Monitoring and interpreting the ocean uptake of atmospheric CO_2.

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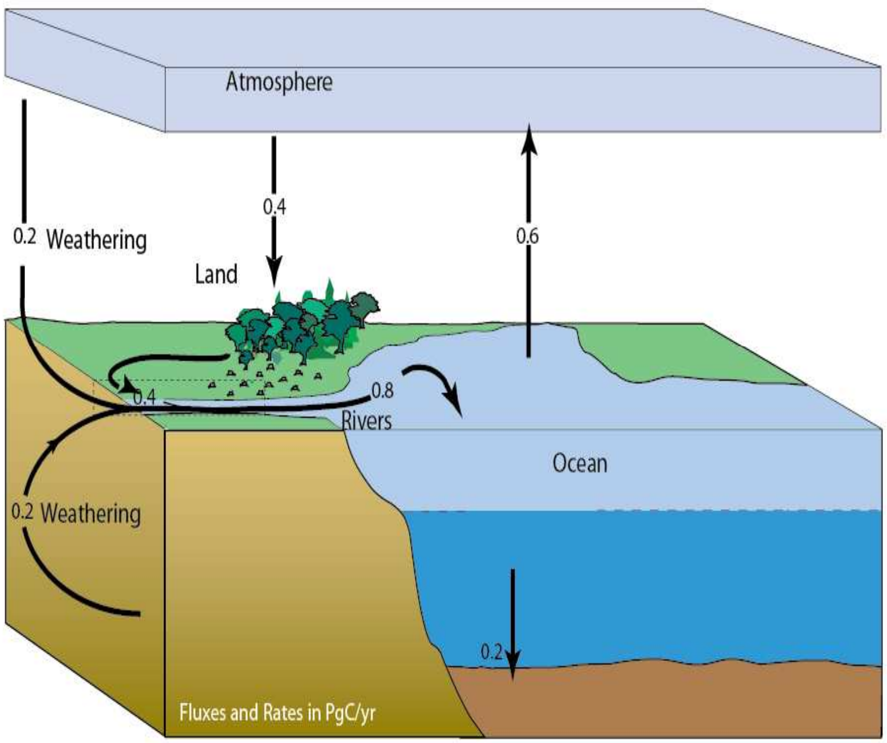
Overview

- The separation between anthropogenic and natural (pre-industrial) fluxes and inventories
- Ocean uptake varies in response to inter-annual and decadal climate variation.
  - e.g. in the Equatorial Pacific (El Niño)
  - The N. Atlantic (NAO?)
  - The Southern Ocean (SAM)
- An observing system for atmosphere - ocean CO_2 fluxes

Atmosphere-Ocean CO_2 fluxes

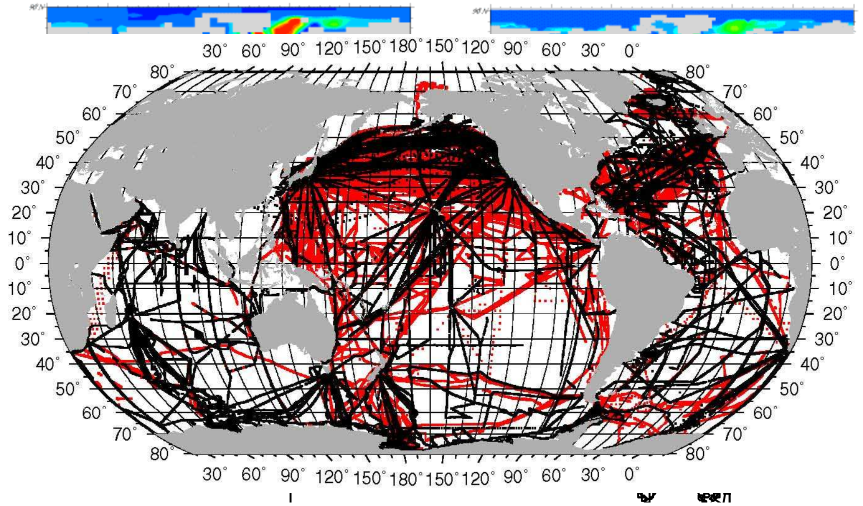
- The "anthropogenic" component of air-sea flux cannot be directly measured.
- Net atmosphere-ocean flux wasn't zero before the industrial period, even globally integrated, (land was a net sink, oceans a net source).
- IPCC AR4 lists 7 different ways of calculating net atmosphere-ocean flux, each measuring subtly different quantities:

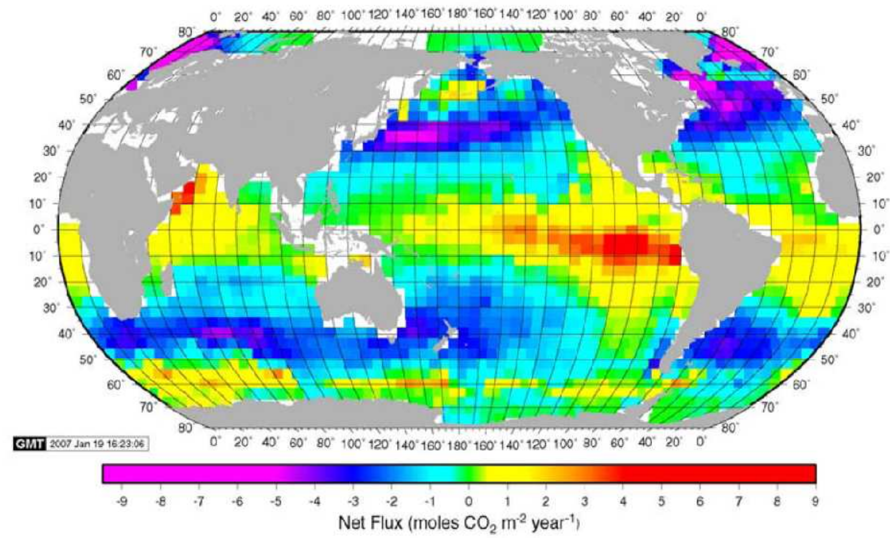


Pre-industrial net fluxes of CO_2

Major methods of quantifying the ocean sink

- Models: the anthropogenic CO_2 is rigorously defined (but not practically measurable)
- Atmospheric O_2/N_2 ratio: separates CO_2 sink accompanied by stoichiometric O_2 release ("land") from the rest ("ocean").
  - Unresolved problem: dissolved organic carbon in the ocean is a reservoir of ~700PgC: variations in this will be counted as "land".
- Direct measurement of air-sea flux: measures total flux: most informative, but most difficult.

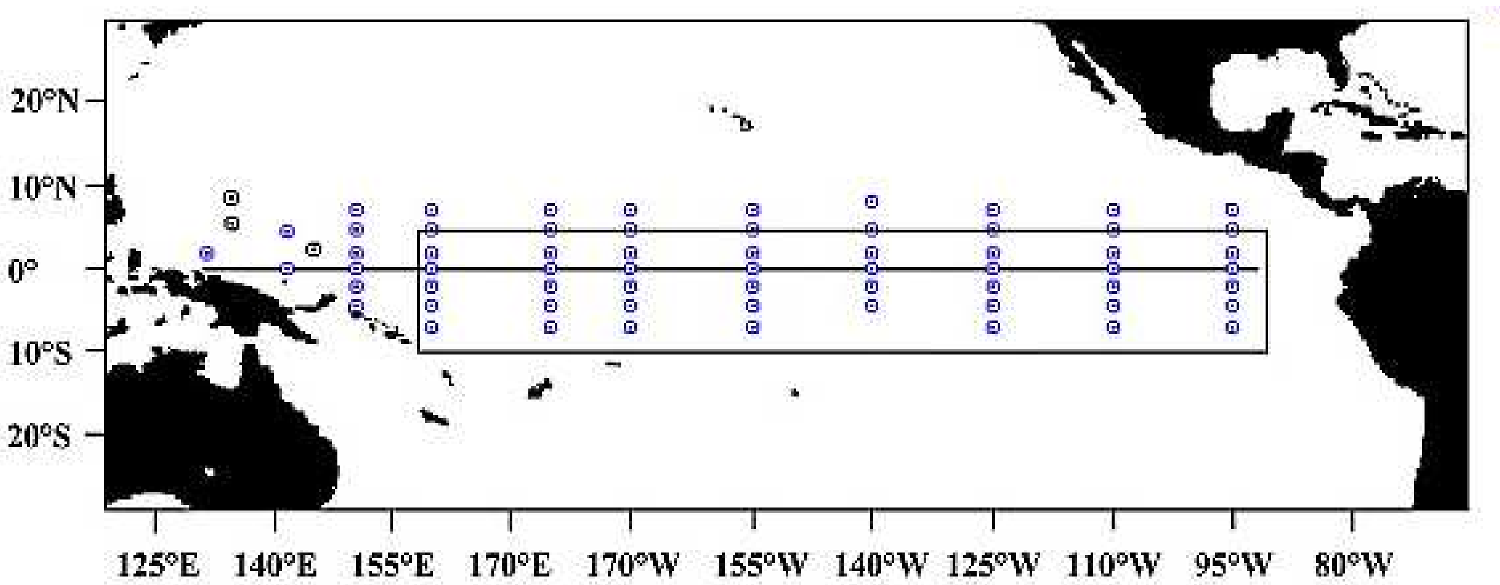




Regional variations in ocean-atmosphere flux

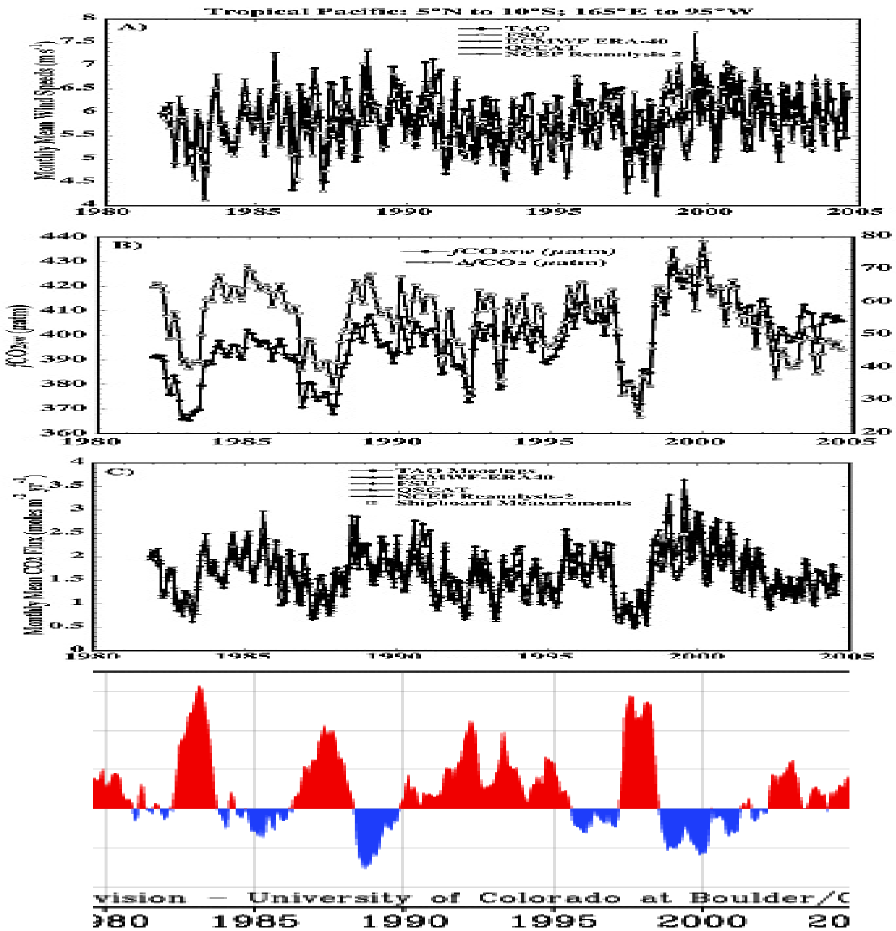
- We have sufficient data to study these from:
  - The equatorial Pacific
  - The Indian ocean sector of the Southern Ocean
  - The North Atlantic

Equatorial Pacific



- Regular sampling in conjunction with servicing the TAO array, since mid seventies.

Equatorial Pacific: fCO_2 flux and ENSO



winds

fCO_2 and ΔfCO_2

Efflux of CO_2

ENSO index

Feely RA et al., “Decadal variability of the air-sea CO2 fluxes in the equatorial Pacific Ocean” JGR (2006) doi: 10.1029/2005jc003129

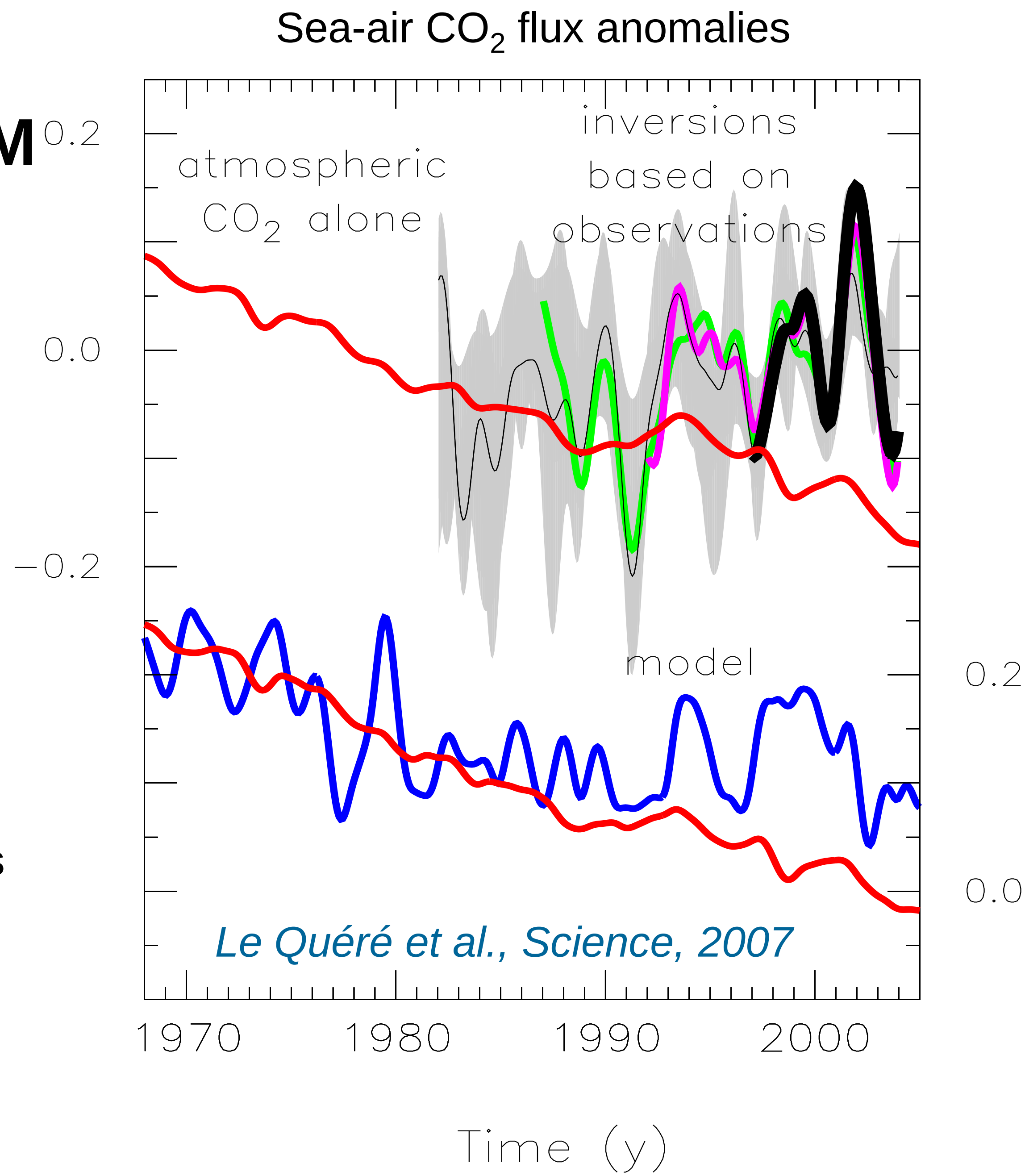
- Strong modulation of CO_2 efflux by the ENSO cycle

Southern Ocean: CO2 flux and SAM

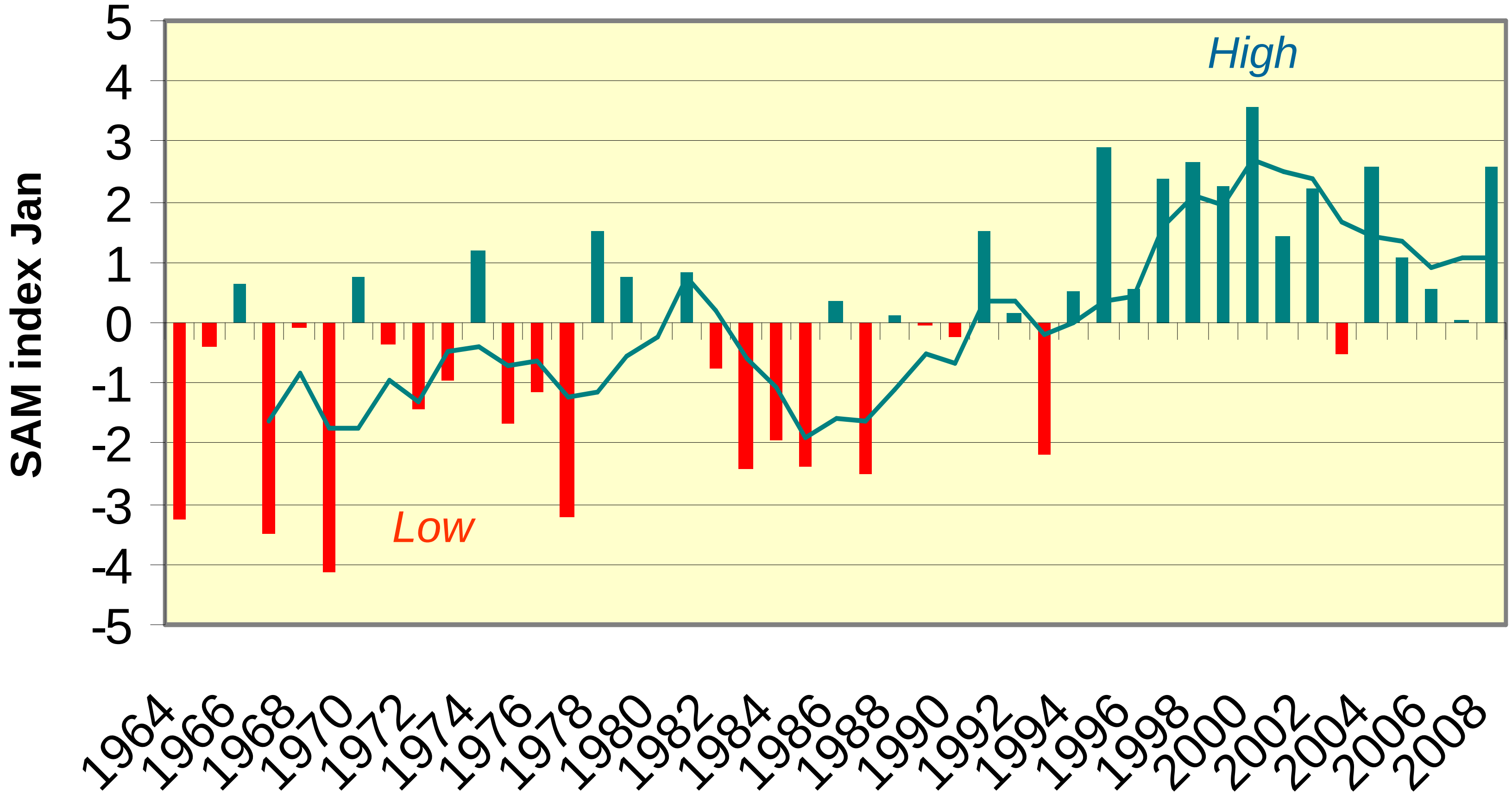
Atmospheric CO2 data and ocean models suggest a flattening out of of the total Southern Ocean carbon sink since 1980.

Changes associated with wind speed change in the Southern hemisphere

What can oceanic fCO2 measurements tell us about this evolution ?

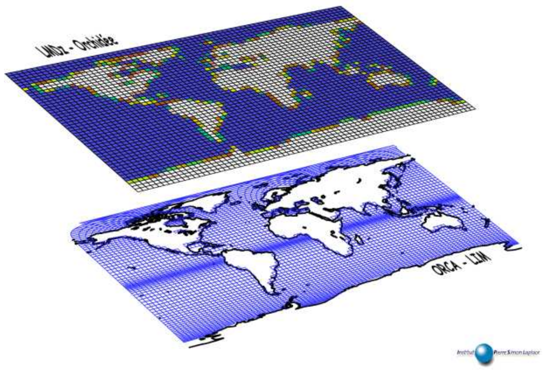


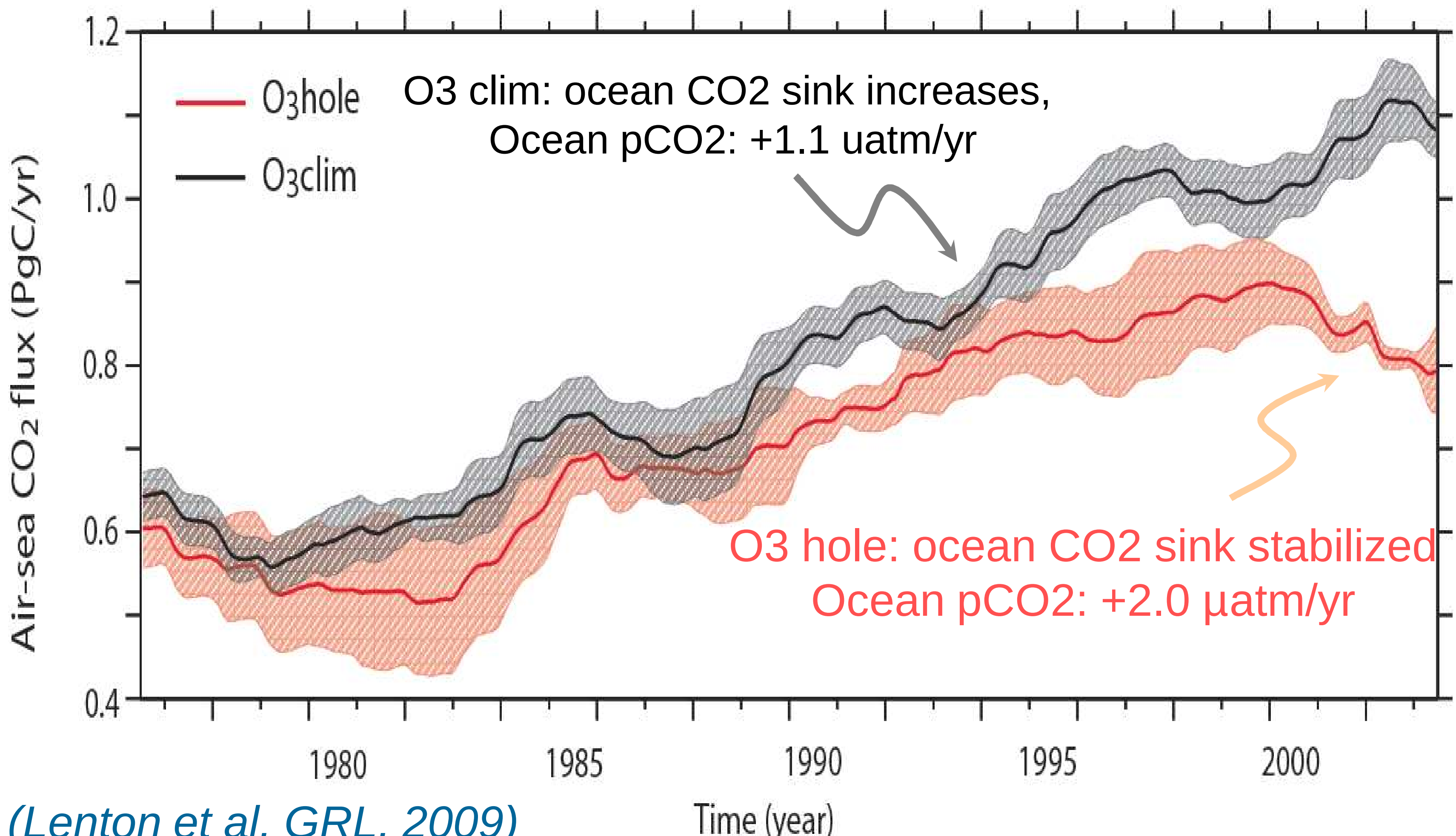
Climate Change in the Southern Ocean
The Southern Annular Mode (~ Patm 40S-60S observed)



Source Marshall

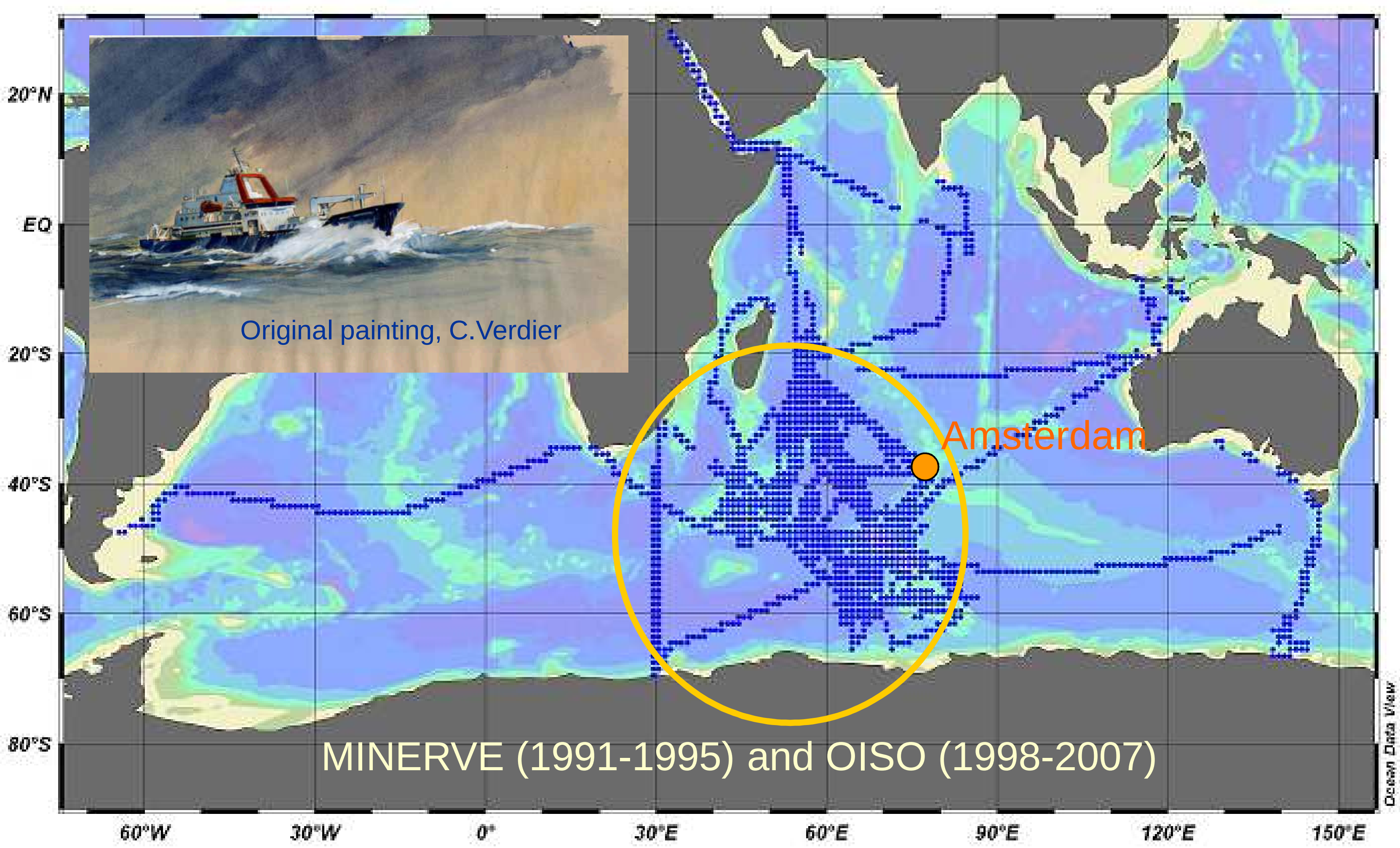
Air-sea CO2 fluxes in the Southern Ocean
Results from a coupled climate/carbon model
(IPSL/LOOP with and without O3 hole)

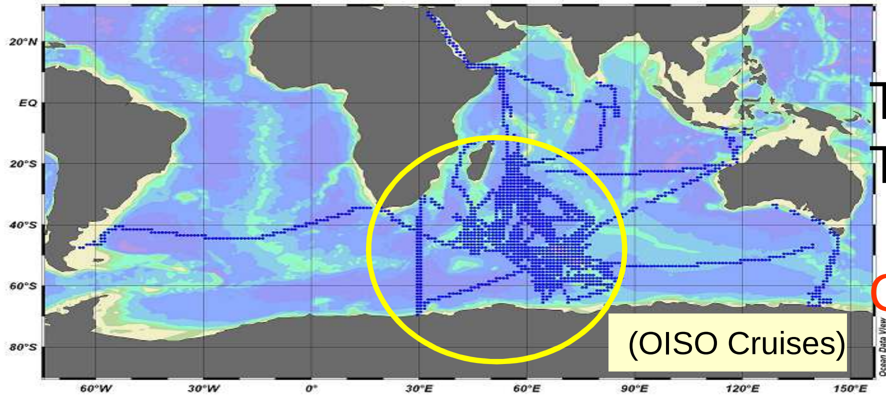




(Lenton et al, GRL, 2009)

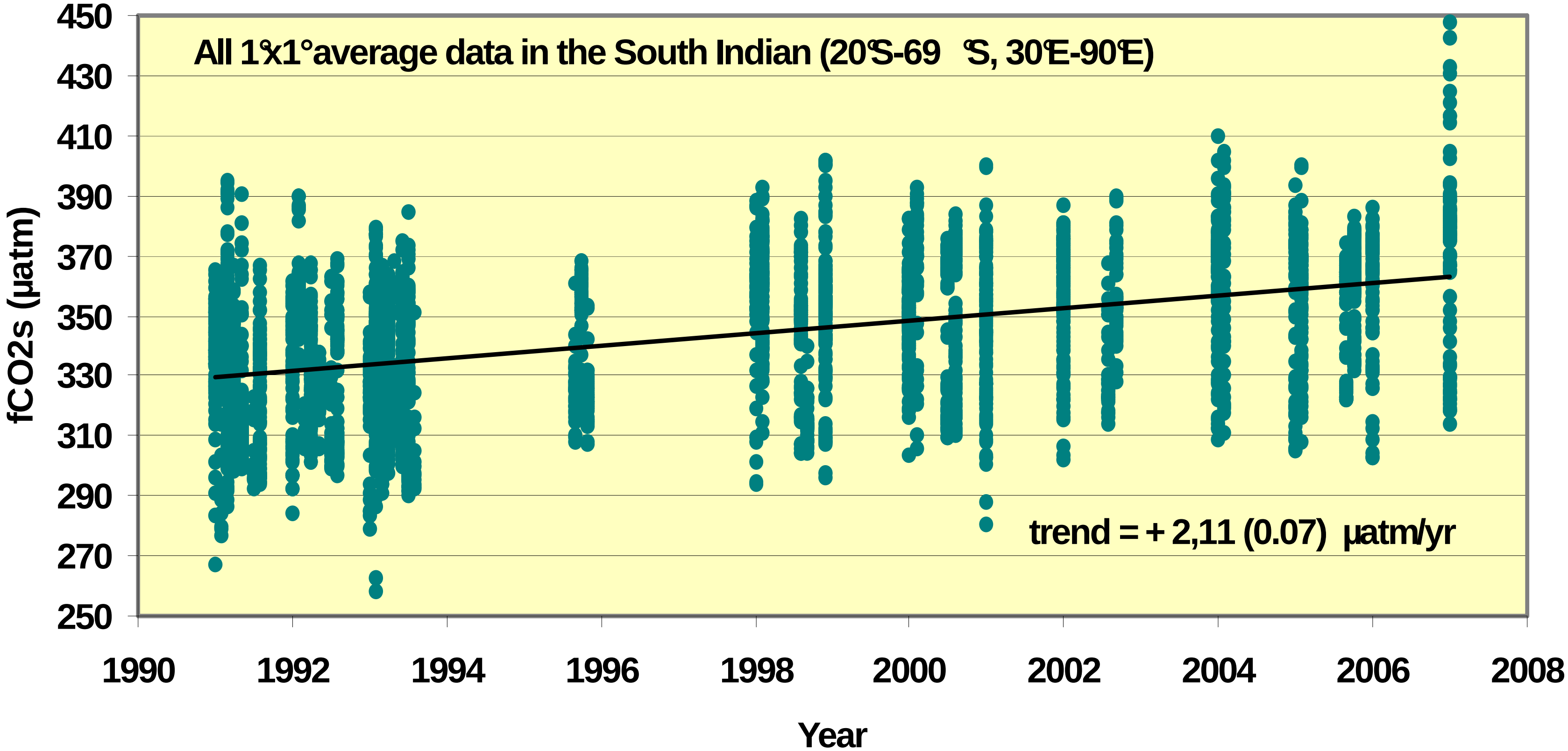
Exploring fCO2 trends from observations:
first step, selecting all data in the south-western indian ocean





Trend atmosphere: + 1.7 µatm/yr
Trend ocean: + 2.1 µatm/yr

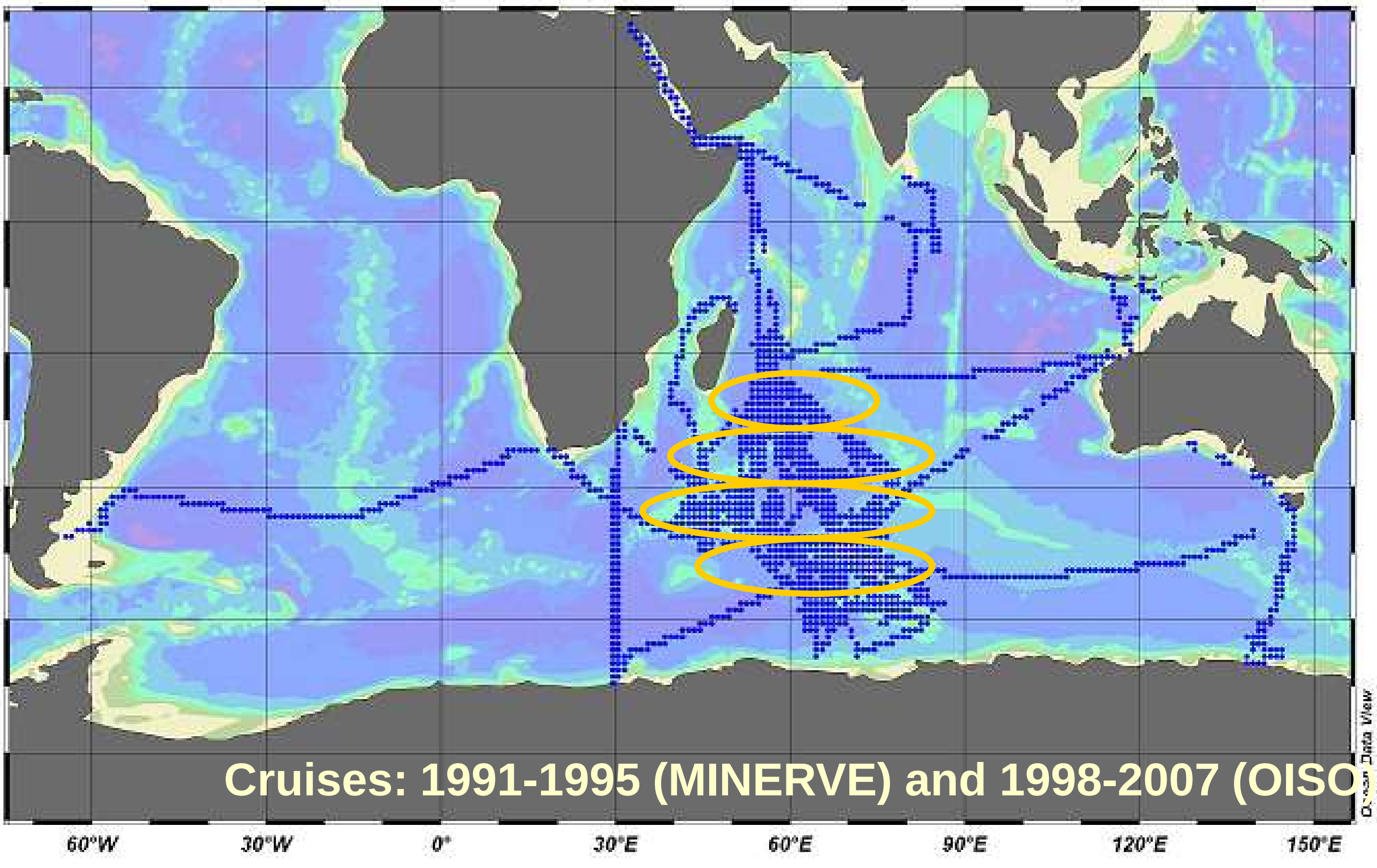
Ocean sink decreases ? : -0.4 µatm/yr



All data in SOCAT and CDIAC

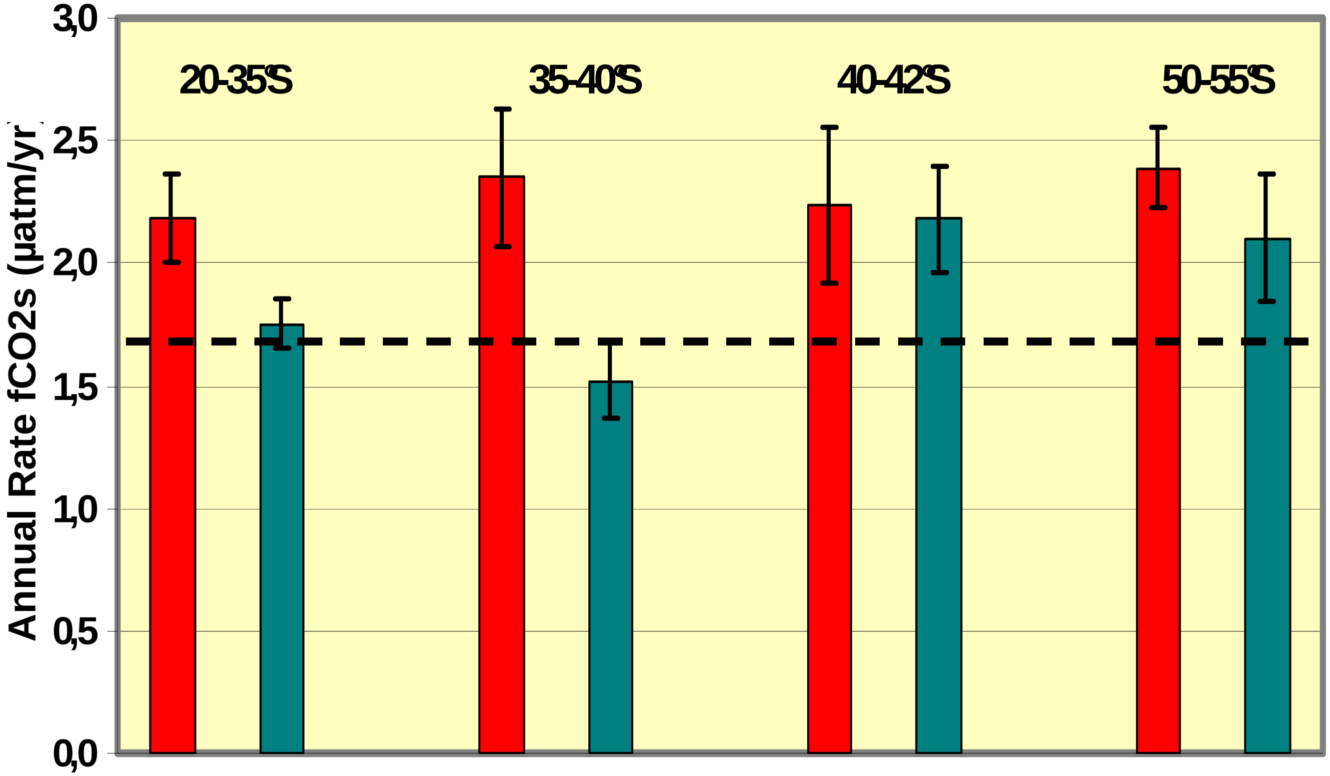
Metzl, DSR, 2009

Process analysis: exploring fCO2 trends
in four selected regions and only for summer/winter:



Metzl, DSR 2009

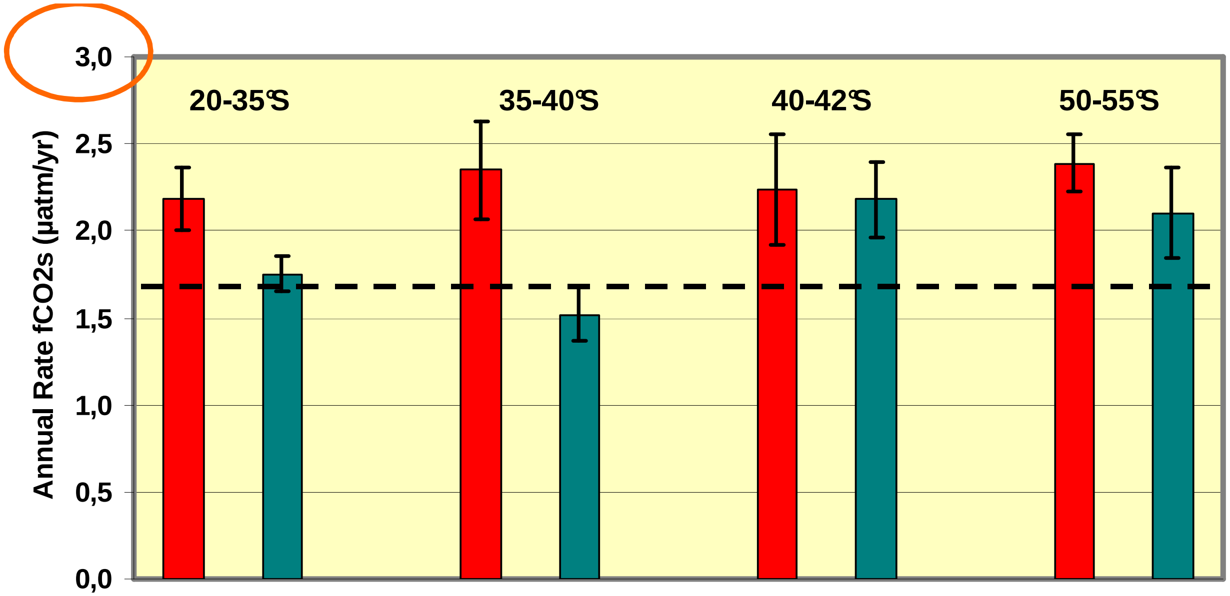
Austral summer and winter ocean fCO2 trends (µatm/yr)
in four regions in the South-Western Indian Ocean



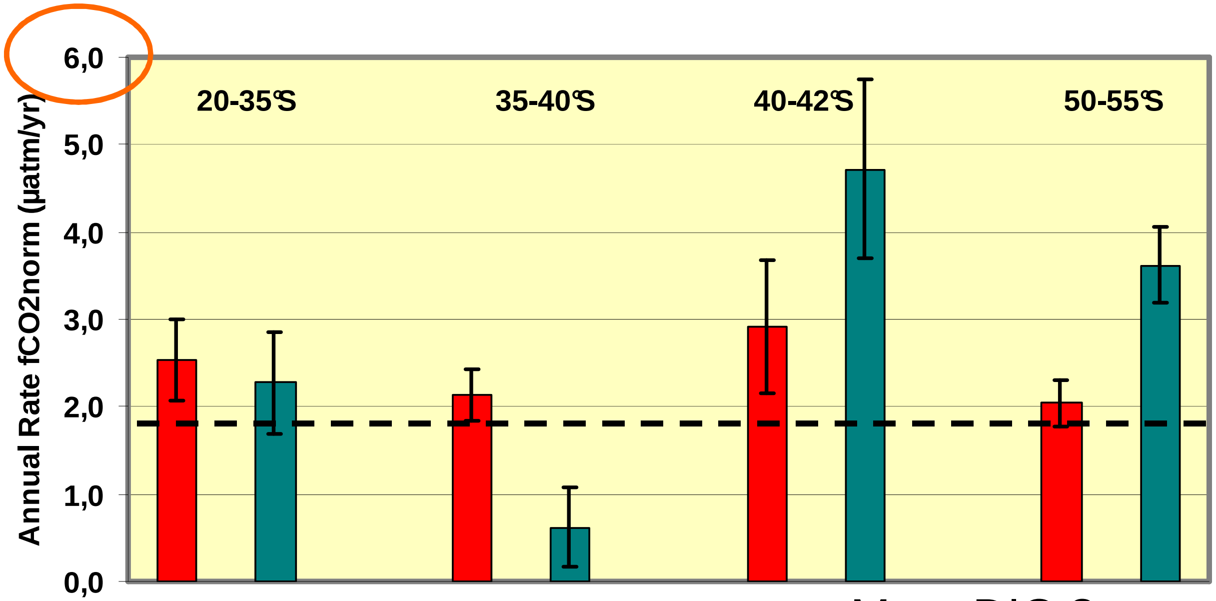
Average:
2.1 (+0.3) µatm/yr

Almost always above the atmospheric CO2 rate
(the sink decreases ???)

Metzl, DSR 2009



Average:
2.1 (+0.3) µatm/yr



Temperature
Normalized fCO2
2.6 (+1.2) µatm/yr

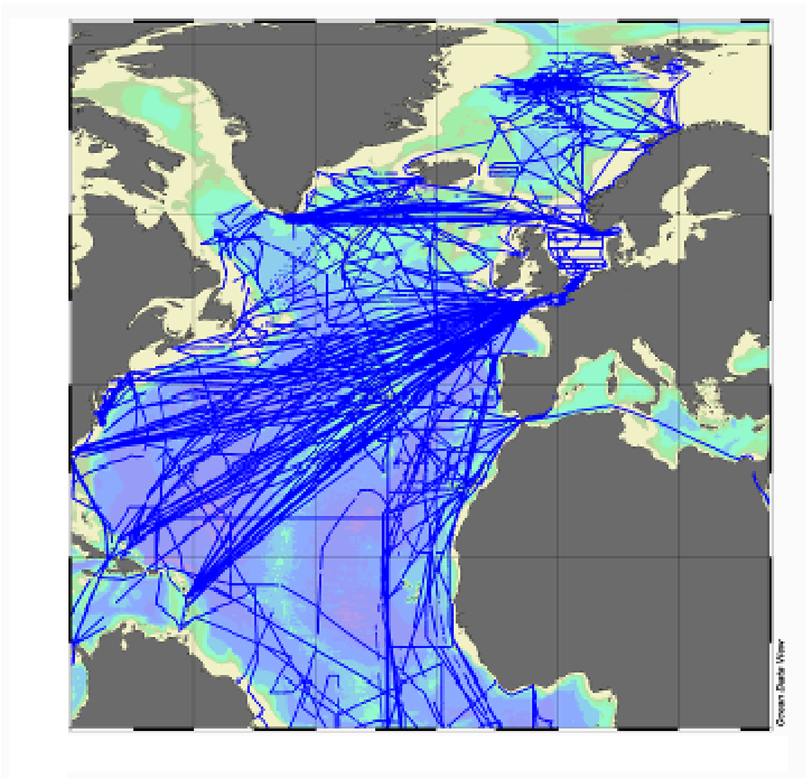
Contrasting results in winter, north and south of 40°S
Link with SAM ?

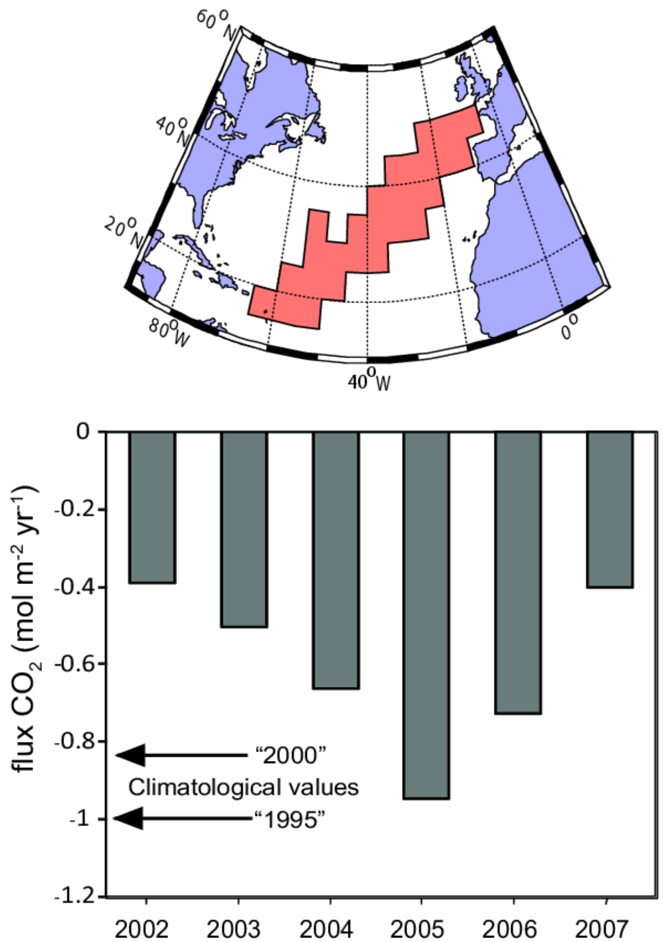
Less DIC ? More DIC ?

Decreasing ΔfCO_2, increasing winds → near-constant flux

Metzl, DSR 2009

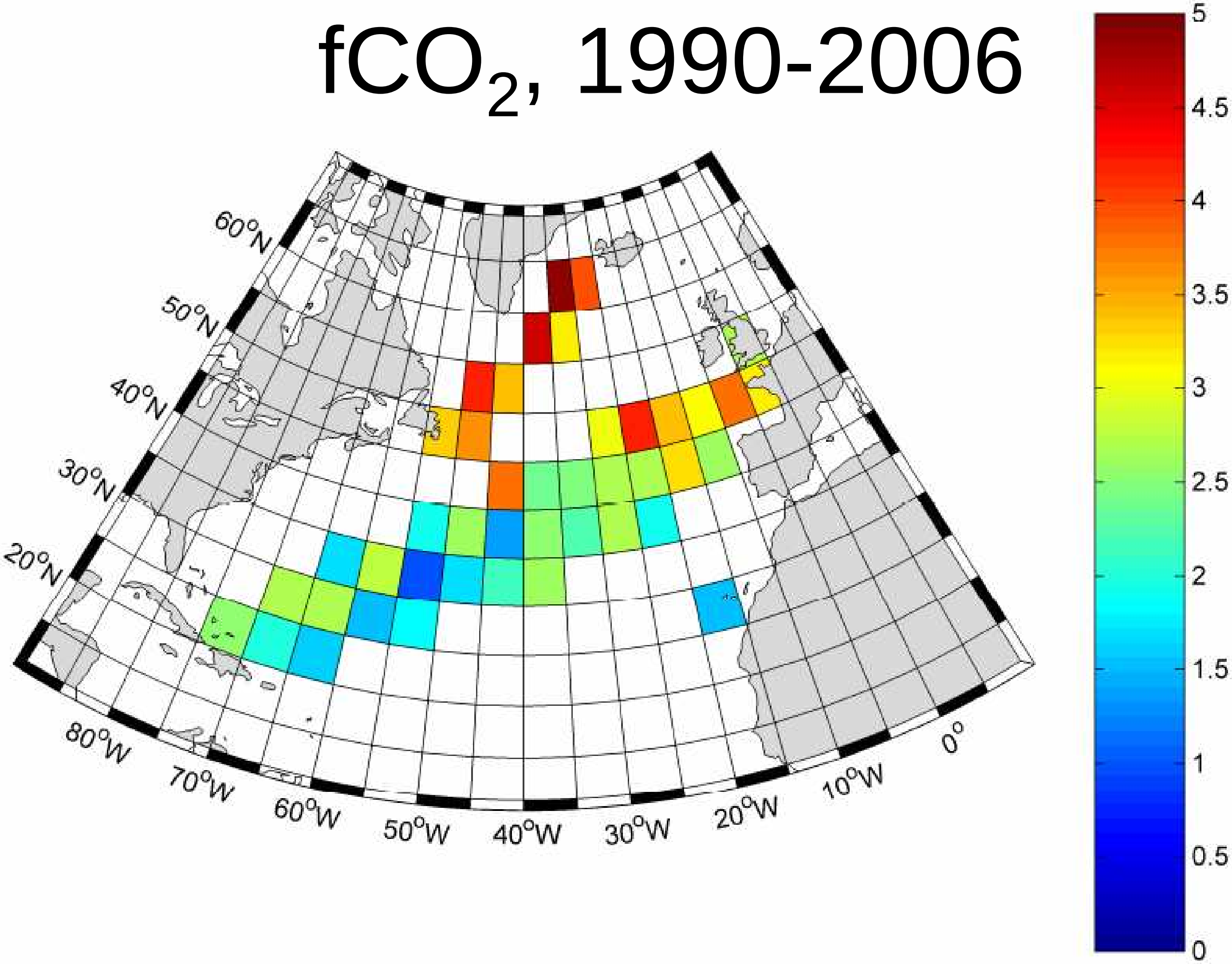
Change in surface fluxes along a North Atlantic shipping route





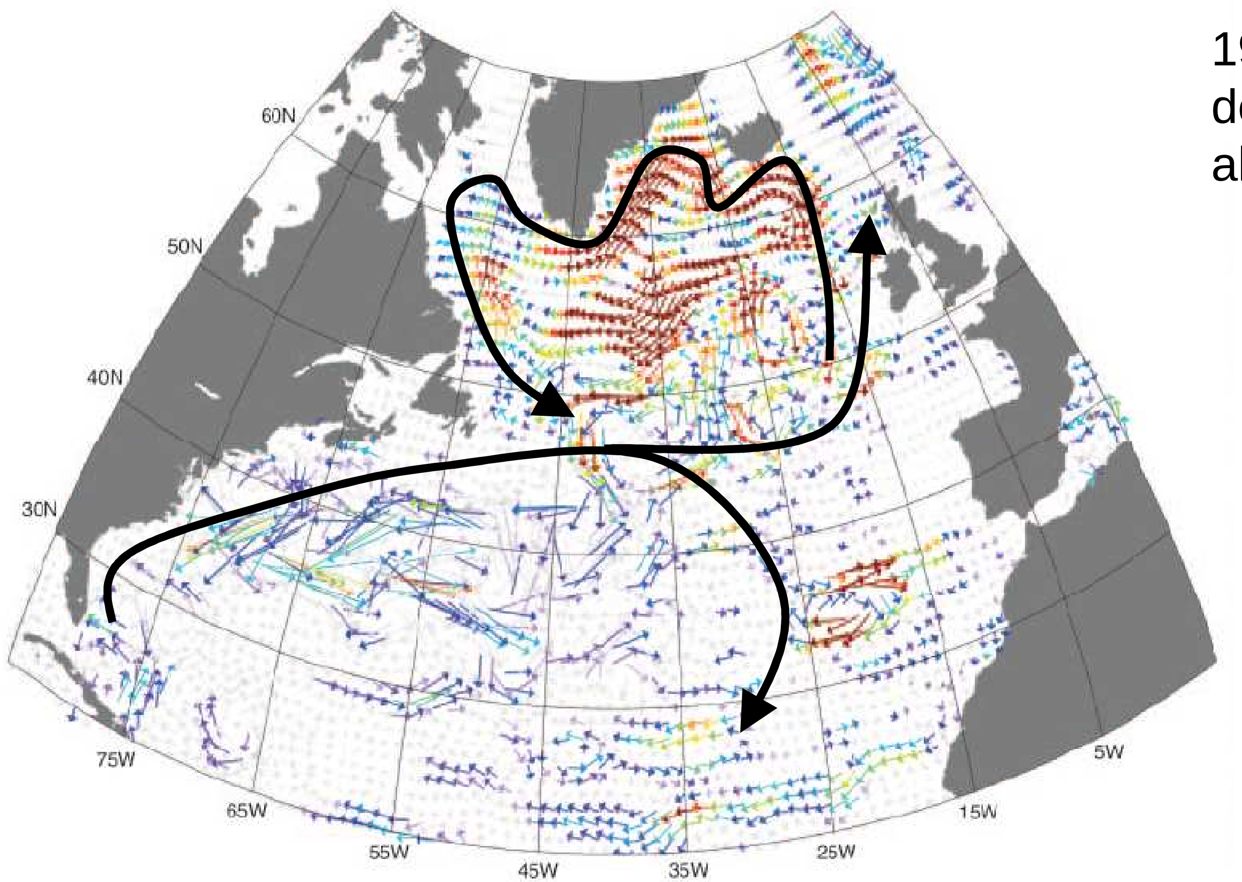
Watson et al., Science 326 1391-1393, 2009

Annual average rise in sea surface fCO_2, 1990-2006



Schuster, U., et al., Deep Sea Res. II, 56, 620-629 (2009)

Spin-down and shrinking of the North Atlantic subpolar gyre, related to phase of the NAO?



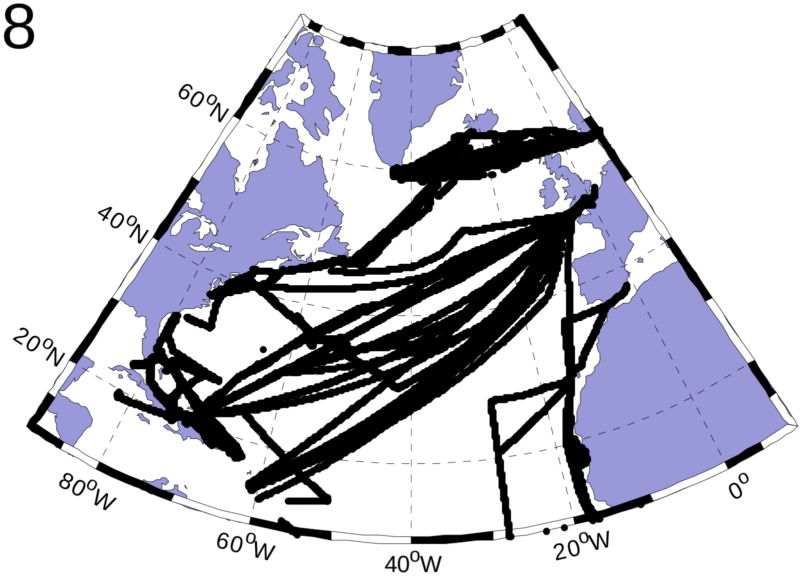
1992 to 2002 determined by altimetry data

from Häkkinen and Rhines (2004) *Science* **304**: 555 - 559

The Carbo-ocean North Atlantic observing system

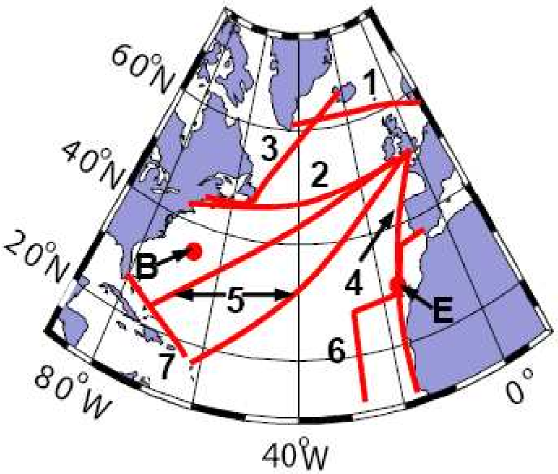
- The first operational multi-ship voluntary observing network for sea surface pCO_2 and air-sea flux.
- Co-ordinated with European, US and Bermudan co-investigators
- Funded 2005-2008

Watson et al., Science 326, 1391-1393, 2009



2005 measurements

Year 2005 coverage



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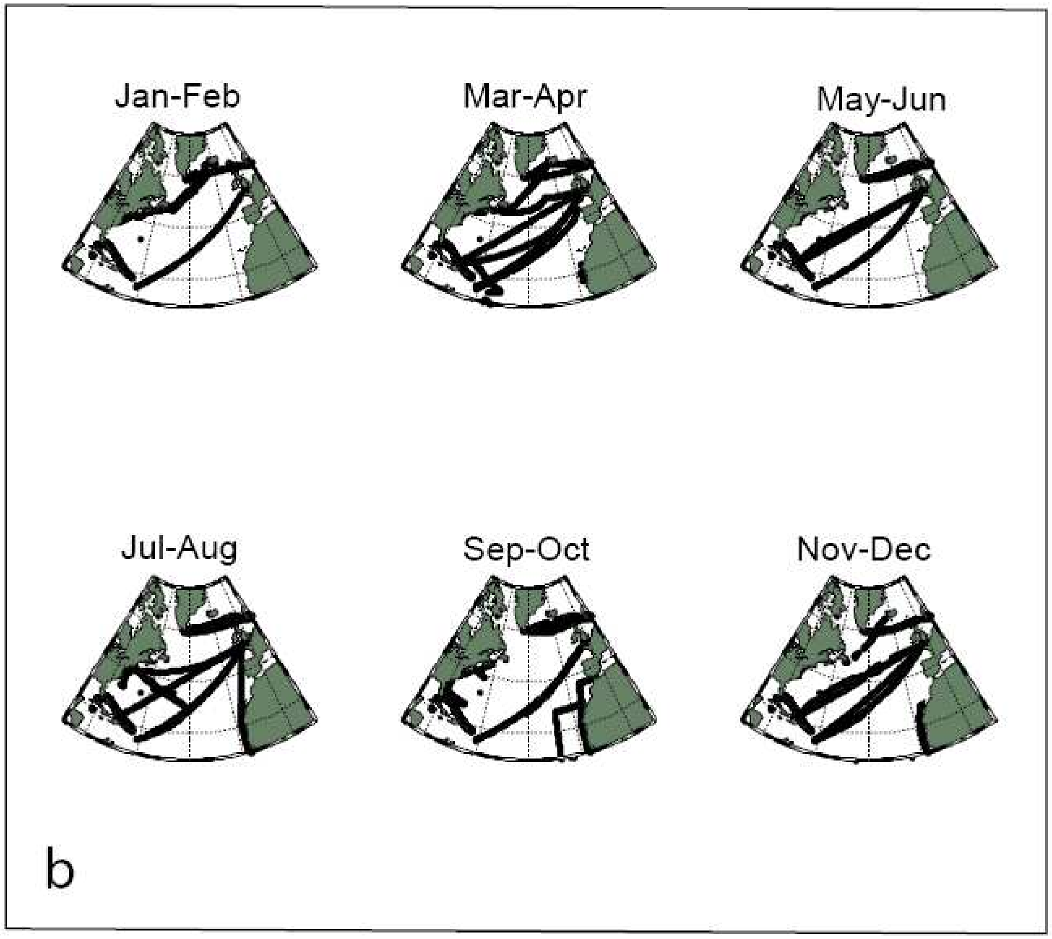
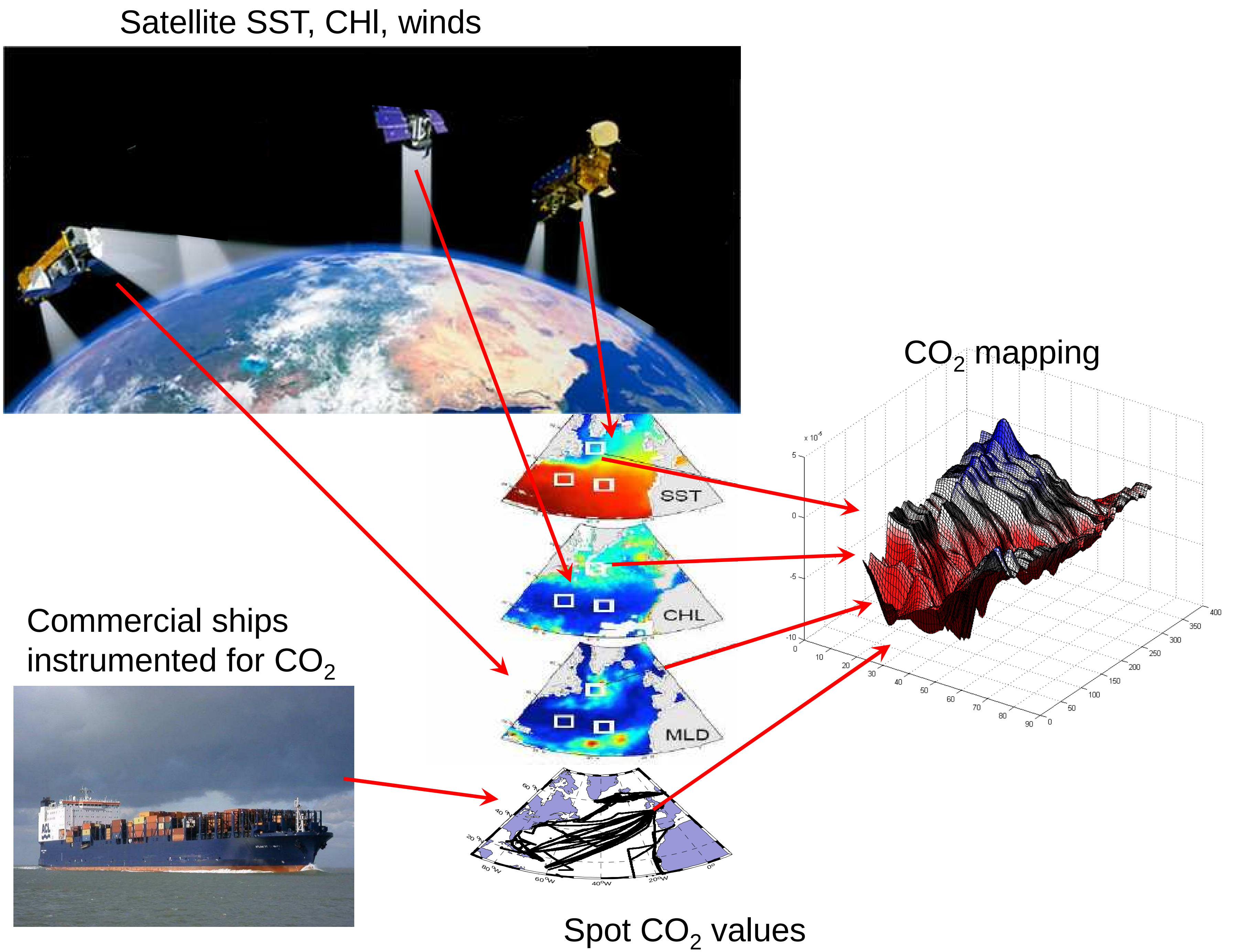


b

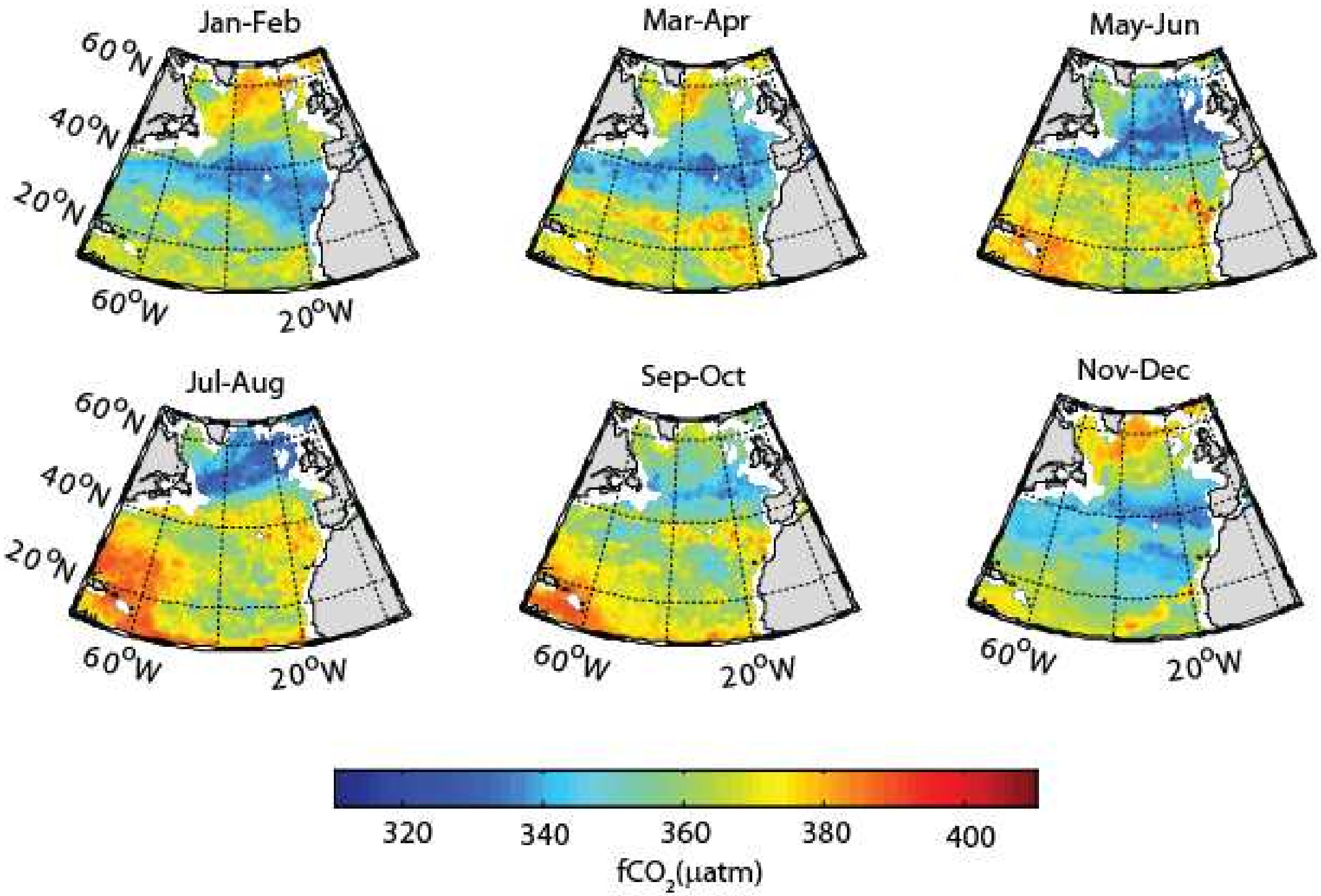
Constructing basin-wide mappings

- For each pCO_2 measurement, assign SST, mixed layer depth,
- SST from re-analysis, mixed layer depth from FOAM (UK Met office data –assimilated operational model)
- Find pCO_2 as a function of these variables using
  - multiple linear regression
  - Neural network
- Interpolate to generate a pCO_2 map for the whole area
- Calculate fluxes

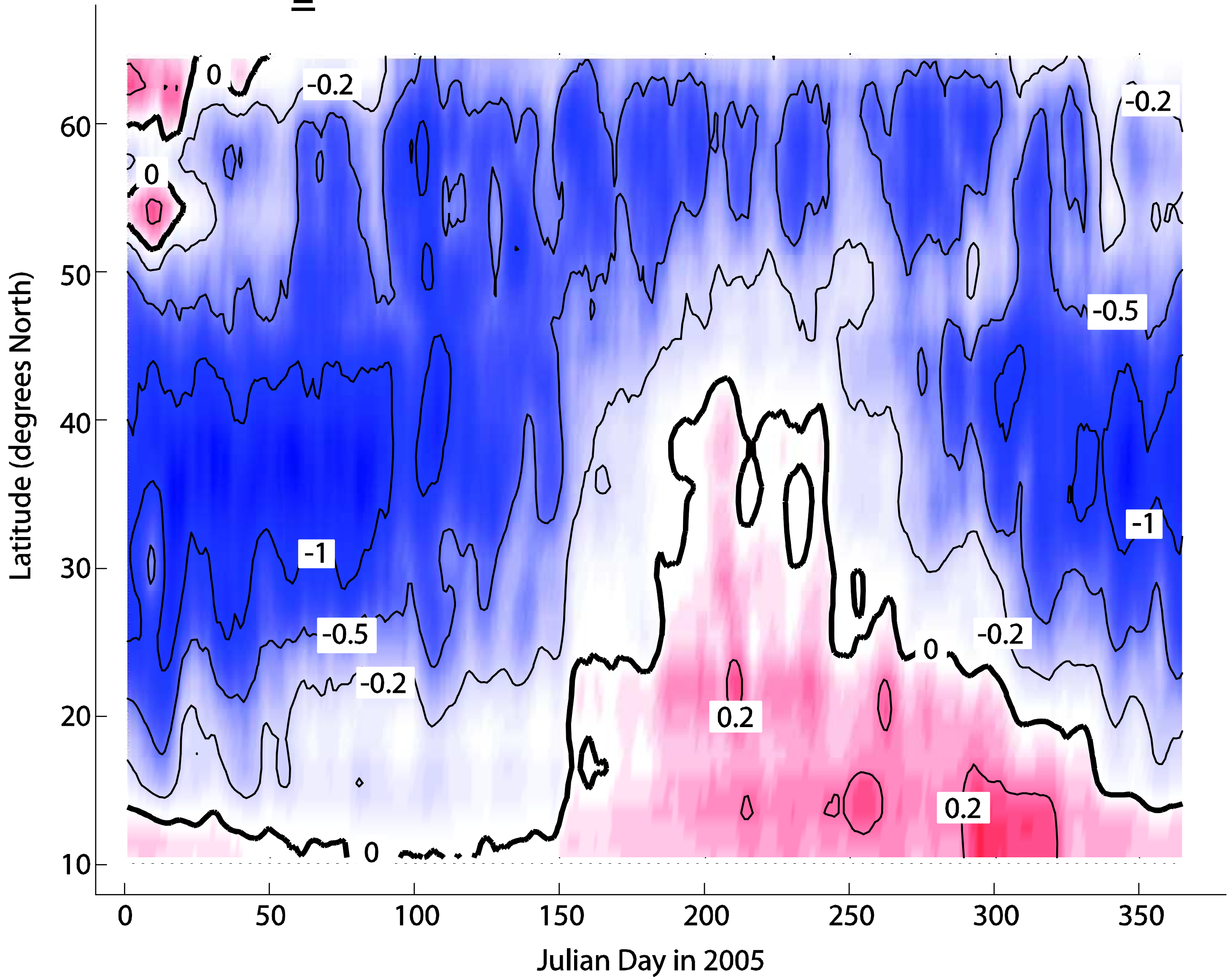


Satellite SST, CHl, winds
CO_2 mapping
SST
CHL
MLD
Commercial ships
instrumented for CO_2
Spot CO_2 values

fCO_2 mappings from neural nets



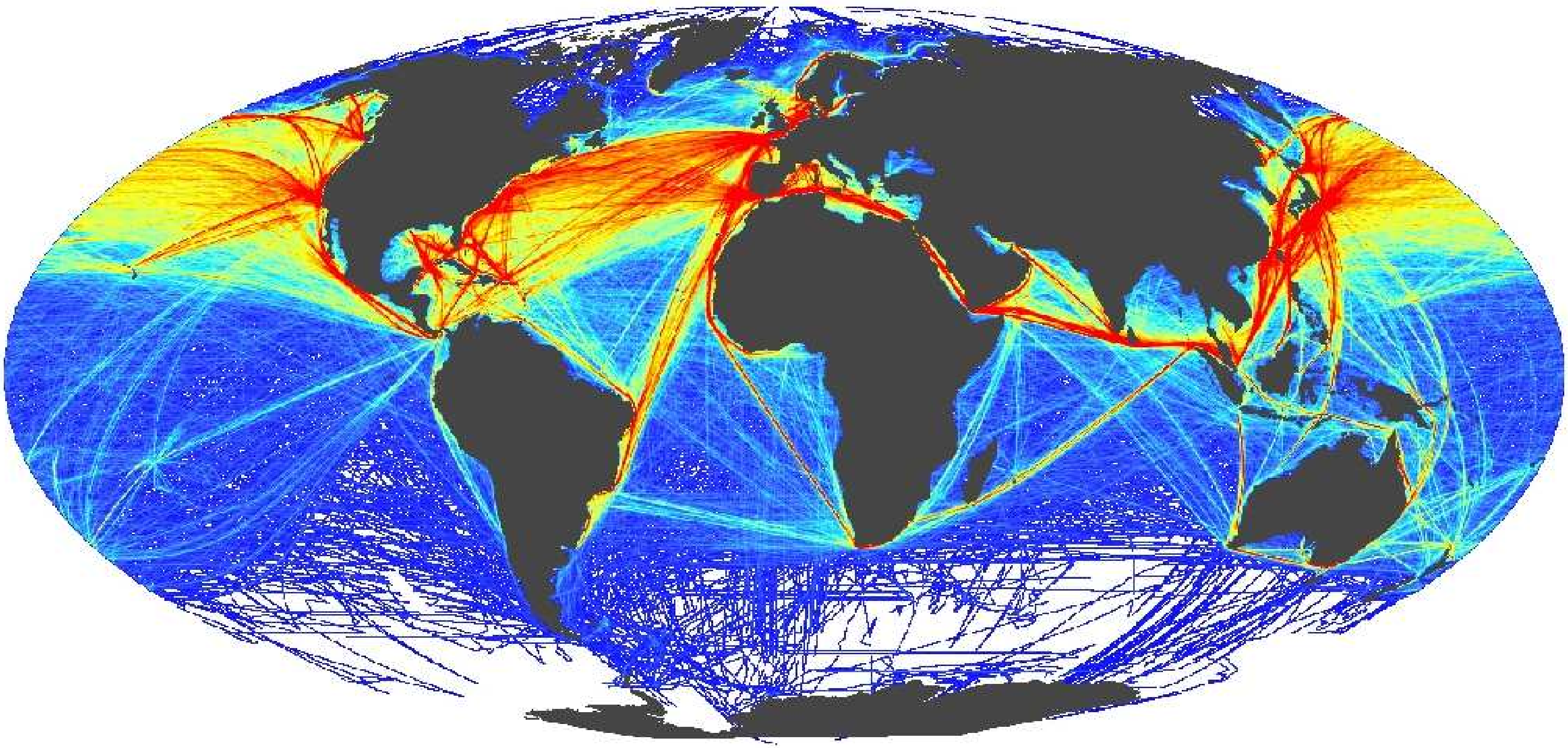
CO_2 flux into the North Atlantic in 2005



Uncertainty on estimates of ocean fluxes obtained from commercial shipping network

- There is no single correct method to calculate the uncertainty.
- Use two methods:
  - Geostatistics; calculate variograms, estimate using Kriging theory.
  - Sample the output of a high resolution model of the N. Atlantic along “ship tracks” and reconstruct the fluxes into the model ocean from these alone. Then compare to the actual fluxes, which are known for a model.
- Both methods suggest the precison on the overall, annual flux is <10%.
- Overall accuracy including uncertainties in gas transfer velocities, is ~20%.

Shipping density and shipping routes: data from 2004-2005



B. S. Halpern *et al.*, *Science* **319**, 948-952 (2008).

Conclusions

- We conventionally model separate anthropogenic and “natural” fluxes. However this separation is not easy (and not practically observable) and needs more thought.
- Ocean uptake tends to be thought of as dependable and constant, but wherever we have been able to observe it, it varies with climate indices regionally.
  - e.g. in the Equatorial Pacific (El Nino)
  - The N. Atlantic (NAO)
  - The Southern Ocean (SAM)
- The ocean uptake can and should be monitored and observed continuously: it’s completely within our grasp to do this at least for the Northern hemisphere oceans
  - Eventually we expect carbon climate feedbacks to slow the ocean sink: an observing system could give early warning of their onset.