Global ocean uptake and storage of anthropogenic carbon estimated using transit-time distributions

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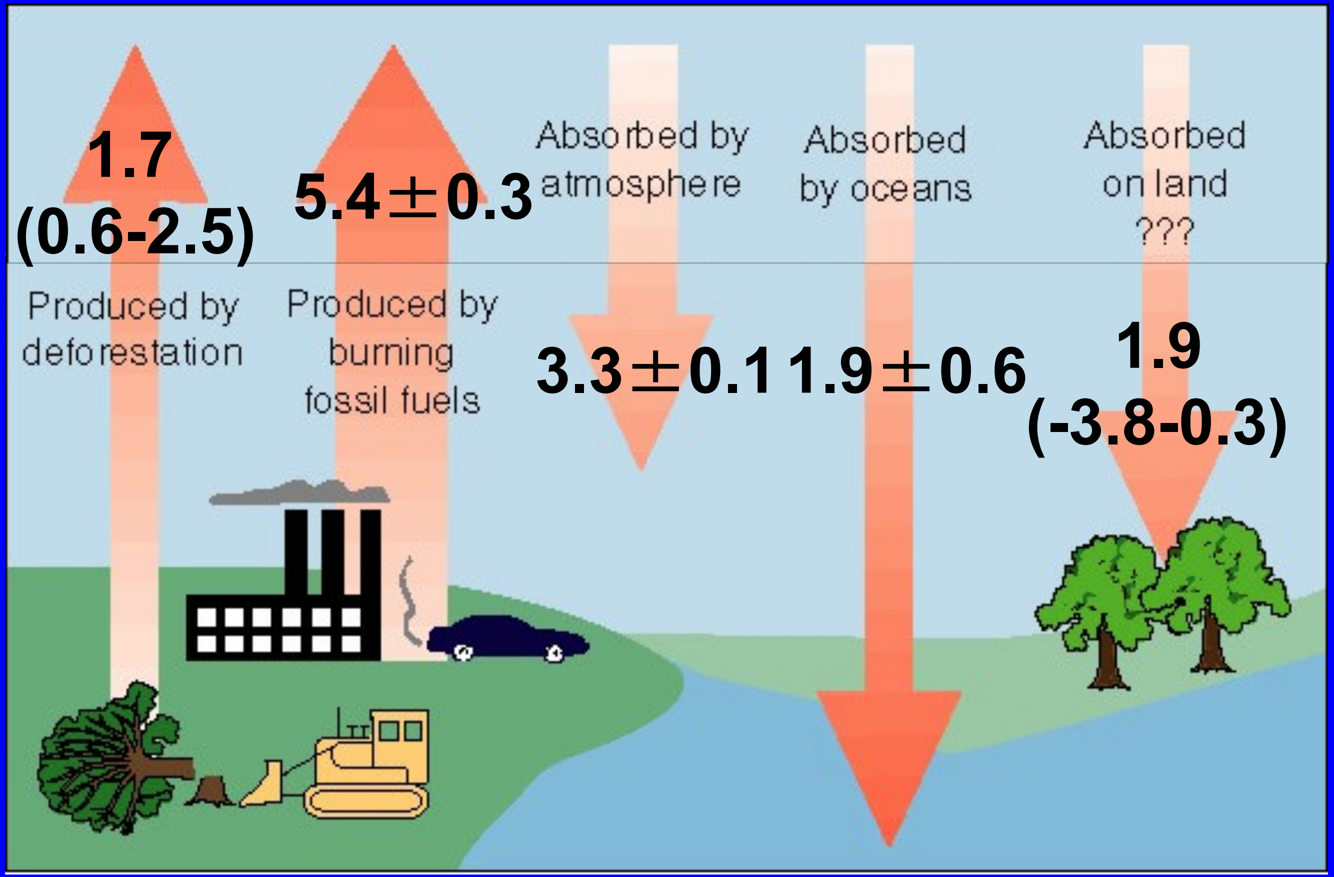
Sources and sinks of anthropogenic carbon (in PgC/y)



- Total emissions (1800-1994): 340-420 PgC
- Increase in atmosphere: 165 PgC
- Balance taken up by the ocean and land biosphere

Principal Goal

Reconstruct the history of anthropogenic carbon in the ocean over the industrial period

Motivation:

- **Insights into physical mechanisms driving ocean uptake**
- **Evaluation and improvement of forward biogeochemical models to more accurately predict future uptake**

Anthropogenic carbon and its trend are much harder to discern in the ocean than in the atmosphere

- Anthropogenic carbon is not directly measurable
- The anthropogenic signal in the ocean (ΔDIC) is only a few percent of the **(unknown)** natural background of dissolved inorganic carbon (DIC)
- Carbon in the ocean participates in complex in-situ biogeochemistry
- Due to long transport timescales the ΔDIC concentration in the ocean is highly heterogeneous

“Back-calculation” methods (e.g., “ΔC* method”) for inferring ΔDIC attempt to separate the small anthropogenic component from the large background

Basic idea (Brewer, 1978; Chen and Millero, 1979; Gruber *et al*., 1996): ΔDIC can be estimated by correcting measured DIC for changes due to biological activity

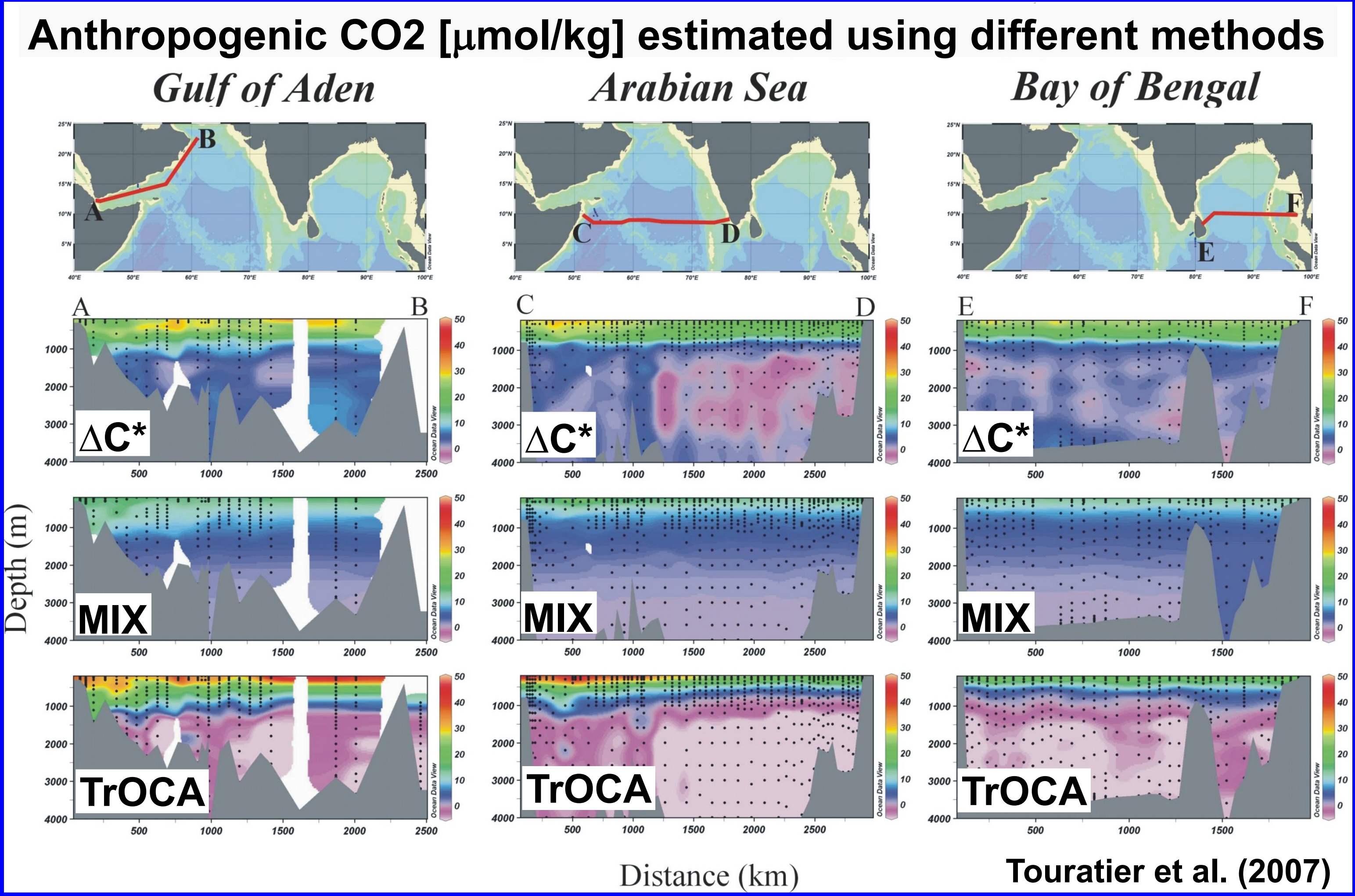
$$\Delta DIC = DIC_{meas} - \delta DIC_{bio} - \delta DIC_{diseq} + \ldots$$

Assumptions:

- Stoichiometric (Redfield) ratios are known and constant
- Transport is dominated by advection (“weak mixing”)
- Air-sea disequilibrium of CO_2 has remained roughly constant

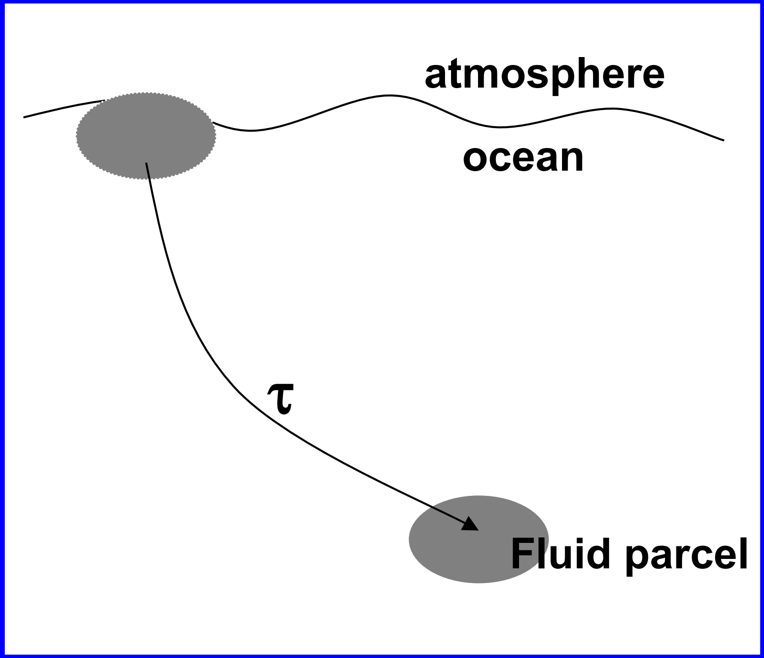
Fundamental limitation: can only provide an estimate for the 1990’s

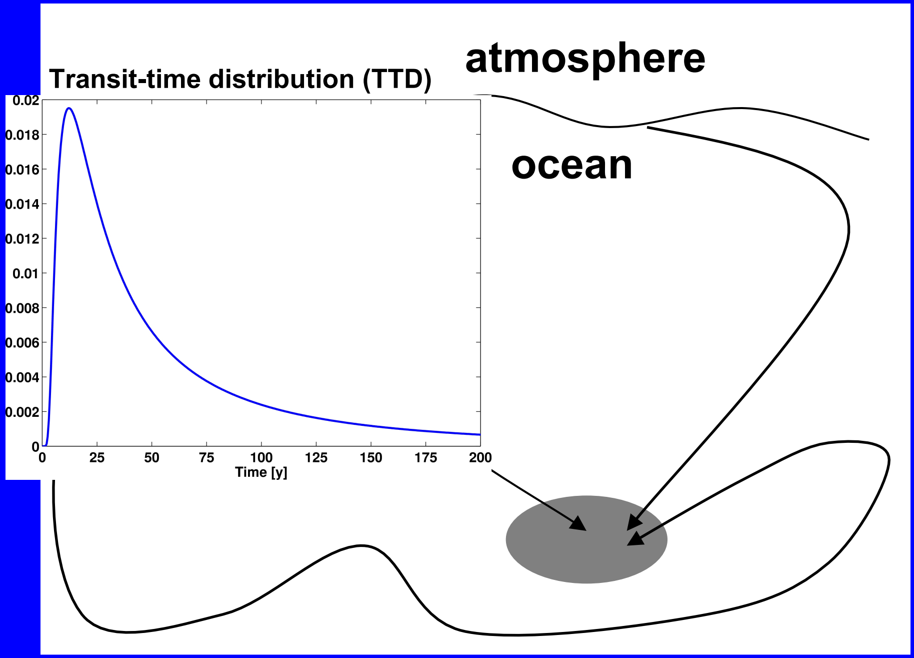
Different back-calculation methods for estimating ΔDIC in the ocean give quantitatively different results



Integrated inventories differ on average by 20% between different methods

Transient tracers such as CFCs are conventionally used to estimate a surface-to-interior transit time. But this implicitly assumes that transport is purely advective.





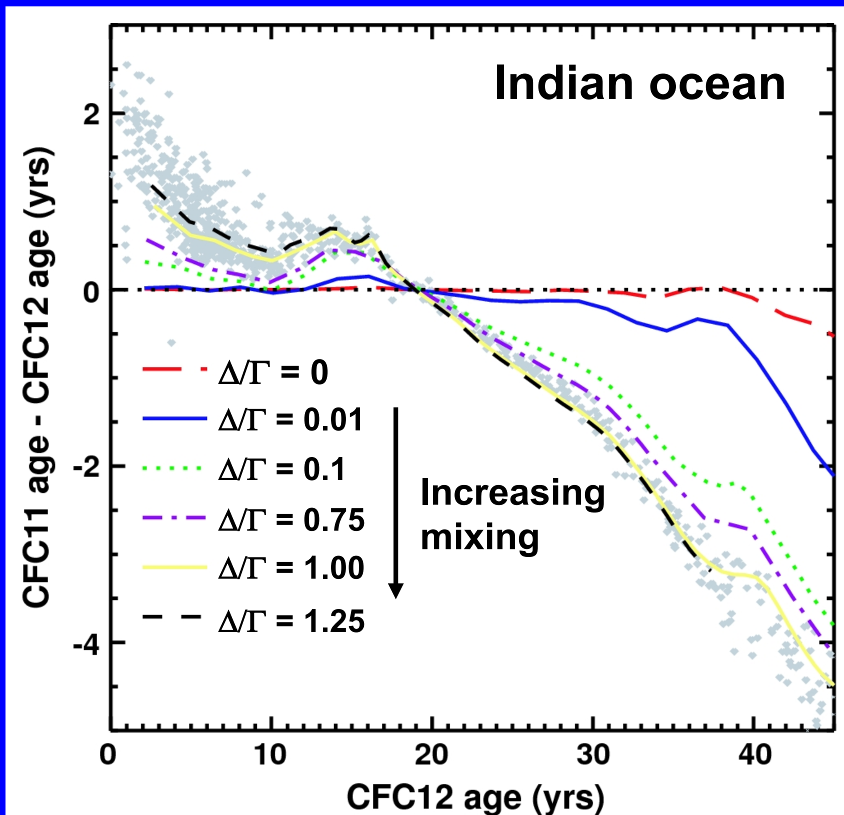
$$C(\mathbf{x},t) = C_{\rm surf}(t-\tau)$$

$$C(\mathbf{x},t) \;=\; \int_{-\infty}^{t} C_{\rm surf}(t')\mathcal{G}(\mathbf{x},t-t';\partial\mathcal{D})dt'$$

(Holzer and Hall, 2000; Khatiwala et al, 2001)

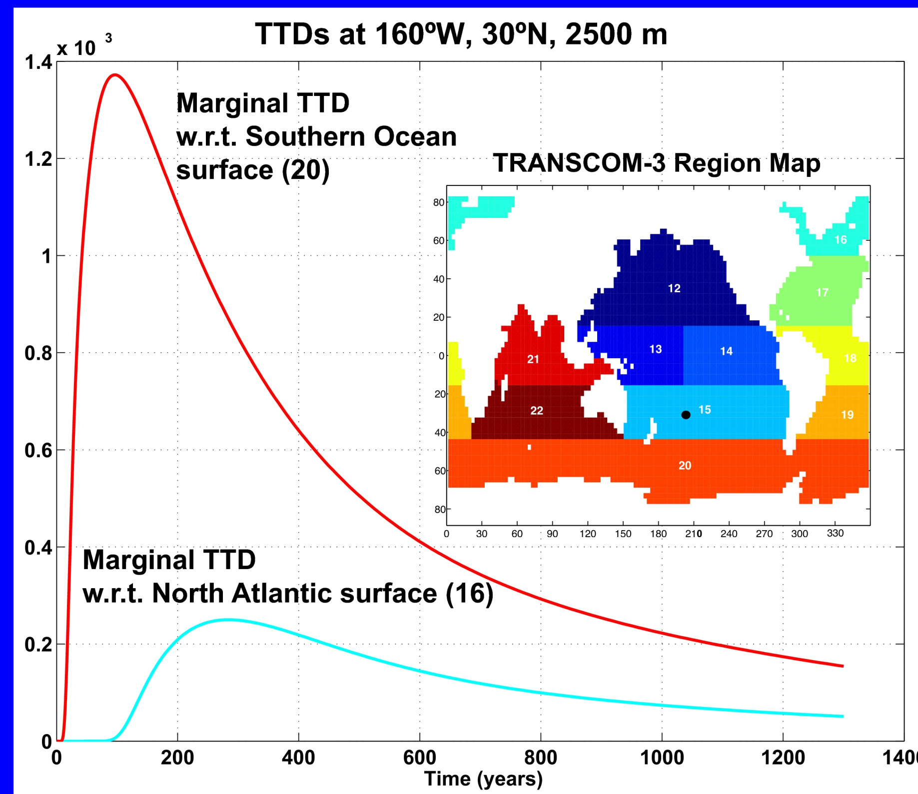
Observational evidence and numerical models both suggests that TTDs are broad, implying strong mixing

Tracer observations



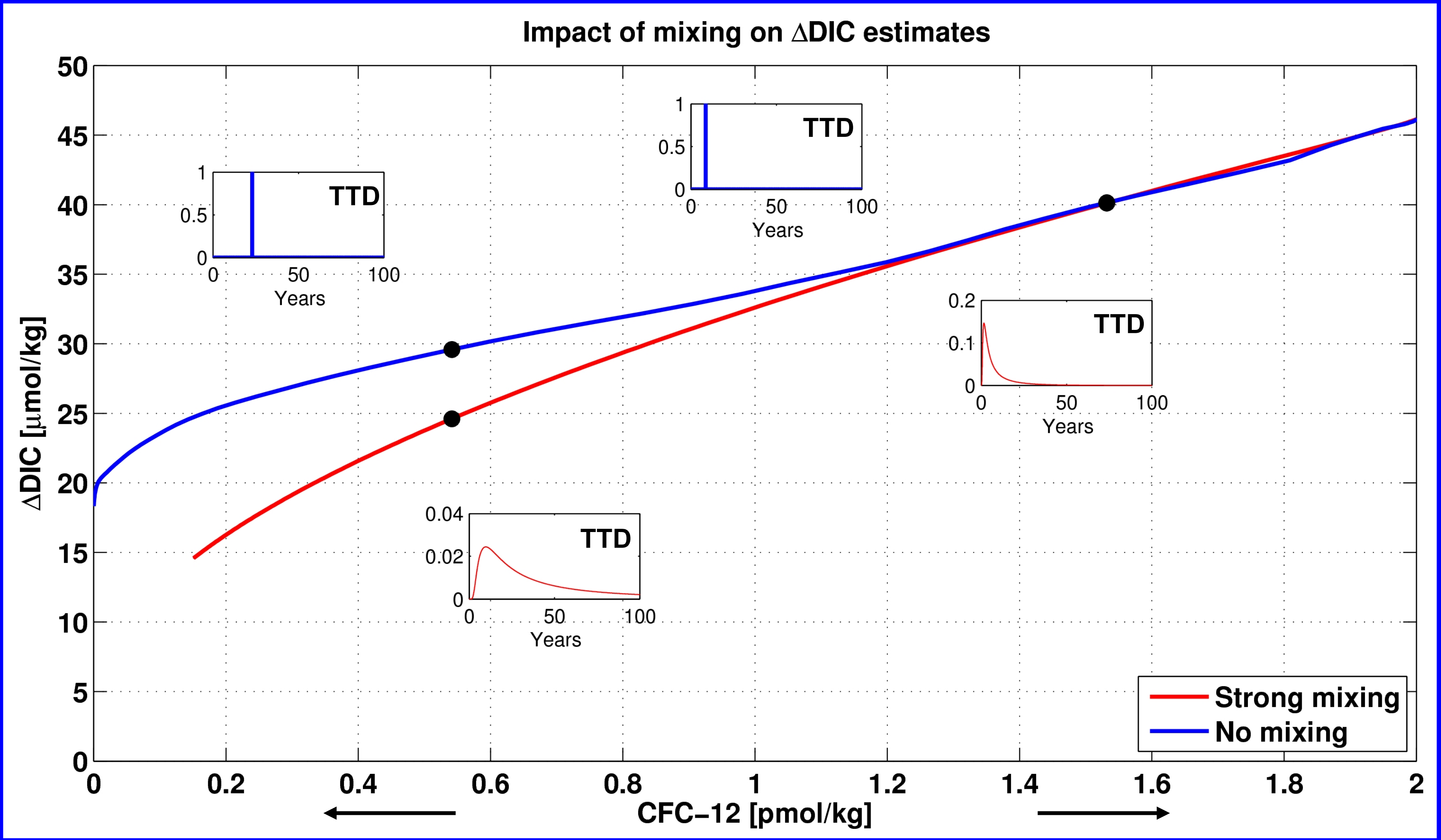
(Hall et al, 2004)

Explicit numerical simulation of TTD



Simulated in 1º data assimilated (ECCO) model using the ***transport matrix method*** (Khatiwala, 2007)

Neglecting mixing introduces a positive bias in the ΔDIC estimate at shallow and intermediate depths and a negative bias in deep waters

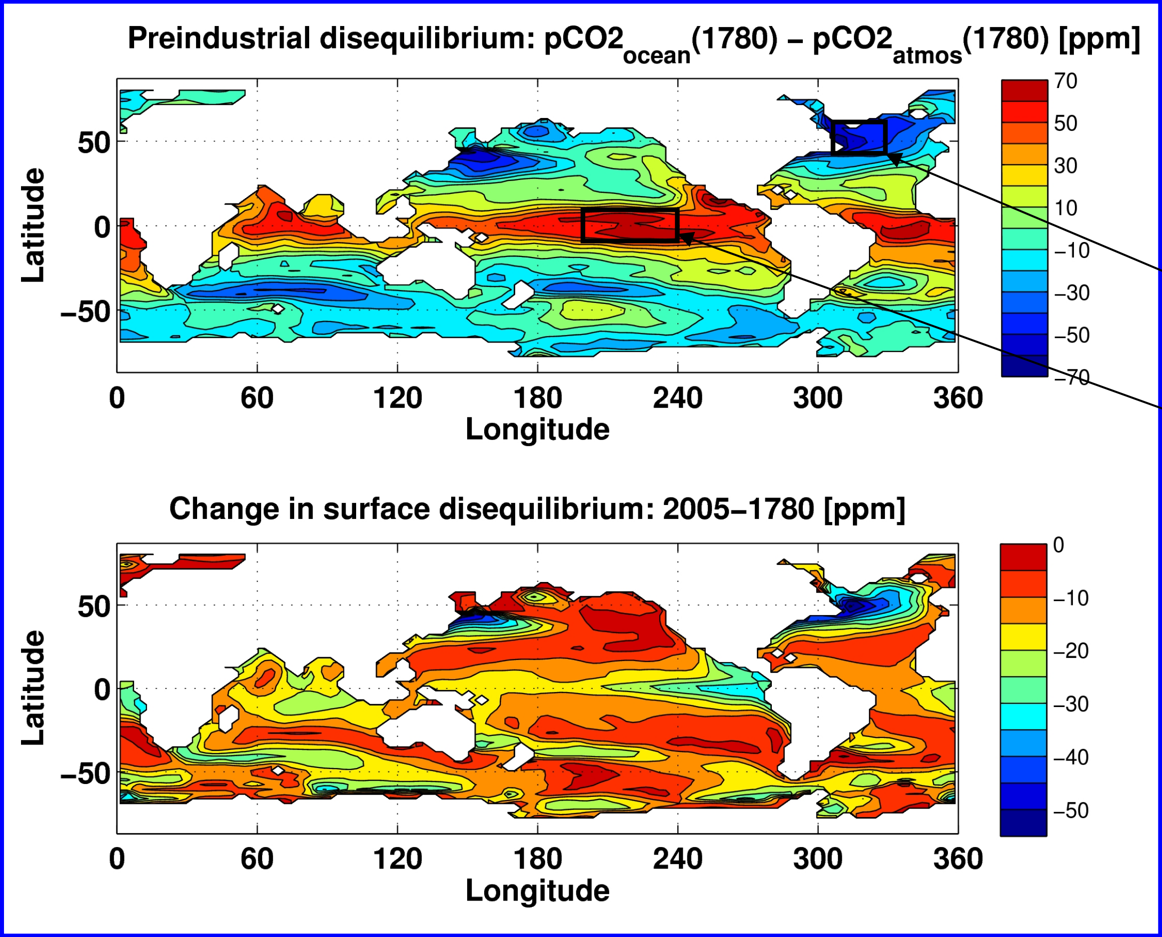


Older

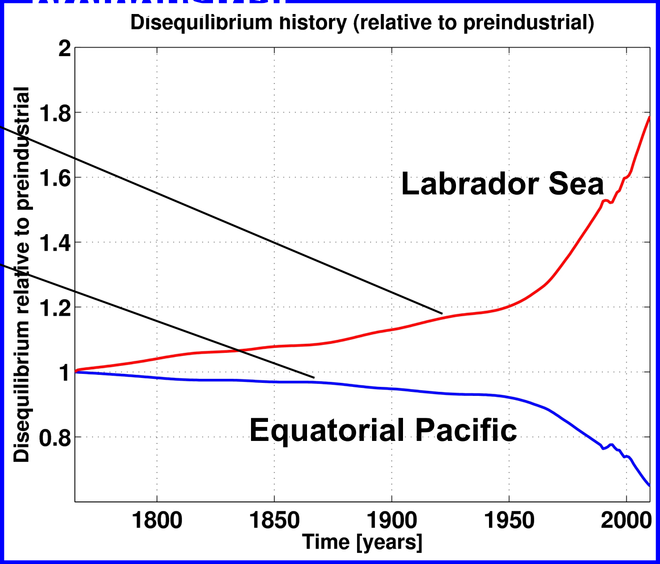
Younger

Assuming constant disequilibrium introduces a positive bias of O(10-20%) in estimated ΔDIC

$DIC_{surface}(t) = DIC_{equilib}(pCO_2^{atmos}(t), T, S, Alk) + \delta DIC_{air\text{-}sea\ disequilib}(t)$



Surface disequilibrium history relative to preindustrial



(Khatiwala, 2007)

The Transit-time Distribution (TTD) Method

The basic ideas underlying the TTD approach:

- ΔDIC can be treated as a conservative tracer
- Ocean transport can be characterized by a TTD
- Ocean circulation is in steady state

$$\Delta\mathrm{DIC}(\mathbf{x},t) \;=\; \sum_i \int_{1780}^{t} \Delta\mathrm{DIC}_{\mathrm{surf}}(t';\partial\mathcal{D}_i)\mathcal{G}(\mathbf{x},t-t';\partial\mathcal{D}_i)dt'$$

To apply this, we need two pieces of information:

- The transit time distribution $\mathcal{G}$, and
- The surface history of anthropogenic carbon, ΔDIC_{surf}

To estimate $\mathcal{G}$, we use measurements of transient and steady state tracers along with their known surface history

$$C_{\text{meas}}(\mathbf{x},t) = \sum_i \int_{-\infty}^{t} C_{\text{surf}}(t';\partial\mathcal{D}_i)e^{-\lambda(t-t')}\mathcal{G}(\mathbf{x},t-t';\partial\mathcal{D}_i)dt'$$

This is an underdetermined deconvolution problem! We regularize it using a Bayesian ("maximum entropy") approach.

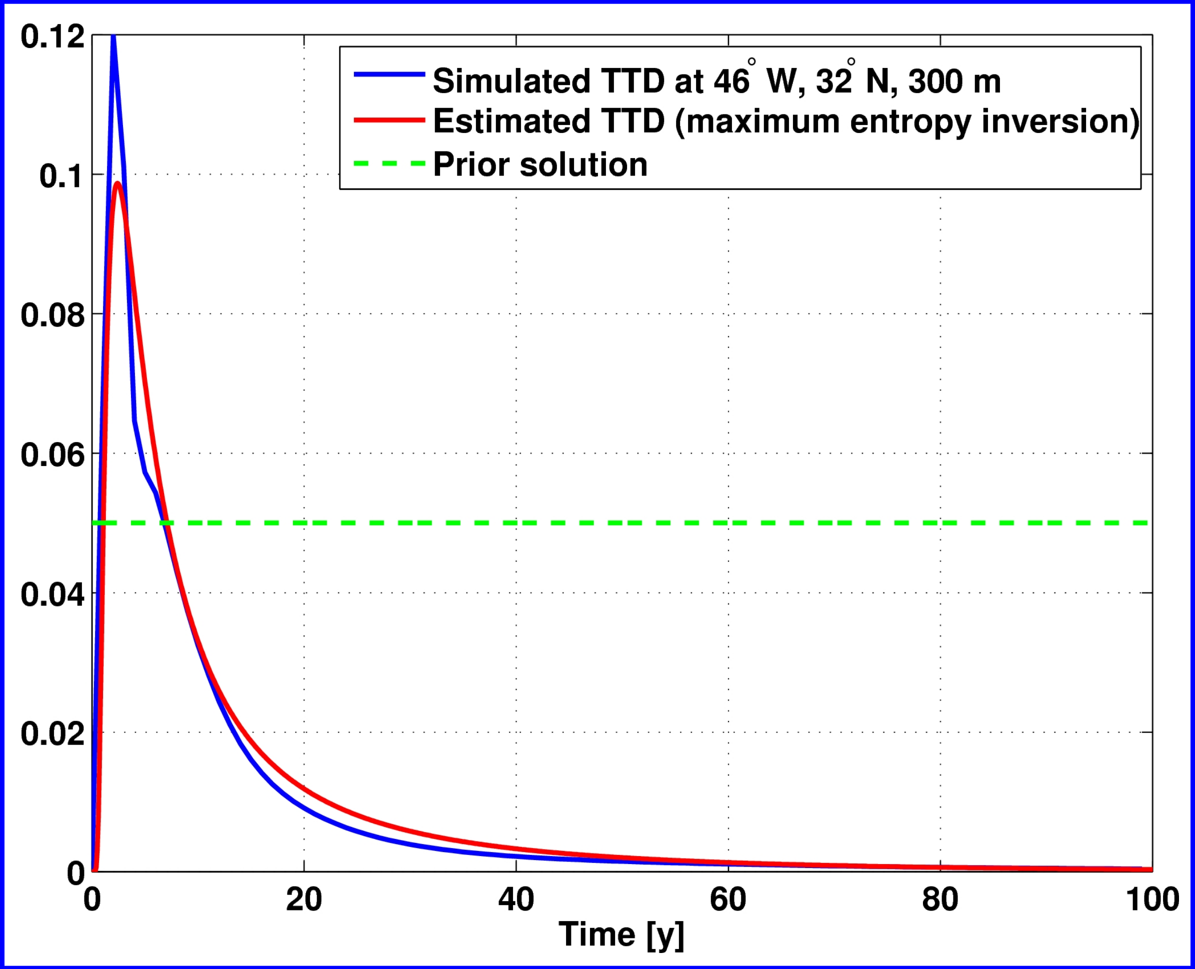
Minimize the cost functional (subject to the data constraints):

$$J[\mathcal{G}] = -\sum_i \int \mathcal{G}(\mathbf{x},t';\partial\mathcal{D}_i)\log\frac{\mathcal{G}(\mathbf{x},t';\partial\mathcal{D}_i)}{\mathcal{H}(\mathbf{x},t';\partial\mathcal{D}_i)}dt'$$

(e.g., Tarantola, 2006; Primeau, 2007)

The variational problem has the following solution:

$$\mathcal{G}(\mathbf{x}, t; \partial\mathcal{D}_i) \;=\; \mathcal{H}(\mathbf{x}, t; \partial\mathcal{D}_i) e^{-\sum_j \alpha_j(\mathbf{x}) C^j_{\text{surf}}(t_j - t; \partial\mathcal{D}_i) e^{-\lambda_j t}}$$



To determine the unknown surface ΔDIC history, we equate the instantaneous net air-sea flux of ΔDIC to the rate of change in its inventory:

$$\sum_i A_i F_i^{\mathrm{air-sea}}(t) \;=\; \frac{d}{dt}\iiint_{\mathrm{ocean}} \Delta\mathrm{DIC}(x', t)\, d^3x'$$

$$\begin{aligned}
F_i^{\mathrm{air-sea}}(t) \;&=\; -k_i\left[\Delta p\mathrm{CO}_2(t)_i - \Delta p\mathrm{CO}_2^{\mathrm{atm}}(t)\right] \\
&=\; -k_i \Delta\delta p\mathrm{CO}_2(t)_i \\
&\approx\; -k_i \epsilon_i \Delta p\mathrm{CO}_2^{\mathrm{atm}}(t)
\end{aligned}$$

Computing the inventory:

$$\Delta\mathrm{DIC}(\mathbf{x},t) = \sum_i \int_{1780}^{t} \Delta\mathrm{DIC}_{\mathrm{surf}}(t';\partial\mathcal{D}_i)\mathcal{G}(\mathbf{x},t-t';\partial\mathcal{D}_i)dt'$$

$$\begin{aligned}\Delta\mathrm{DIC}_{\mathrm{surf}}(t;\partial\mathcal{D}_i) &\equiv \mathrm{DIC}_{\mathrm{surf}}(t)_i - \mathrm{DIC}_{\mathrm{surf}}(1780)_i \\ &= f\left(p\mathrm{CO}_2(t)_i\right) - f\left(p\mathrm{CO}_2(1780)_i\right) \\ &\approx f\left(p\mathrm{CO}_2(1780)_i + (1+\epsilon_i)\Delta p\mathrm{CO}_2^{\mathrm{atm}}(t)\right) - f\left(p\mathrm{CO}_2(1780)_i\right)\end{aligned}$$

- *f* represents carbonate chemistry: DIC = $f(pCO_2, T, S, Alk, \ldots)$

$$p\mathrm{CO}_2(1780)_i \approx p\mathrm{CO}_2(T_{\mathrm{obs}})_i - (1+\epsilon_i)\Delta p\mathrm{CO}_2^{\mathrm{atm}}(T_{\mathrm{obs}})$$

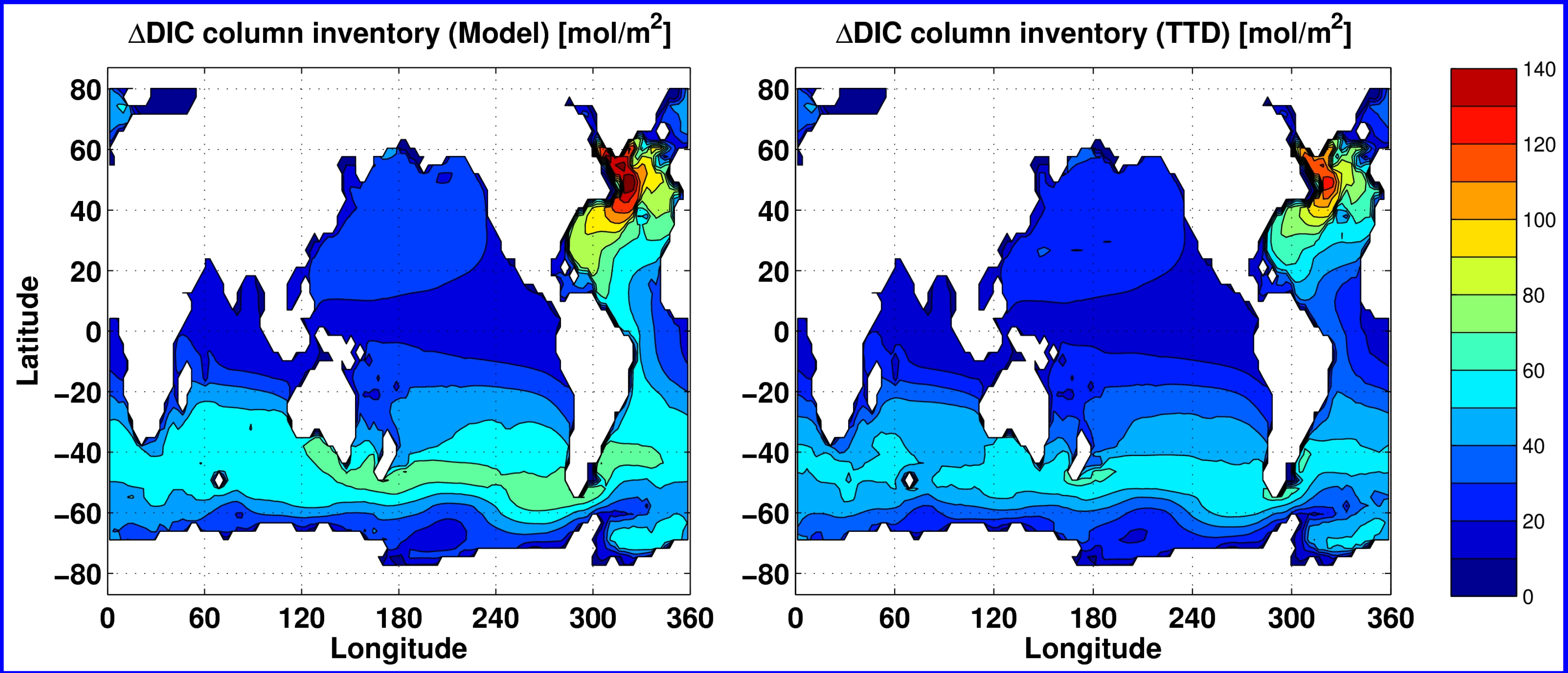
Finally, solve the nonlinear problem for the unknown ε_i using least-squares

$$\mathbf{M}(\epsilon) = \mathbf{0}$$

Verification of TTD method in an Ocean GCM

- Simulate anthropogenic carbon, CFCs, ^{14}C in a global ocean model to evaluate the TTD methodology
- MIT biogeochemical model: fully prognostic and includes representations of both the solubility and biological pumps
- The TTD method is applied to synthetic tracer "observations" simulated in the model to invert for the anthropogenic carbon uptake

Simulated and inferred column inventory of ΔDIC

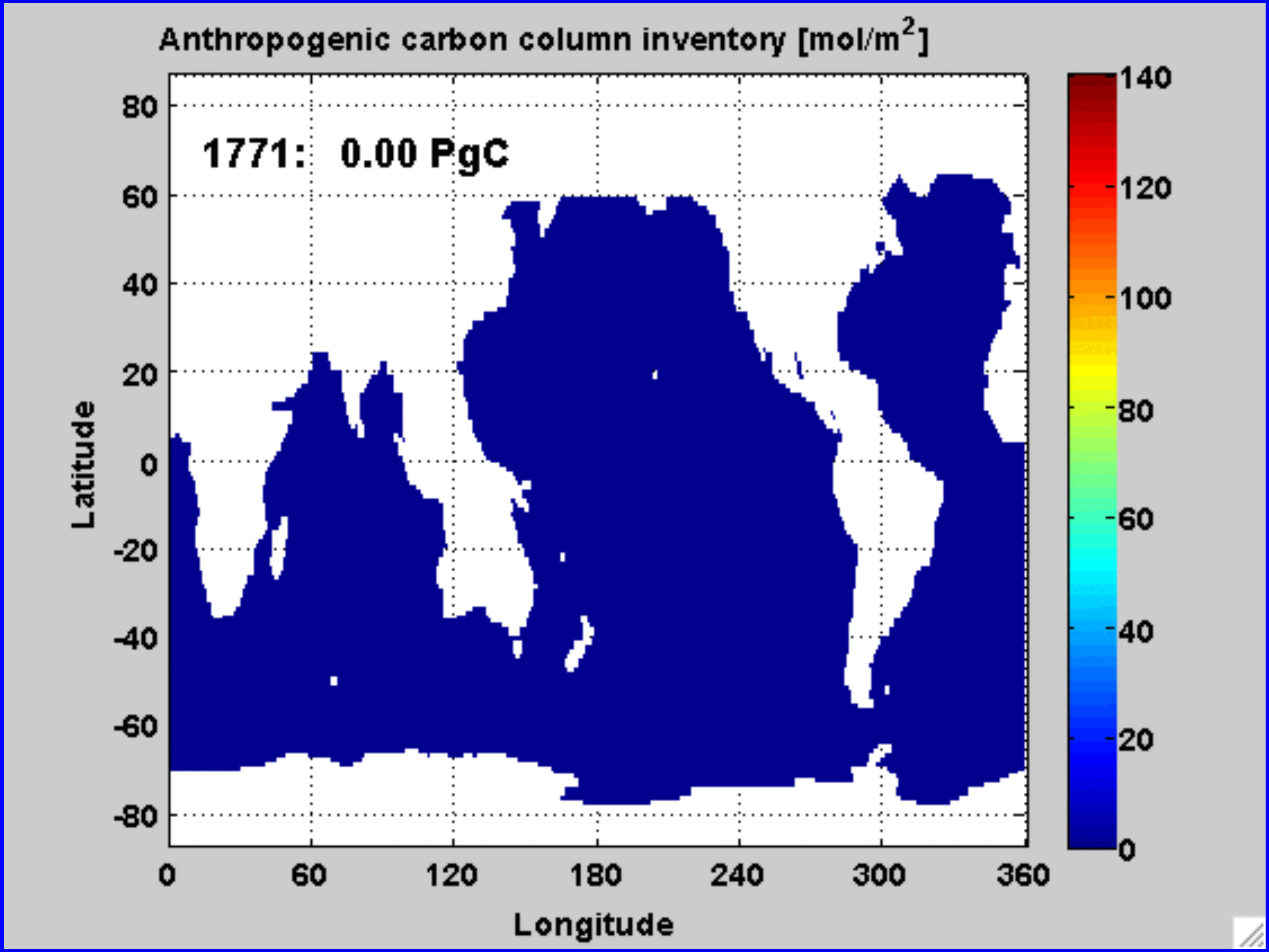


- Largest differences (O(5 mol/m^2)) in Southern Ocean
- Total simulated inventory (in 1995): 123.7 PgC
- Total inventory from inversion: 127.6 PgC
- Total inventory assuming constant disequilibrium: 145.8 PgC

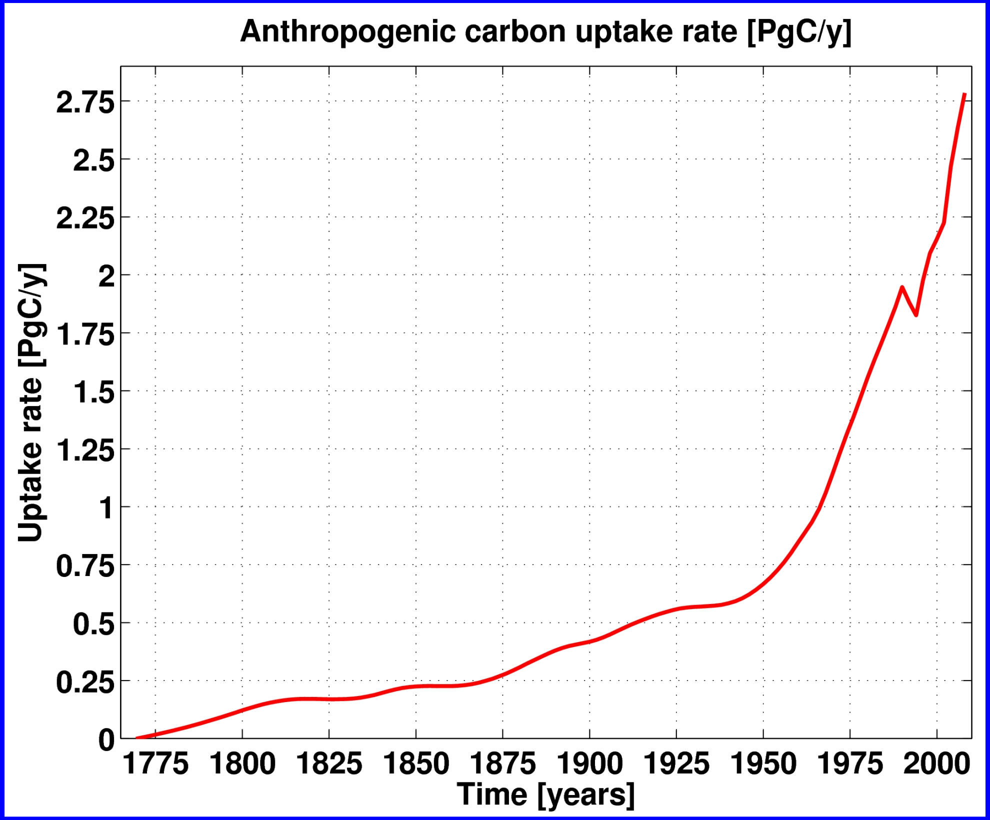
Application to data from the GLobal Ocean Data Analysis Project (GLODAP)

- GLODAP is a database of tracer measurements made during the WOCE period (1990's)
- Includes CFCs, carbon, ^{14}C, O_2, nutrients, etc
- TTD method is applied to CFC-11, CFC-12, ^{14}C, "PO_4^*", temperature, and salinity data
  - Estimate $\mathcal{G}$ and ΔDIC_{surf}
  - Prior $\mathcal{H}$ from analytical solution to 1-d advection-diffusion
  - Convolve ΔDIC_{surf} with $\mathcal{G}$ to predict interior ΔDIC

Column inventory of anthropogenic carbon over the industrial period

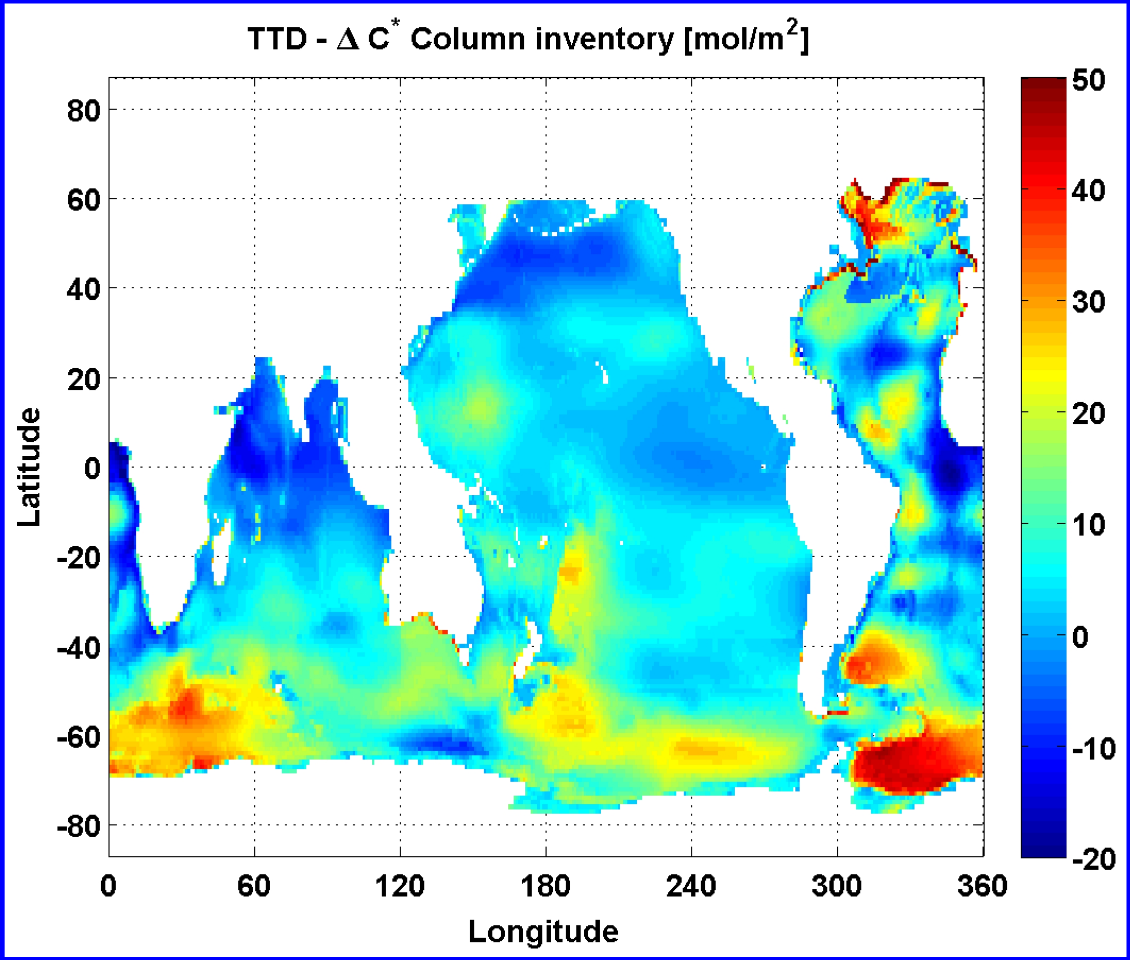


Anthropogenic carbon uptake history 1765-2005

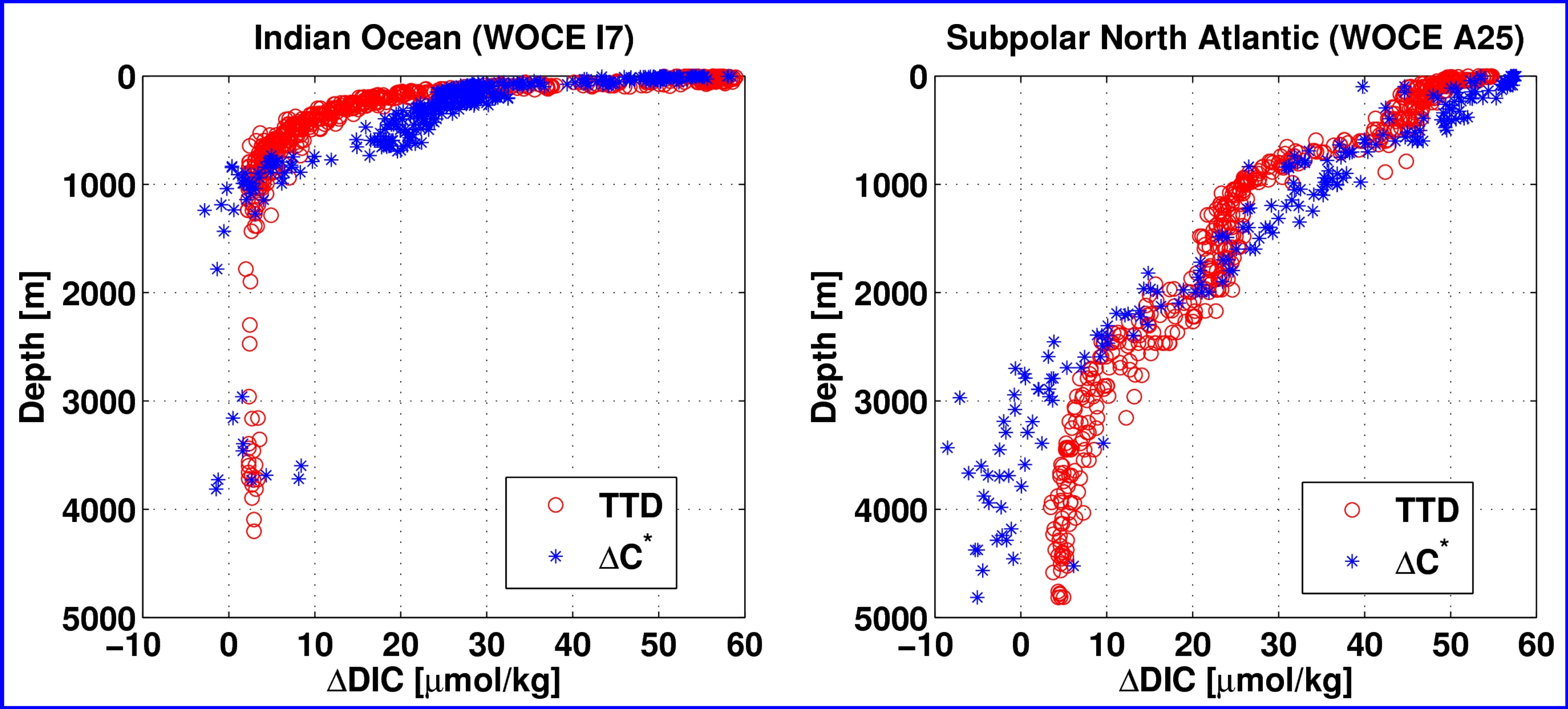


- TTD-based global ocean uptake (1980's-1990's): 1.7-2.1 PgC/y
- Atmospheric O_2/N_2 ratio: 1.9 ± 0.6 (Manning and Keeling, 2006)
- Air-sea pCO_2 difference: 2.0 ± 60% (Takahashi et al, 2002)
- Air-sea ^{13}C disequilibrium: 1.5 ± 0.9 (Gruber and Keeling, 2001)

Comparison of inventory with ΔC^* method (1994)



- TTD method total inventory: 126.2 ± 14 PgC
- ΔC^* method (Sabine et al, 2004) total inventory: 106 ± 21 PgC



- The methods tend to agree in the upper ocean, but disagree in the intermediate and deep ocean
- ΔC^* method tends to overestimate in the upper ocean and underestimate in the deep ocean

Summary and Conclusions

- Tracer-constrained TTDs have been used to reconstruct the history of anthropogenic carbon in the ocean
- TTD-derived inventory of anthropogenic carbon in the ocean (in 1994) is 126.2 $\pm$ 14 PgC
- In contrast, the ΔC^* method gives an inventory of 106 $\pm$ 21 PgC
- Substantial differences in spatial distribution of ΔDIC between TTD and ΔC^* estimates
- Global uptake of 1.7-2.1 PgC/y during 1980's-1990's

Unresolved Issues and Future Directions

- Error analysis
- Improved prior $\mathcal{H}$ (from ECCO simulations)
- Accounting for seasonal cycle
- Comparison of regional fluxes with atmospheric inversions
- Evaluation of forward biogeochemical models
- Use inversion as initial conditions for eddy-resolving biogeochemical simulations