

The background image is a composite. The top half shows a sunset over a calm ocean, with the sun low on the horizon and a warm orange and yellow sky. The bottom half shows the same ocean surface but with a heatmap overlay, where colors range from blue (cooler) to red (warmer), indicating temperature variations in the water. The text is overlaid on the upper and middle portions of the image.

Anthropogenic CO₂ in the Indian Ocean

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History of determination of Anthropogenic CO₂ in the Ocean

Brewer, 1978; Chen & Millero, 1979

Gruber et al, 1996; Peng, 1998; Goyet et al, 1999

**Thomas et al., 2001; Touratier & Goyet, 2004; Waugh et al.,
2004; Lo Monaco et al., 2005 ; Perez, 2005; Friz, 2006 ...**

Estimation of Anthropogenic CO₂ in the Ocean

$$C_T = C_T^{phys} + C_T^{bio} + C_T^{ant}$$



$$C_T = C_T^{280} + C_T^{dis} + C_T^{bio} + C_T^{ant}$$

$$C_T^{bio} = 0.74AOU - 0.5(A_T - A_T^0)$$

$$\Delta C^* = C_T - C_T^{bio} - C_T^{280}$$

$$C_T^{ant} = \Delta C^* - C_T^{dis}$$

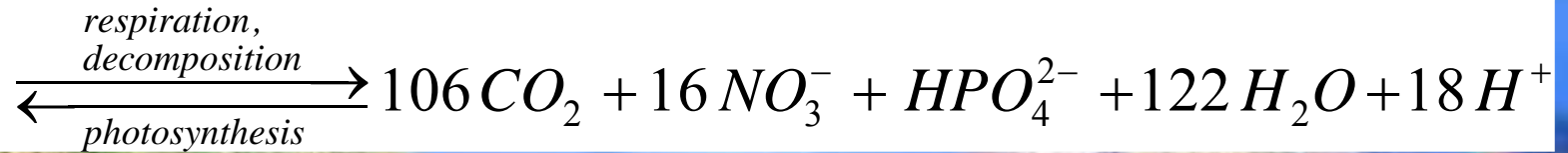
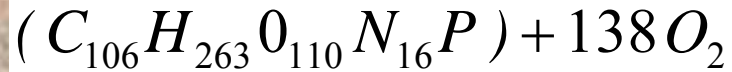
SURFACE : $C_T^{dis} = \Delta C_t^*$

SUB-SURFACE : $C_T^{dis} = \overline{\Delta C_t^*}$

$$\Delta C_t^* = C_T - C_T^{bio} - C_T^{280}$$

MID-DEPTH : $C_T^{dis} = \overline{\overline{\Delta C_t^*}} \& \overline{\Delta C^*}$

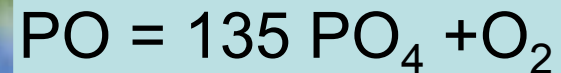
DEEP : $C_T^{dis} = \overline{\Delta C^*}$



Broecker (1974, Earth Planet. Sci. Lett., 23: 100-107)

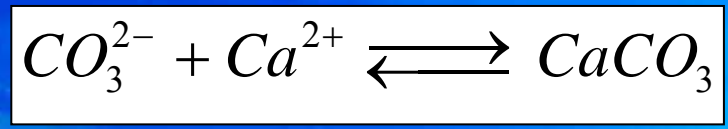
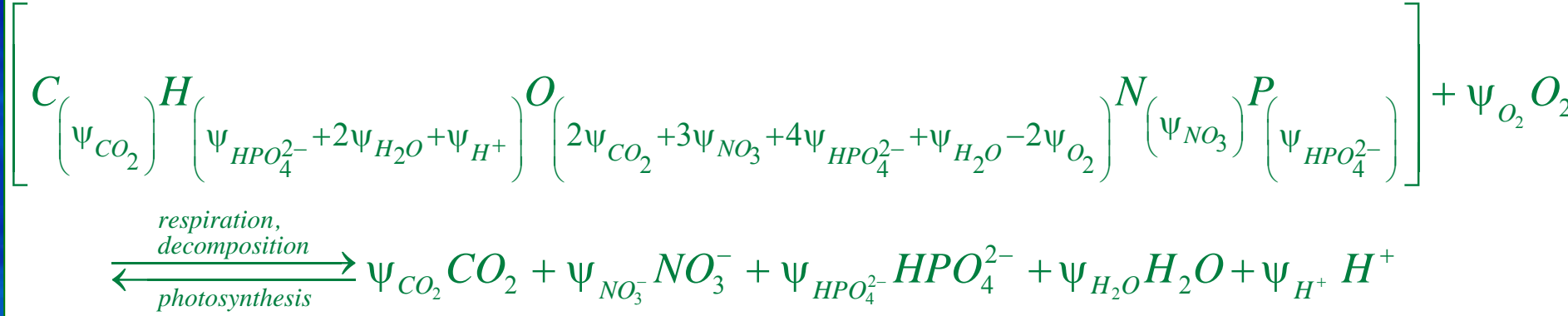


and



$$TrOCA = O_2 + a \left(C_T - \frac{1}{2} A_T \right)$$

$$C_{ant}^{TrOCA} = \frac{TrOCA - TrOCA^0}{a}$$



$$C_T = [CO_2] + [HCO_3^-] + [CO_3^{2-}]$$

$$A_T = [HCO_3^-] + 2[CO_3^{2-}] + [B(OH)_4^-] + [OH^-] + [HPO_4^{2-}] + 2[PO_4^{2-}] + [SiO(OH)_3^-] + [NH_3] + [HS^-] + \dots - [H^+] - [HSO_4^-] - [HF] - [H_3PO_4] - \dots$$

$$C_T = \frac{\psi_{CO_2}}{\psi_{O_2}} O_2 + \frac{1}{2} A_T CaCO_3$$

$$A_T = \frac{\psi_{HPO_4^{2-}} - \psi_{H^+}}{\psi_{O_2}} O_2 + A_T CaCO_3$$

$$C_T = \frac{\psi_{CO_2}}{\psi_{O_2}} O_2 + \frac{1}{2} \left[A_T + \frac{(\psi_{H^+} - \psi_{HPO_4^{2-}})}{\psi_{O_2}} O_2 \right] \Rightarrow O_2 = a \left(C_T - \frac{1}{2} A_T \right)$$

$$TrOCA = O_2 + a \left(C_T - \frac{1}{2} A_T \right) \quad \text{with} \quad a = \frac{\psi_{O_2}}{\psi_{CO_2} + \frac{1}{2} (\psi_{H^+} - \psi_{HPO_4^{2-}})}$$

$$TrOCA^0 = O_2^0 + a \left(C_T^0 - \frac{1}{2} A_T^0 \right)$$

$$C_T - C_T^0 = C_{ant}^{TrOCA} = \frac{TrOCA - TrOCA^0}{a}$$

How is TrOCA0 computed?

TrOCA0 is computed using the GLODAP world ocean database (9618 hydrographic stations collected on 95 cruises since the 1990s).

1) Using the $\Delta^{14}\text{C}$ property

- $\Delta^{14}\text{C} < -175 \text{ ‰}$ (age > 1400 yr) \rightarrow anthropogenic $\text{CO}_2 = 0$

1212 sampling points in the northern Pacific Ocean at 1000-2000 m (oldest water masses) and in deep waters of the northern Indian Ocean.

Using the associated properties O_2 , C_T , and A_T , the corresponding TrOCA0 values are computed using the relationship:

$$\text{TrOCA}^0 = \text{O}_2^0 + a \left(\text{C}_T^0 - \frac{1}{2} \text{A}_T^0 \right)$$

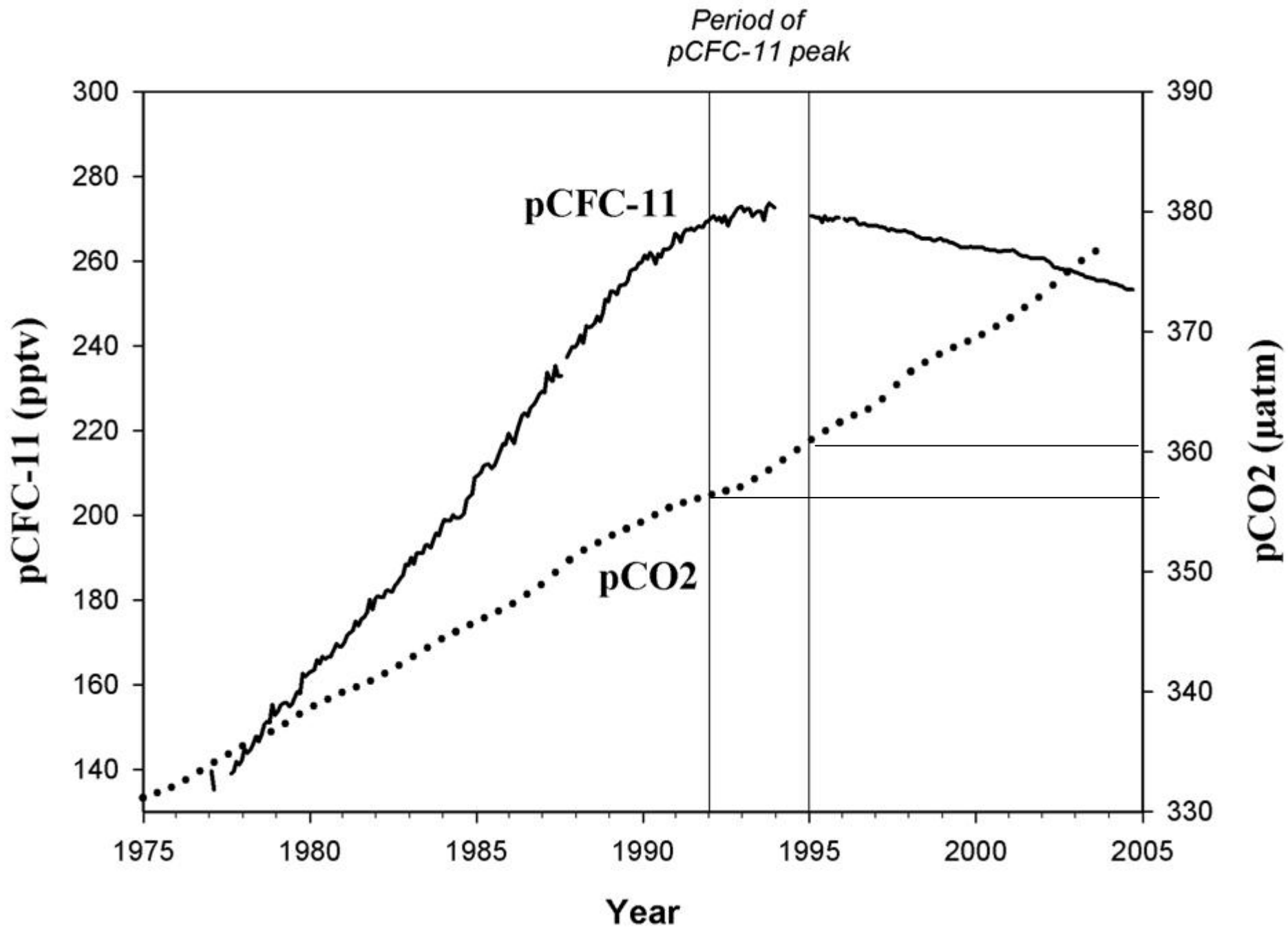
2) Using the pCFC-11 property

- maximum values of pCFC-11 (typically between 262.9 and 271.3 pptv).

This selected dataset (1445 points) corresponds to the years 1992-1995).

- TrOCA0 is computed from:

$$\text{TrOCA}^0 = \text{TrOCA} - a(\text{C}_T - \text{C}_T^0) = \text{TrOCA} - a C_{\text{ant}}^{92/95}$$



$$C_{ant}^{92/95} = C_T^{357} - C_T^{280}$$

$$C_T^X = f(S, \theta, A_T, pCO_2 = X \mu atm)$$

$$TrOCA^0 = e^{\left(b + c\theta + \frac{d}{A_T^2} \right)}$$

$$\begin{cases} a = 1.279 \pm 7.3 \times 10^{-3} \\ b = 7.511 \pm 5.2 \times 10^{-3} \\ c = -1.087 \times 10^{-2} \pm 2.5 \times 10^{-5} \\ d = -7.81 \times 10^5 \pm 2.9 \times 10^4 \end{cases}$$

$$TrOCA = O_2 + 1.279 \left[C_T - \frac{1}{2} A_T \right]$$

$$TrOCA^0 = e^{\left(7.511 - (1.087 \times 10^{-2}) \theta - \frac{7.81 \times 10^5}{A_T^2} \right)}$$

$$C_{ant}^{TrOCA} = \frac{TrOCA - TrOCA^0}{1.279}$$

Uncertainties

$$\begin{aligned} \delta_{C_{ant}^{TrOCA}}^2 = & \left\{ \left(\frac{\partial C_{ant}^{TrOCA}}{\partial C_T} \right) \delta_{C_T} \right\}^2 + \left\{ \left(\frac{\partial C_{ant}^{TrOCA}}{\partial O_2} \right) \delta_{O_2} \right\}^2 + \left\{ \left(\frac{\partial C_{ant}^{TrOCA}}{\partial A_T} \right) \delta_{A_T} \right\}^2 + \left\{ \left(\frac{\partial C_{ant}^{TrOCA}}{\partial \theta} \right) \delta_{\theta} \right\}^2 \\ & + \left\{ \left(\frac{\partial C_{ant}^{TrOCA}}{\partial a} \right) \delta_a \right\}^2 + \left\{ \left(\frac{\partial C_{ant}^{TrOCA}}{\partial b} \right) \delta_b \right\}^2 + \left\{ \left(\frac{\partial C_{ant}^{TrOCA}}{\partial c} \right) \delta_c \right\}^2 + \left\{ \left(\frac{\partial C_{ant}^{TrOCA}}{\partial d} \right) \delta_d \right\}^2 \end{aligned}$$

$$\begin{aligned} \delta_{C_T} = 2 \mu\text{mol kg}^{-1}, \delta_{O_2} = 1 \mu\text{mol kg}^{-1}, \delta_{A_T} = 4 \mu\text{mol kg}^{-1}, \delta_{\theta} = 0.01 \text{ } ^\circ\text{C}, \\ \delta_a = 7.3 \times 10^{-3}, \delta_b = 5.2 \times 10^{-3}, \delta_c = 2.5 \times 10^{-5}, \text{ and } \delta_d = 2.9 \times 10^4, \end{aligned}$$

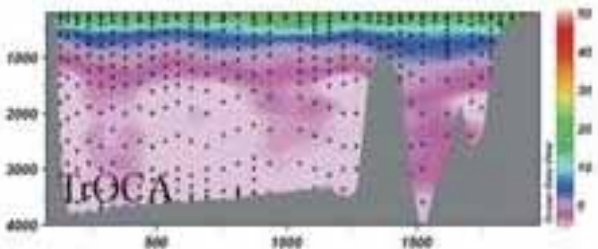
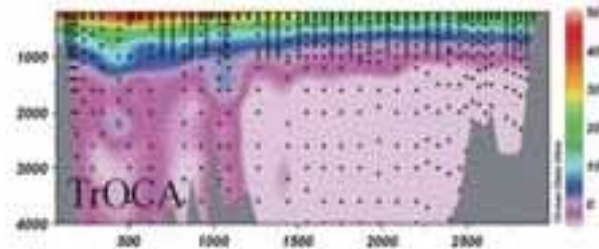
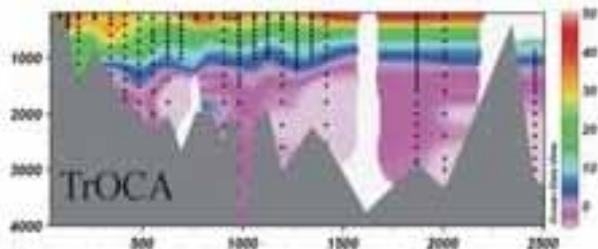
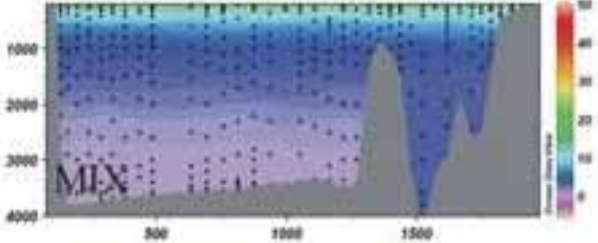
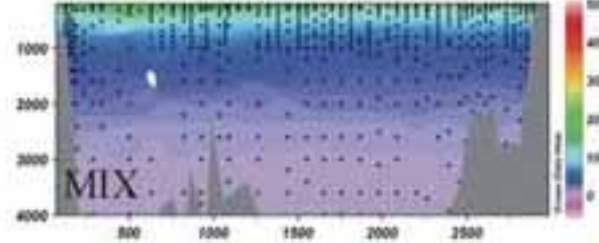
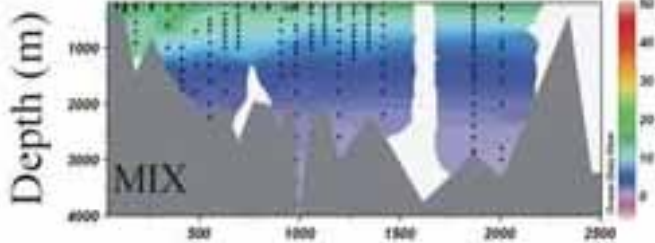
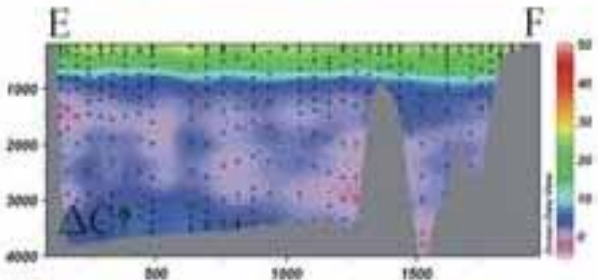
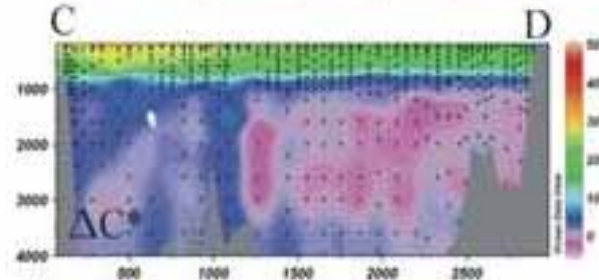
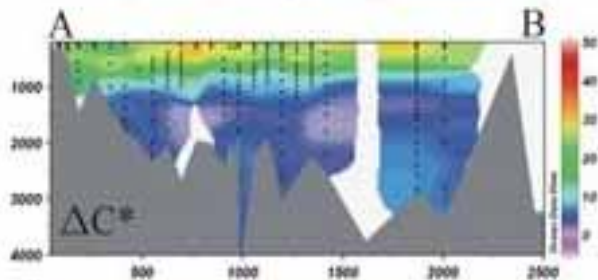
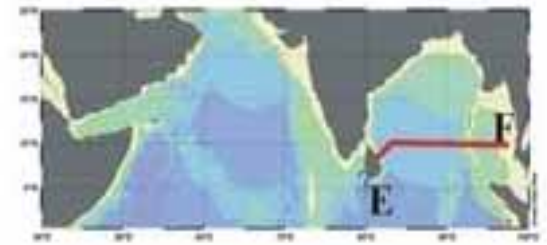
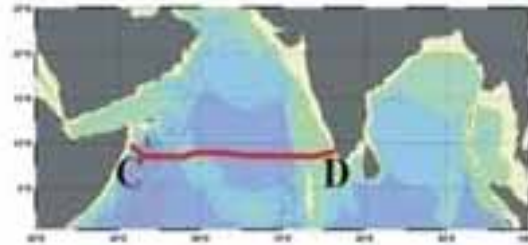
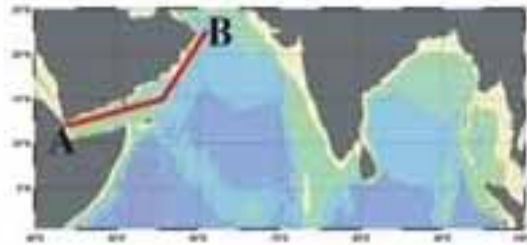
$$\delta_{C_{ant}^{TrOCA}} = 6.25 \mu\text{mol kg}^{-1}$$

Anthropogenic CO₂ ($\mu\text{mol kg}^{-1}$)

Gulf of Aden

Arabian Sea

Bay of Bengal



Distance (km)

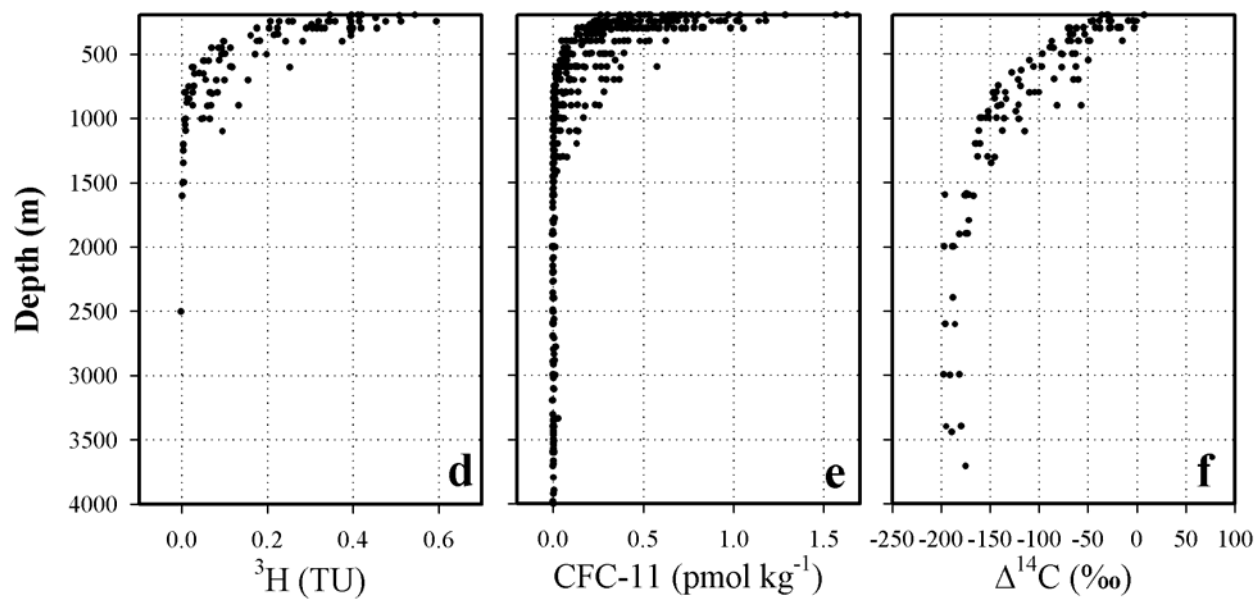
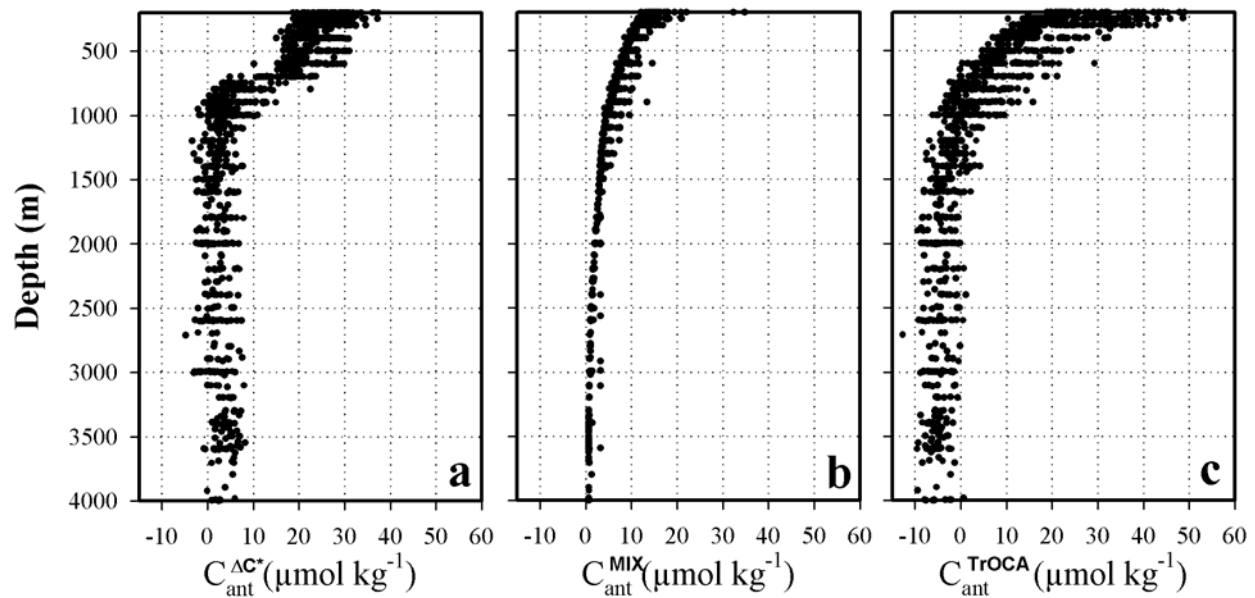
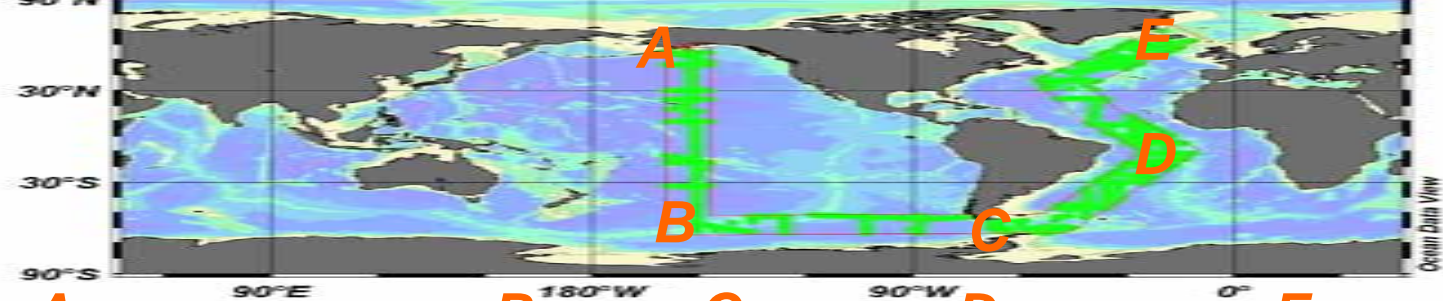
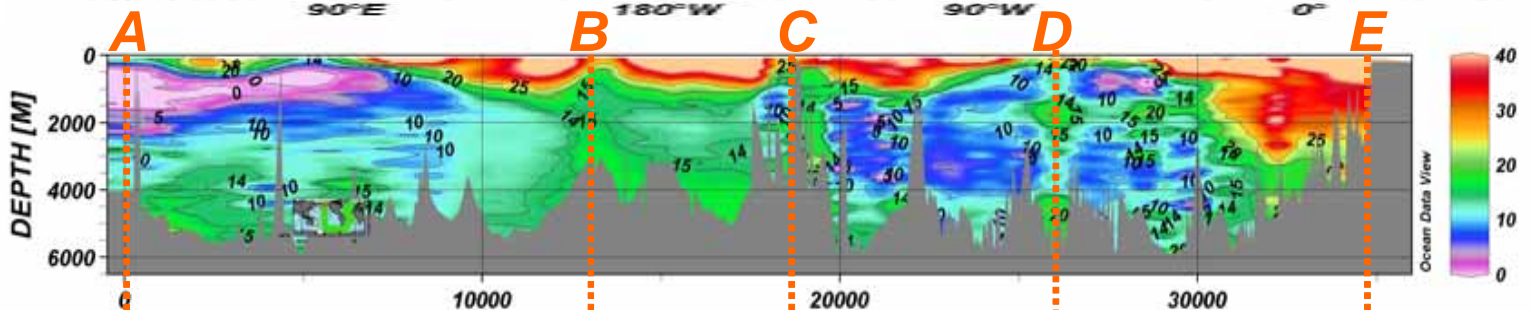


Table 1. Spearman correlations between the four anthropogenic tracers (anthropogenic CO₂, Tritium, CFC-11, Δ¹⁴C). The concentration of anthropogenic CO₂ is estimated using three different approaches (ΔC*, MIX, and TrOCA). All coefficients (R) values are significant at the 0.05 level.

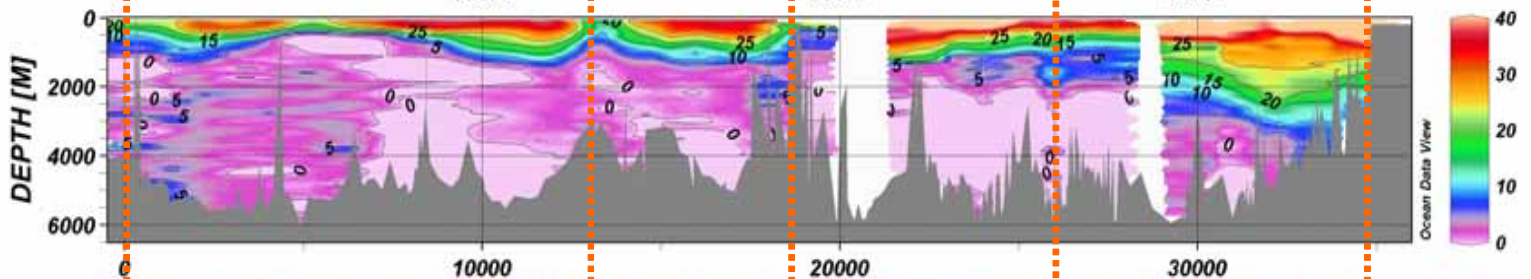
	ΔC*	MIX	TrOCA	Tritium	CFC-11
MIX	0.86	****	****	****	****
TrOCA	0.93	0.95	****	****	****
Tritium	0.87	0.97	0.96	****	****
CFC-11	0.87	0.95	0.93	0.99	****
Δ¹⁴C	0.89	0.98	0.96	0.97	0.97



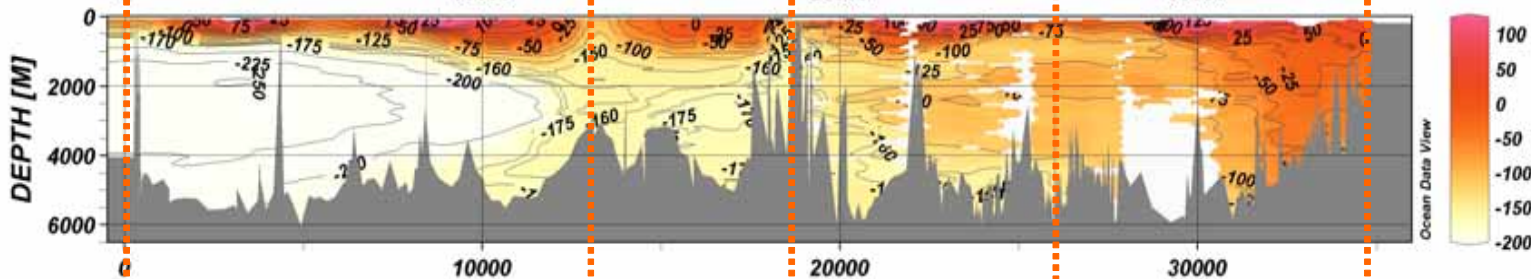
C_{ANT}^{TrOCA}
($\mu\text{mol kg}^{-1}$)



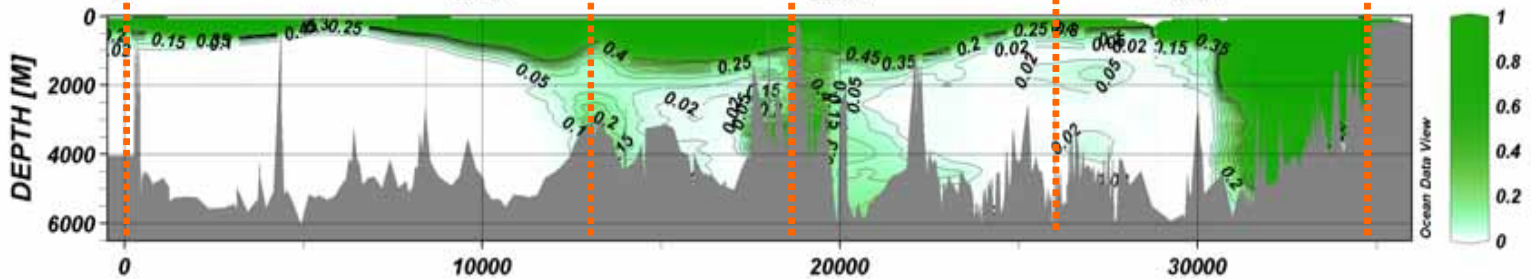
$C_{ANT}^{\Delta C^*}$
($\mu\text{mol kg}^{-1}$)



$\Delta^{14}\text{C}$
(‰)



CFC-11
(pmol kg^{-1})



On-going work

- Critical assessment of Cant estimates
- Time-series sites in key regions

What should we continue to measure?

- C_T , A_T , ^{13}C , O_2 , nutrients, DOC
- CCl_4 , $^3H/^3He$
- New tracers

PERSPECTIVES



Revised estimates of C_{ant}^{TrOCA}

Create reliable estimates of C_{ant}^{TrOCA} in the upper ocean

Provide estimates of future evolution of anthropogenic carbon in the ocean (including semi-enclosed seas)

The end



Thank You !

