980 : TRACER-DERIVED TRANSIT TIME DISTRIBUTIONS IN THE NORTH ATLANTIC ALONG 36°N AND INFERRED ANTROPOGENIC CARBON CONCENTRATIONS

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Introduction and method:

We use the Waugh et al. (2004) Transit Time Distributions (TTDs) method to derive concentration of anthropogenic carbon in the ocean from dichlorofluoromethane (CFC-12) and sulfur hexafluoride (SF_6) measurements. Using the concept of TTDs makes no assumptions about the magnitude of mixing in comparison to the common tracer ages. The TTD is a type of green's function that propagates a boundary condition on tracer mole fraction from the surface water to the interior. We assume that the transport is steady and that a TTD can be modelled as an Inverse Gaussian function (G) characterized by a mean transit time (Γ) associated with a width (Δ) that implicitly includes the effects of mixing on transport.

For a passive tracer, c, with a known surface layer time history, $c_0(r_s,t)$, interior values at any point,r, and time, t, can be written:

$$c(r,t) = \int_0^{\infty} c_0(t-t')G(r,t')dt' \quad (1)$$

$$G(t) = \sqrt{\frac{\Gamma^3}{4\pi\Delta^2 t^3}}\exp\left(\frac{-\Gamma(t-\Gamma)^2}{4\Delta^2 t}\right) \quad (2)$$

The observed CFC-12 and SF_6 data are used to constrain transit time distribution G at each location, which then is used to propagate the antropogenic component of total dissolved inorganic cabon .

We used the "CO2sys" program (Lewis and Wallace, 1998) to calculate the DIC from the partial pressure of atmospheric CO_2 (pCO_2), total alkalinity, temperature and salinity (program available at http:cdiac.esd.ornl.gov/oceans/co2rprt.html)

The anthropogenic component of total dissolved inorganic cabon is defined by

$$\Delta DIC(t) = DIC(t) - DIC(1780) \quad (3)$$

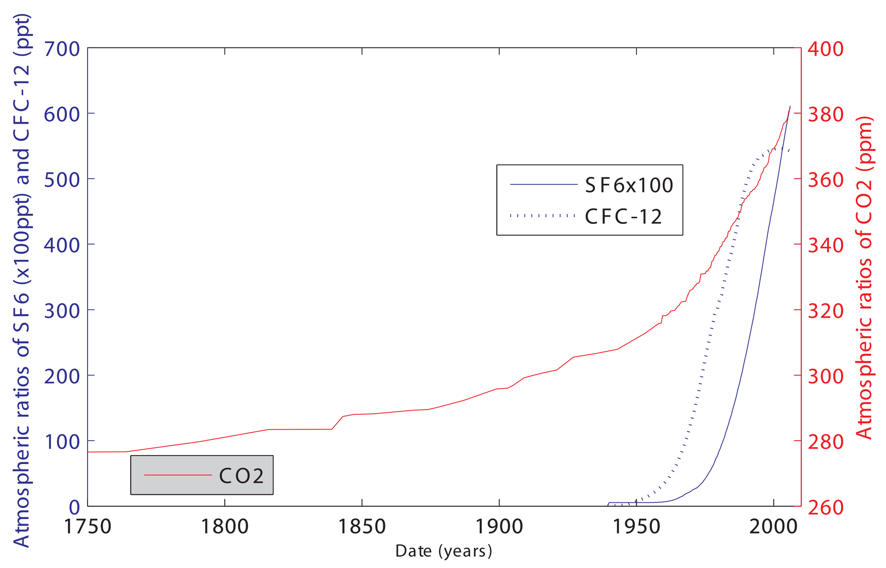

Fig. 1: Atmospheric mixing ratios of CFC-12, SF_6 and CO_2 for the Northern Hemi-sphere atmosphere.

Plotted in **Figure 1** are the atmospheric time histories for the atmospheric ratios of SF_6, CFC-12 and CO_2. CFC-12 has continuously increased from the 40's reaching its maximum of ~ 546 ppt around 2002. Since then, CFC-12 is decreasing showing in 2005 levels similar to the ones measured in 1998 (542 ppt). The use of the CFC-12 as a transient tracer is then limited to the 1940-1998 period. SF_6 is a good complementing dating tool of post-1970s waters because, unlike the CFC-12 , which have not changed consistently for the last 2 decades, the SF_6 continues to increase.
Note that CFC-12 and SF_6 are imperfect proxy for CO_2 as they don't cover the periode before the 40's.

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References:
Waugh et al., 2004. Deep Sea Research I, 51, 1475-1491.
Lewis and Wallace, 1998. ORNL/CDIAC-105.
Tanhua et al., 2007. PNAS, 104, 9, 3037-3042.

Data and TTDs calculations:

The CFC-12 and SF_6 data used here were measured along 36°N in the North Atlantic during the May-June 2005 Charles Darwin cruise (Figure 2).
We can distinguish from the vertical tracers distributions (Figure 3), the well ventilated surface and mode waters separated from the deep tracer maximum of the Upper (~ 1500m) and Lower (~3800m) North Atlantic Deep Waters by a tracer mimimum at ~ 1000 m. The Western Basin is well ventilated compared to the Eastern Basin. The large signal increase of the SF_6 concentration towards the surface suggests that the time scale of SF_6 is well suited for studying the ventilation of the waters above 2500m and in particular in the 0-1000 m region where the CFC-12 gradients are vanishing.

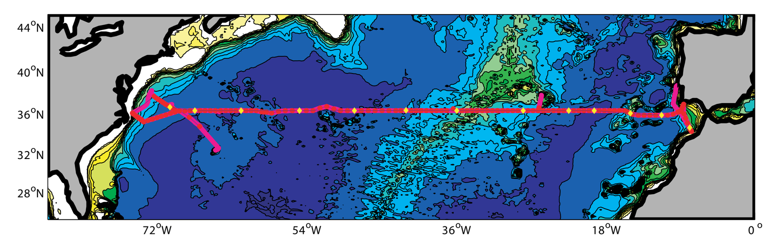

Fig. 2: Cruise track of the 36°N transatlantic hydrographic section

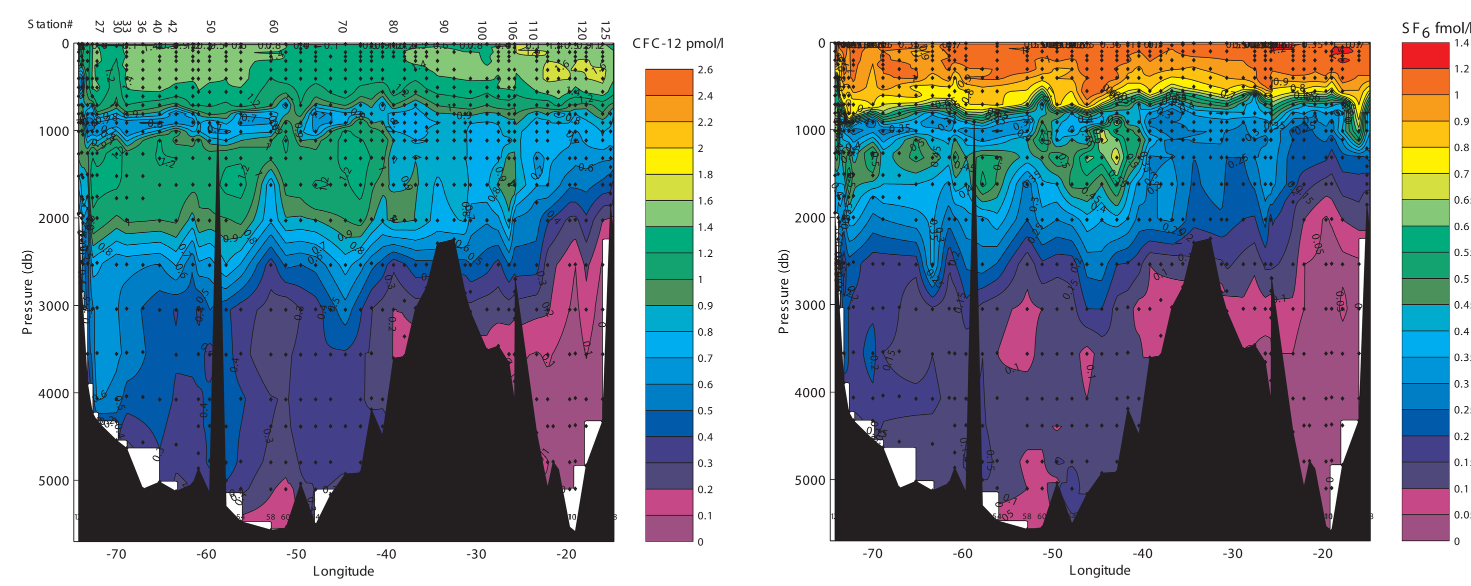

Fig. 3: Vertical distributions of CFC-12 (pmole/l) and SF_6 (fmol/l) along 36°N.

The TTD parameters Γ and Δ were determined at each location using the CFC-12 and the SF_6 measurements with the following assumptions :
- Form of the TTD with $\Delta=\Gamma$
- Tracer saturations to be 85% in the surface waters and 60 % in the intermediate and deep waters (Figure 4 and 5).

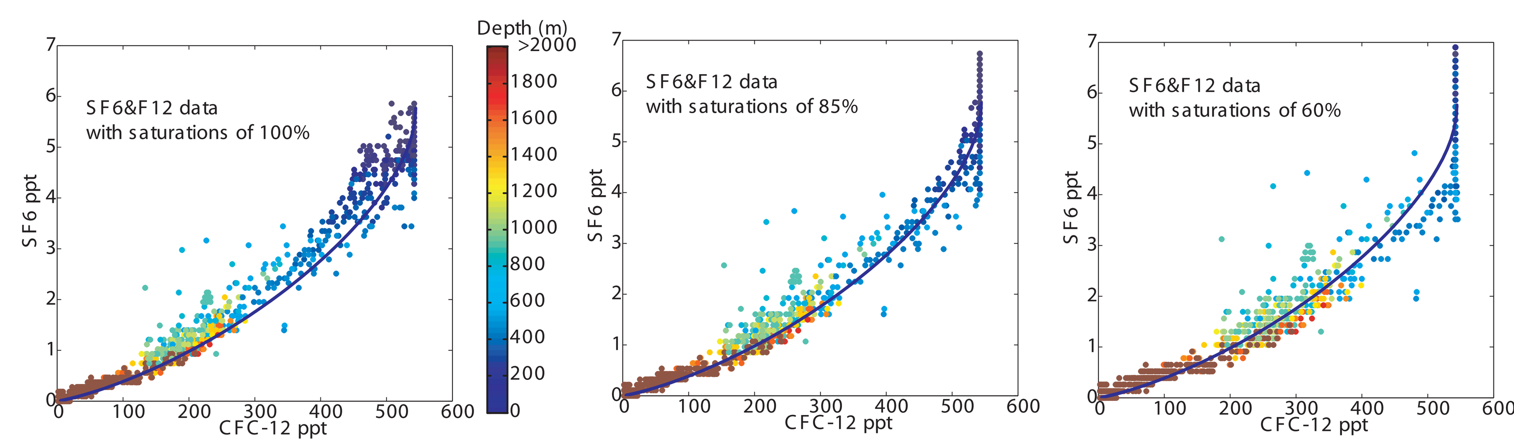

Fig. 4: Relationship between SF6 and CFC-12 for the idealized TTDs (with $\Delta=\Gamma$, curve) and for the observed SF6 and CFC-12 data points (dots) adjusted to differents saturations. The dots colors indicate the depth of the data point. The best curve/data fits are a saturation of 85% for the surfaces/subsurfaces waters and a saturation of 60% for the waters intermediate and deep waters.

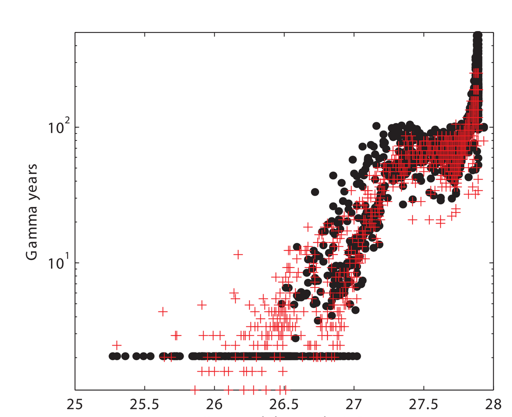

Fig. 5: Distribution of Gamma (Γ) against potential density inferred from pSF6 (red) and pCFC-12 (black) when considering a tracer saturation of 85%. Note, that the SF6 data allow for the Γ determination for the most recently ventilated surface waters.

Results: Inferred Cant, profiles and inventories

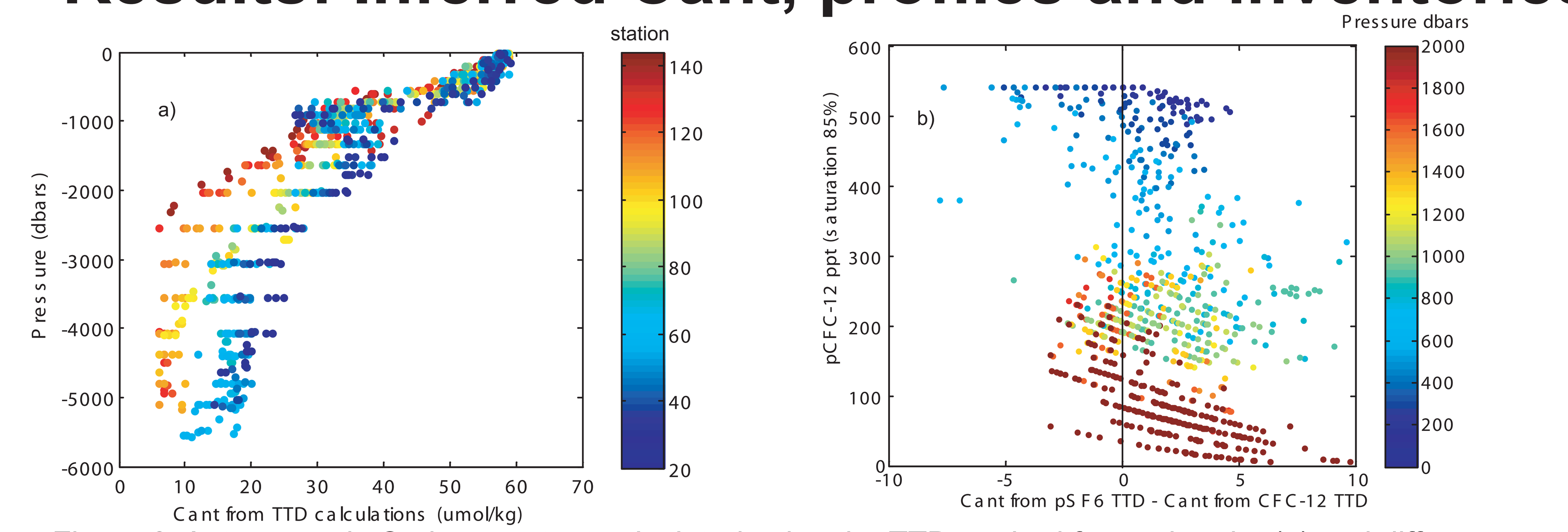

Figure 6: Antropogenic Carbon content calculated using the TTD method for each point (a) and difference based on either the SF6 or the CFC-12 measurements were used (b).

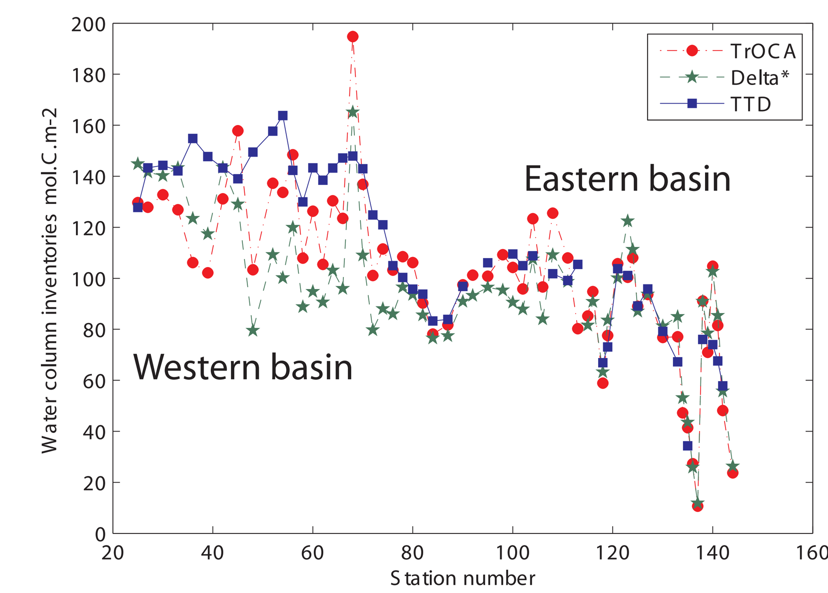

Figure 7: Comparison between the different Cant depth-integrated water-columns inventory estimates along 36N (cruise track see Fig.2).

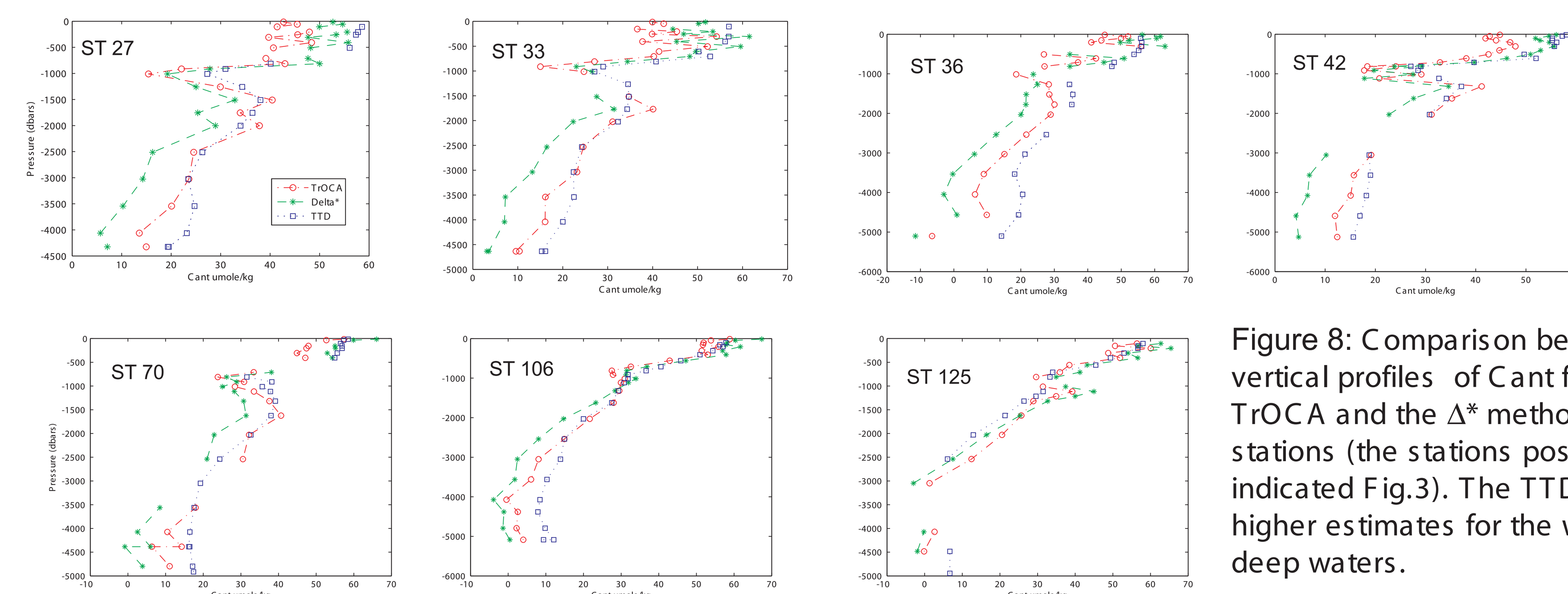

Figure 8: Comparison between estimated vertical profiles of Cant from the TTD, the TrOCA and the Δ^* method at different stations (the stations position are indicated Fig.3). The TTD method reveals higher estimates for the well ventilated deep waters.

Conclusions and remarks:

The 36°N SF_6 and CFC-12 data set is used successfully to determine Cant from the TTD method (Fig.6) . The TTDs are estimated directly from the tracers observations.The combination of SF_6 and CFC-12 provides Cant estimates for the deep waters as well as for the surface waters.
The resulting depth-integrated water-columns inventories of Cant are presented Fig. 7 and compare to the estimates from the TrOCA and Δ^* methods. Overall, the inventories from the TTD method are higher than the inventories the TrOCA and Δ^* methods. This is due to a higher inventories from the TTDs in the western basin: in the eastern basin, the results are relatively close but in the western basin, the TTD estimates show a larger Cant uptake than the TrOCA and Δ^* methods. These results revealing more Cant with the TTD method in the deep ocean (Fig. 8) are in agreement with Tanhua et al. (2007). In that regard, the 36°N track across the North Atlantic appears to be a particulary good position to quantify the larger uptake of Cant in the well ventilated western basin compare to the eastern basin using the TTD method.
Note that we assumed steady state and that the CO_2 desequilibrium (it could have been assumed constant ~ 10%) was neglected. Also for very old waters SF_6 and CF-12 are not good proxy of CO_2.