Detecting decadal scale increases in anthropogenic CO2 in the ocean

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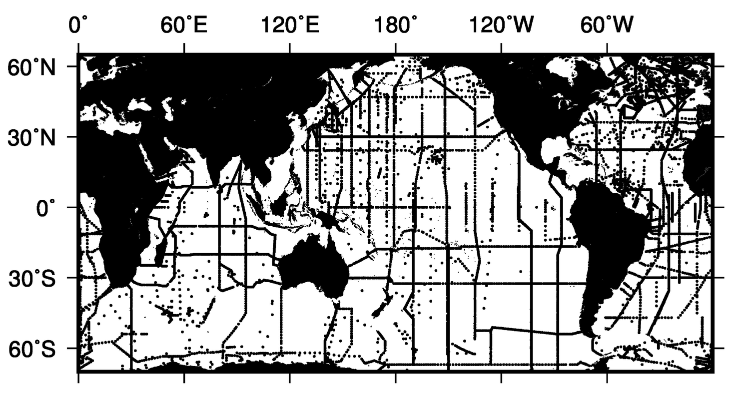
Anthropogenic C storage estimation

- Ocean absorbed a large part of anthropogenic carbon (C^{ANT})
  - 30% of total C^{ANT} (e.g., Sabine et al., 2004)
  - About 2.6 PgC / yr is estimated by model (e.g., Le Quere 2013)
- Based on direct observations, along the obs. line
  - Highest accurate obs. are needed (decadal changes in dissolved inorganic carbon (C_T) are very small
  - Biases (of nutrients, oxygen, alkalinity) between cruises were unclear

Available observations



Valuable efforts

CDIAC has been collecting ocean carbon observations, and **CARINA** and **PACIFICA** now provide the QCed data of carbon & nutrients (after synthesis based on the cruises = less bias)

Objective

We estimate anthropogenic carbon storage changes in the 2000s, based on new, QCed ocean seawater samplings, with evaluation uncertainties, and compare the results between two methods; 1. Isopycnal surface method (small changes can be detectable) and 2. Based on gridded values (many data and variability can be included easily)

Calculation of C^{ANT}

C* method (e.g., Gruber et al. 1996)

$$C^{ANT} = C_{Tm} - \gamma \times AOU - 0.5 \times (A_{Tm} - A_{T0}) + C_{T0} + C_{Tdiseq}$$

For decadal changes (Murata et al., 2007)

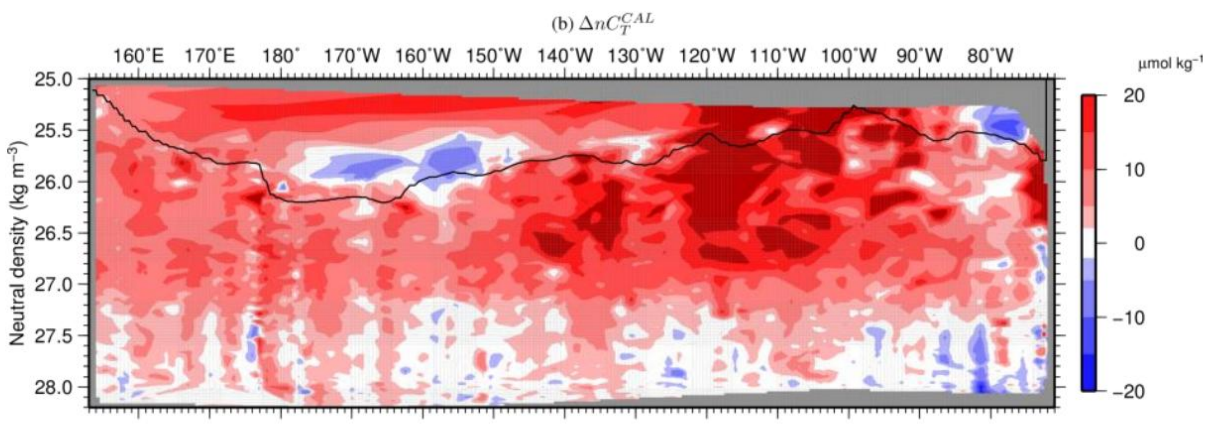
$$\Delta C^{ANT} = \Delta C_{Tm} - \gamma \times \Delta AOU$$

γ : Redfield ratio (C:O), C_{Tm} : DIC, A_{Tm} : Alkalinity

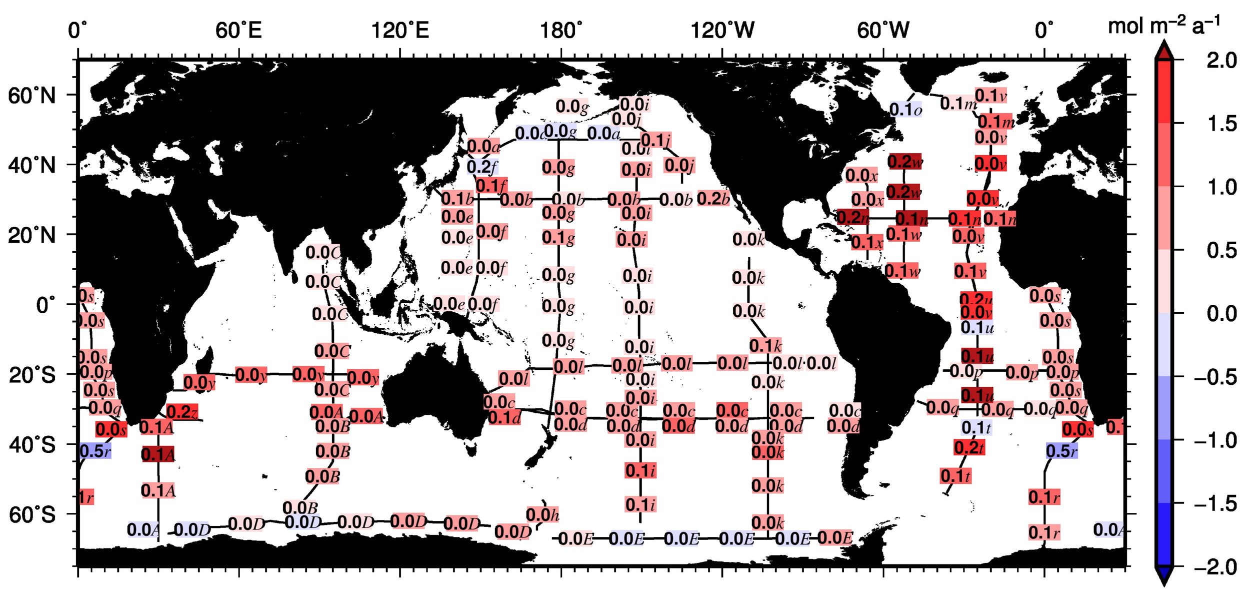
Isopycnal method

We calculate ΔC^{ANT} on isopycnal surface along the sections and water column summation of ΔC^{ANT} with layer thickness assuming the differences in the deep layers assumed to be 0 (neutral density (σ_N) > 27.6-28.3 depend on basins).

An example of ΔC^{ANT} along a line (Pacific 30S)



Water column ΔC^{ANT} map based on σ_N



Area bins are 20° $\times$ 10° along the lines and the figures denote standard deviation.
The large values were detected near 30°S and in the Atlantic, and standard deviation. were very small, but... we miss the uncertainties due to spatio-temporal variabilities.

Grid method

To take into account uncertainties far from observations and to include more data, we made grid datasets with horizontally 2° $\times$ 2° and vertically 32 levels, for 2 periods (1985-1995, 1996-2010).

3 Major assumptions

To make the grid datasets, we assumed

- For C_T, O, and Alk, assuming constant values and changes for each water masses (mean values and temporal changes at each segments on TS relationships as estimation parameters)
- For T & S, assuming regional mean values and their changes at each depths
- For all girdded values, a value at one grid is similar to the ones adjacent grid points (smoothing)

A part of likelihood

Using the assumptions, we made the likelihood for the observations.

$$p(y_o|y_g,\sigma_o) \times p(y_g|m_g,c_g,\sigma_g,\alpha_g) \times \; p(m_g|m_{mg},\sigma_{mg},\alpha_{mg})...$$

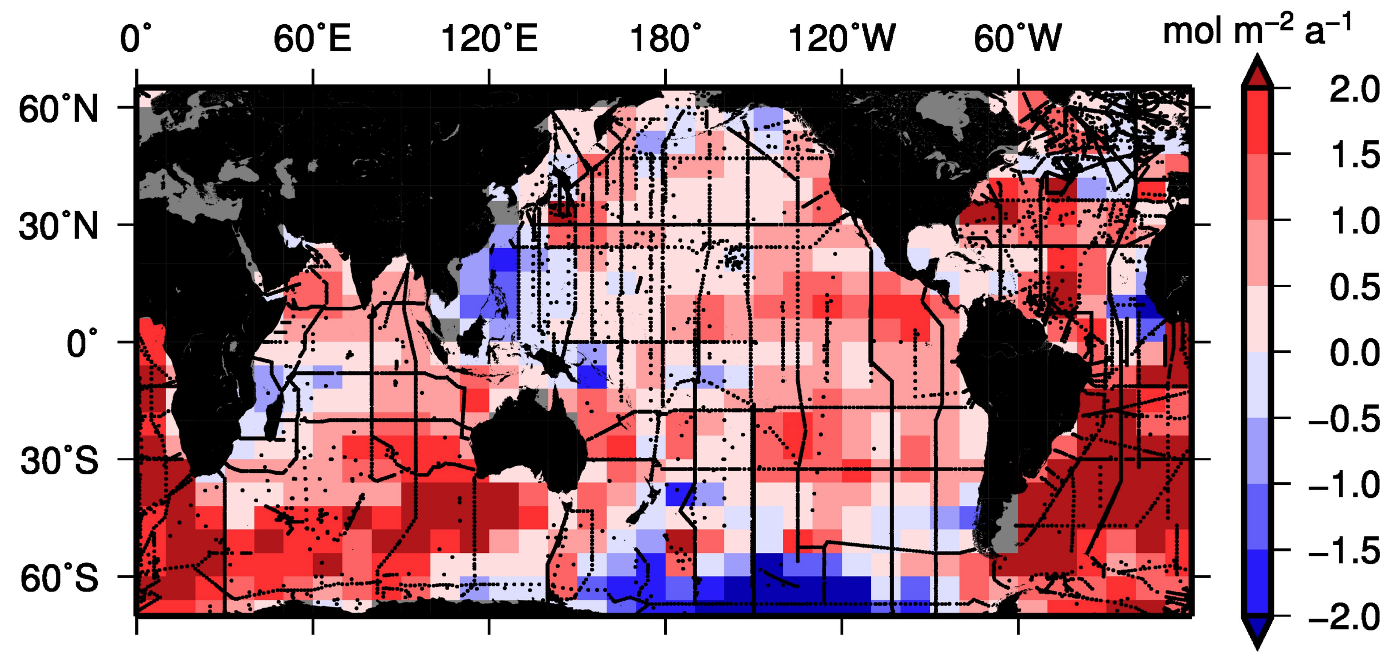
$p(y_o|y_g,\sigma_o)$
probability of observing y_o, given a grid value y_g and standard deviation σ_o (gaussian)

$p(y_g|m_g,c_g,\sigma_g,\alpha_g)$
probability of obtaining y_g, given a mean value m_g, changes c_g in a segments, standard deviation σ_g, and smoothing parameter α_g. (GMCAR distribution: e.g., Jin et al. 2005)

Here, statistical parameters (σ_o, σ_g...) were generated randomly by (flat) gaussian / gamma / uniform distributions.

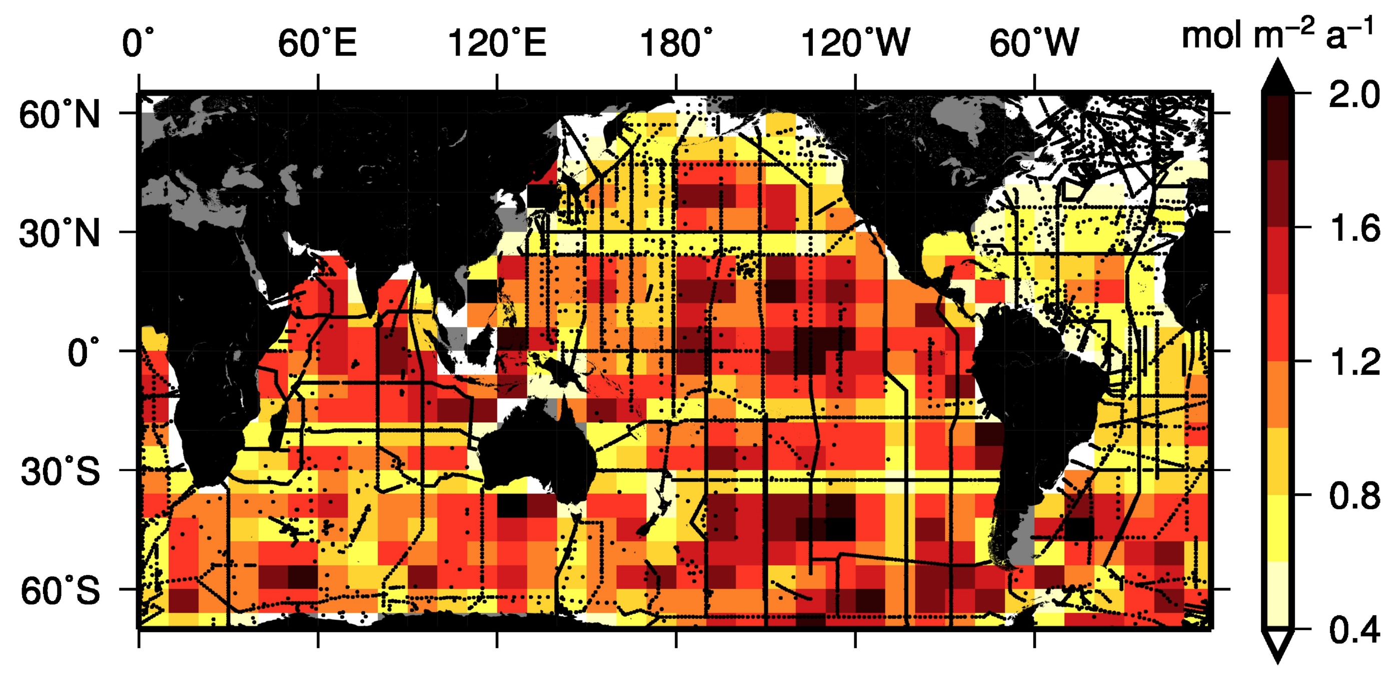
Using the likelihood, we obtained the 3000 sets of grid values and parameters estimated through MCMC sampling. Based on the 3000 sampling sets, we estimated the CO_2 changes and their uncertainties.

Water column C^{ANT} map based on MCMC



General features were similar to the ones based on isopycnal method. However, negative regions were due to strong water mass shift / large estimation uncertainties (which were not included in the isopycnal methods).

Estimation error



Large uncertainties (~ 100%) were estimated, especially far from observation lines. The uncertainties were also strongly affected by the isopycnal heaving and horizontal water mass shifts.

Summary

By integration, uncertainties can be reduced.

The uncertainties of basin scale ΔC^{ANT} is 10-80%.

For global, the uncertainty was about 15% respect to the total changes based on the isopycnal method.

Basin	σ_N (grid) PgC / 10yr
Atlantic	11.1 $^{(15.9)}$ ± 1.7
Pacific	8.2 $^{(9.1)}$ ± 2.6
Indian	7.9 $^{(7.9)}$ ± 2.4
Southern	1.5 $^{(1.0)}$ ± 0.8
Global	28.7 $^{(33.9)}$ ± 4.4

Especially, in the Southern Ocean, more obs. are needed.

Note 34PgC from the grid method is larger than 28PgC (26PgC from model, Le Quere 2013), but we did not discuss the difference because of the large uncertainties (4.4PgC for Err standard deviation, over 10PgC for 95% confidence levels).

Discussion

- Changes can be easily detected with the isopycnal methods.

  We can make advantages of HQ data through this method. But, to quantify, we missed large uncertainties mainly due to isopycnal heaving.

- From gridded data, local uncertainties were very high.

  It is clear that we need more observations.

- The map in the gridded values can be improved.

  Using other relationships (nutrients, etc... like eMLR) can be useful for more exact estimation. Synthesis with surface fluxes may also improve the estimation. For more appropriate uncertainty estimation, we should take into account temporal changes explicitly.