

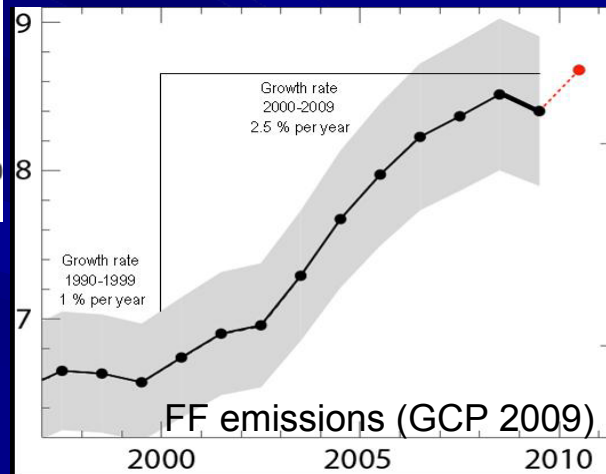
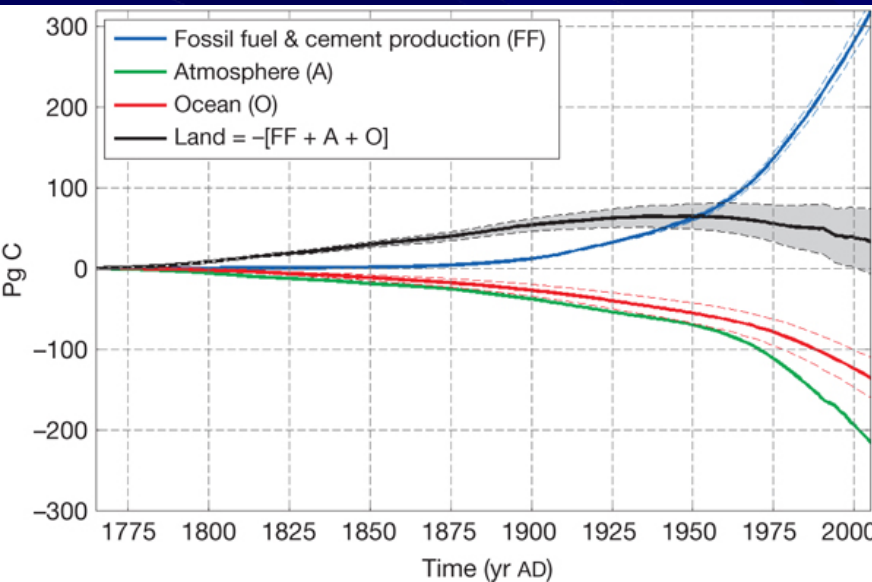
# Carbon Changes in the Interior Ocean

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Samar Khatiwala  
Christopher L. Sabine

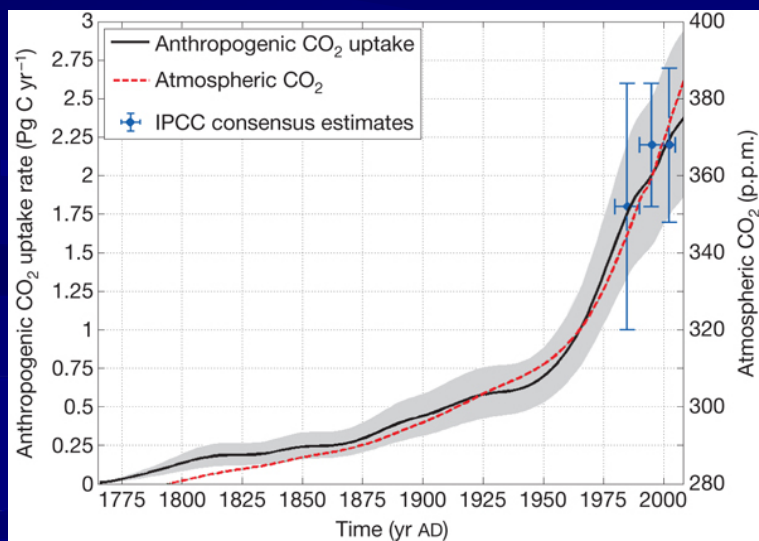
# The Anthropogenic Perturbation

Three estimates of the global inventory of anthropogenic carbon for year 1994 (excluding marginal seas):

- Sabine et al., 2004:  $106 \pm 17$  PgC
- Waugh et al., 2006: 94 – 121 PgC
- Khatiwala et al., 2009:  $114 \pm 22$  PgC ( $140 \pm 25$  PgC in 2008)

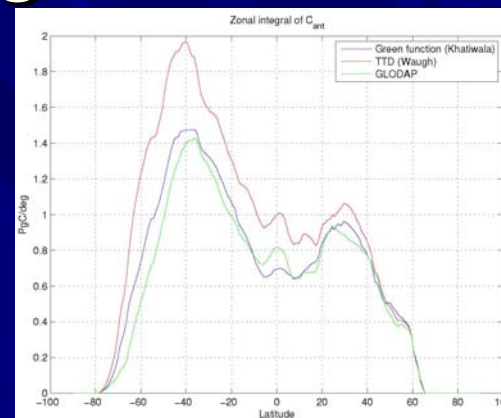
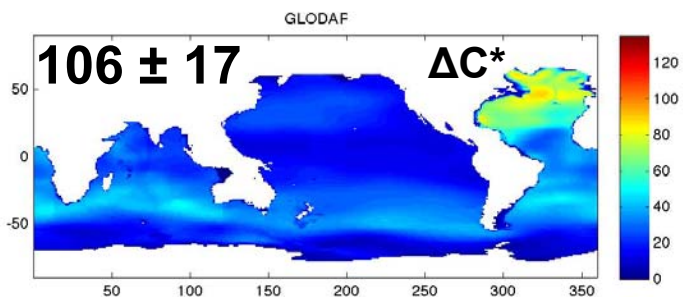
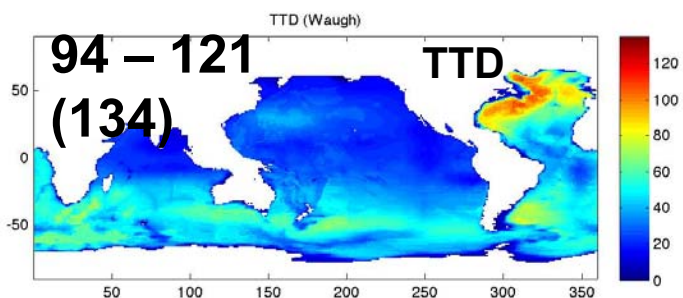
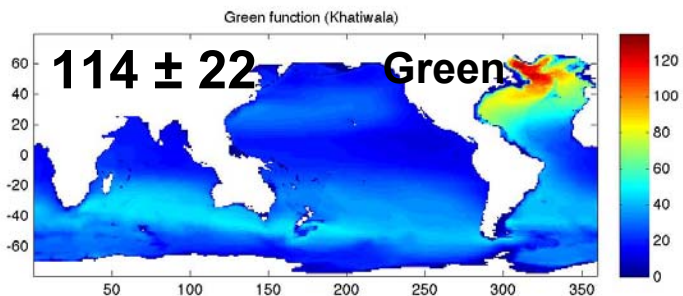


Khatiwala et al., 2009

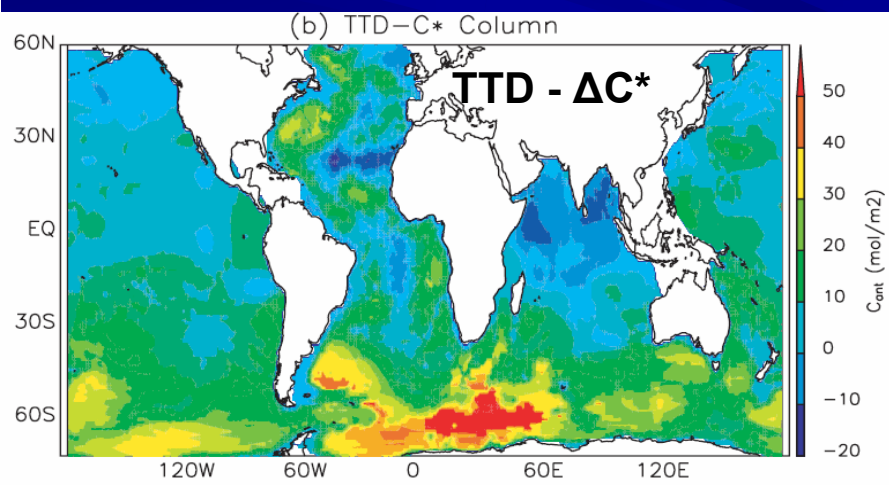


The ocean has absorbed ~46% of the total Fossil fuel + cement production emissions  
 Currently the ocean is absorbing ~2.3 PgC/year and the emissions is ~ 8.4 PgC/year.  
 The ocean is currently absorbing ~25% of the emissions

# Interior ocean anthropogenic carbon



$\Delta C^*$  - Green



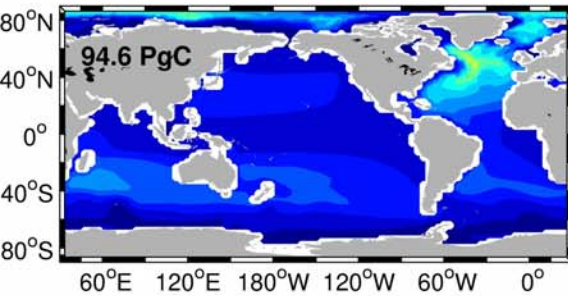
Waugh et al.,  
2006

The different estimates are all within the uncertainties. Differences are in the details.

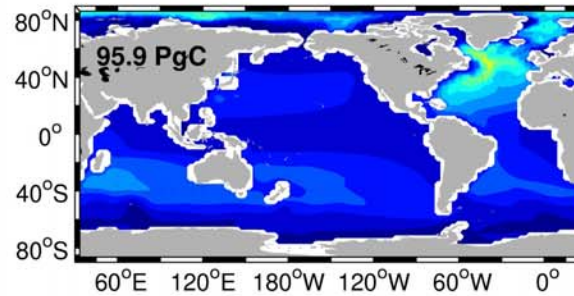


# Column Inventory of $C_{ant}$ (1990-2005 mean) [mol/m<sup>2</sup>]

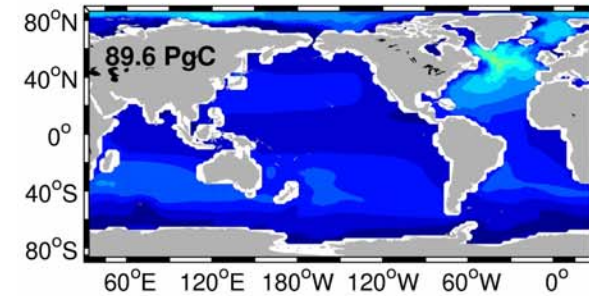
ETH-k15



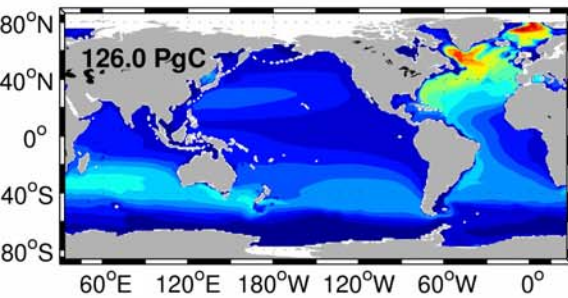
ETH-k19



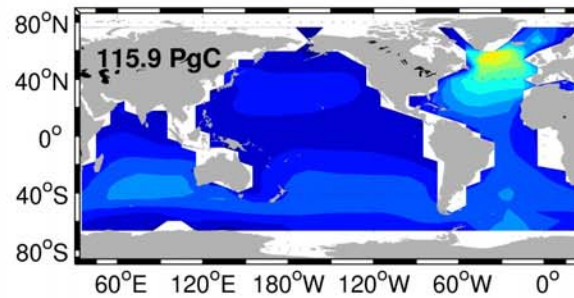
WHOI/BEC



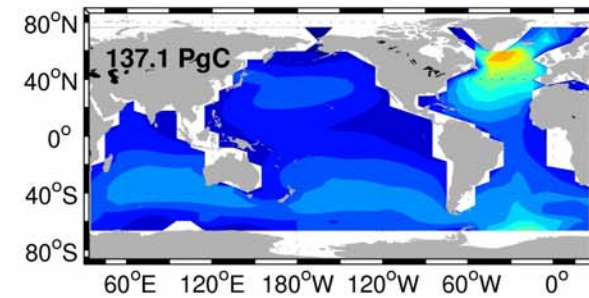
OIP



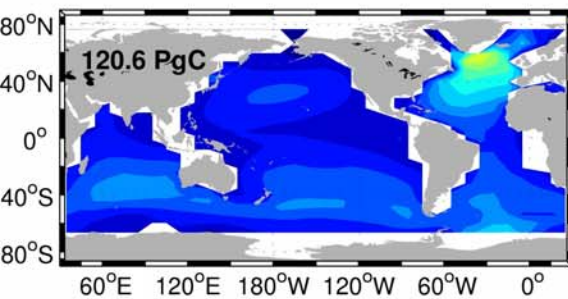
EnKF-CSTAR



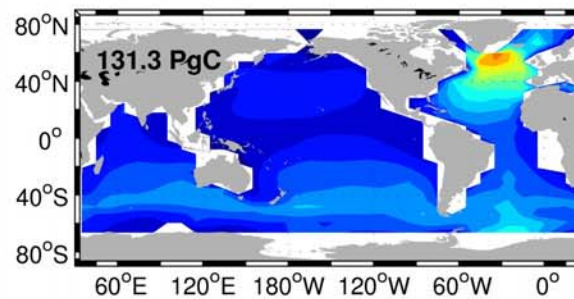
EnKF-CFC



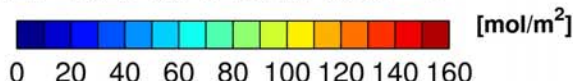
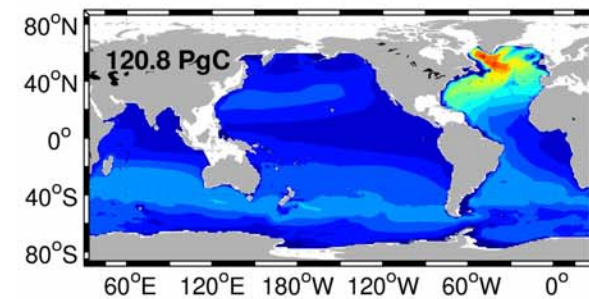
EnKF-TTD



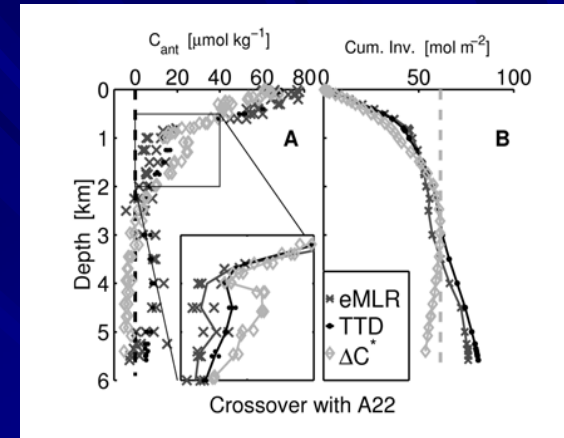
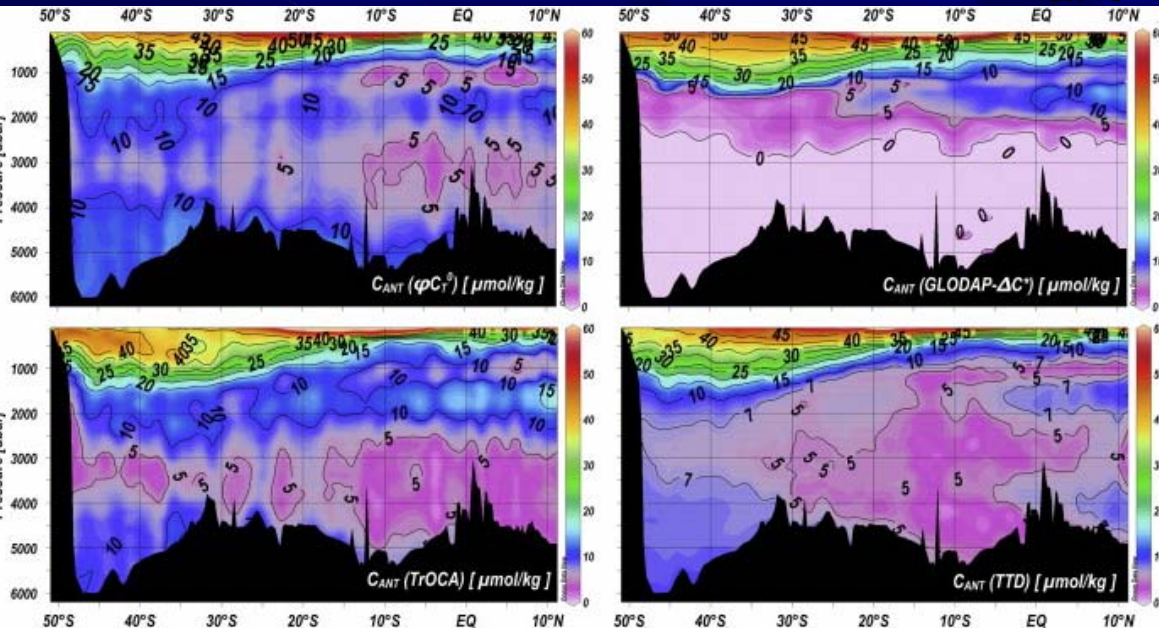
EnKF-TROCA



Green Function

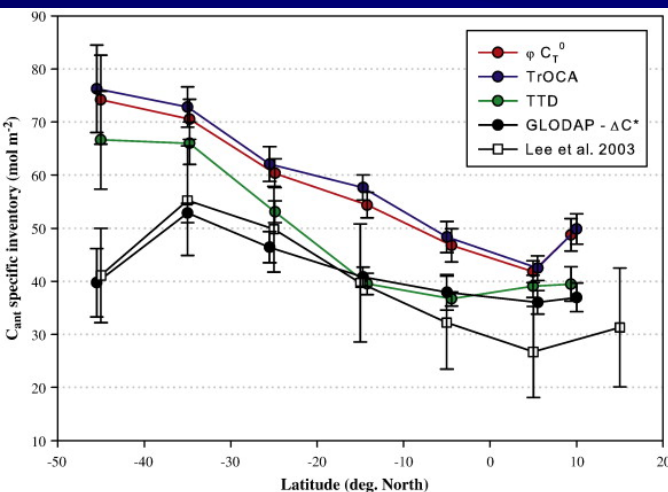


# A vertical view of the $C_{ant}$ distribution



Tanhua et al., 2010  
Northwest Atlantic Ocean

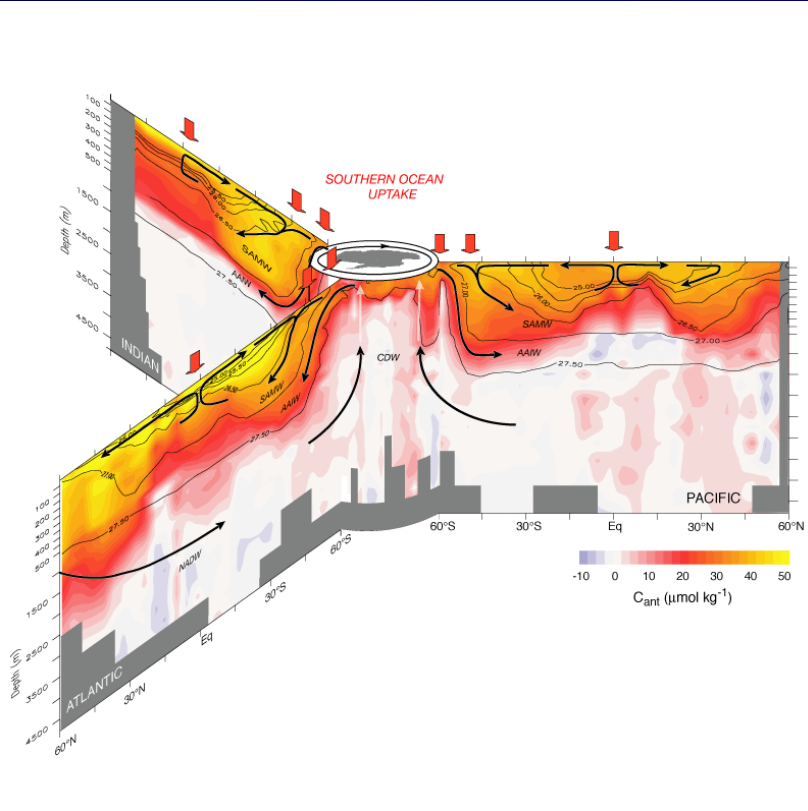
Rios et al., 2010  
Southwest Atlantic Ocean



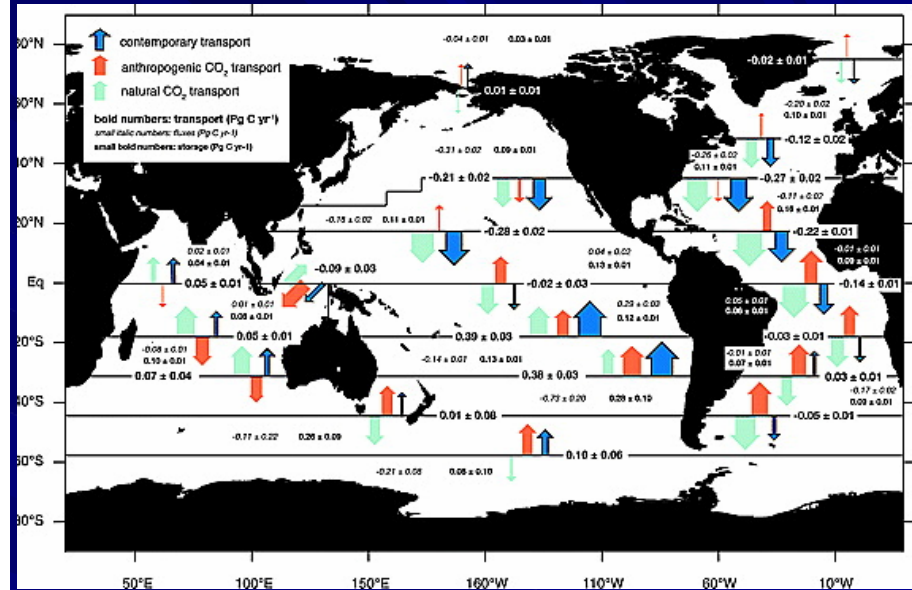
The distribution in the vertical does matter!



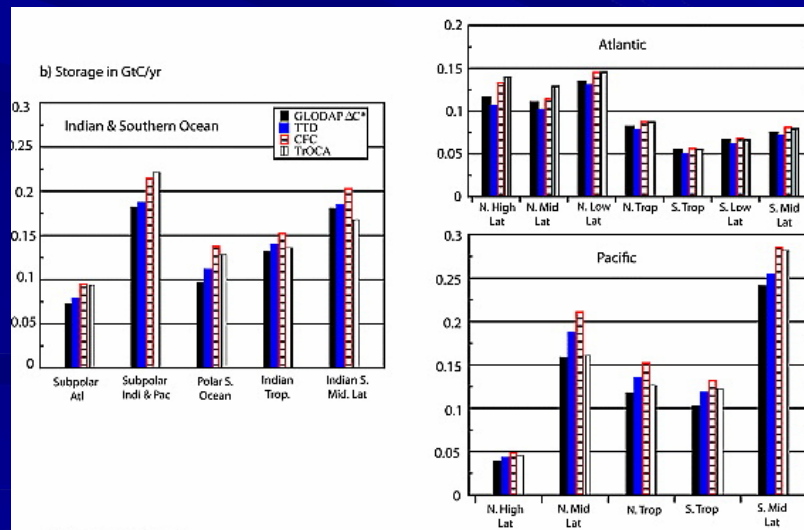
# Ocean inversions



Gruber et al., 2009

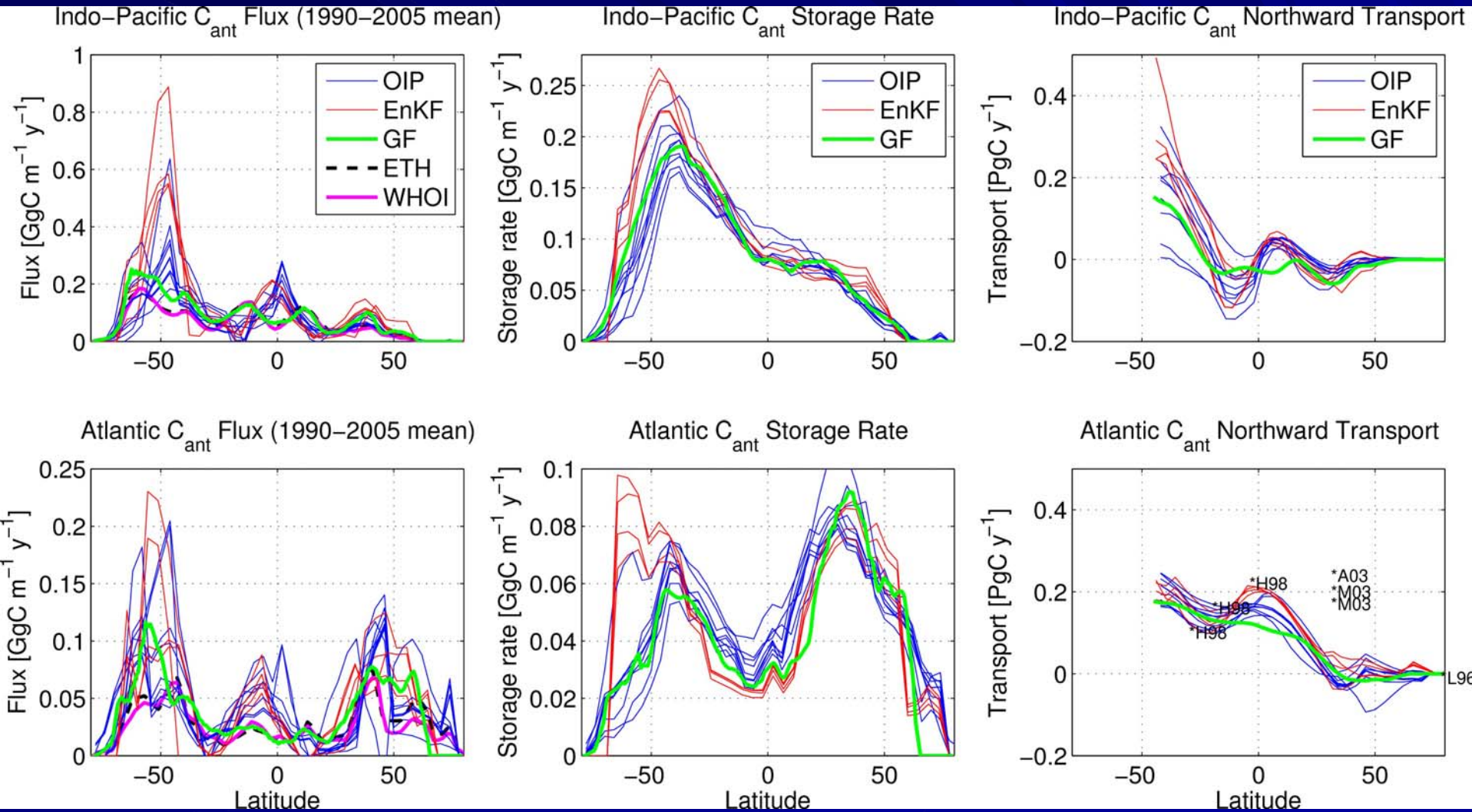


Gruber et al., 2009

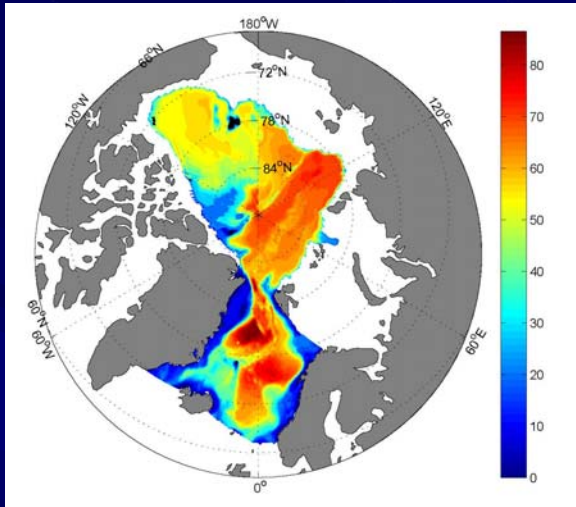


Gerber et al., 2009

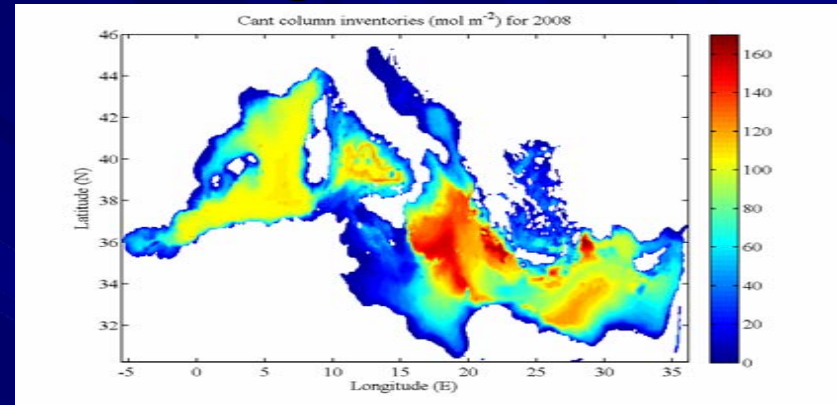
# Uptake and Transport



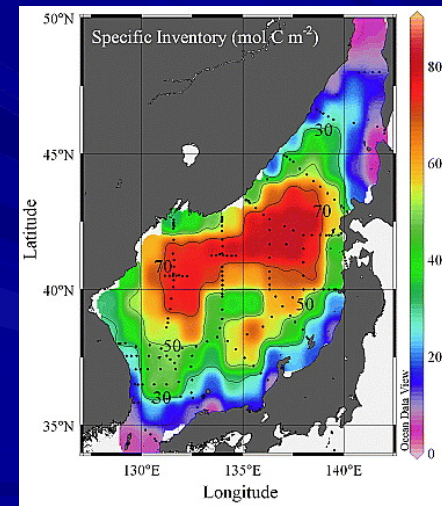
# Don't forget the Marginal Seas



Olsen et al., 2010 and Tanhua et al., 2009



Schneider et al., 2010

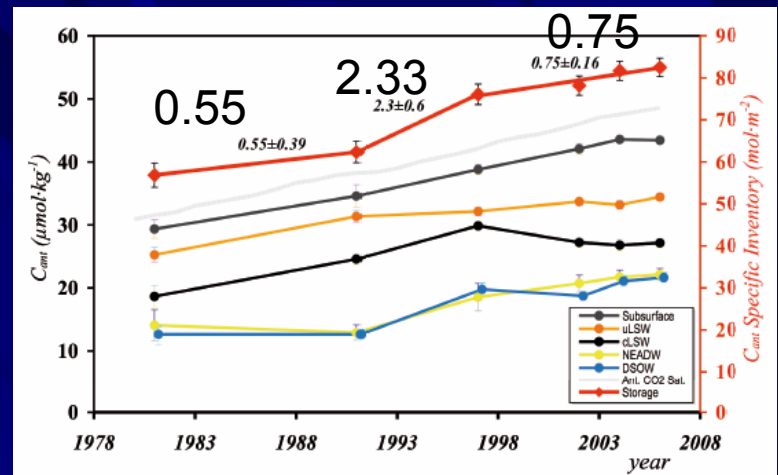


Park et al., 2006

**The Marginal Seas add up to > 8 PgC, i.e. ~6% of the total (Lee et al., 2010)**

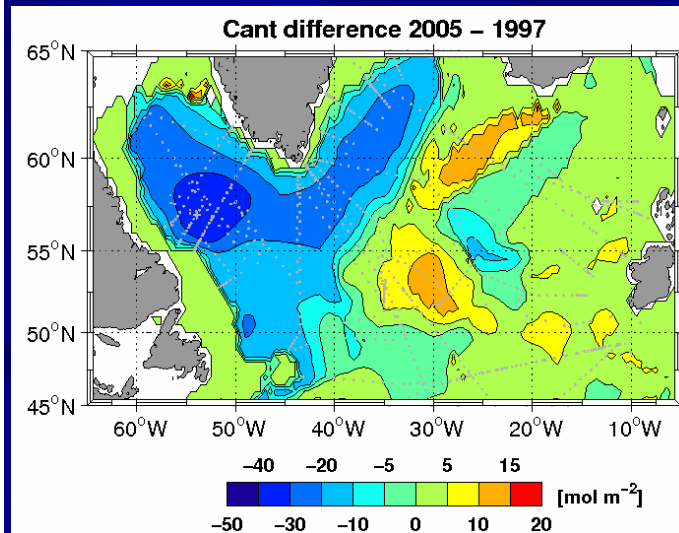
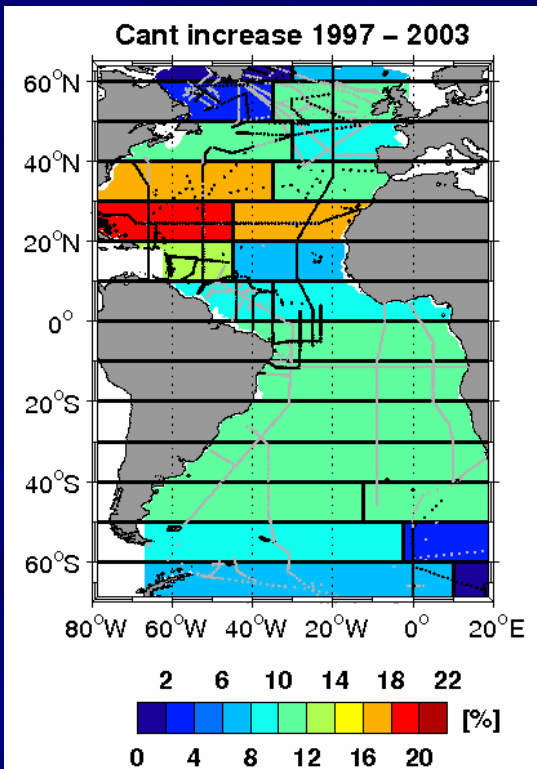


Decadal scale variations in circulations has the potential to bias storage rate estimates of carbon.



Perez et al. (2010) suggest a correlation Between NAO and  $C_{ant}$  storage rate

High NAO  $\blacktriangleright$  high  $C_{ant}$  storage rate



Steinfeldt et al. 2009 found variations in storage rate that are probably linked to decadal scale fluctuations in Labrador Sea Water formation.

# Carbon feedbacks

## DIC increase

Decreased Buffer Capacity ↑

Carbon Over-Consumption ↓  
Increased Carbon Export

## Acidification

Increased Dissolution of Calcium Carbonate ↑↓

Reduced Calcification ↓  
Less CO<sub>2</sub> Released During Calcification

Reduced Particle Ballast ↑  
Less Particle Flux

## Extended Oxygen Minimum Zones

Denitrification ► Decreased Carbon Particle Export ↑  
Nitrogen Fixation ► Increased Carbon Particle Export ↓

## Warmer Ocean

CO<sub>2</sub> Outgassing ↑

Enhanced recycling of OM ↑

## Increased Stratification

Favored conditions for Coccolithophores Over Diatoms ↑

## Reduced MOC

Reduced Transport of C<sub>ant</sub> to the Deep Ocean ↑

Reduced upwelling ↓

Less nutrients available for PP ↑

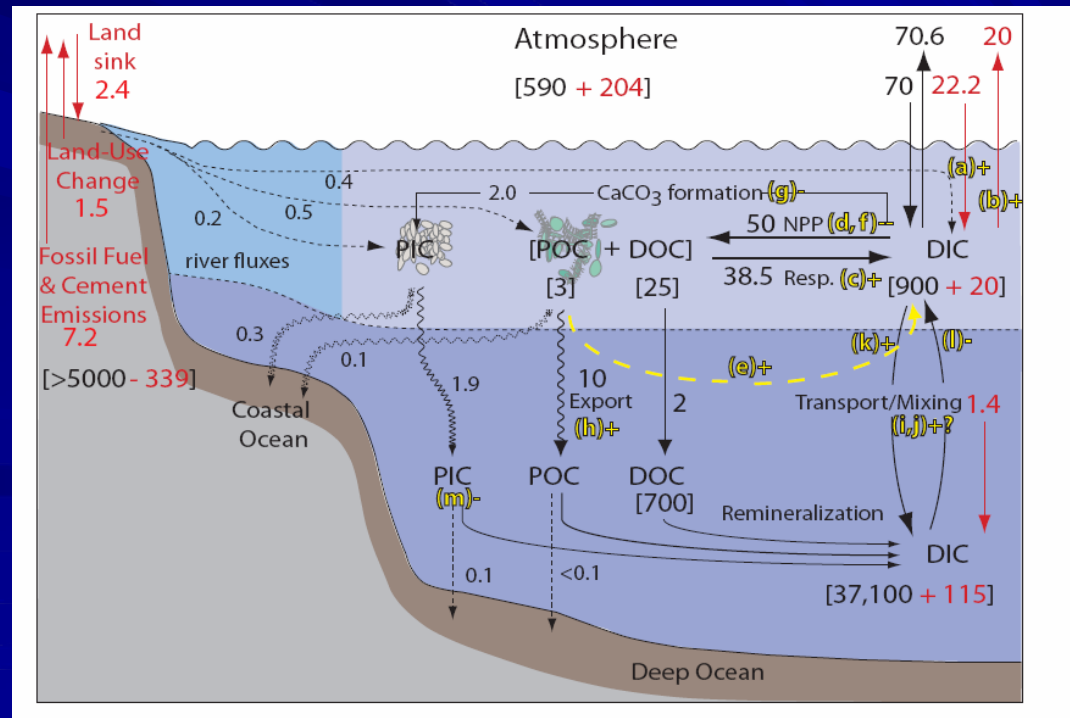
## Increased Southern Ocean Winds

Increased Overturning ? ?

# Challenges

The current scientific paradigm is that anthropogenic  $\text{CO}_2$  is entering the ocean as a passive thermodynamic response to rising atmospheric  $\text{CO}_2$ . The current challenge for the scientific community is to determine whether these feedbacks are occurring and how they will modify the ability of the ocean to store  $C_{\text{ant}}$  over the next few decades.

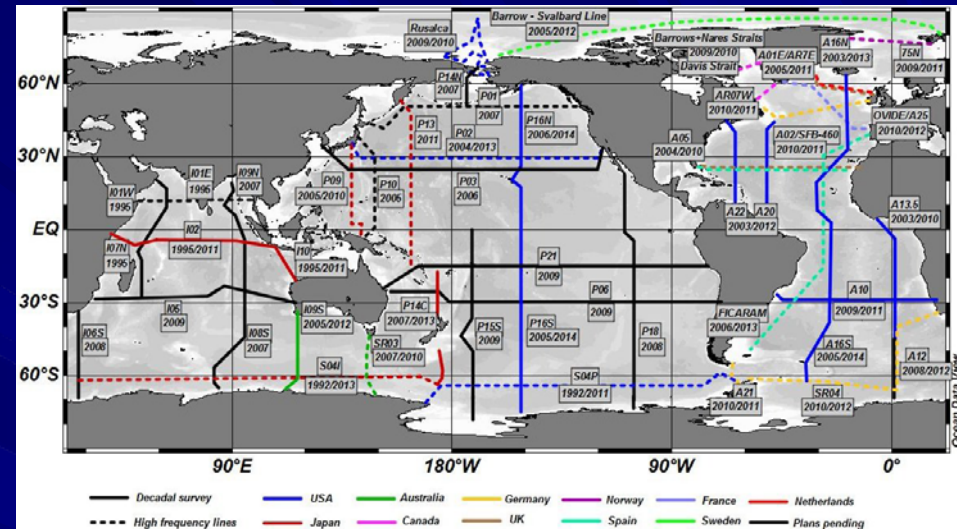
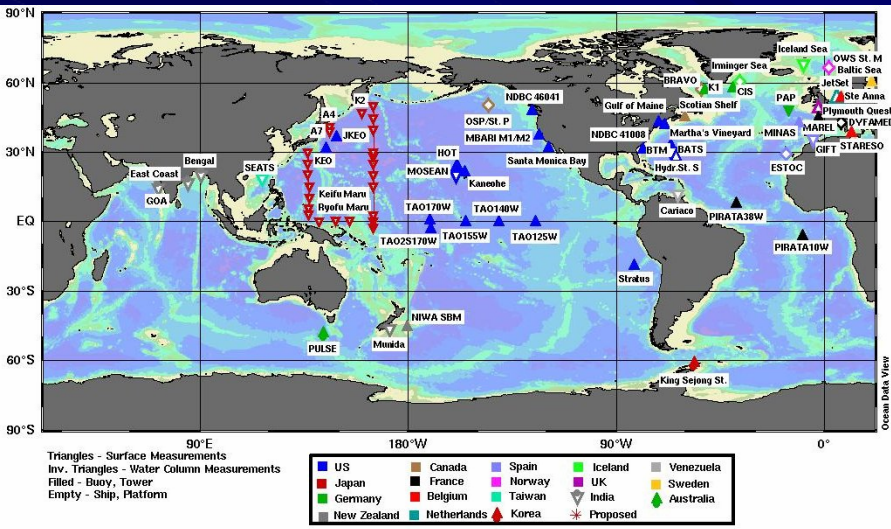
Sabine and Tanhua 2009



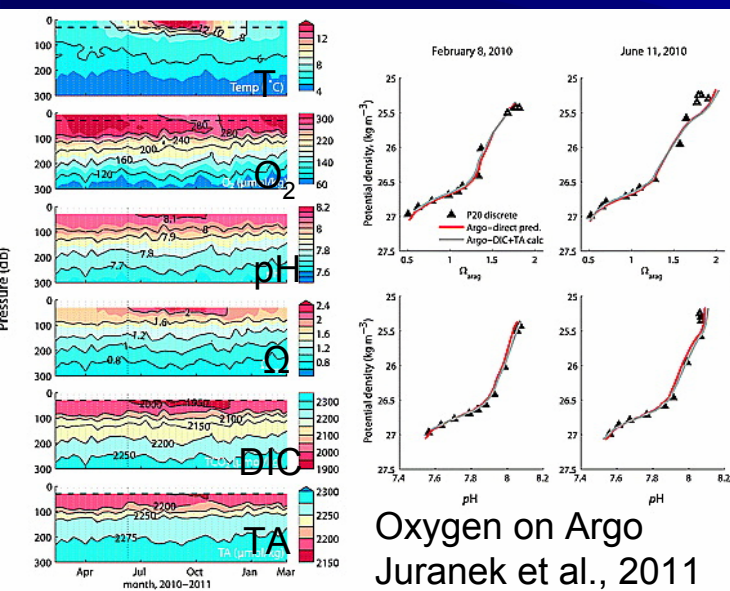
Sabine and Tanhua 2009



# What is the status of observations?

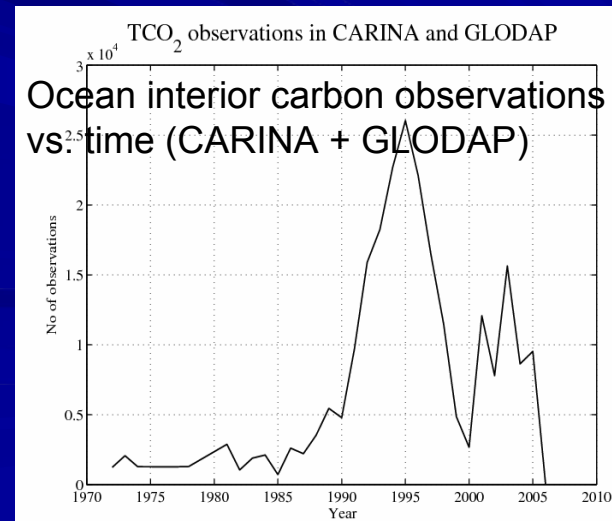


## Time-series with carbon measurements



Oxygen on Argo  
Juraneck et al., 2011

## Hydrographic sections with carbon measurements



# Interior carbon observations

Ocean interior observations remain the best mechanism for verifying the changes in ocean *Can*t inventory. It is extremely difficult to predict how the many possible carbon cycle feedbacks will affect ocean carbon storage; modeling and proxy techniques are limited by our current understanding of the ocean carbon cycle. It is critically important that we understand how *Can*t is accumulating in the ocean on time scales relevant to human civilization (years to decades). CO<sub>2</sub> emissions are growing at an ever increasing rate and the momentum of the carbon and climate system is such that decisions made today will still impact the climate for hundreds to thousands of years from now.

The best way to improve our understanding is to continue using a broad suite of approaches with both observations and models to examine both ocean carbon uptake and ocean carbon storage over a range of time scales.

Sabine and Tanhua 2009