An Observing System Simulation Experiment (OSSE) for ocean carbon uptake between the WOCE (1990s) and CLIVAR (2000s) decades

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Monitoring of ocean carbon uptake:

A number of methods are currently applied to carbon monitoring:

- Data-anchored methods
  - **interior DIC from WOCE/CLIVAR**
  - pCO_2/CO_2 flux-based estimates
- Modeling methods
  - Forward models
  - Inversions

Here we focus on estimating decadal changes from WOCE/CLIVAR Repeat Hydrography measurements

Will be approached through Ocean Model, where an Observing System Simulation Experiment (OSSE) will be performed using a Forward Model

LSCOP report of Bender et al. (2002):

This report set specific threshold for desired *uncertainty* of Repeat Hydrography network for monitoring ocean uptake over decadal timescales at approximately 10%

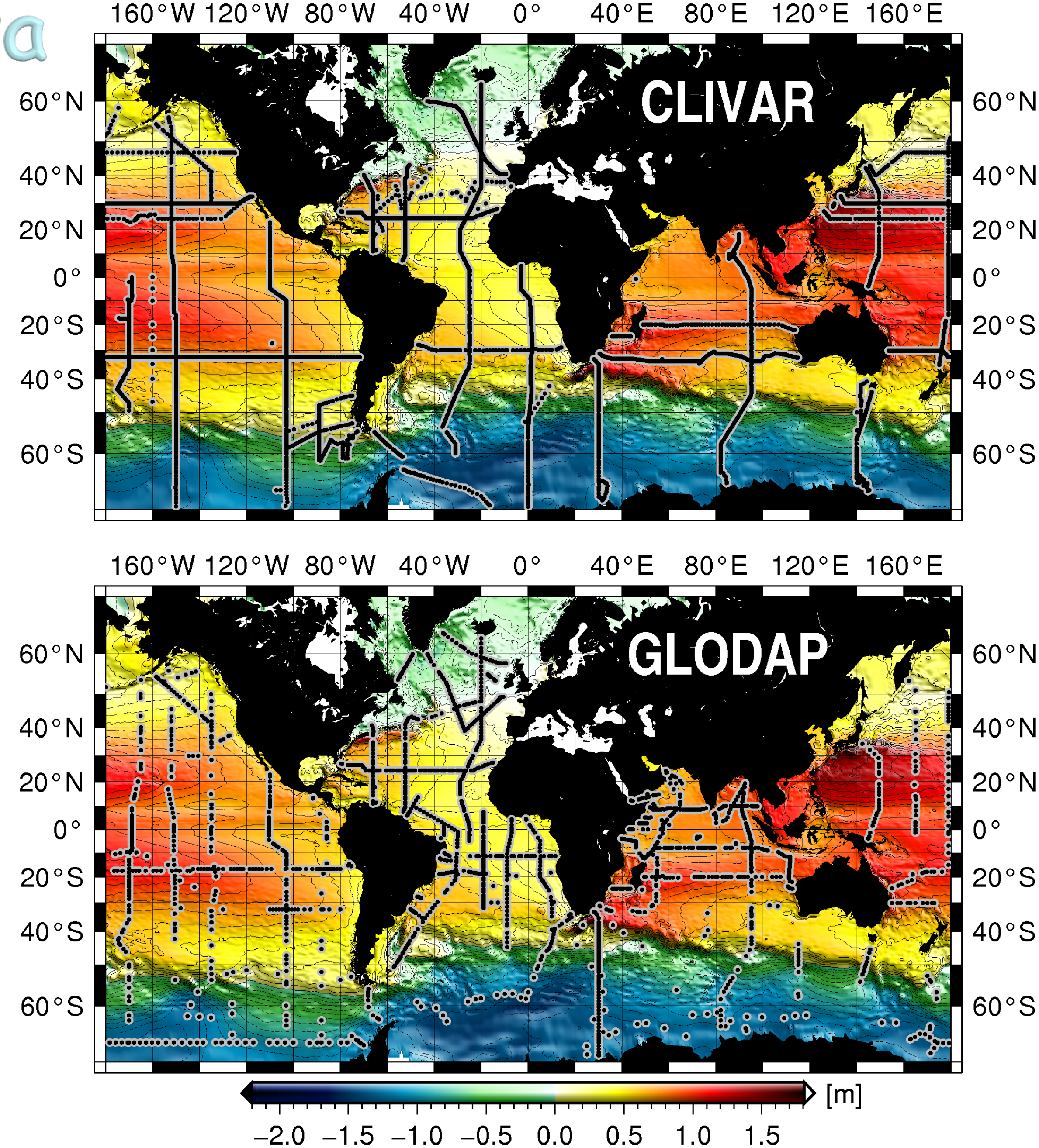
Given that ocean uptake may be expected to be of order ~25PgC/ decade, approximate uncertainty limit should be of order ~1PgC for each of the major basins per decade

Can the now ubiquitous eMLR method [*Friis et al.*, 2005] that is widely used for quantifying and characterizing decadal changes within this window of uncertainty?

This project set out to provide test-of-concept and skill assessment in an ocean modeling context

Available data sets

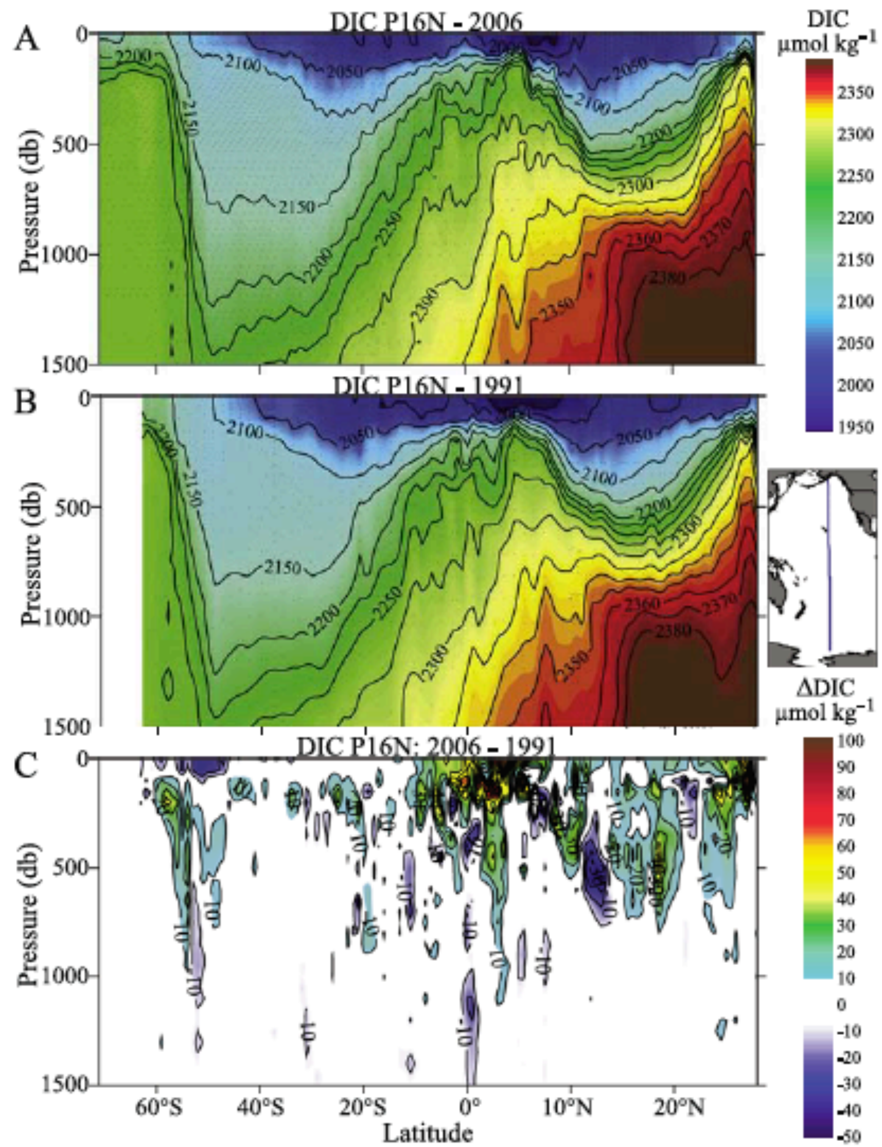
- Station locations are not always co-located
- Data are not well distributed in time or space
- Even when repeat cruises exist, direct difference is affected by natural variability, which masks the signal



Carbon in the ocean interior

- Two meridional sections in the Pacific, repeated 15 years apart
- Difference shows positive and negative values
- Signal is small relative to noise.
  - How can we improve signal/noise ratio and recover useful information about the evolution of the oceanic anthropogenic carbon sink?

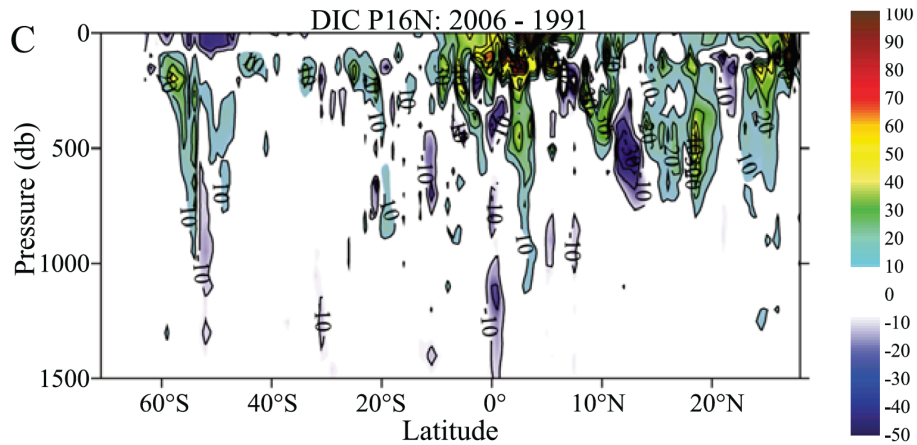
Sabine et al. (2008)



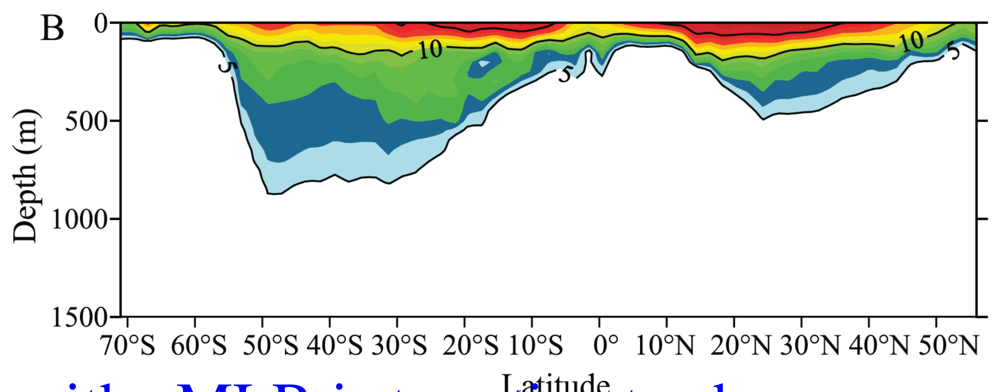
For estimations of anthropogenic carbon changes between WOCE and CLIVAR cruises, the extended-MLR (eMLR) method of *Friis et al.* [2005] has become ubiquitous.

Sabine et al. (2008)

Simple differencing of DIC along 152°W from study of Sabine et al. [2008]



Anthropogenic carbon concentration changes resulting from eMLR method



It is often stated that the goal with eMLR is to estimate changes in Canthro along sections, and then extrapolate to basin scale

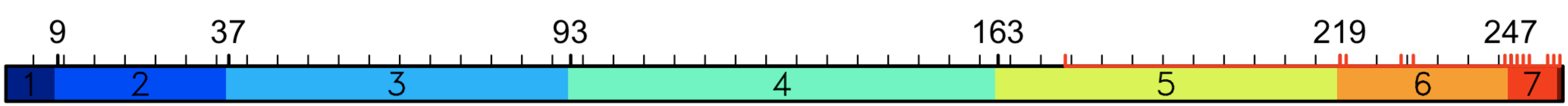
For eMLR method of Friis et al. [2005], which regression formula is the most able to remove natural variability?

Testing different regression formulae

- Given 8 variables, one can make 255 models

$$Z \subseteq \{S, \theta, NO_3, PO_4, Si, AOU, O_2, Alk\}$$

- Z_1 ➔ DIC = y_o + a S + ε
- Z_2 ➔ DIC = y_o + a θ + ε
- …
- Z_9 ➔ DIC = y_o + a S + b θ + ε
- …
- Z_{255} ➔ DIC = y_o + a S + b θ + c NO_3 + …+ h Alk + ε



Ocean Model Description & Experimental Design:

Will present model output from GFDL's MOM4-TOPAZ model
CORE forcing over 1958-2005: blend of reanalysis/satellite fields
Model has 40 levels and ~1° horizontal resolution
Model includes full suite of major macro-nutrients and carbon

Two runs have been performed over 1850-2005:

(a) **Contemporary carbon**: case with full transient in atmospheric CO_2 concentrations

(b) **Natural Carbon**: case with pre-anthropogenic atmospheric CO_2 boundary conditions

The **anthropogenic carbon** signal is then fully resolved by the model, and taken as the difference between **Contemporary** & **Natural** carbon

Goal: sample model at WOCE/CLIVAR locations, perform basin-scale eMLR, and evaluate skill

Application of eMLR within Observing System Simulation Experiment:

For the test-case of the North Atlantic (where ~1/3 of anthropogenic carbon in ocean resided in mid-1990s), what is *skill* of eMLR method?

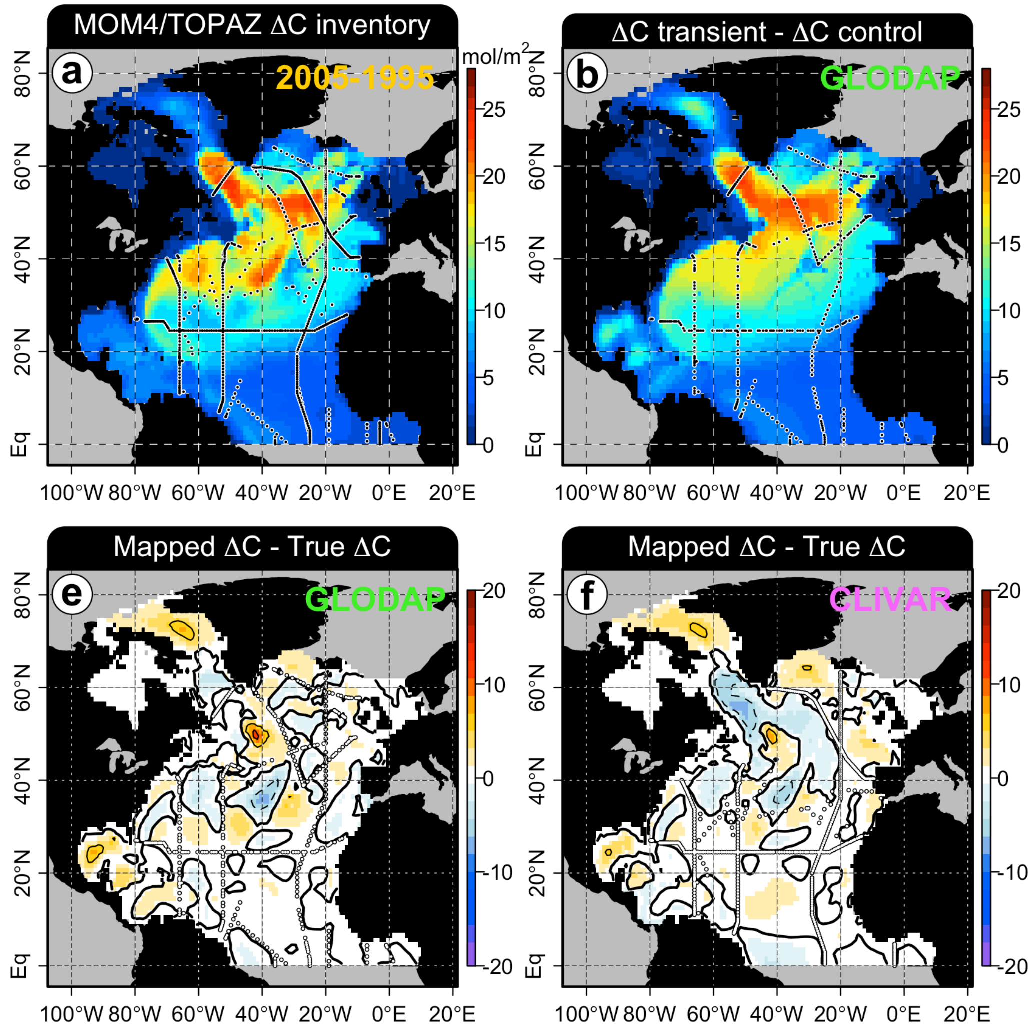
We have decided to apply eMLR along vertical levels of model rather than along sections, while using Akaike Information Criterion (AIC) to test systematically different regression models
After performing regressions level-by-level, construct column inventory changes through vertical integral

Major assumption: For both WOCE and CLIVAR, we assume that both surveys were performed as “synoptic snapshots”

Geographic patterns of the column inventories

Absolute mapping errors estimated from true values in the North Atlantic

True signal at GCM resolution



Interpolated signal from true values sampled at GLODAP stations

- Mapping induces a smoothing
- Mapping error is of similar magnitude for or GLODAP

Mapping errors are small in the North Atlantic

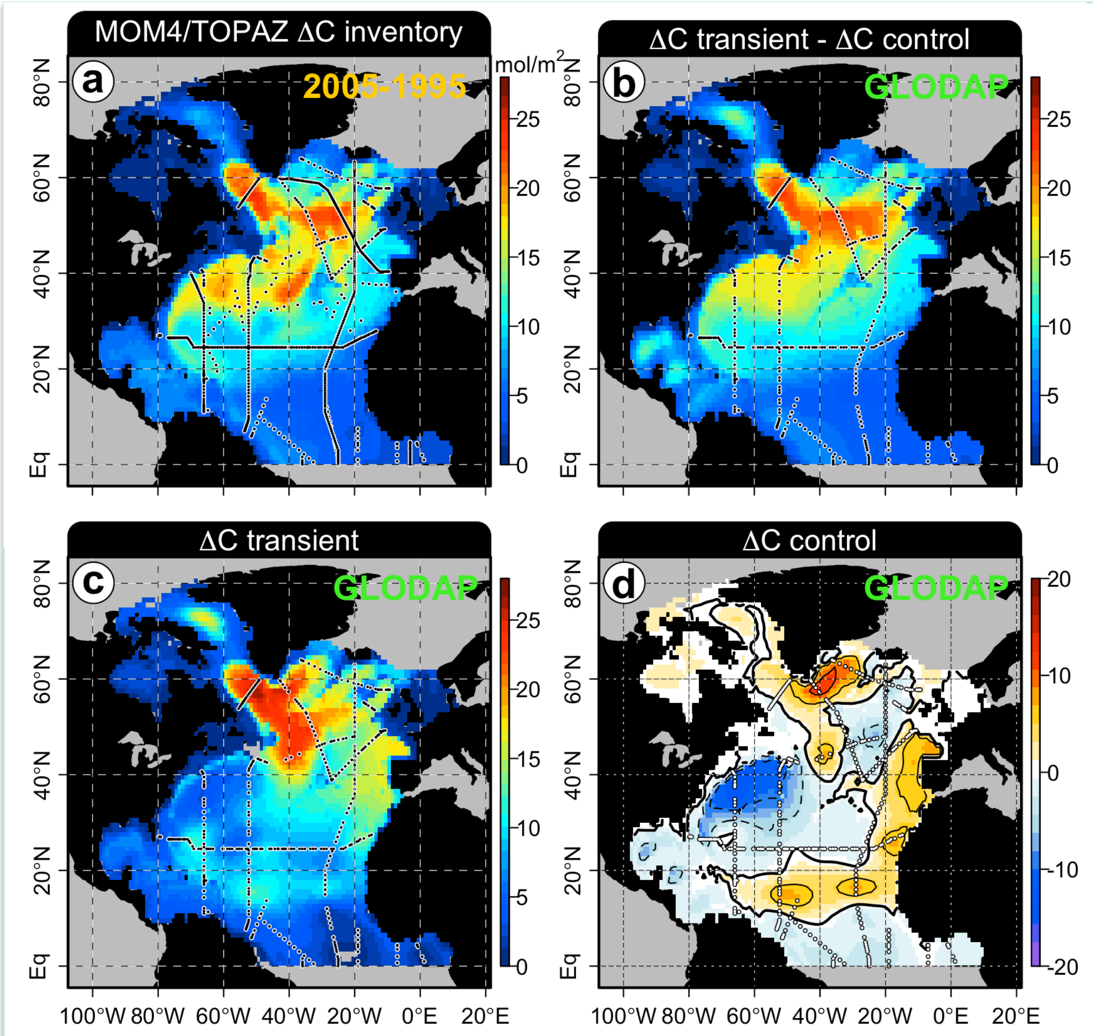
Geographic patterns of the column inventories

Natural variability is a large signal.
eMLR must remove this large signal

True signal at GCM resolution:
Transient - control

Interpolated signal from GLODAP stations
Transient only

= real world, what one measures



Interpolated signal from true values sampled at GLODAP stations

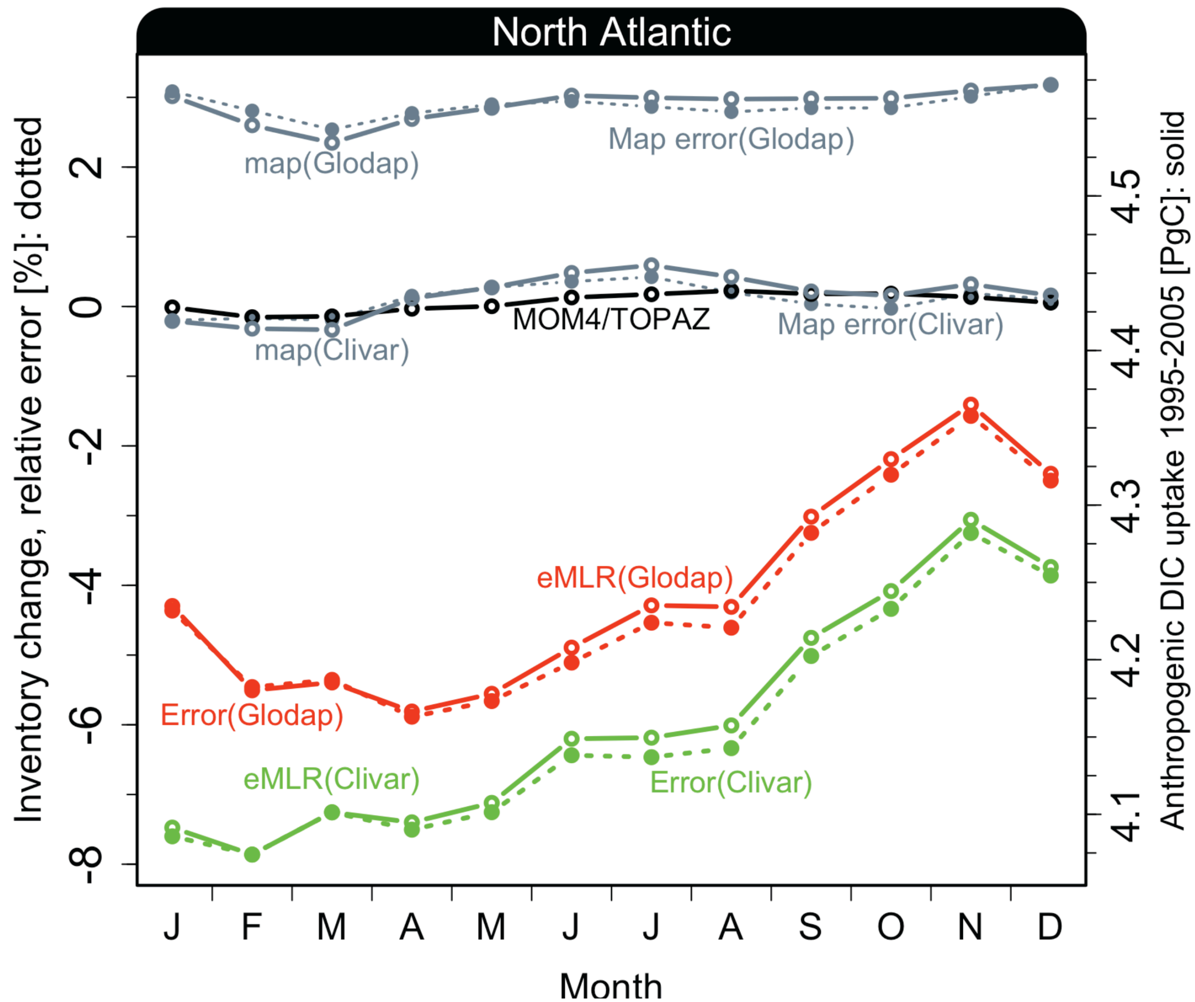
Interpolated signal from GLODAP stations
Control only

Month-by-month evolution of the anthropogenic basin-scale carbon inventory change for MOM4-TOPAZ Observing System Simulation Experiment :

Uncertainty for OSSE is well within threshold specified by *Bender et al.* [2002]!!!

Mapping errors are of order ~2% for WOCE/GLODAP

Black line is full model C_{anthro} inventory for North Pacific



Summary: North Atlantic Carbon OSSE

- An accuracy target of better than 10% is achievable for the change in inventory estimate
- Mapping errors do not introduce large errors in the North Atlantic
- No one regression model can give a perfect solution, but stitching multiple models as a function of depth can give very accurate results.

PART 2. IMPLICATIONS/FUTURE DIRECTIONS:
Case of equatorial "re-emergence" of carbon in Pacific:

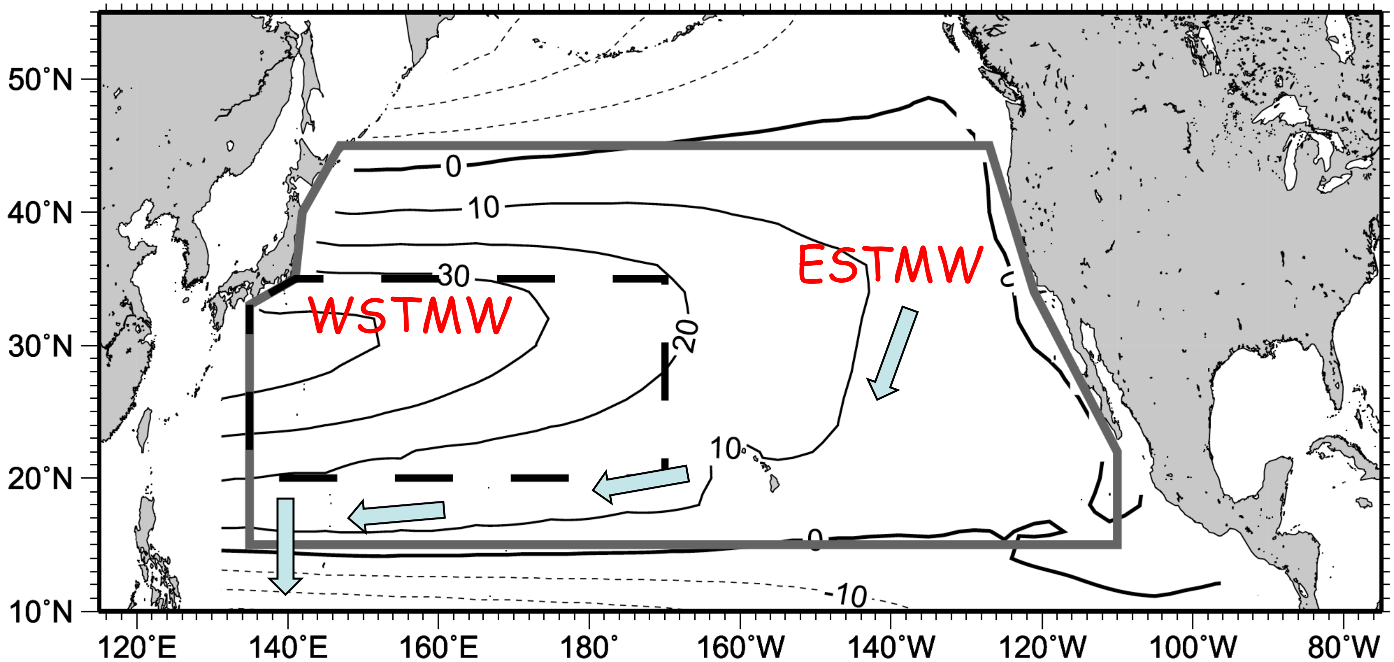
Interested in issue of *transport* of anthropogenic carbon and ask how large rate of "re-emergence" of anthropogenic carbon is in warm pool region. How much of anthropogenic carbon returns to surface ocean relatively quickly after entering interior?

Focus here is on subtropical cells, connecting subducting regions in extratropics to upwelling regions in equatorial Pacific via the Equatorial Undercurrent (EUC), estimate using EUC properties at 150°W

DIC_TRANSPORT = (EUC_TRANSPORT)*(DIC_CONCENTRATION)

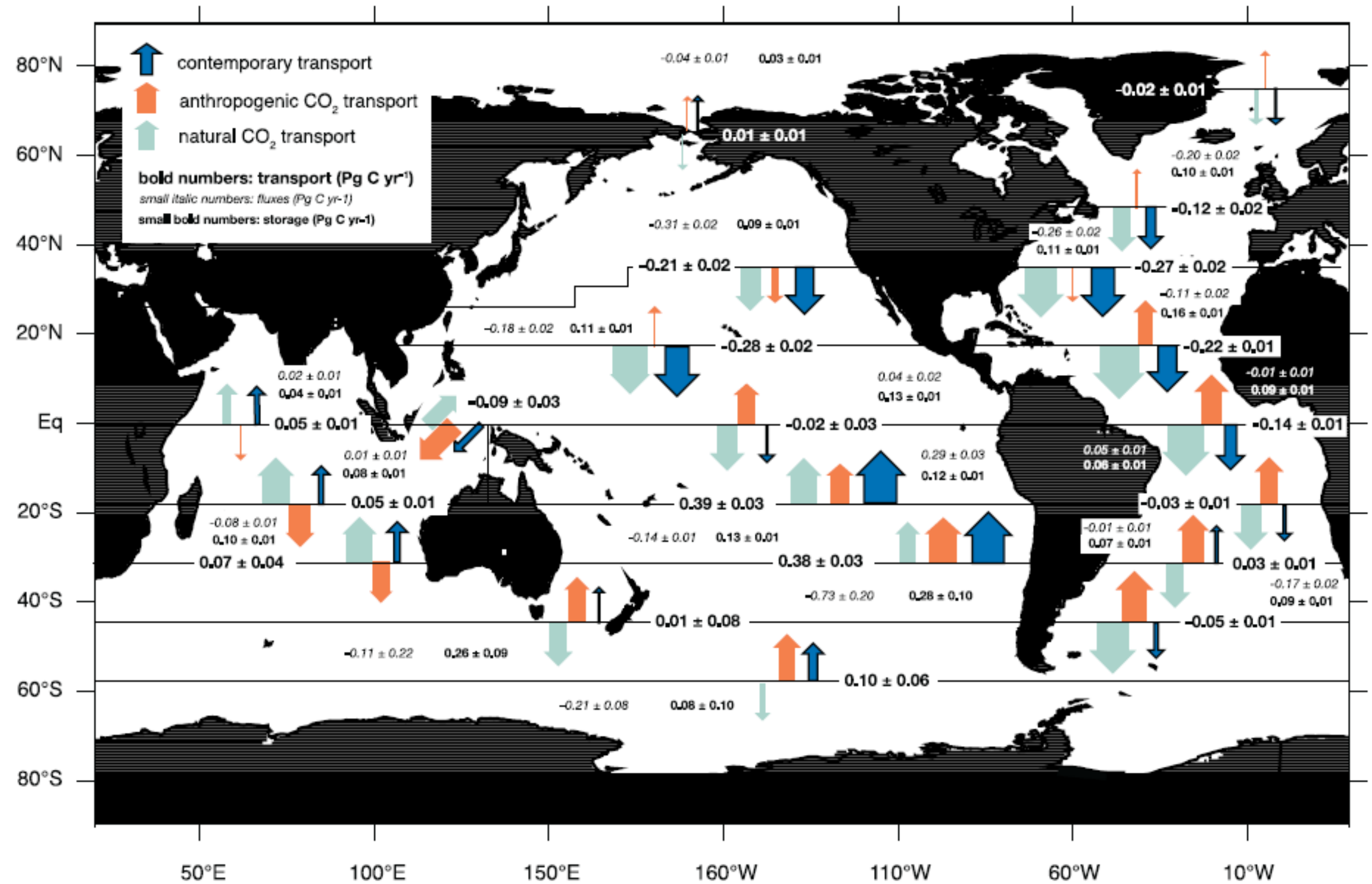
Re-emergence rate in DIC_anthro in NINO3 region: 0.4 PgC/year
(~20% of global uptake rate)

Hypothesis to be tested: Eastern Subtropical Mode Waters (ESTMWs) undergo inter-gyre exchange and access equatorial regime, whereas Western Subtropical Mode Waters (WSTMs) tend to recirculate within the North Pacific



- Approach through combined use hydrographic measurements (DIC, nutrients, etc.), ARGO, and remotely sensed wind products;
- Don’t need to wait until carbon sensors are on ARGO!!!!

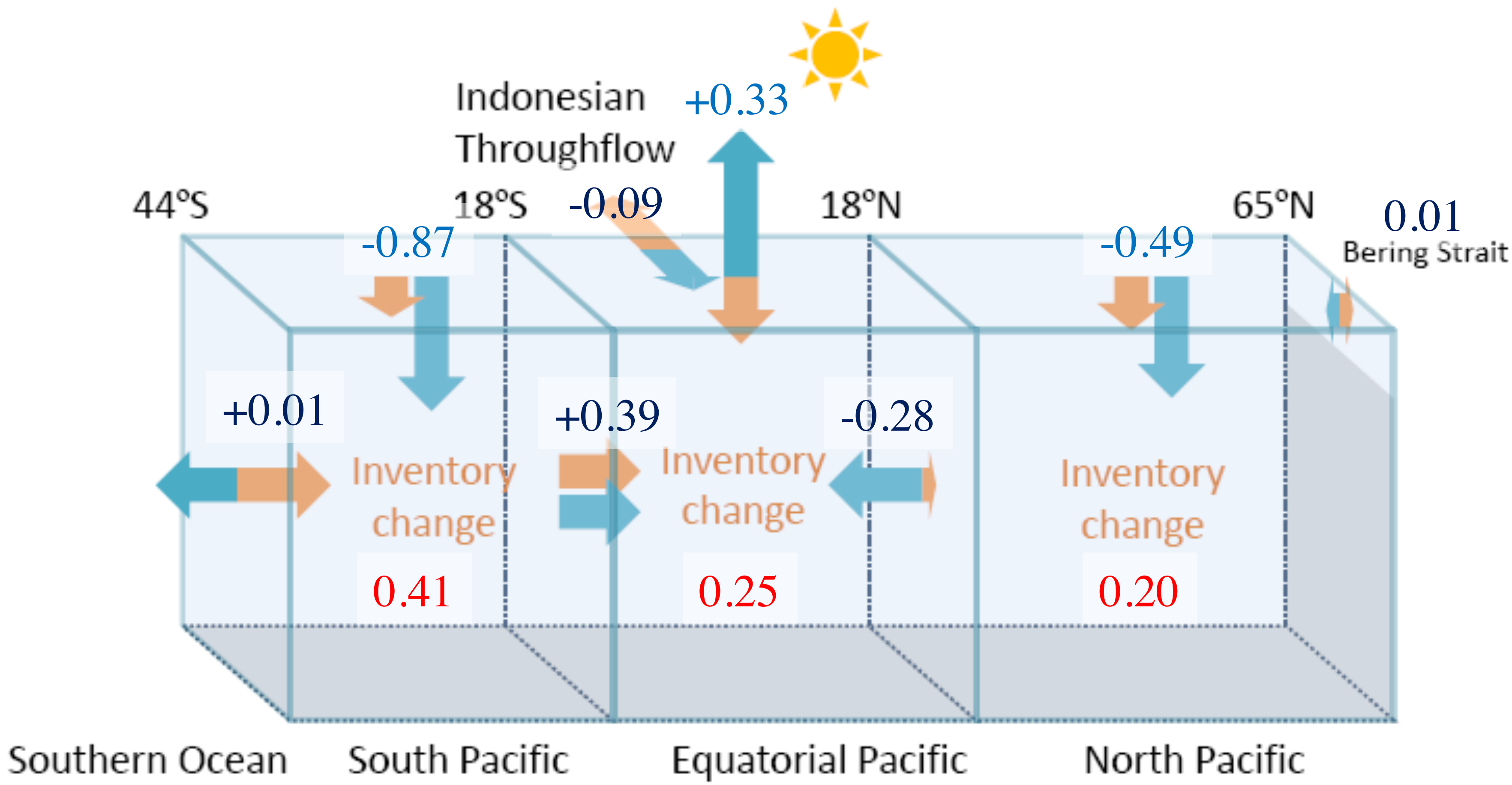
Begin by considering published distribution of integrated carbon transports in the ocean interior [*Gruber et al.*, 2009] from ocean inversion study



Indicative of strong asymmetry in *integrated* supply of DIC_{anthro} to equatorial Pacific via inter-gyre exchange!!

More focused CO_2 budget for Pacific

results of inversion of Gruber [2009] (Unit: PgC $year^{-1}$)



Natural (preindustrial) and anthropogenic components

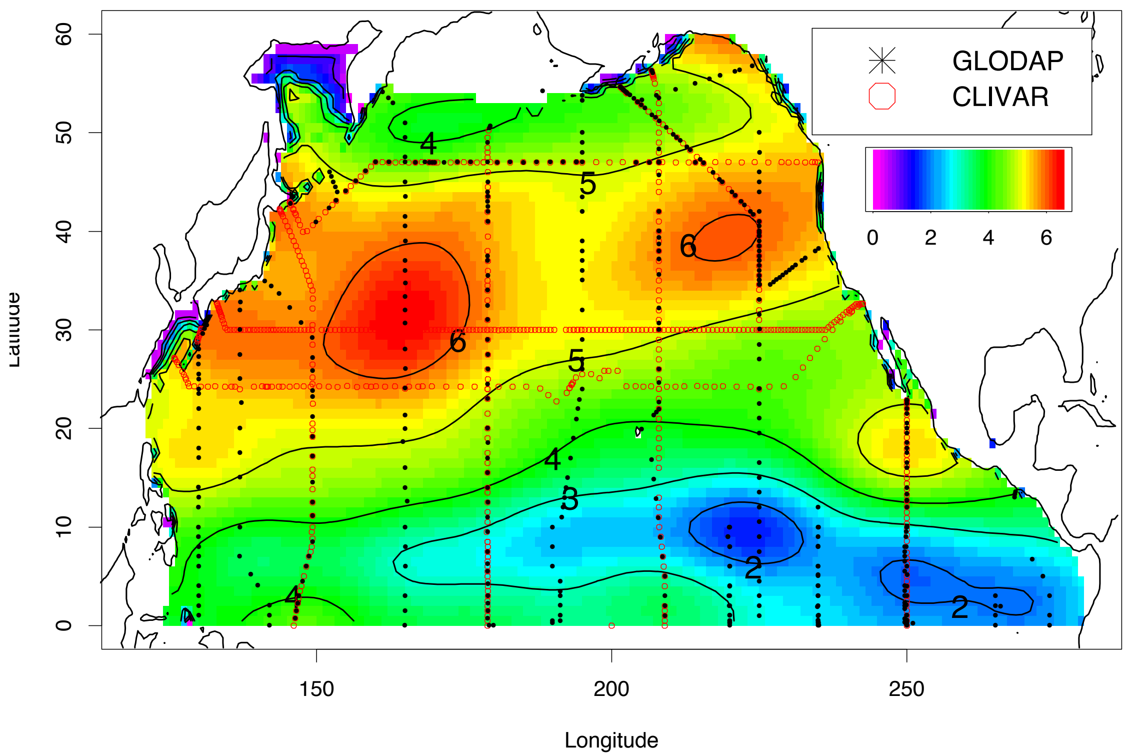
What is intergyre exchange of carbon between the North Pacific subtropical gyre and the Equatorial Pacific?

- Want to consider vertical structure of inter-gyre transport of DIC_{anthro} across 15°N
- Will need two products:
  - Estimate of DIC_{anthro}
  - Estimates of physical transport
- Goal will be to achieve this calculation through synthesis of (a) *remotely sensed winds*, (b) *ARGO (T/S)*, and (c) *hydrographic measurements (DIC, nutrients, etc.) from WOCE/CLIVAR/etc*

Work in this direction has started using ***data*** with an application of the eMLR method over the North Pacific (30 layers)

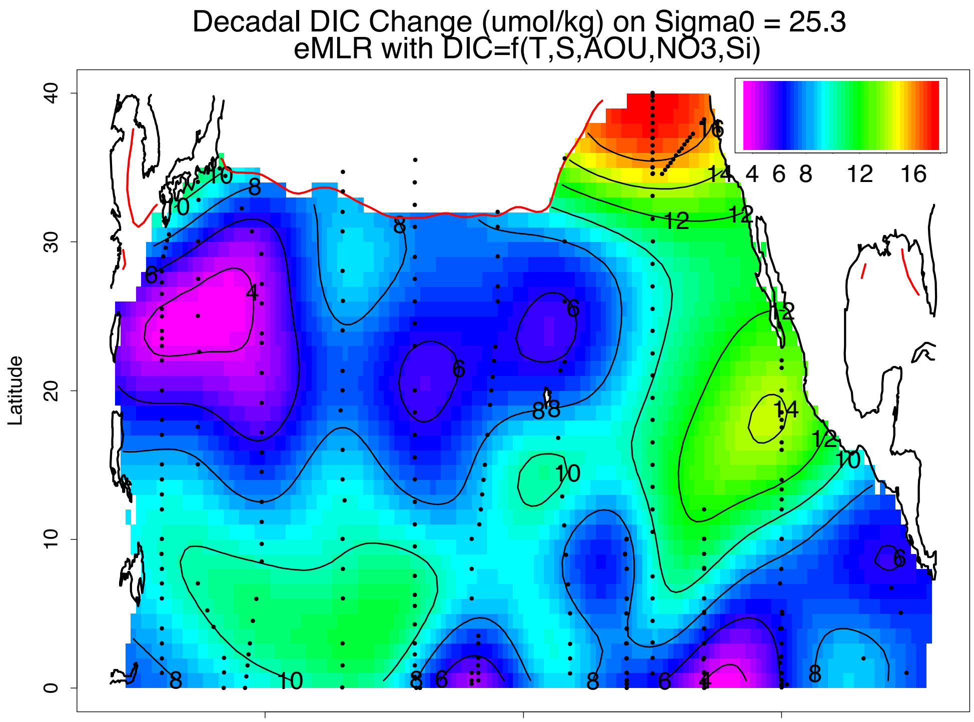
This figure shows the estimate of the change in column inventory of anthropogenic carbon in the North Pacific between the 1990s (WOCE decade) and 2000s (CLIVAR decade)

DIC Column (60-1150m) Inventory Change (mole/m^2)
Total = 3.0 x 10^14 mole or 3.6 PgC



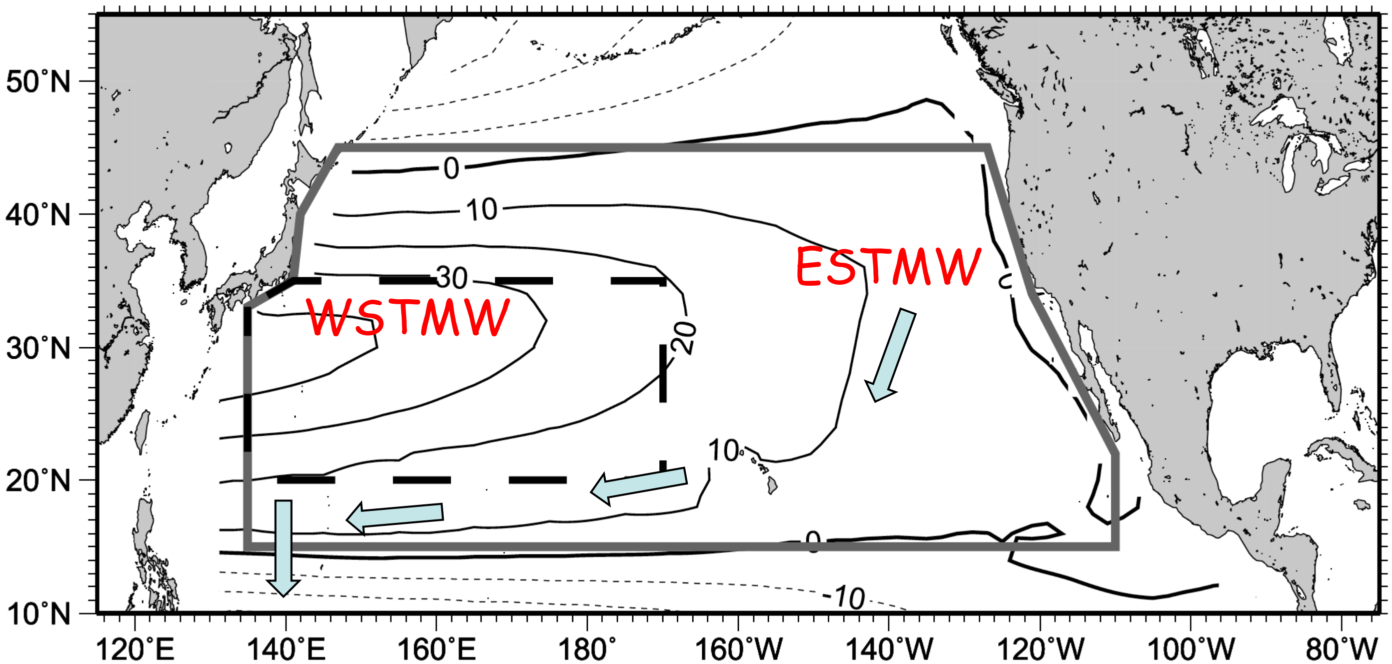
Predictor variables from WOCE/CLIVAR: T,S,AOU, NO3,SIO3

Assumption: WOCE and CLIVAR were “snapshots” in 1995 and 2005, respectively



Preliminary analysis of decadal change in DIC concentrations between WOCE (1990s) and CLIVAR (2000s) decades using horizontal isopycnal application of eMLR on σ_0**=25.3**

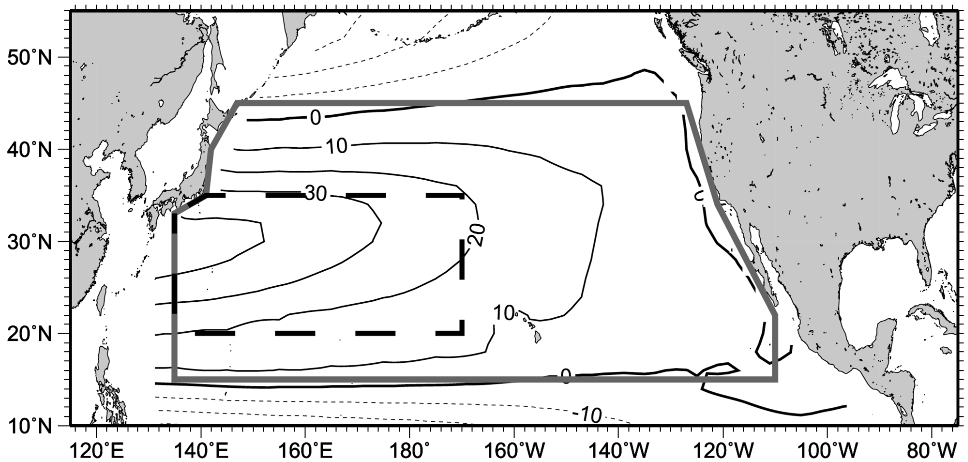
Layer-based eMLR revealing of dynamical features: distinction between WSTMW and ESTMW arises from calculation, with much higher DIC_{anthro} in ESTMW



Physical transports:

Data-based method of *Suga et al.* [2008] for estimating ocean interior circulation (physical state) from combined use of ARGO and surface winds (Ekman pumping)

Sverdrup transport estimated from ERA-40 reqnalysis product



Importantly, this method frees on from the constraints of where WOCE/ CLIVAR has sampled; can choose 15°N as "reference section", with transports being calculated as a residual

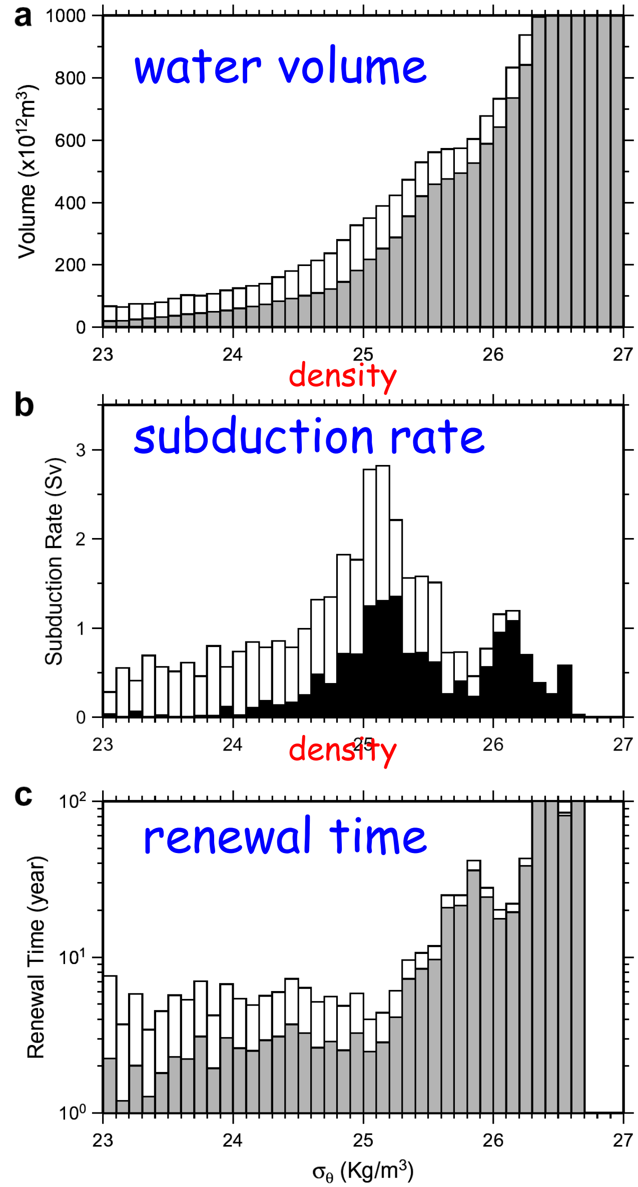
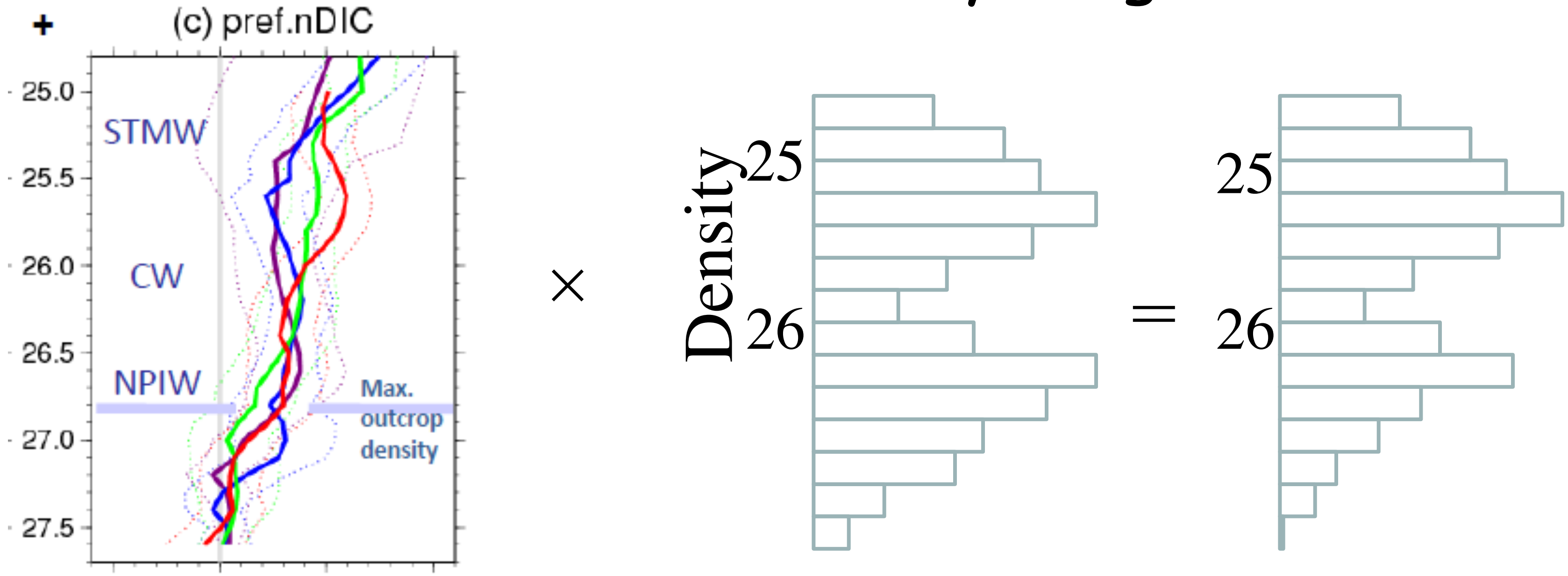


Fig. 5. (a) Volume of water, (b) subduction rate, and (c) renewal time for each σ_θ interval of 0.1 kg m^{-3} in the subtropical gyre, defined as the region of the positive Sverdrup stream function north of 15°N, as indicated in Fig. 2. The shaded (unshaded) portion of the bars in (a) represents the permanent (seasonal) pycnocline. Blackened (unblackened) portions of the bars in (b) indicate contributions from lateral induction (vertical pumping). The total height of the bars (shaded portion of the bars) in (c) indicates the renewal time, defined as the total volume (the volume of the permanent pycnocline) divided by the subduction rate.

Evaluating the Transport of anthropogenic CO_2 in each density range



Rate of CO_2 concentration change

Rate of subduction (transport)

Rate of CO_2 transport by subduction (to other regions)

General point: Don't need to wait for carbon sensors on ARGO; can work with combined ARGO/Satellite/hydrographic data

Conclusions

- Observing System Simulation Experiment with North Atlantic Carbon uptake: indicates that basin scale monitoring on decadal timescales can fall within threshold of acceptable uncertainty specified by Bender et al. [2002] (LSCOP report)
- Caveats: (a) With TOPAZ component of MOM4p1-TOPAZ model, fixed stochiometry; should be tested with flexible stochiometry version, complementary assessment of uncertainty (b) Have assumed WOCE/CLIVAR are synoptic surveys
- For Pacific, horizontal (layer) eMLR can facilitate interpretation of processes controlling carbon accumulation in ocean interior, with important case being application to acidification of equatorial Pacific waters