IS THERE A HIGHER C_{ANT} STORAGE

IN THE INDIAN OCEAN?

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ICES/CIEM PICES IOC-UNESCO

and by International Council for Science Scientific Committee on Oceanic Research

GLOBEC WCRP

IMEDEA, CSIC – UIB, Mallorca, Spain

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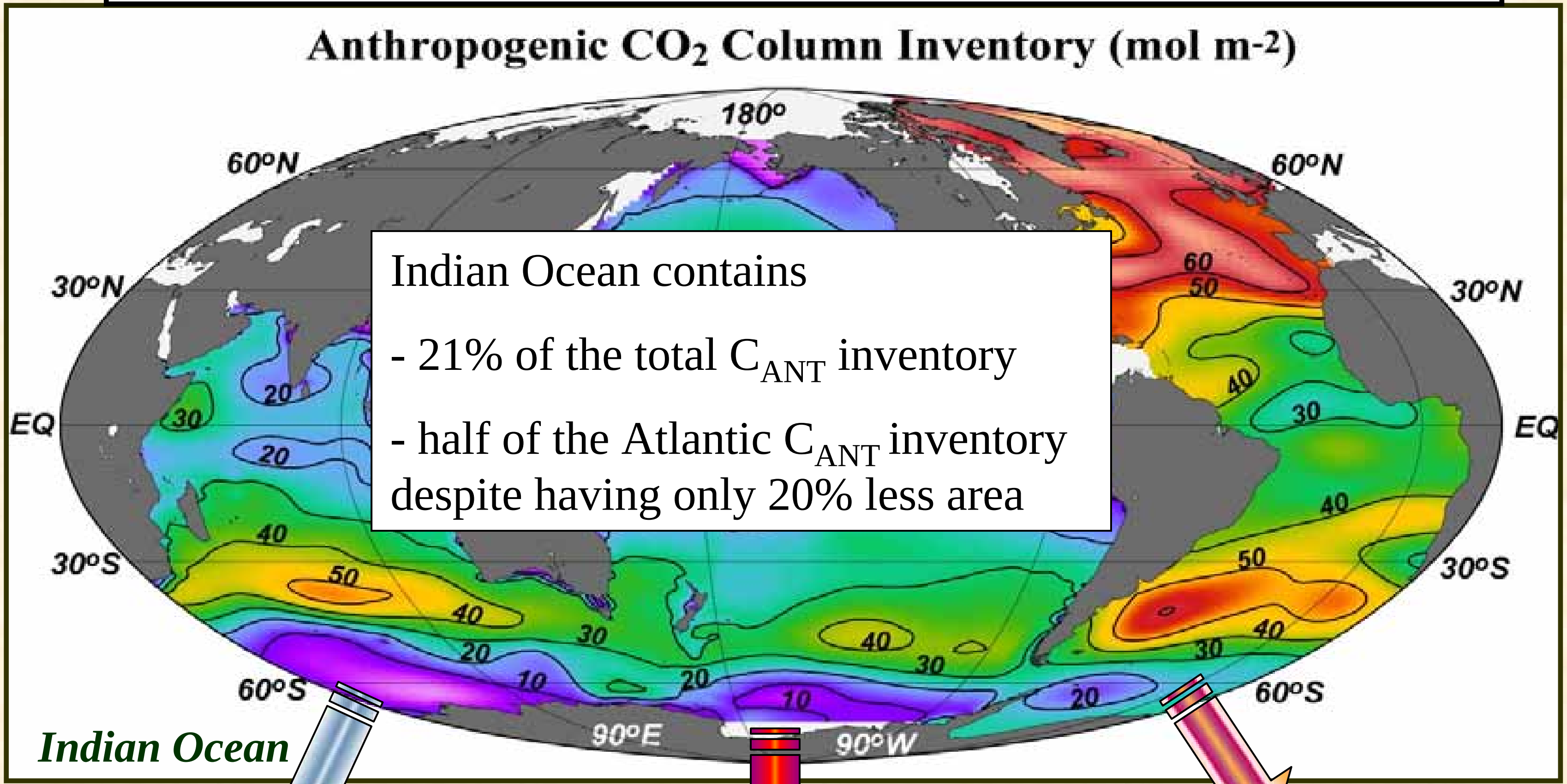
C_{ANT} ALONG CD139 CRUISE (2002) 32ºS INDIAN OCEAN

C_{ANT} inventory referred to 1994 = 110 ± 13 Pg C



Indian Ocean contains

- 21% of the total C_{ANT} inventory

- half of the Atlantic C_{ANT} inventory despite having only 20% less area

Pacific Ocean

Atlantic Ocean

20.3 ± 3 Pg

44.5 ± 5 Pg

44.8 ± 6 Pg

(Sabine et al, Science 2004)

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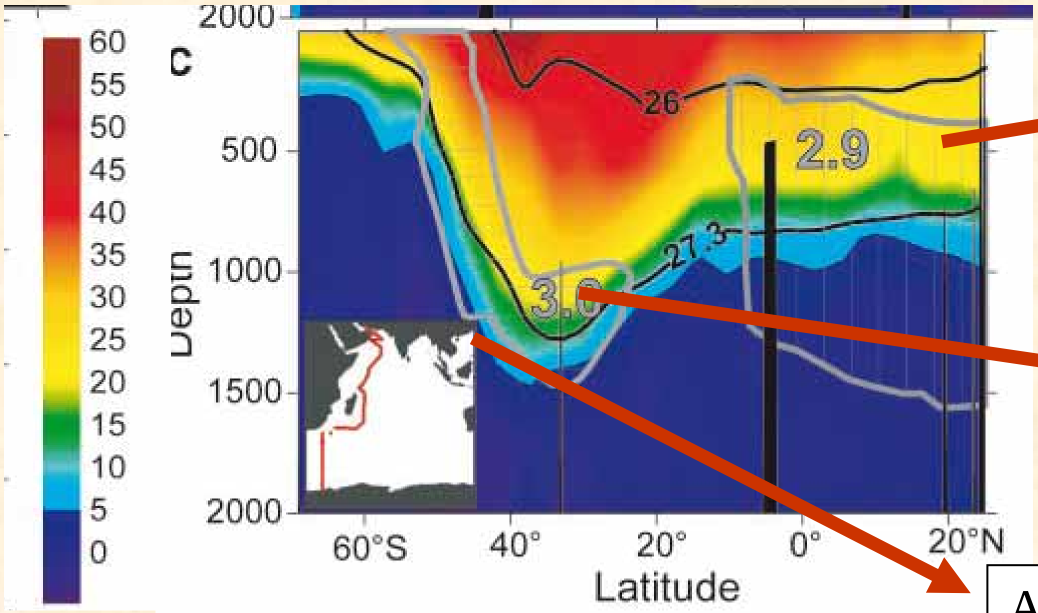
Indian Ocean C_{ANT} vertical distribution μmol/kg



(Sabine et al, Science 2004)

RedSea /Persian Gulf Intermediate Water

Antarctic Intermediate Water (AAIW)

AAIW marks the deepest C_{ANT} penetration in the Subtropical gyre

No C_{ANT} in deep and bottom waters

C_{ANT} ALONG CD139 CRUISE (2002) 32ºS INDIAN OCEAN

Hypothesis:

C_{ANT} penetrates deeper than 1000-1500 m

How to assess this question:

compare different C_{ANT} methods -> difficult:
every method has high uncertainties

help: relation of C_{ANT} with tracers (CFC_{12}, CCl_4)

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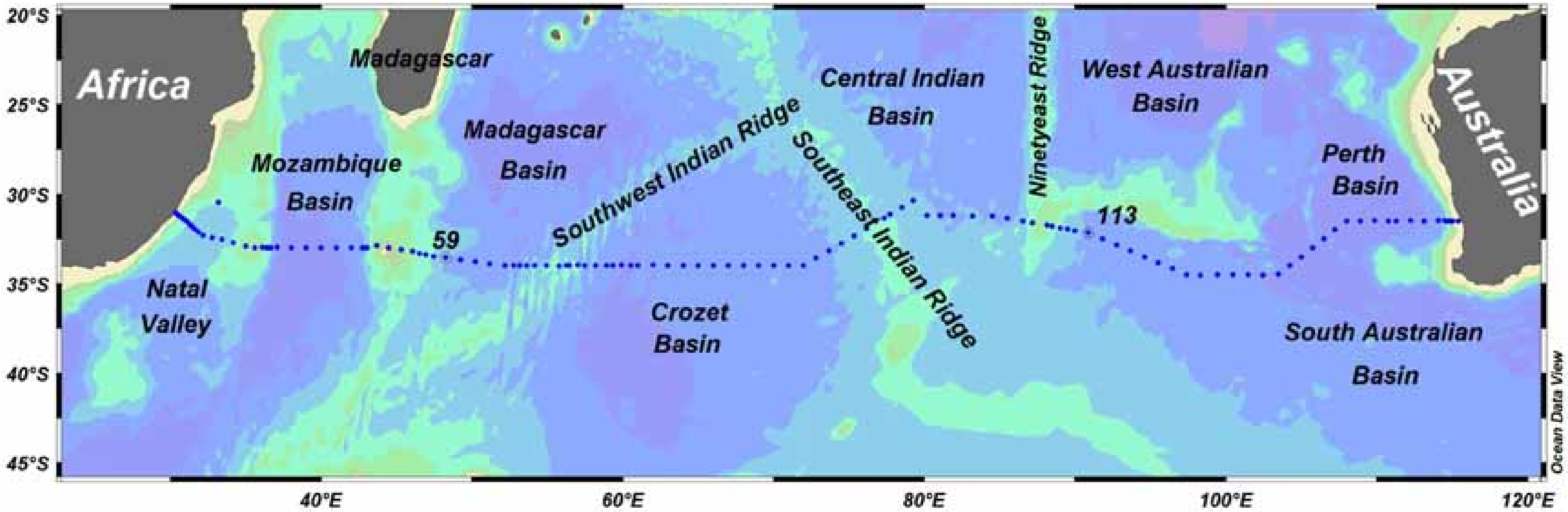
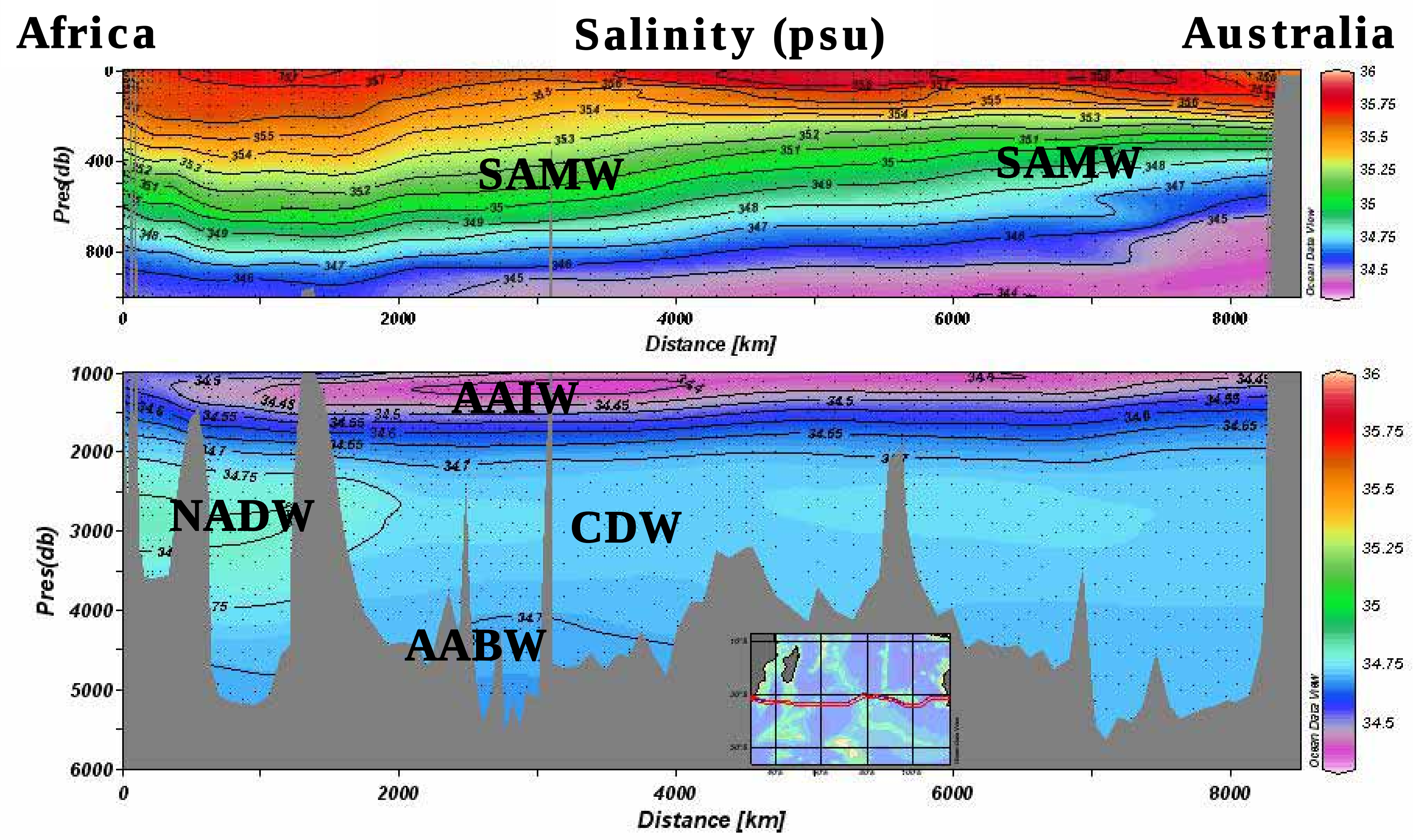


- On board R/V Charles Darwin, CD139 cruise, 1/3 – 15/4/2002, from Durban to Freemantle
- P.I.: Harry Bryden (National Oceanographic Centre, Southampton, UK)
- Physics: temperature, salinity, ADCP, LADCP
- Chemistry: oxygen, salinity, nutrients, CO_2 (pH & TA, TIC), CFCs (11, 12, 113), CCl_4.

C_{ANT} ALONG CD139 CRUISE (2002) 32ºS INDIAN OCEAN



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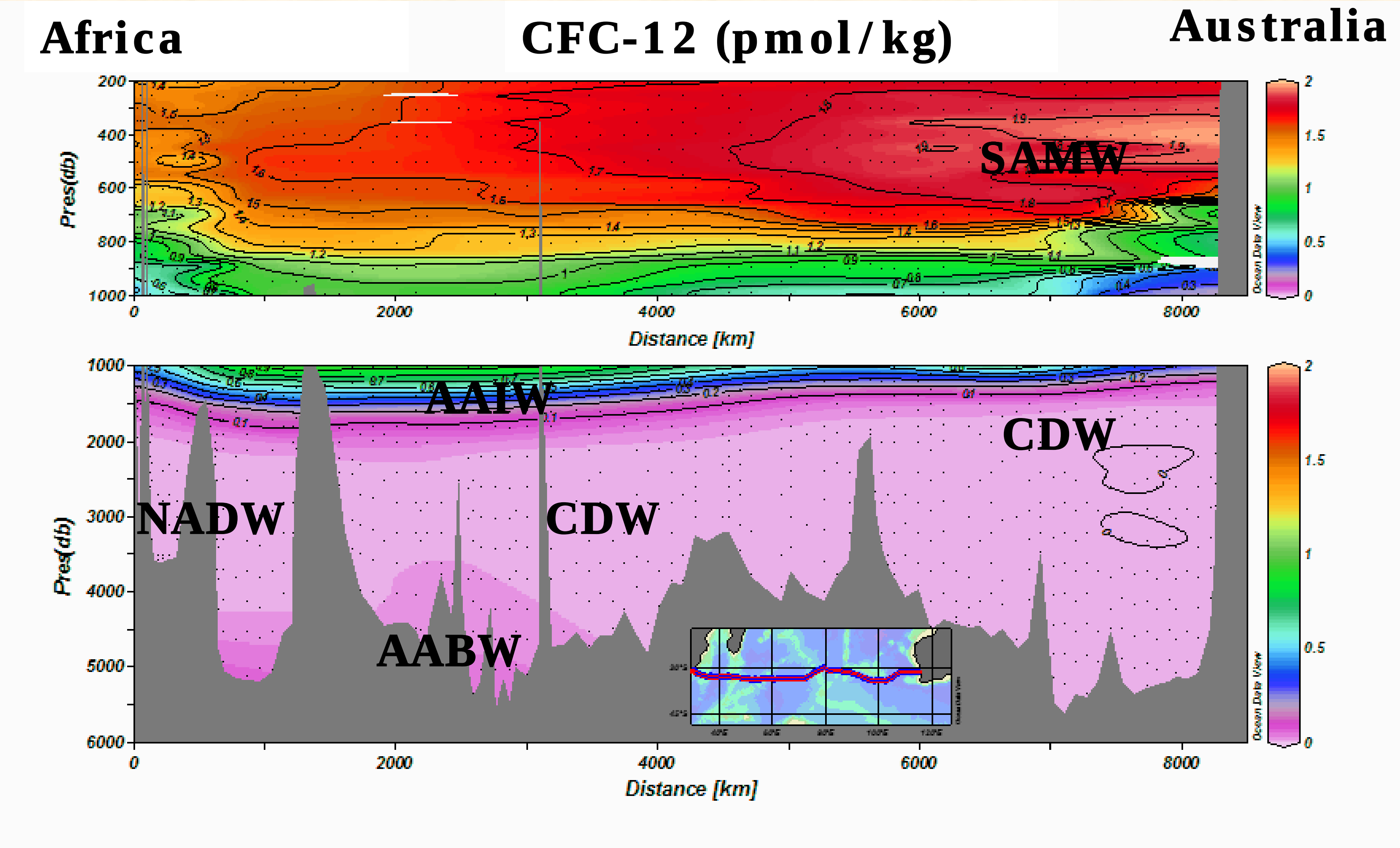


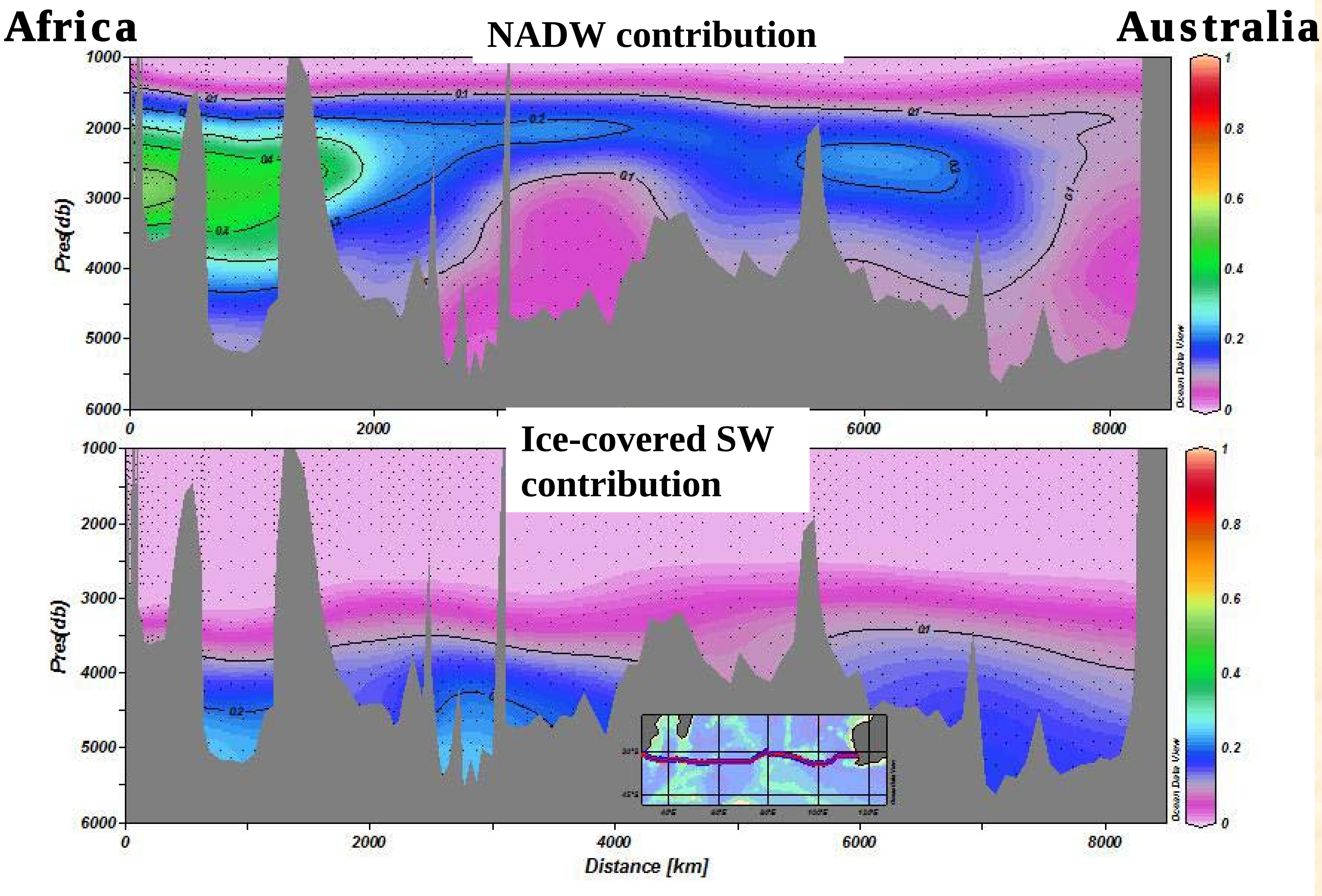
C_{ANT} ALONG CD139 CRUISE (2002) 32ºS INDIAN OCEAN

C_{ANT} TECHNIQUES

1. C_{ANT} SAB99: method by Sabine et al. (GBC,1999), using their ΔC_{Dis}
2. C_{ANT} LM05: method by LoMonaco et al. (JGR, 2005)

C_{ANT} ALONG CD139 CRUISE (2002) 32ºS INDIAN OCEAN

2. Back-calculation technique by Lo Monaco et al. (JGR, 2005): OMP



C_{ANT} ALONG CD139 CRUISE (2002) 32ºS INDIAN OCEAN

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3. C_{ANT} TrOCA: Touratier & Goyet (Tellus, 2007)
4. C_{ANT} TTD
5. C_{ANT} from OCCAM model

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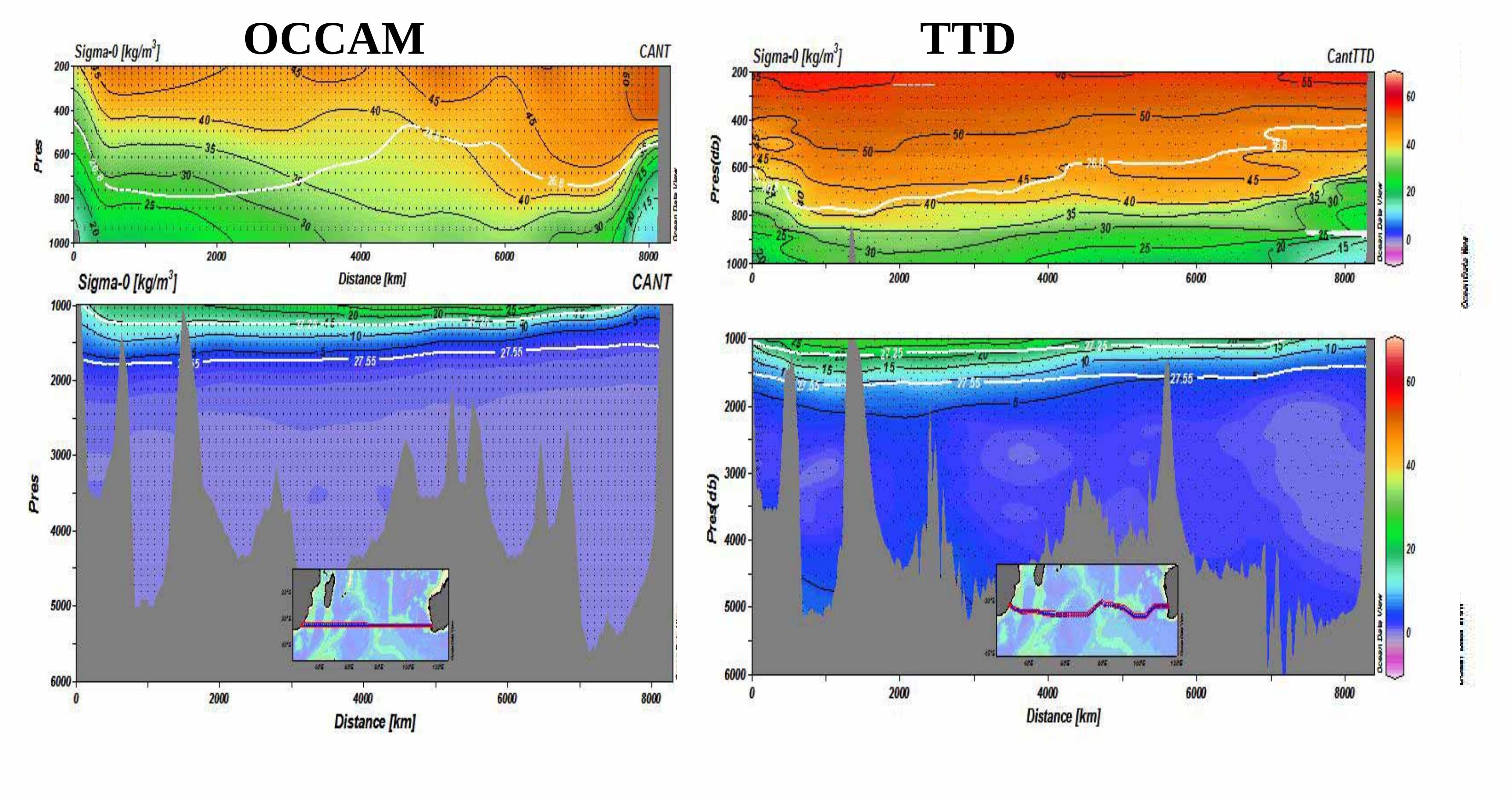
C_{ANT} vertical distributions



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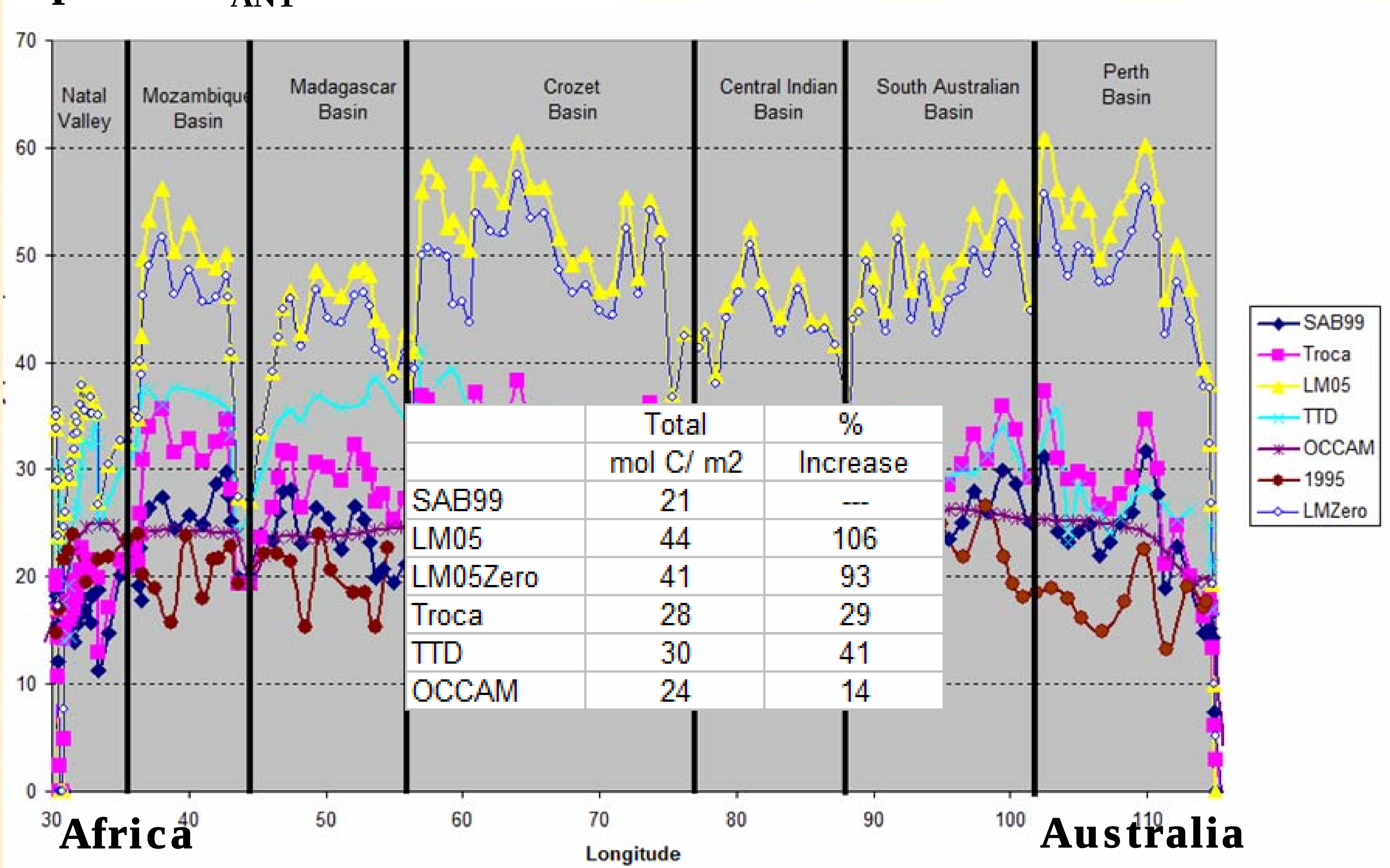
Specific C_{ANT} inventories



	Total mol C/ m2	% Increase
SAB99	21	---
LM05	44	106
LM05Zero	41	93
Troca	28	29
TTD	30	41
OCCAM	24	14

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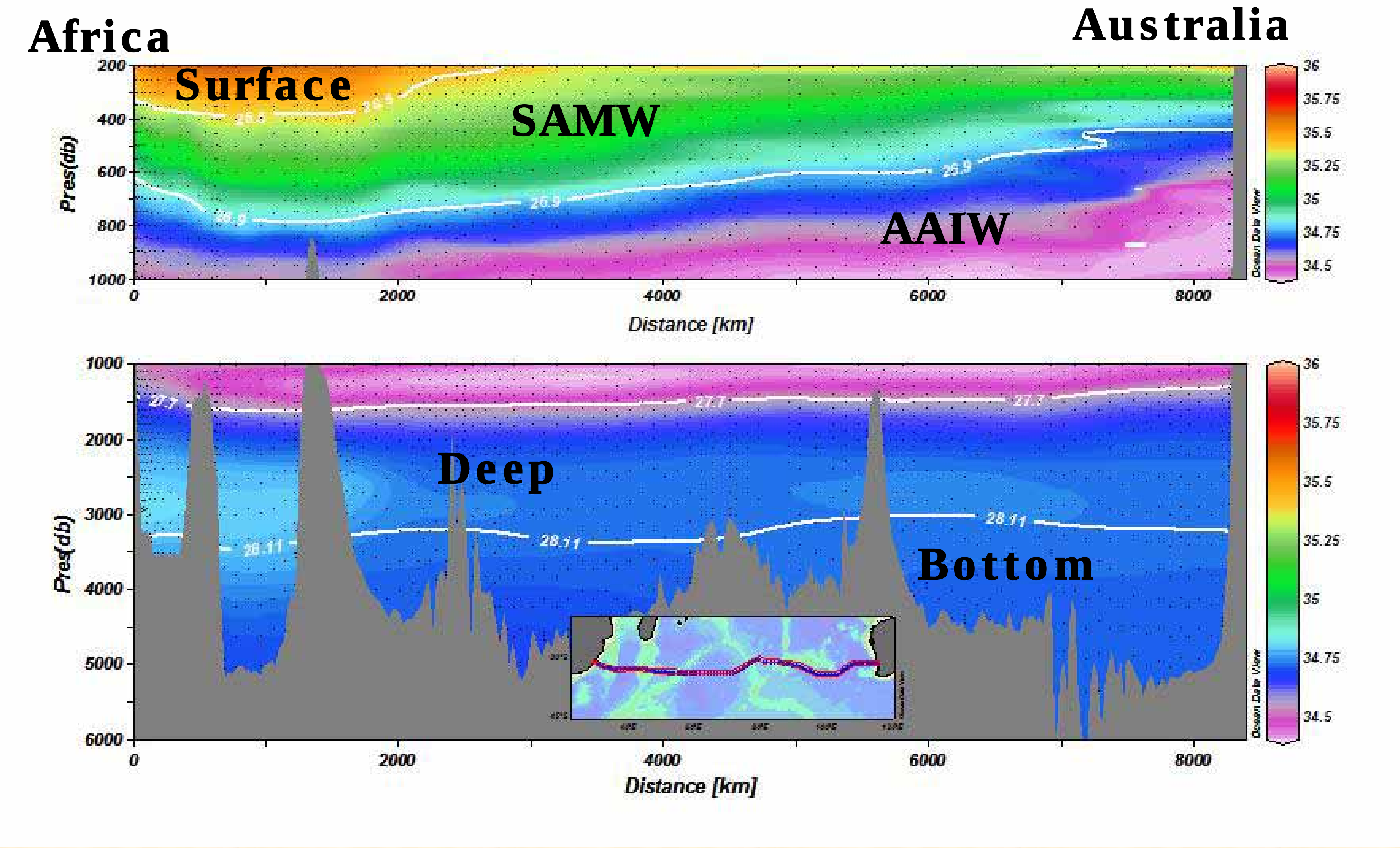
Neutral density layers & salinity



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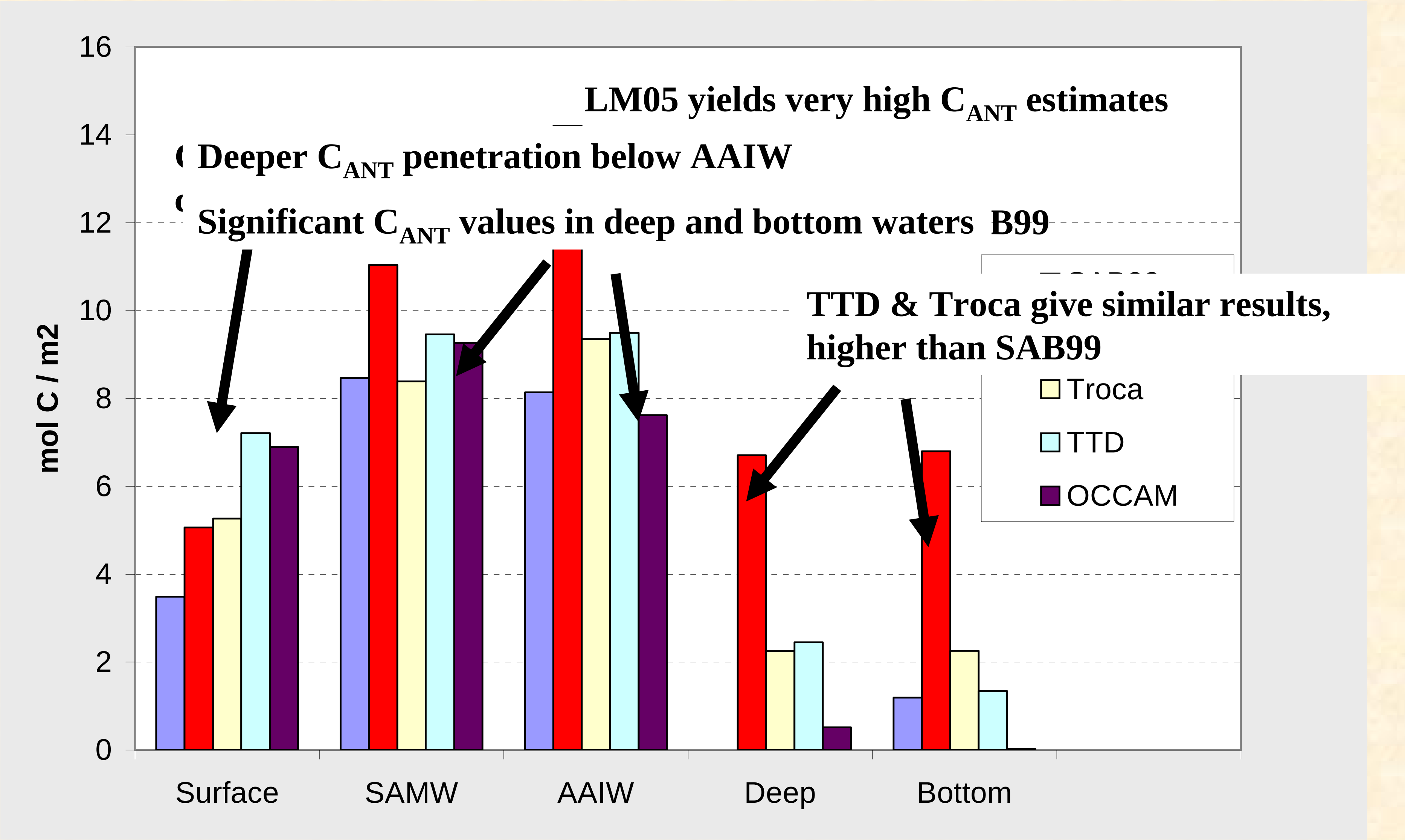
Specific C_{ANT} inventories



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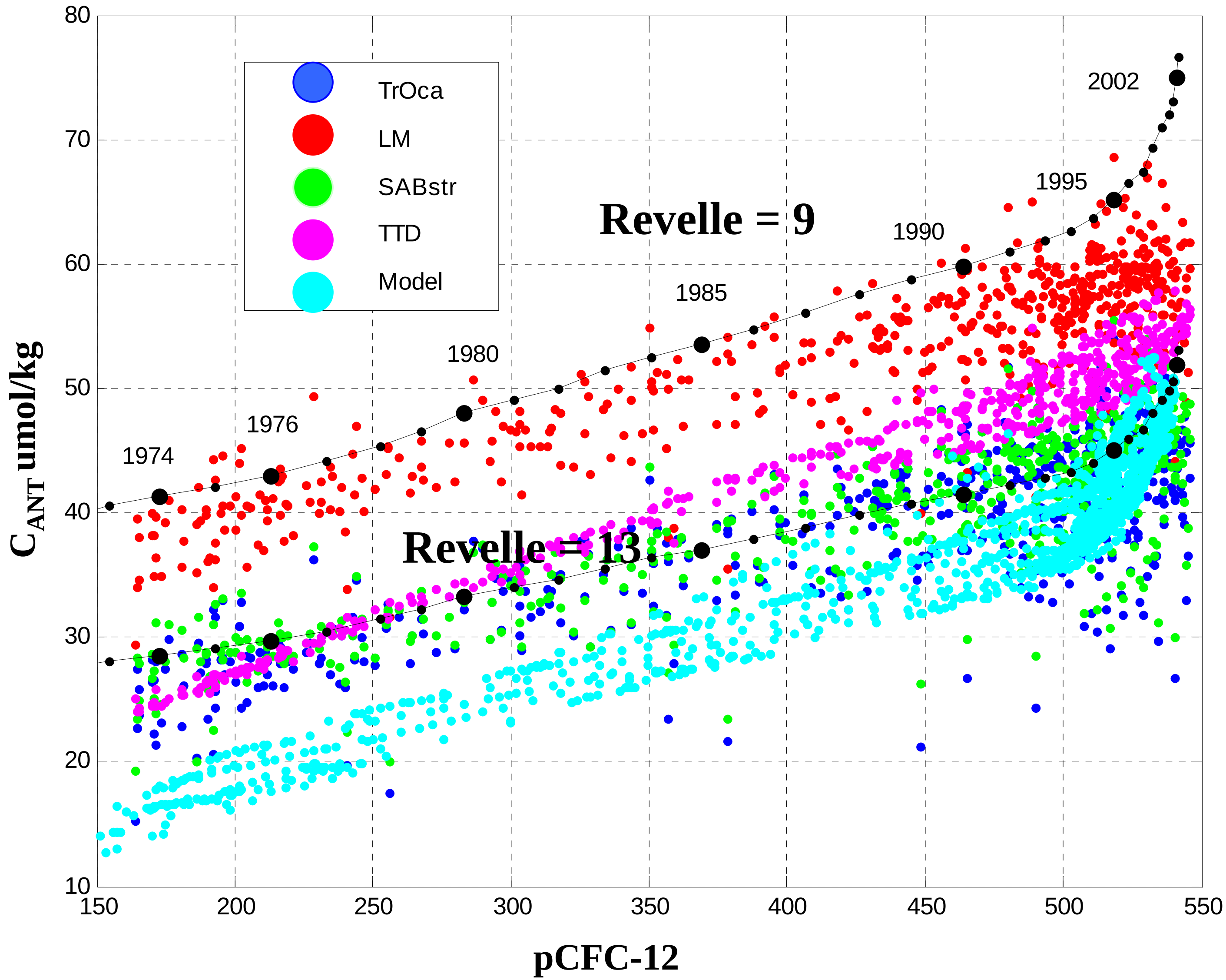
Surface, SAMW waters and upper AAIW



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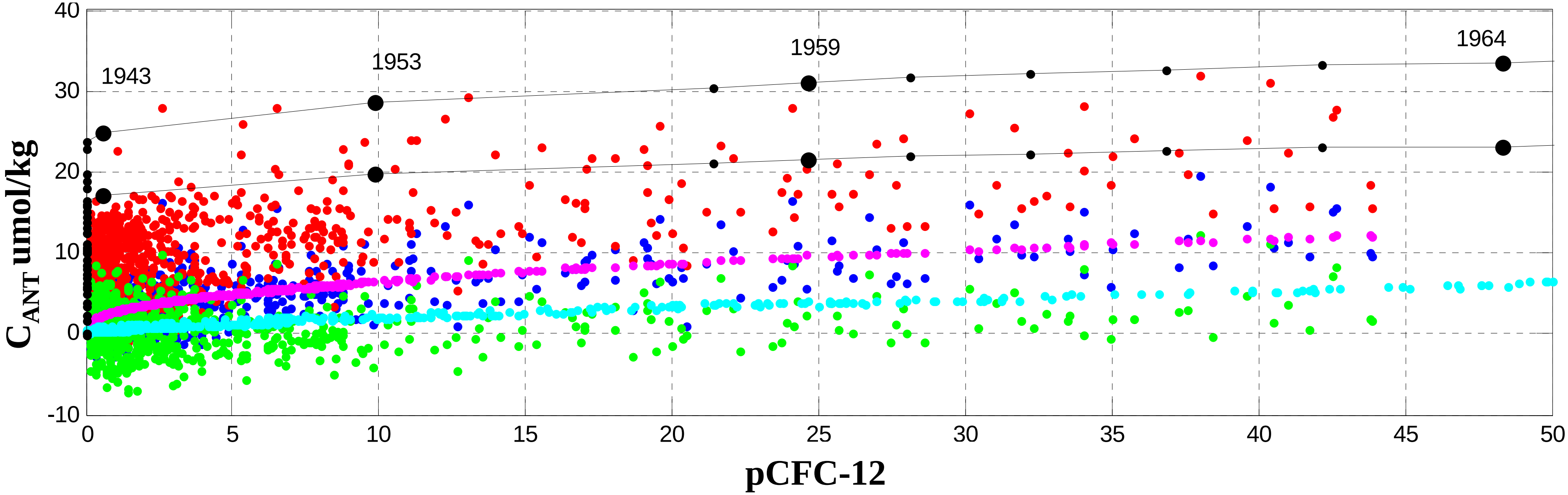
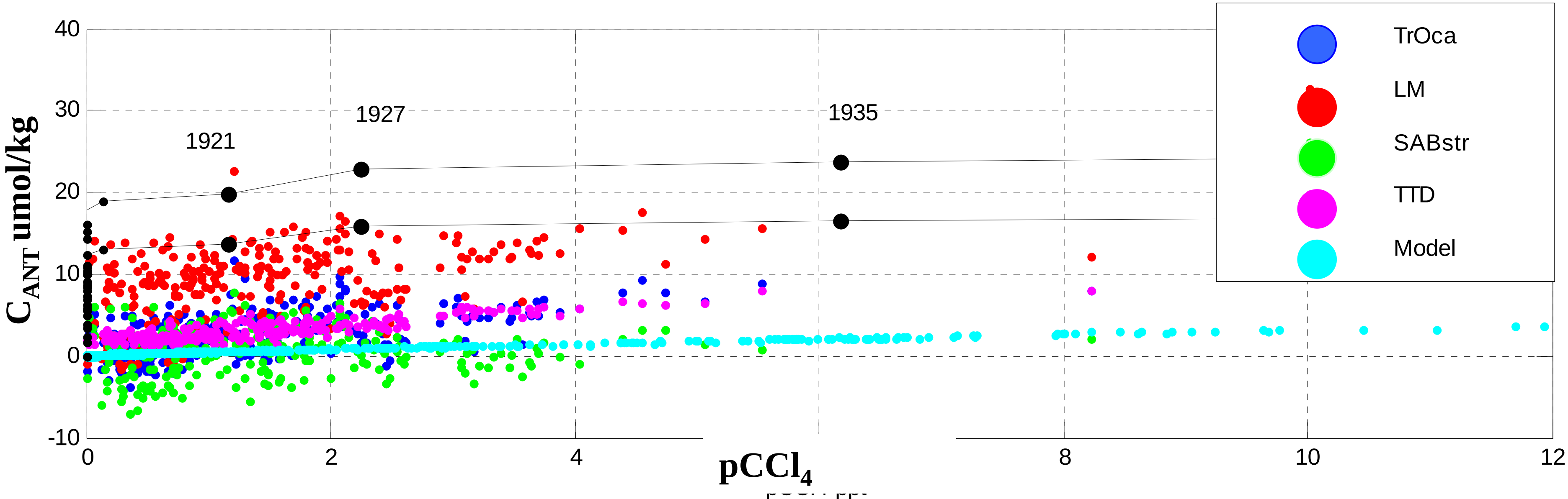
Deep and bottom waters





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Summary table

Reliability code (subjective)

1- plus

2- medium

3- low

	Upper	SAMW	AAIW	Deep	Bottom	**Mean**
SAB99	3	2	3	3	3	**low**
LM05	3	2	2	3	3	**medium-**
TrOCA	3	2	2	2	2	**medium+**
TTD	2	1	2	3	3	**medium+**
OCCAM	1	2	2	3	3	**medium**

C_{ANT} ALONG CD139 CRUISE (2002) 32ºS INDIAN OCEAN

Hypothesis:

C_{ANT} penetrates deeper than 1000 m (Sabine et al 1999)

seems to be hinted by any other method

How to assess this question:

difficult: every method has uncertainties

absolutely true, no method is perfect

help: relation of C_{ANT} with tracers (CFC_{12}, CCl_4)

questions still arise, saturation, mixing, etc..

community should combine methods and time-evolution studies at specially sensitive regions

OPEN DISCUSSION: KEY REGION ….. THE SO

C_{ANT} ALONG CD139 CRUISE (2002) 32ºS INDIAN OCEAN

Back-calculation technique by Sabine et al. (GBC, 1999) to estimate C_{ANT}.

$$C_{ANT} = \frac{\Delta C^*}{C - AOU/R_C - \frac{1}{2}(\Delta TA + AOU/R_N) + 106/104 \cdot N^* - C^{280}} - \Delta C_{Dis} = C - AOU/R_C - \frac{1}{2}(\Delta TA + AOU/R_N) + 106/104 \cdot N^* - C^{280} - \Delta C_{Dis}$$

- C is the current total inorganic carbon
- Δ TA = TA - TA^0, current alkalinity - preformed alkalinity

  $TA^0 = 378.1 + 55.22 \cdot Sal + 0.0716 \cdot PO - 1.236 \cdot Tpot$
- AOU is the Apparent Oxygen Utilization, assuming oxygen saturation
- C^{280} is the inorganic carbon in equilibrium with the preindustrial atmosphere.

  C^{280} = f (Tpot, Sal, TA^0, pCO_{2280}) from thermodynamic equations

  pCO_{2280} = CO_2 fugacity at a 100% of water vapor pressure in uatm = f(Tpot, Sal, 280)

  C^{280} in GSS96 => constants by Goyet & Poisson (1989) & a constant pCO_{2280} = 280 uatm

  linearilized equation:

  $C^{280} = 2072 - 8.982 \cdot (Tpot - 9) - 4.931 \cdot (Sal - 35) + 0.842 \cdot (TA^0 - 2320)$
- $N^* = (0.87 \cdot (NO_3 - 16 \cdot PO_4 + 2.9))$ term accounting for the denitrification

C_{ANT} ALONG CD139 CRUISE (2002) 32ºS INDIAN OCEAN

ΔC_{Dis} is obtained with own CD139 data using CFC_{12} ages and limit at 40 years

a) Old deep waters, $C_{ANT} = 0 \Rightarrow \Delta C^* = \Delta C_{Dis}$

b) In upper waters, having the age: $\Delta C_{Dis} = \Delta C^*t|_{\sigma=cte}$

$\Delta C^*_t = C - C_{Bio} - C_t$ where $C_t = f(Tpot, Sal, TA^0, pCO_{2t})$

pCO_2 in the atmosphere at 2002 – age (t)

c) In between => weigthed mean ΔC^* and $\Delta C^*t|_{\sigma=cte}$

ΔC_{Dis} is obtained with own CD139 data using CFC_{12} and CCl_4 ages

a) Tpot<3ºC, (assumed 100% saturation) deep waters, $\Delta C_{Dis} = \Delta C^*t_{CCl4}|_{\sigma=cte}$

$\Delta C^*_t = C - C_{Bio} - C_t$ where $C_t = f(Tpot, Sal, TA^0, pCO_{2tCCl4})$

pCO_2 in the atmosphere at 2002 – age CCl4(t)

b) In upper waters, having the CFC age: $\Delta C_{Dis} = \Delta C^*t_{CFC12}|_{\sigma=cte}$

$\Delta C^*_t = C - C_{Bio} - C_t$ where $C_t = f(Tpot, Sal, TA^0, pCO_{2t})$

pCO_2 in the atmosphere at 2002 – age CFC12 (t)

c) In between => weigthed mean a & b

C_{ANT} ALONG CD139 CRUISE (2002) 32ºS INDIAN OCEAN

Back-calculation technique by Lo Monaco et al. (JGR, 2005):

$$C_{ANT} = C_T - C_{Bio} - C_T^{0\,obs} - (C_T - C^{Bio} - C^{0\,obs})_{REF}$$

C_T = measured TIC

$C_{Bio} = 0.73 \cdot (O_2^0 - O_2) + 0.5 \cdot (TA - TA^0)$ => biological activity variation in TIC

TA^0 => preformed TA

$O_2^0 = O_2^{sat} - \alpha \cdot K \cdot O_2^{Sat}$ => αO_2 = 12% undersaturation

K = > mixing ratio of ice-covered water (OMP)

$C_{0\,obs}$ => preformed TIC

currently observed in the formation area water masses

REF = reference water where no C_{ANT} should be detected.

C_{ANT} ALONG CD139 CRUISE (2002) 32ºS INDIAN OCEAN

Back-calculation technique by Lo Monaco et al. (JGR, 2005)

$$TA^0 = k(S)\, TA^0(S) + k(N)\, TA^0(NADW)$$

$$C^{0,obs} = k(S)\, C^{0,obs}(S) + k(N)\, C^{0,obs}(NADW)$$

southern relationships:

winter surface data from the Atlantic and Indian oceans (WOCE and OISO cruises)

$TA^0(S) = 0.0685\ PO + 59.787\ S - 1.448\ \theta + 217.15$ (± 5.5 µmol/kg, $r^2 = 0.96$, n = 243)

$C^{0,obs}(S) = -0.0439\ PO + 42.79\ S - 12.019\ \theta + 739.83$ (± 6.3 µmol/kg, $r^2 = 0.99$, n = 428)

northern relationships

subsurface data from the North Atlantic and Nordic Seas (WOCE and KNORR cruises)

$TA^0(N) = 42.711\ S + 1.265\ \theta + 804.6$ (± 9.3 µmol/kg, $r^2 = 0.92$, n = 297)

$C^{0,obs}(N) = 10.69\ S + 0.306\ NO + 1631.6$ (± 9.2 µmol/kg, $r^2 = 0.79$, n = 364)

mixing ratios of southern and northern waters:

k(S) + k(NADW) = 1 determined from OMP analysis

C_{ANT} ALONG CD139 CRUISE (2002) 32ºS INDIAN OCEAN

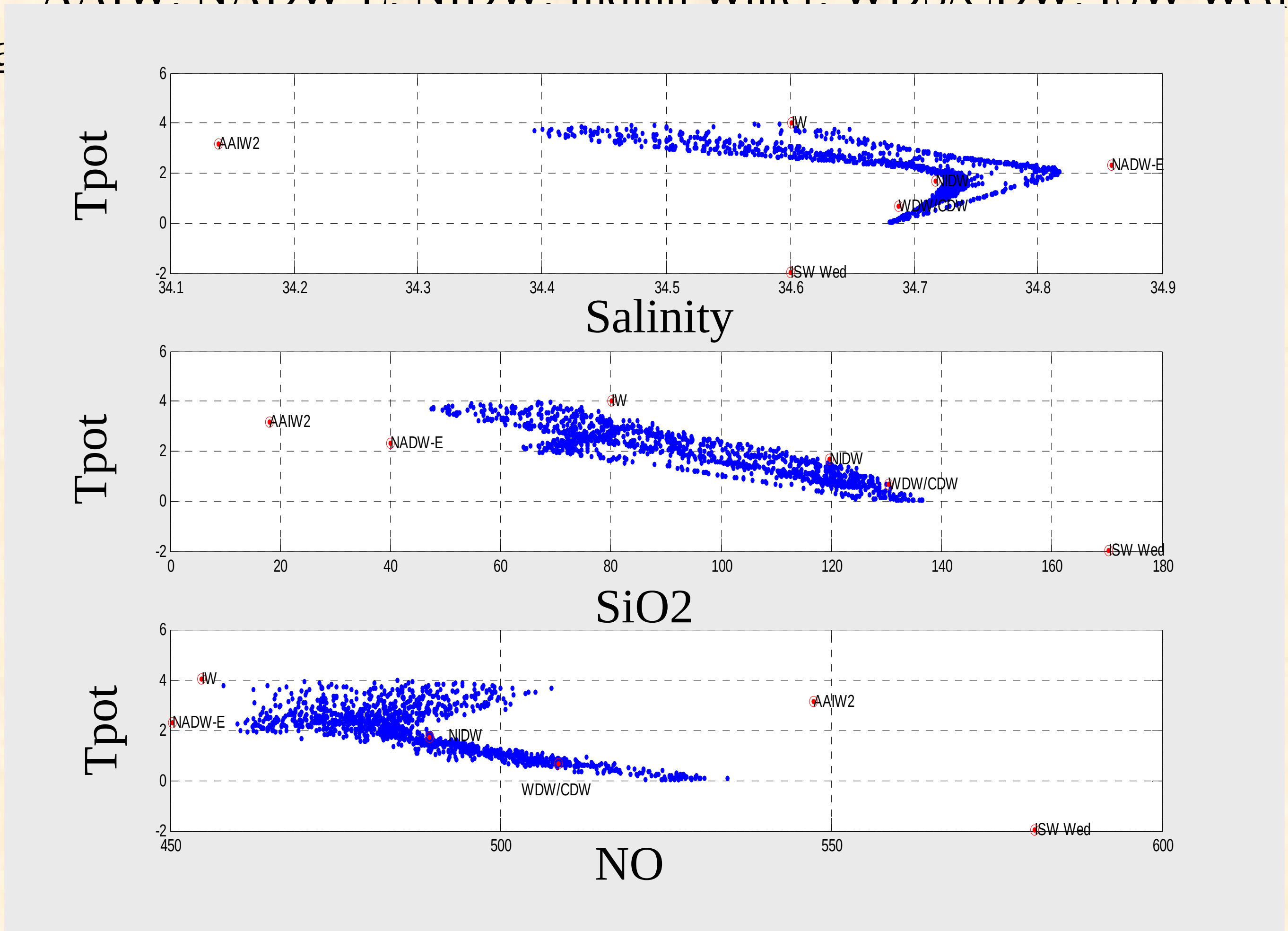
Back-calculation technique by Lo Monaco et al. (JGR, 2005):

OMP analysis modified from Lo Monaco et al. (JGR, 2005)

<u>Endmembers</u>:

AAIW, NADW-E, NIDW, Indian Water, WDS/CDW, ISW Weddell

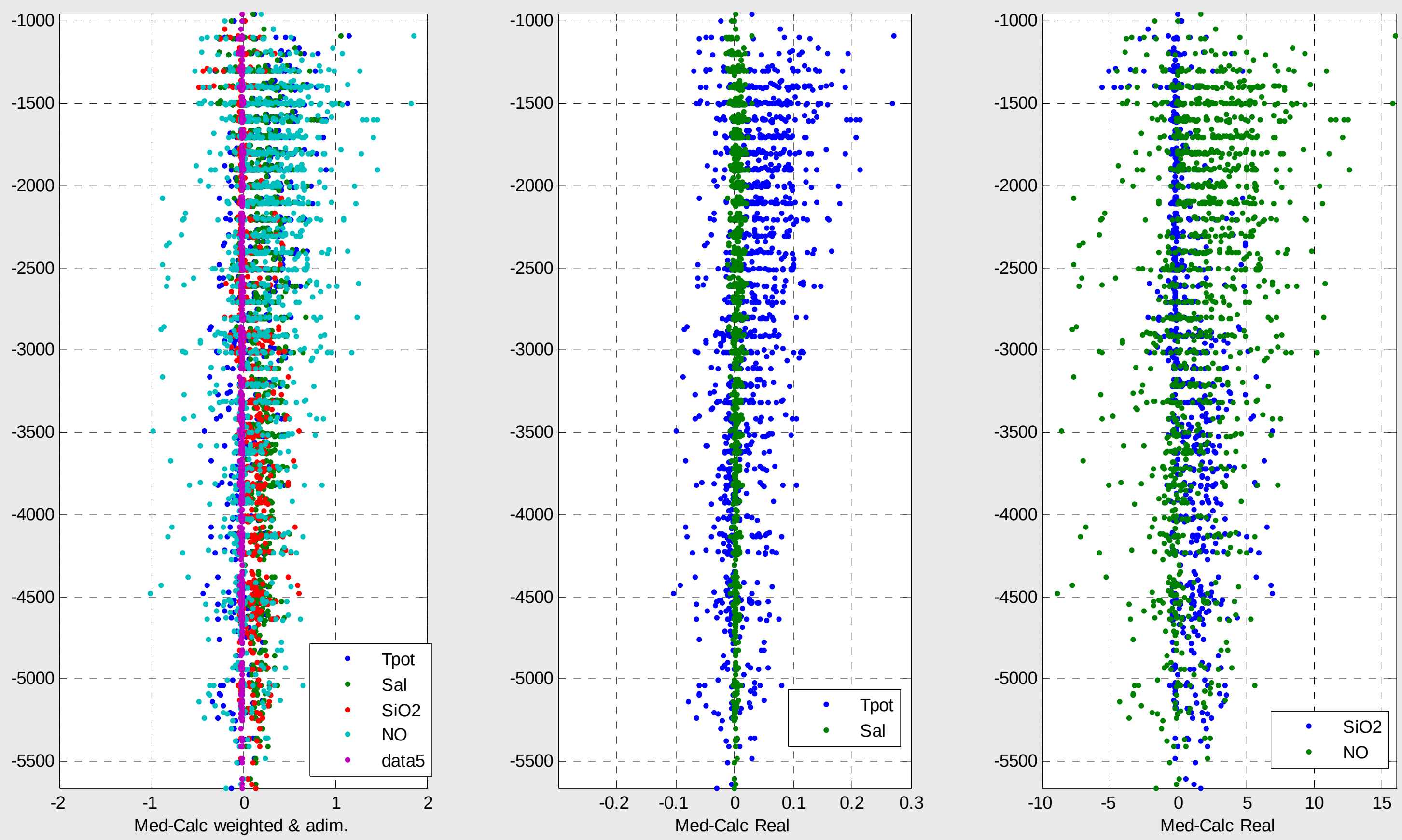
<u>Varia</u>



C_{ANT} ALONG CD139 CRUISE (2002) 32ºS INDIAN OCEAN

Back-calculation technique by Lo Monaco et al. (JGR, 2005): OMP

	Tpot,	Sal,	SiO_2	NO	
STD Res.	0.0481	0.0051	1.3	3	
R^2	0.9979	0.9967	0.9973	0.9611	(n=1299)



C_{ANT} ALONG CD139 CRUISE (2002) 32ºS INDIAN OCEAN

Back-calculation technique by Lo Monaco et al. (JGR, 2005):

$$C_{ANT} = C_T - C_{Bio} - C_T^{0\,obs} - (C_T - C^{Bio} - C^{0\,obs})_{REF}$$

REF = NADW= reference water where no C_{ANT} should be detected.

Applied to samples with more 50% NADW from OMP analysis

$(C_T - C^{Bio} - C^{0\,obs})_{REF} = -\,54.4 \pm 1.4$ umol/kg

(LoMonaco JGR2005 -51 umol/kg)

$$C_{ANT} = C_T - C_{Bio} - C_T^{0\,obs} - (-\,54.4)$$

C_{ANT} ALONG CD139 CRUISE (2002) 32ºS INDIAN OCEAN

C_{ANT} TrOCA, Touratier et al (Tellus B, 2007):

$TrOCA = O_2 + a \cdot (C_T - 1/2 \cdot TA)$ $\quad$ $a = \psi_{O2} / [\psi_{CO2} + ½ \cdot (\psi_{H+} - \psi_{HPO24-})]$

$C_{ANT}\,(TrOCA) = (TrOCA - TrOCA_{280}) / a$

$$\mathbf{C_{ANT} = (O_2 + 1.279 \cdot (C_T - 0.5 \cdot TA) - \exp(7.511 - 0.01087 \cdot \theta - 781000/TA^2))/1.279}$$

C_{ANT} ALONG CD139 CRUISE (2002) 32ºS INDIAN OCEAN

4. C_{ANT} TTD (Waugh et al., 2004; 2006; Tanhua et al., 2008):

- each water sample has its own “age”, i.e. time since it was last in contact with the atmosphere. The sum of all these ages makes the TTD of a water sample

- the mean age (Γ) and the width of the TTD (Δ) are assumed to be of equal magnitude: realistic assumption of the relation between advective and diffusive transport in the Ocean

- C_{ANT} is an inert passive tracer where air-sea disequilibrium hasn’t changed over time.

C_{ANT} ALONG CD139 CRUISE (2002) 32ºS INDIAN OCEAN

5. C_{ANT} OCCAM

- global, medium-resolution, primitive equation ocean general circulation model (Marsh et al., 2005).

- OCCAM's vertical resolution is 66 levels (5 m thickness at the surface, 200 m at depth), with a horizontal resolution of typically 1 degree.

- Advection is 4th order accurate, and the model is time-integrated using a forward leapfrog scheme with a 1 hour time-step.

- Surface fluxes of heat and freshwater not specified but are calculated empirically using NCEP-derived atmospheric boundary quantities (Large and Yeager, 2004).

- OCCAM incorporates a NPZD plankton ecosystem (Oschlies, 2001; Yool et al., 2007) which drives the biogeochemical cycles of nitrogen, carbon, oxygen and alkalinity.