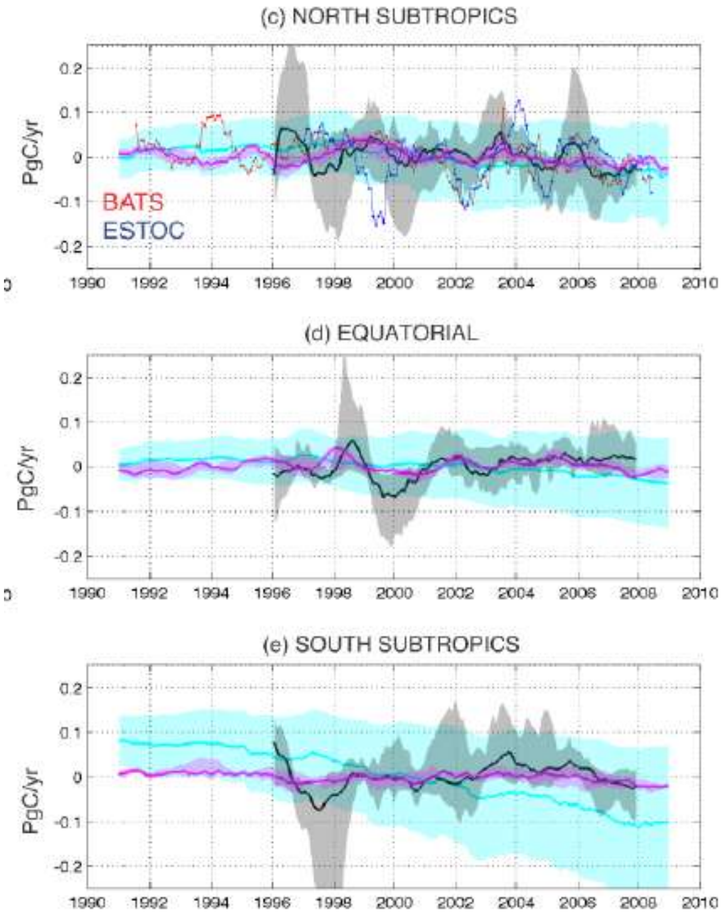
Having to collapse data from 4 decades onto a single "composite" year may bias mean flux

We have no real data, in most ocean regions, to assess interannual or interdecadal variability

Flux Variability



North Atlantic Air-Sea Flux Variability



Interannual variability (IAV);
Subannual variability (SAV); R_V = IAV / SAV

North Atlantic: IAV and SAV both large
Equatorial Pacific: IAV large; SAV small, RV > 0.4 to 1
Sub-tropical Gyres: Rv = 0.2

Climate effects dominate:
ENSO, Southern Annual Mode, NAO

From Wanninkhof et al., 2013

Landschuetzer et al., 2013 and Schuester et al, 2013 find ***temporal trends* in North Atlantic but small IAV overall

The Contemporary Air-Sea CO_2 Flux is Complicated at Regional Scales (by transport)

Contemporary Flux = Preindustrial Flux + Anthropogenic Flux

On global scale:

Preindustrial Flux = Riverine Input – Burial

(see Takahashi)

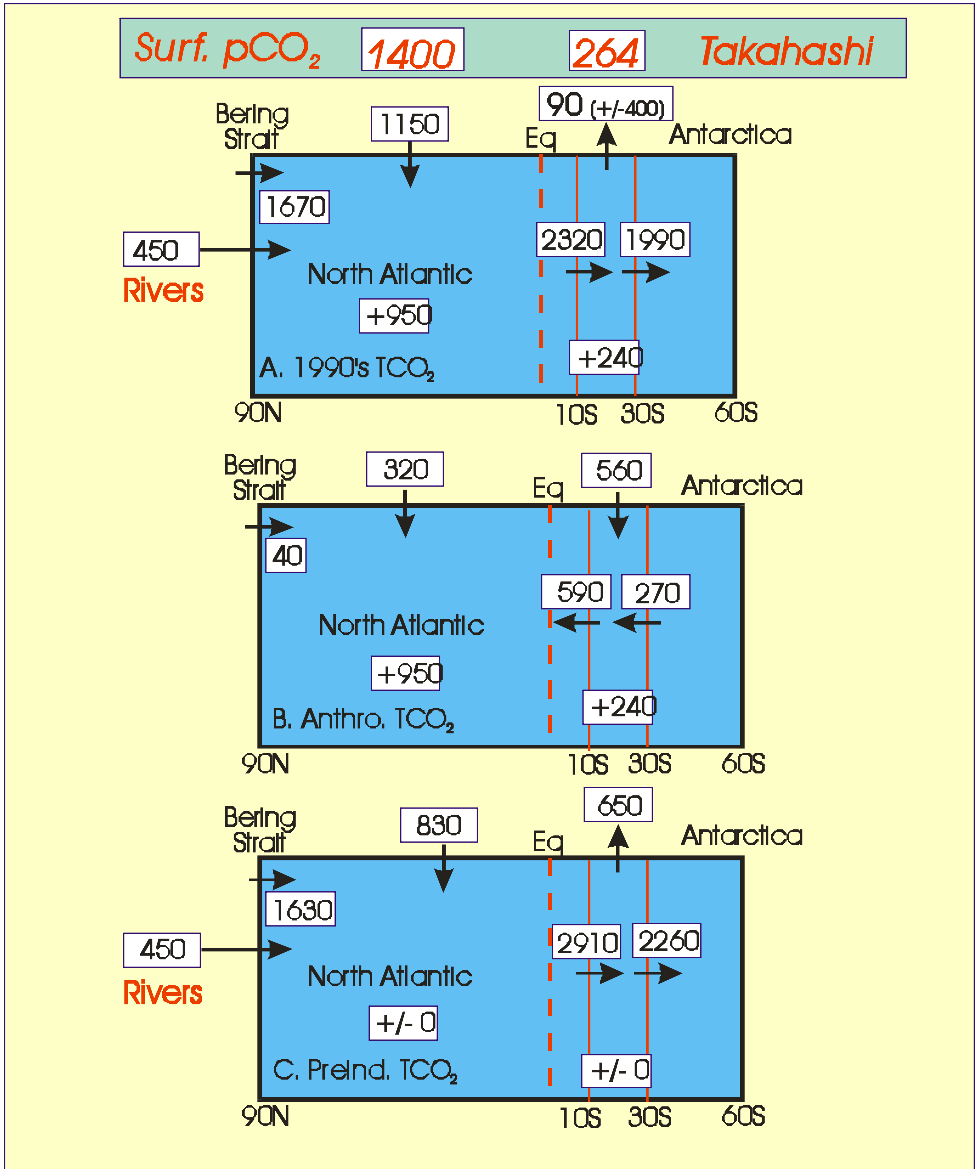
On regional scale this “simple” mass balance is complicated:

1. A “natural”, “non-zero” air-sea CO_2 flux results from (or is balanced by) within ocean divergence and convergences associated with water mass transports and *regional* riverine inputs from land. “Preindustrial Flux”

2. A spatially variable “anthropogenic” air-sea CO_2 flux results from perturbation of the air-sea pCO_2 difference due to anthropogenic carbon emissions.

How to separate these components of the flux estimated by Takahashi et al?

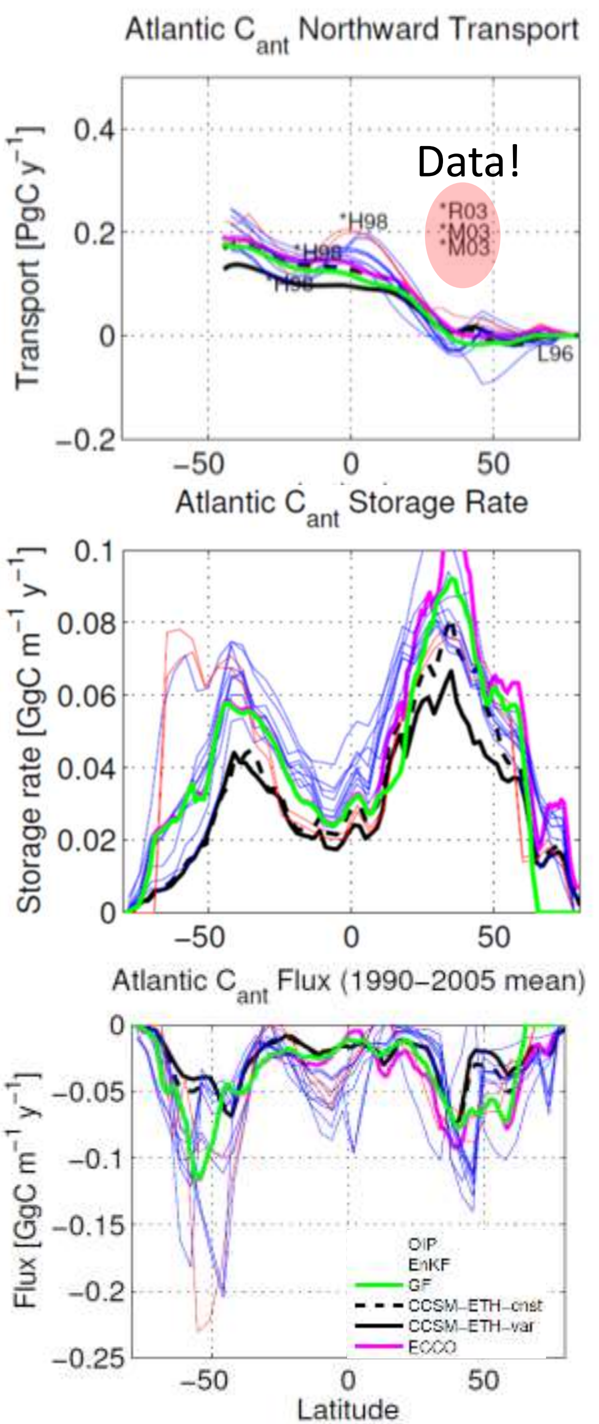
Bringing it All Together
Separating the Components: Holfort et al. (1998)



- Used estimates of meridional transport across ocean basin sections
- Budget was consistent with air-sea flux estimates (Takahashi)
- Transport of C_{ant} could be calculated
- Regional budgets for C_{ant}

$\Rightarrow\Rightarrow$ (observation-based) C_{ant} air-sea flux

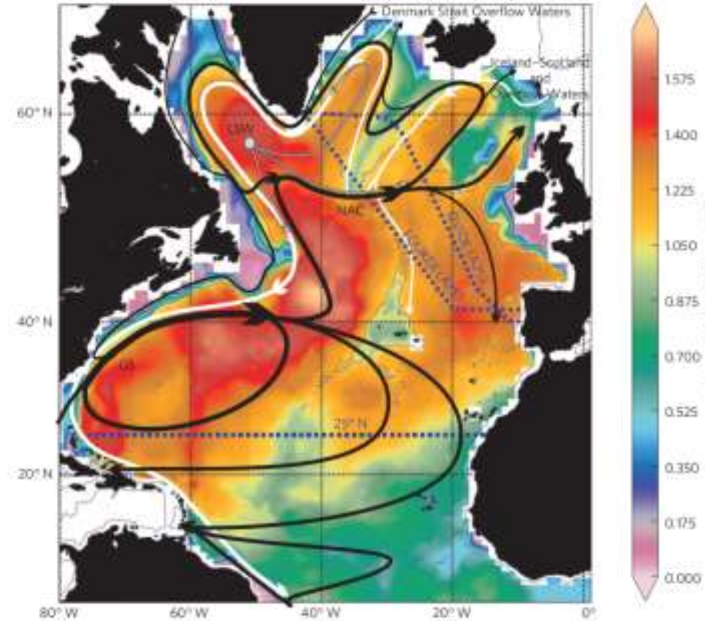
- Dominant role for transport in North/Equatorial Atlantic C_{ant} budget



More recent model- and data-based attempts

Perez et al, 2013

Khatiwala et al., 2013



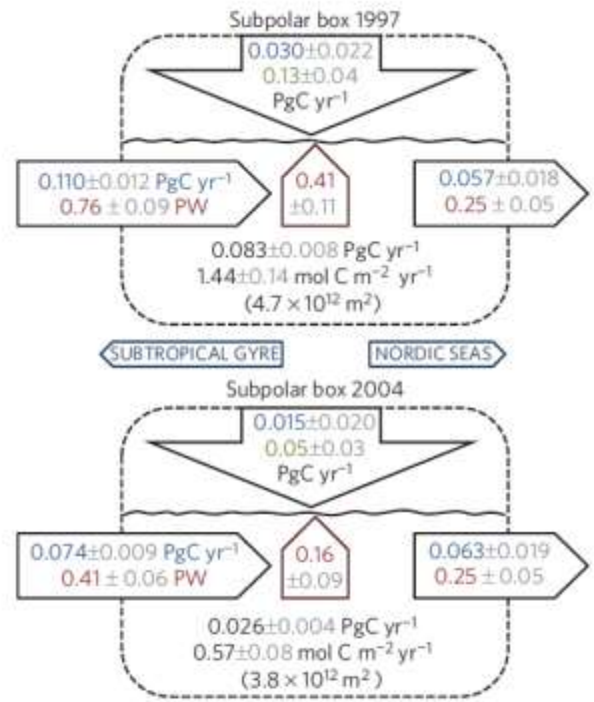


Figure 4 | Variability of the C_{ANT} budget in the subpolar box during high NAO (1997) and low NAO (2002–2006). The arrow and number formats

Ocean Carbon Cycle.
Status Report and Questions:

1. The 1990's-era question:
   How much „excess" (≈ anthropogenic) carbon is there in the oceans and where is it?
   Question largely answered except for „small details" including:
   The entire Southern Ocean… Depth distribution of inventory…etc.

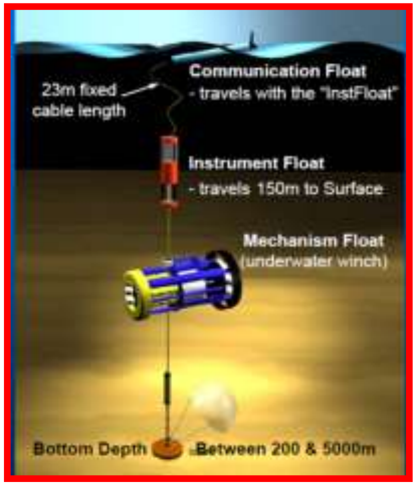
2. The next big questions are:
   Can we attribute atmospheric CO2 growth rate changes on timescales useful for carbon-management assessment? (e.g. land-ocean partitioning)

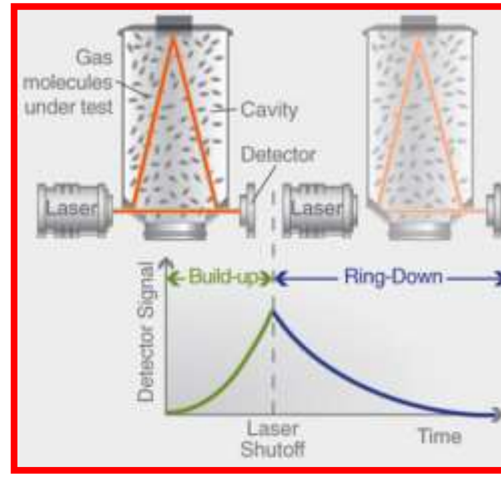
3. How will ocean uptake change in the future? (still a big question....)

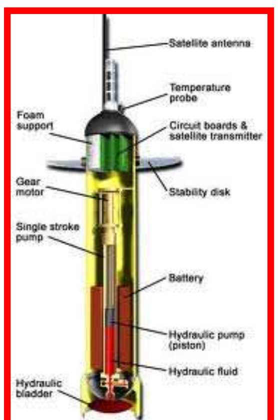
4. Where in the ocean will acidification have largest impact? (new question)

For questions 2 + 3, we need to identify and understand uptake;
Where and how is CO_2 and C_{ant} is taken up from the atmosphere?
What is the spatial-temporal variability of the air-sea CO2 flux?
What determines the uptake rate of CO_2 and C_{ant}? How sensitive is it to change?

For all these questions, ocean data and models are essential. New technologies will allow us to resolve varibility in space and time better than ever before...


Communication Float
- travels with the "InstFloat"
23m fixed
cable length
Instrument Float
- travels 150m to Surface
Mechanism Float
(underwater winch)
Bottom Depth
Between 200 & 5000m


Gas
molecules
under test
Cavity
Detector
Laser
Laser
Build-up
Ring-Down
Detector Signal
Laser
Shutoff
Time


Satellite antenna
Temperature
probe
Foam
support
Circuit boards &
satellite transmitter
Gear
motor
Stability disk
Single stroke
pump
Battery
Hydraulic pump
(piston)
Hydraulic fluid
Hydraulic
bladder