

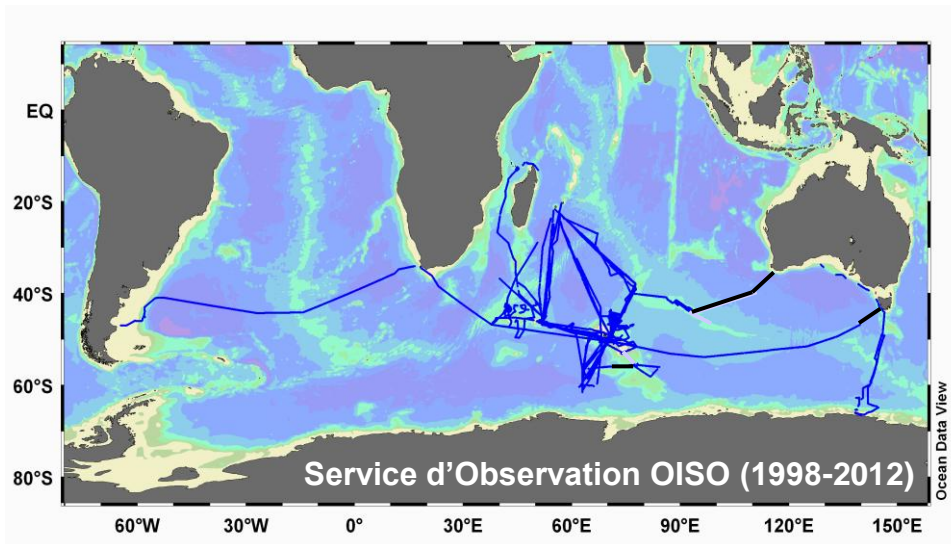


SOUTHERN OCEAN AND CLIMATE  
FIELD STUDIES WITH INNOVATIVE TOOLS

# Variabilité du CO<sub>2</sub> océanique autour de Kerguelen : résultats du S.O. OISO + KEOPS

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## Global Carbon Budget 2014

Anthropogenic CO<sub>2</sub> emissions  
Fossil fuel + Land-se change

**+9.8 GtC/yr**

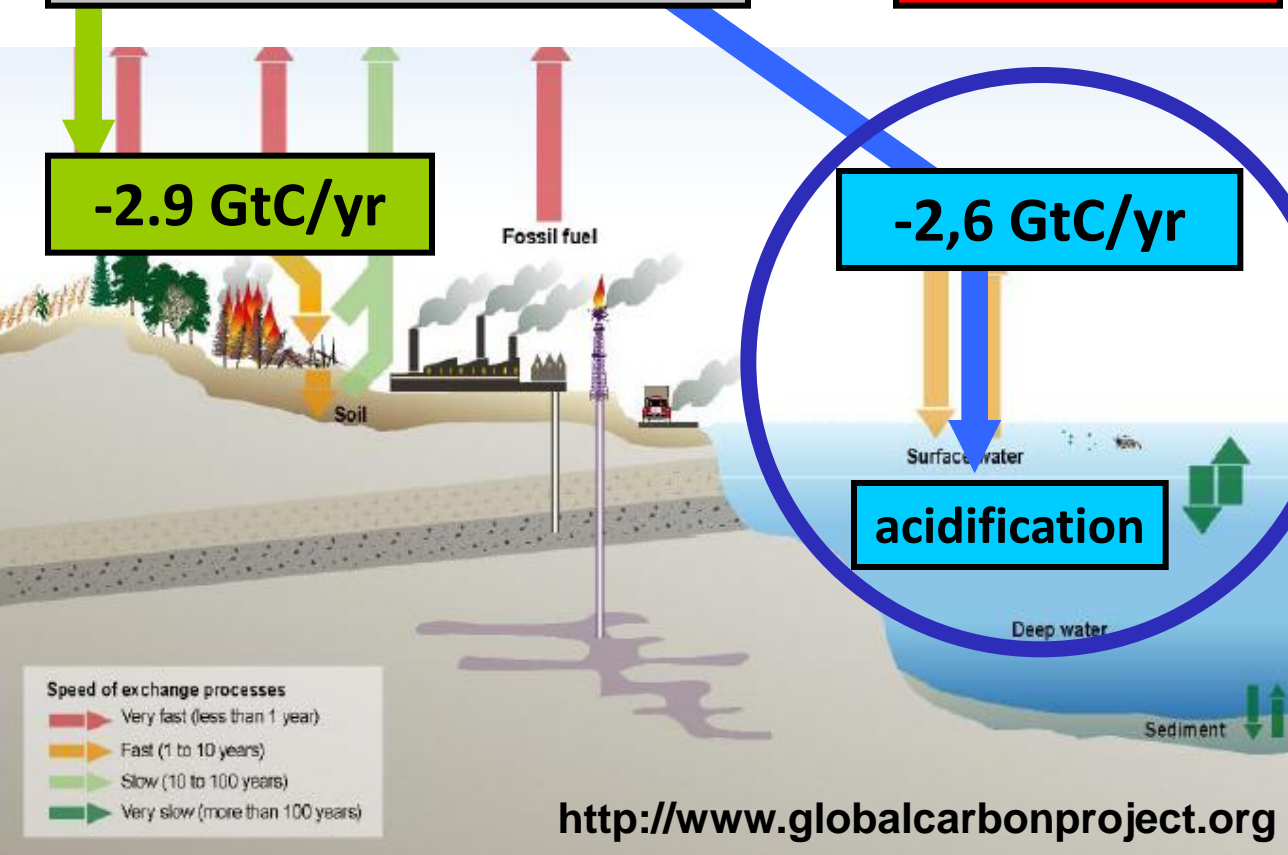
Increase in  
atmospheric CO<sub>2</sub>

**+4.3 GtC/yr**

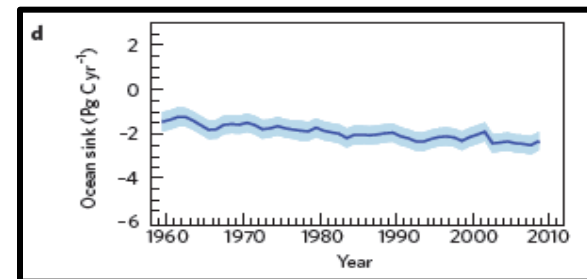
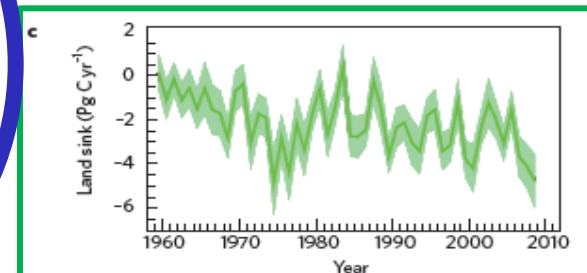
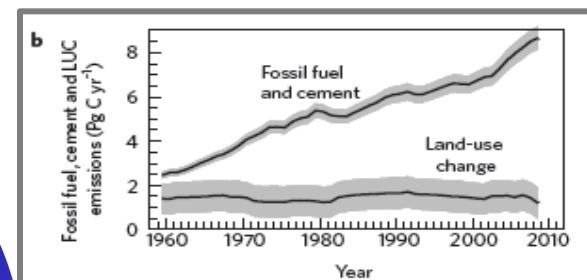
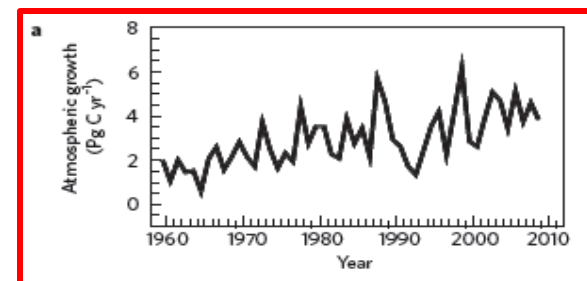
**-2.9 GtC/yr**

**-2,6 GtC/yr**

**acidification**



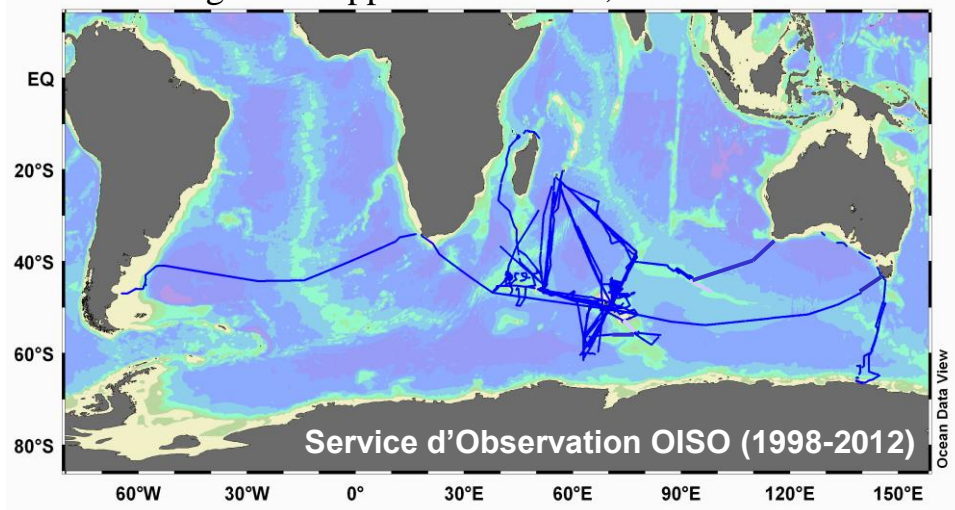
<http://www.globalcarbonproject.org>



## CO<sub>2</sub> observations in the South-West Indian Ocean since 1998

OISO: Océan Indien Service d'Observation

Long-term support from INSU, IPEV and IPSL



Repeated observations, 1 or 2 cruises per year since 1998 (mostly summer, but not only)

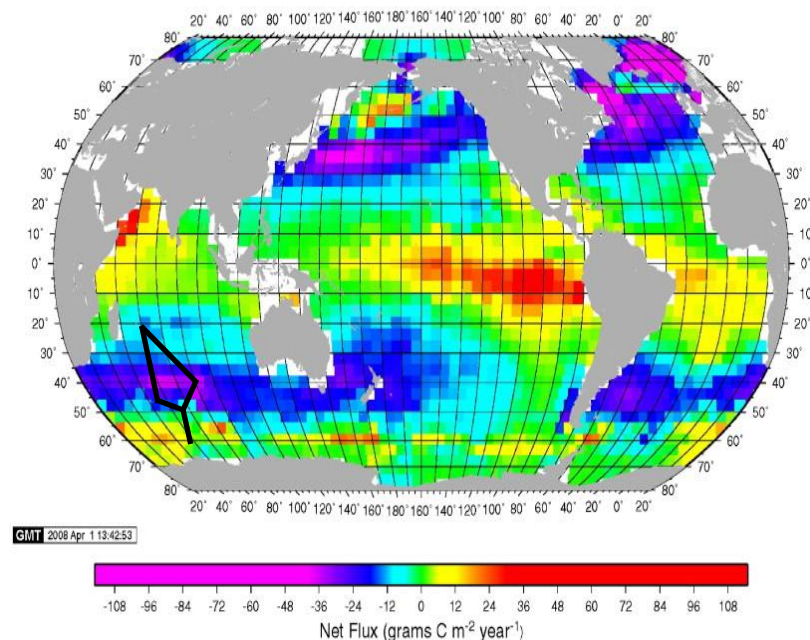
Following INDIGO (1985-87) and MINERVE (1990's)

Objectives : To **monitor** and **understand** the evolution of the oceanic CO<sub>2</sub> system (**mechanisms**)

- Air-sea CO<sub>2</sub> fluxes (temperature effect, photosynthesis, ocean dynamics)
- Storage of anthropogenic CO<sub>2</sub> (impact of climate change)
- Ocean acidification (anthropogenic CO<sub>2</sub> and climate change)

Air-sea CO<sub>2</sub> fluxes (year 2000)

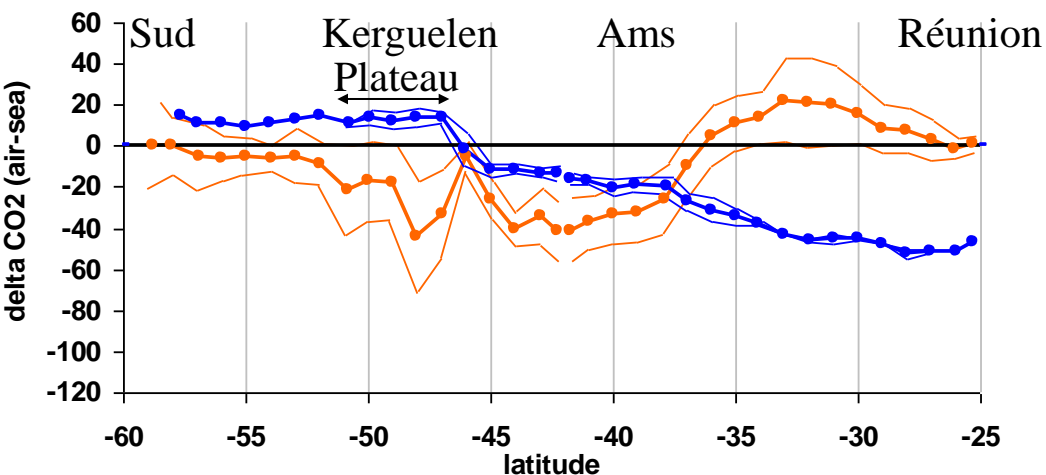
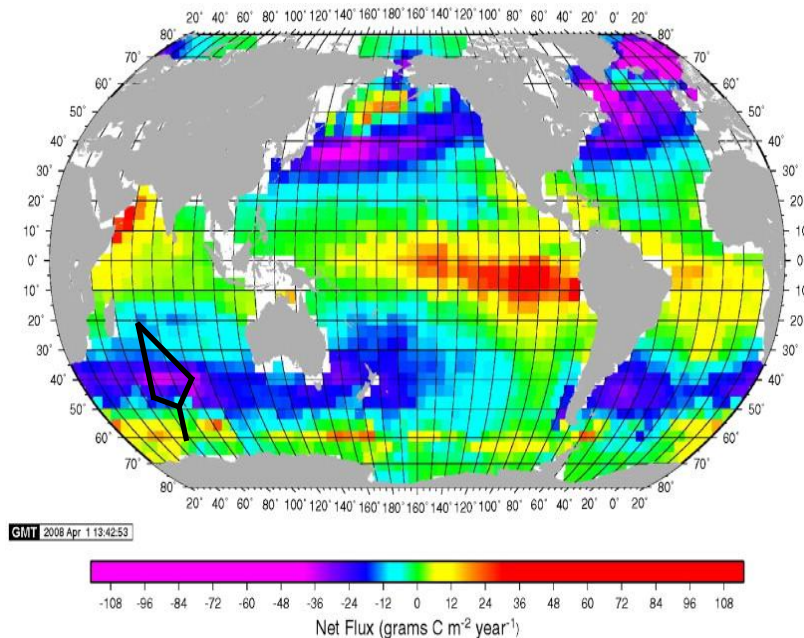
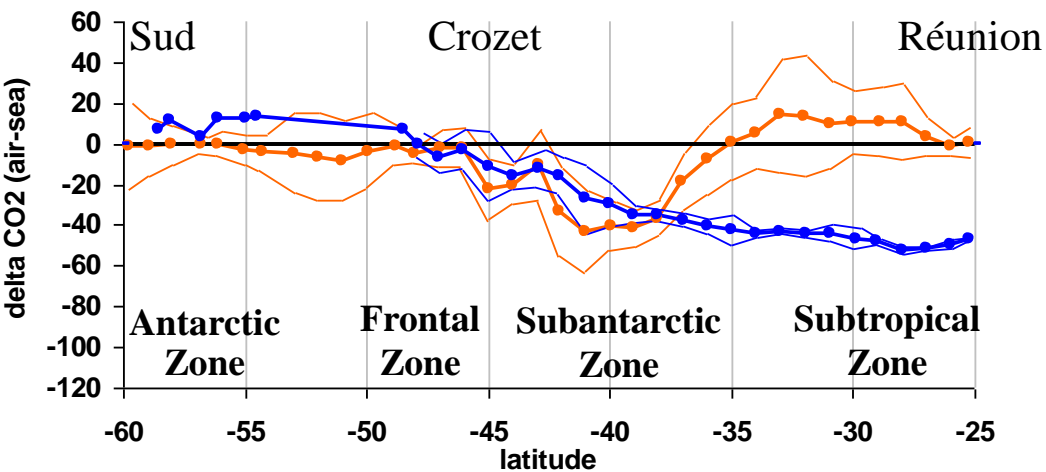
Takahashi et al., 2009



## CO<sub>2</sub> observations in the South-West Indian Ocean since 1998

Summer and winter mean  $\Delta p\text{CO}_2$  observed in the South Indian Ocean (1998-2012)

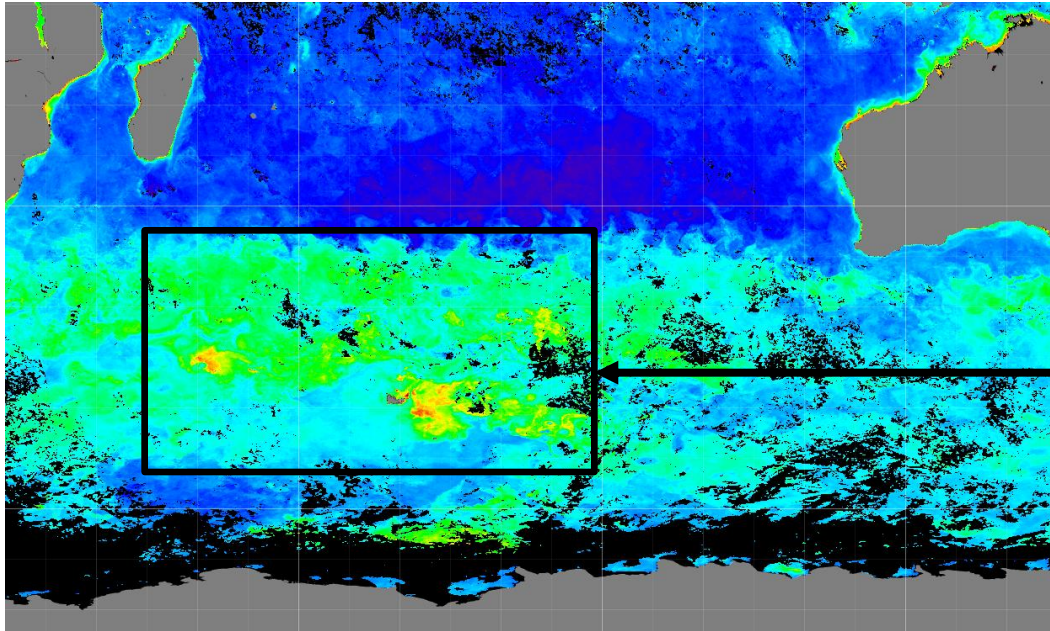
Air-sea CO<sub>2</sub> fluxes (year 2000)  
Takahashi et al., 2009



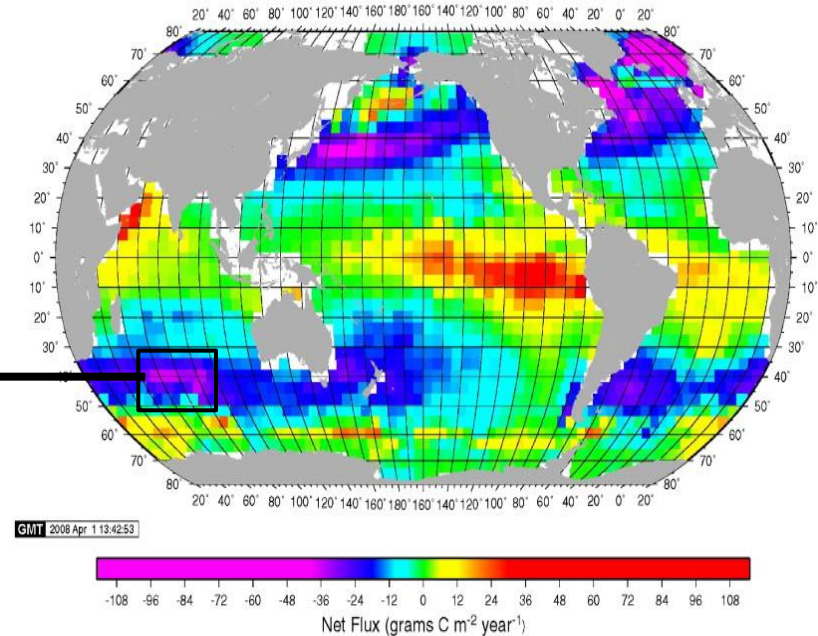
Large CO<sub>2</sub> sink between 40 S and 50 S  
 → Subantarctic zone is always a sink  
 → Island mass effect

## CO<sub>2</sub> observations in the South-West Indian Ocean since 1998

Chlorophyll-a concentration in Nov. 2011 (MODIS)



Air-sea CO<sub>2</sub> fluxes (year 2000)  
Takahashi et al., 2009

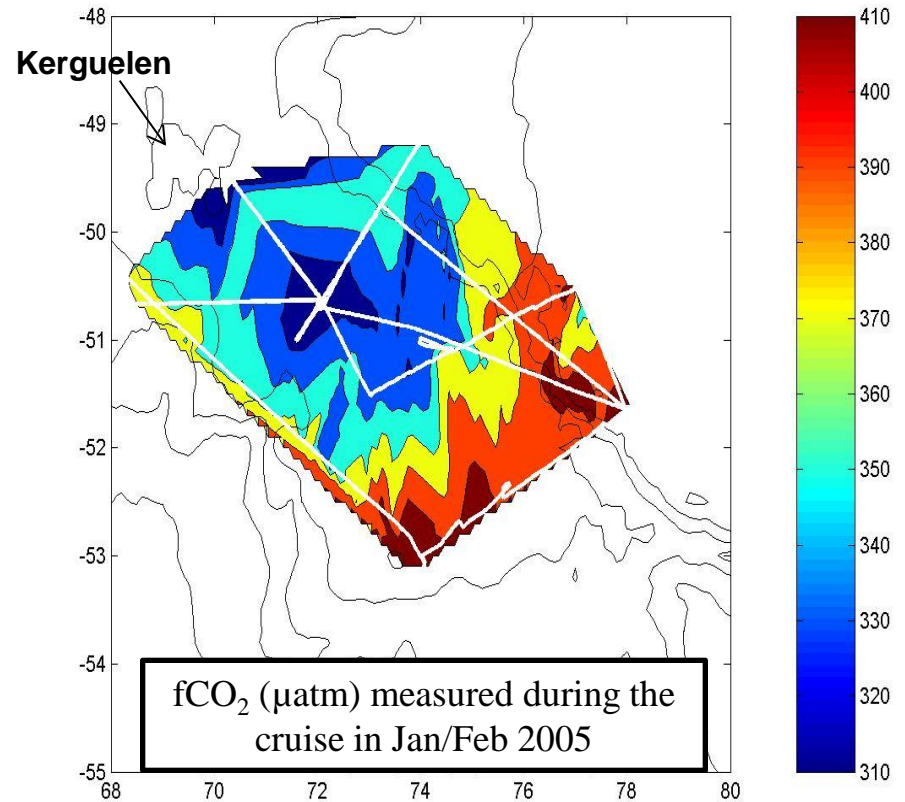
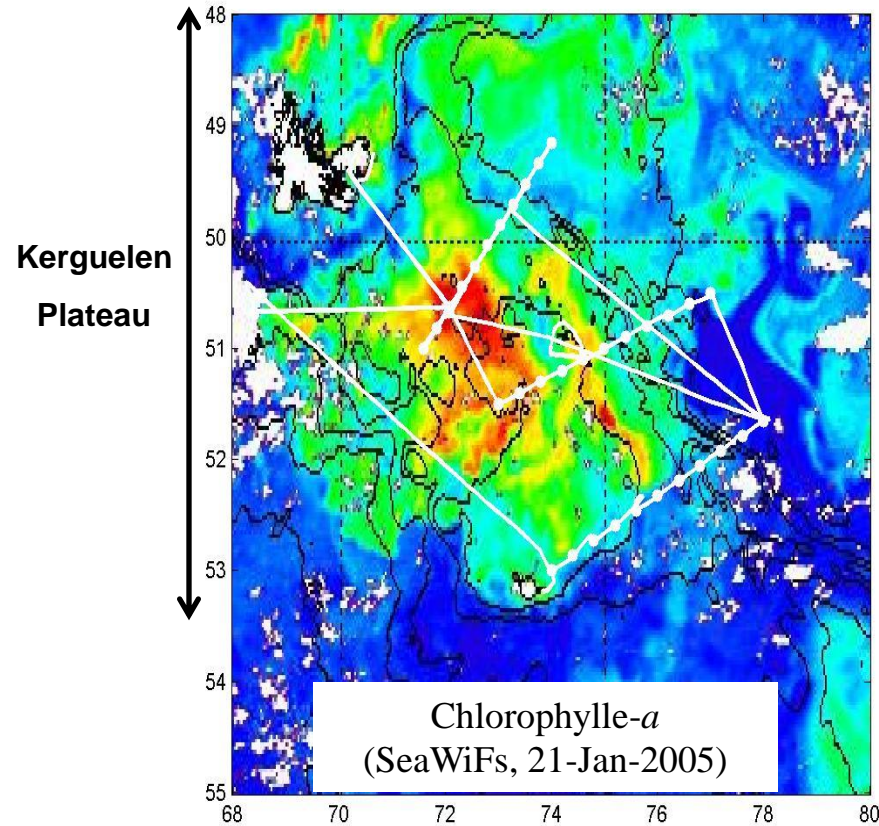


Kerguelen bloom south of the Polar Front (usually HNLC)  
→ iron fertilization from the Plateau (Blain et al., 2007)

Large CO<sub>2</sub> sink between 40° S and 50° S  
→ Subantarctic zone is always a sink  
→ Island mass effect

## Observations above Kerguelen Plateau in Jan/Feb 2005

Chlorophyll and fCO<sub>2</sub> distribution



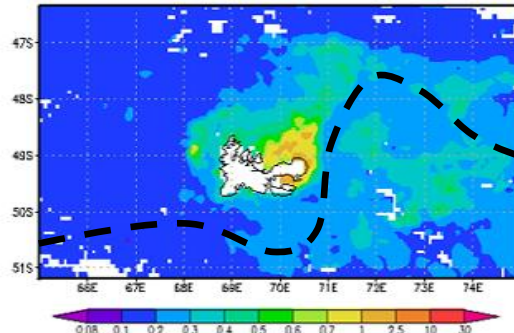
Biological uptake of CO<sub>2</sub> due to iron fertilization = 58±11 µatm  
(difference in and out of the bloom)

→ 2 to 3 times larger than the biological uptake estimated  
during iron fertilization experiments in the SO

Blain et al. (2007)

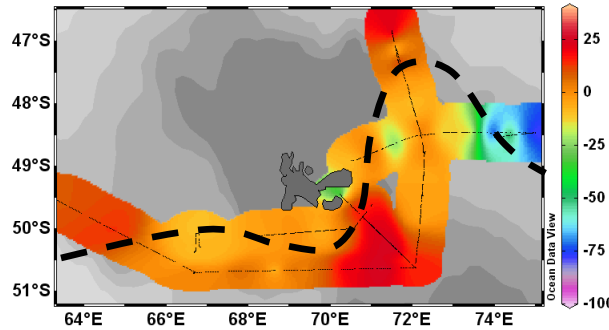
October (until Nov, 2)

Chl-a MODIS ( $\mu\text{g/l}$ )



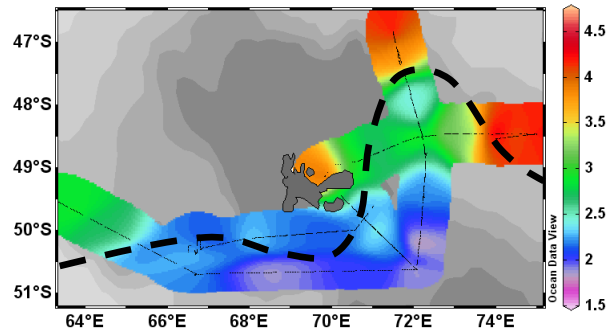
Low biological activity, except for coastal waters → light limitation

$\Delta\text{CO}_2$  ( $\mu\text{atm}$ ) =  $\text{CO}_2\text{sea} - \text{CO}_2\text{air}$



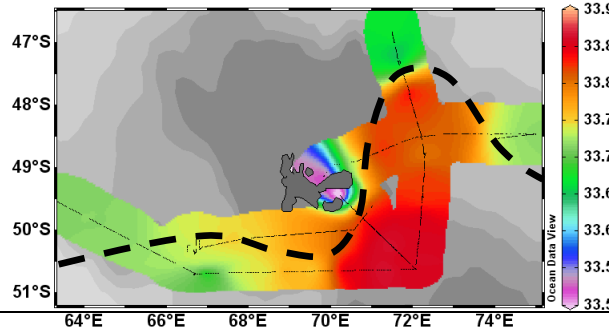
Near equilibrium with atmospheric  $\text{CO}_2$  south of the PF, except for waters above the Plateau ( $\text{CO}_2$  outgassing)

Sea Surface Temperature (C)



Large  $\text{CO}_2$  uptake observed north of the PF early in November (early stratification)

Sea Surface Salinity

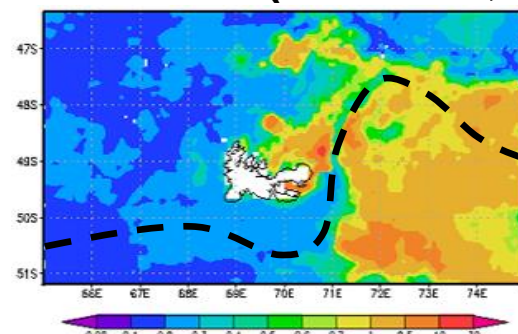
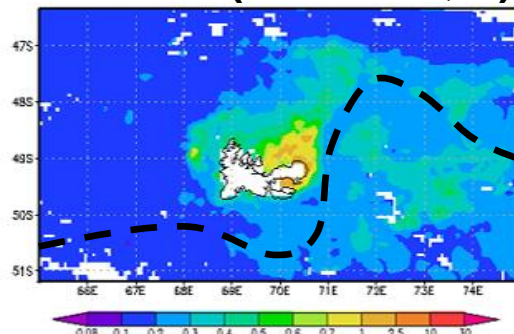


Lo Monaco et al. (in prep.)

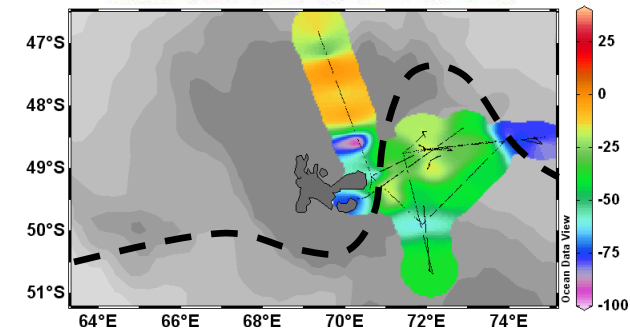
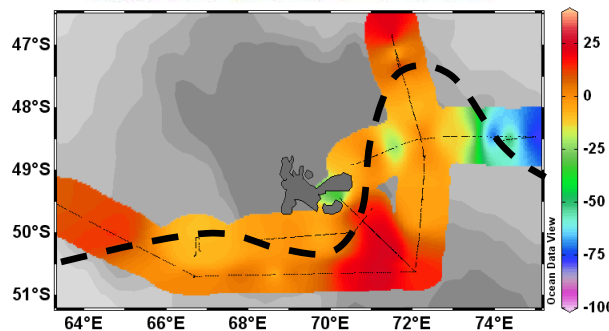
October (until Nov, 2)

November (from Nov,3)

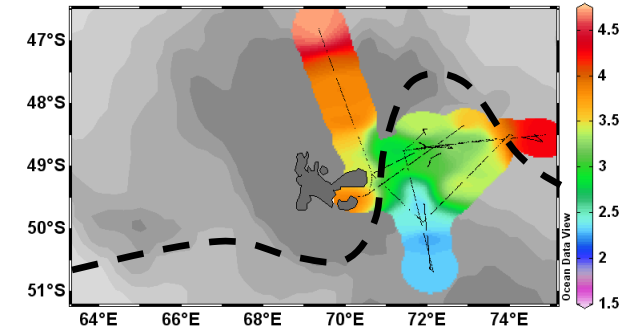
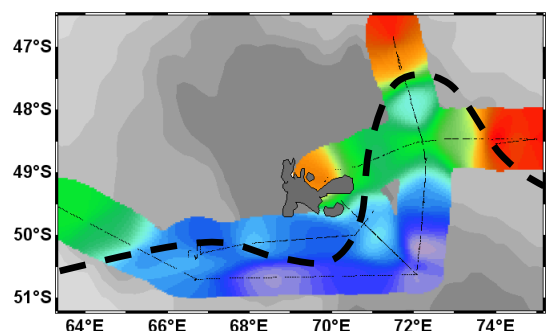
Chl-a MODIS ( $\mu\text{g/l}$ )



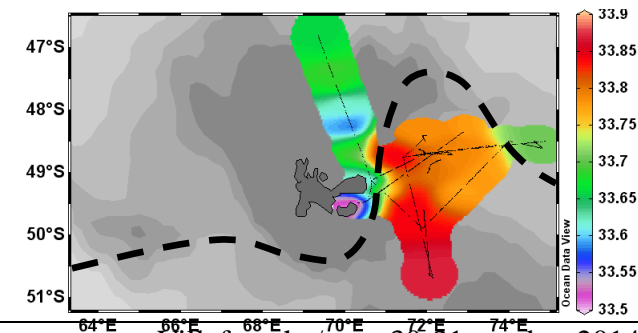
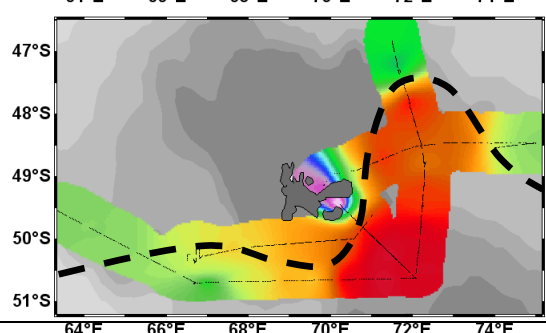
$\Delta\text{CO}_2$  ( $\mu\text{atm}$ ) =  
 $\text{CO}_2\text{sea} - \text{CO}_2\text{air}$



Sea Surface  
Temperature ( C)

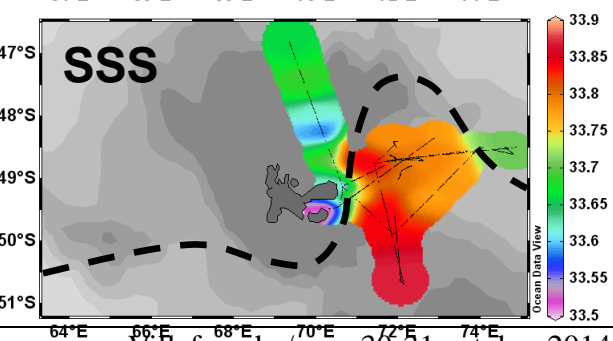
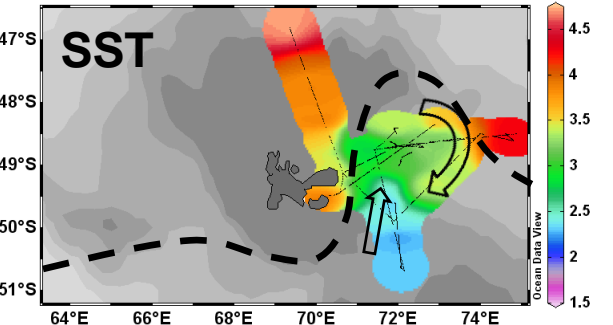
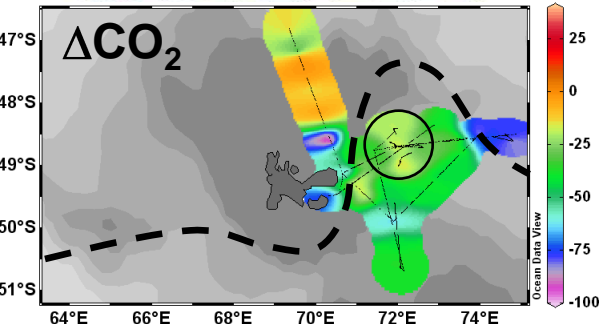
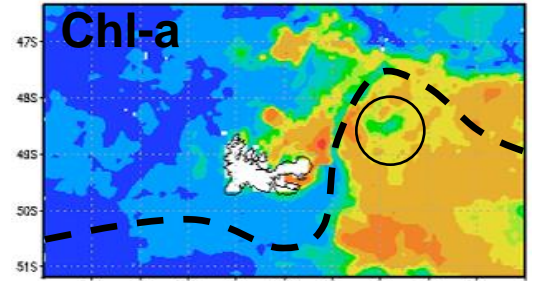
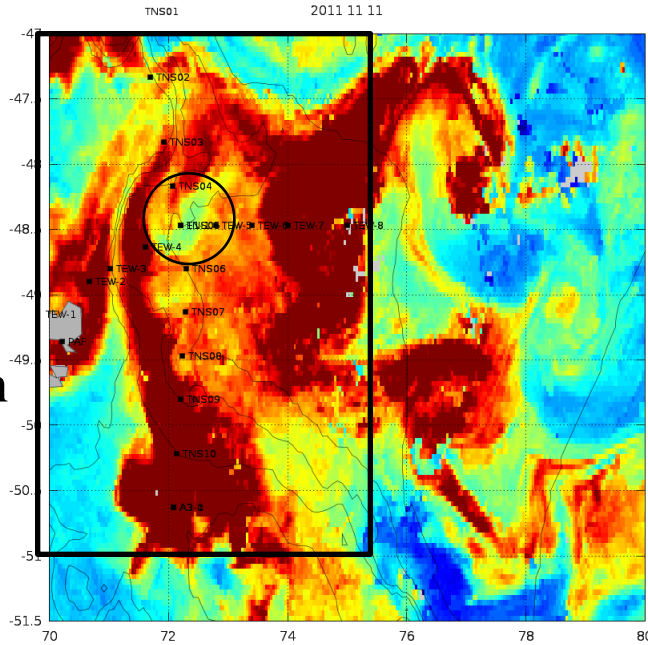


Sea Surface  
Salinity



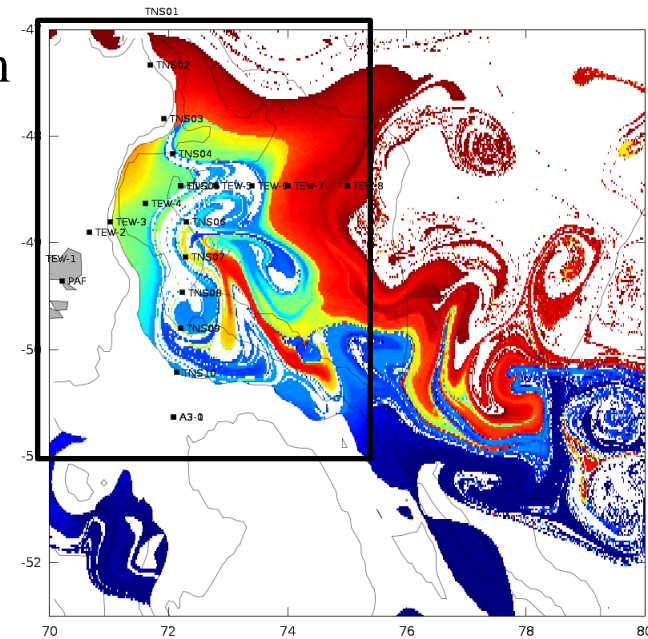
Chlorophyll-a  
satellite image  
(11/11/2011)

Low Chl-a  
concentrations in  
the cold part of  
the Middle zone



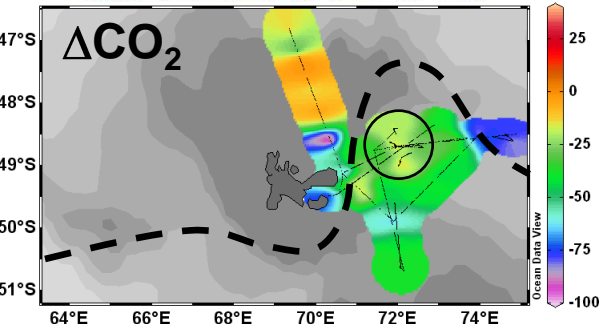
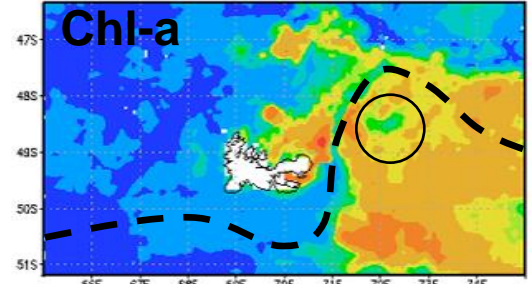
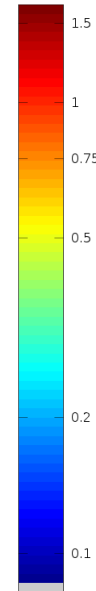
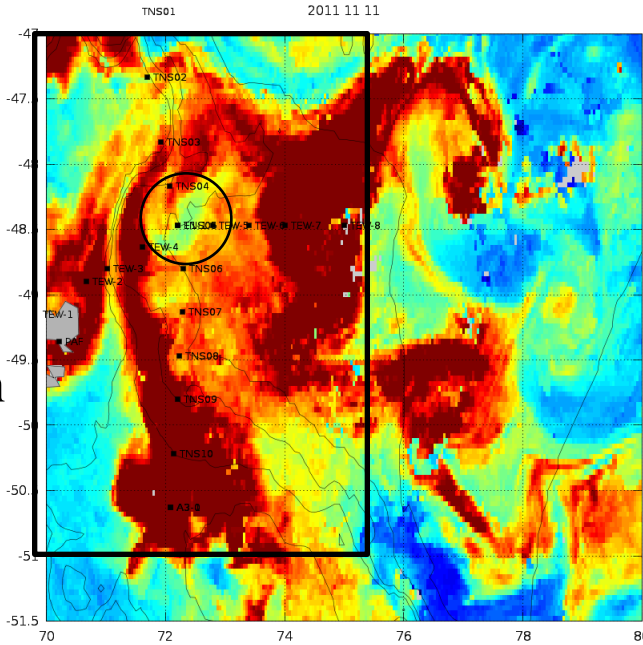
Diagnostics from  
satellite data  
(F. D'Ovidio)

Origin of the  
fertilized waters  
(latitude where  
the water was in  
contact with the  
Plateau)



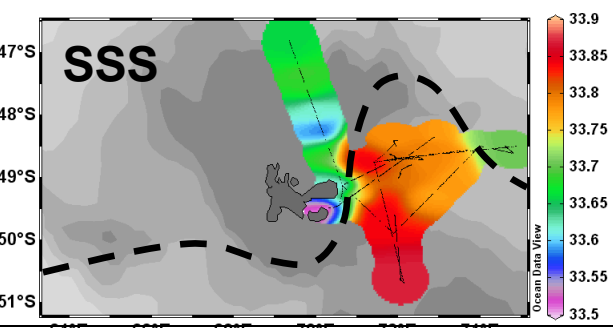
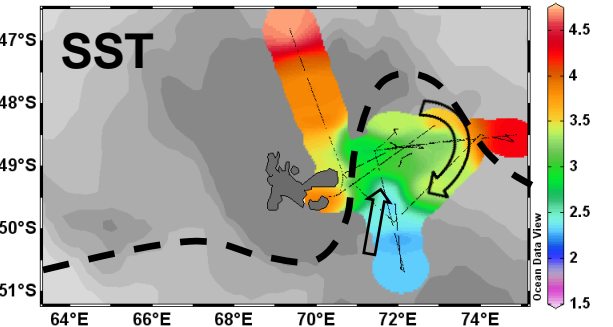
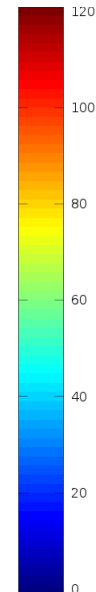
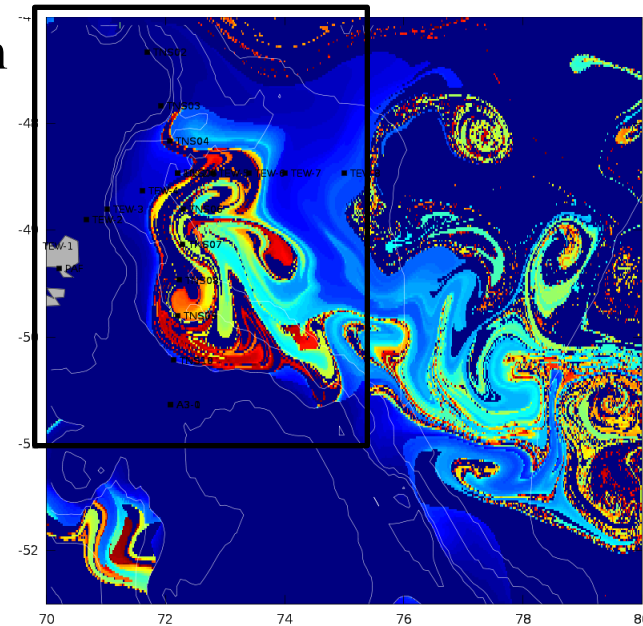
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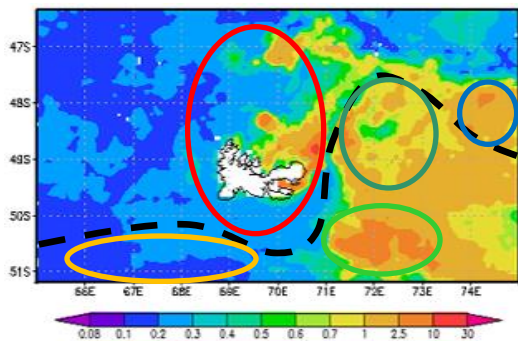
Age of the  
fertilized waters  
(days since the  
water was in  
contact with the  
Plateau)



$\Delta\text{CO}_2$  (sea-air,  $\mu\text{atm}$ )

October    November

Chl-a November 2011



**Plateau (South)**

**Middle zone**

**HNLC (upstream)**

**North PF**

**Plateau <500m**

<b>+17(±9)</b>	<b>-44(±13)</b>
<b>-7(±11)</b>	<b>-27(±11)</b>
<b>-3(±12)</b>	
<b>+18(±12)</b>	<b>-77(±23)</b>
<b>+4(±15)</b>	<b>-33(±33)</b>

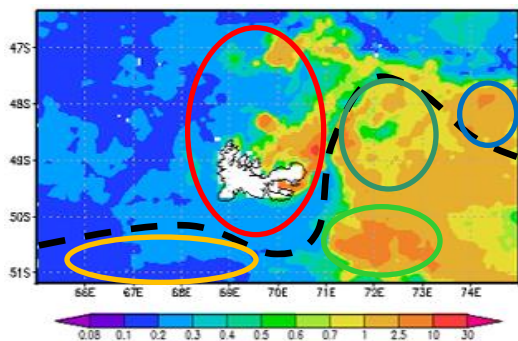
Generally near-equilibrium or  $\text{CO}_2$  outgassing in October due to deep mixing (light limitation),  
small  $\text{CO}_2$  sink in the Middle zone at the end of winter (low biological activity)

Rapid decrease in surface  $f\text{CO}_2$  as soon as MLD is reduced (early in November)

stratification  $\rightarrow$  increase in SST  $\rightarrow$  increase in  $f\text{CO}_2$

reduced vertical mixing + photosynthesis  $\rightarrow$  decrease in surface  $f\text{CO}_2$

Chl-a November 2011



**Plateau (South)**  
**Middle zone**  
**HNLC (upstream)**  
**North PF**  
**Plateau <500m**

$\Delta\text{CO}_2$  (sea-air,  $\mu\text{atm}$ ) Changes in surface  $\text{CO}_2$  ( $\mu\text{atm}$ )

	<u>October</u>	<u>November</u>	<u>Nov-Oct</u>	<u>Warming</u>	<u>Bio/Mix</u>
<b>Plateau (South)</b>	<b>+17(±9)</b>	<b>-44(±13)</b>	<b>-61</b>	<b>+4 (0.3°C)</b>	<b>-65</b>
<b>Middle zone</b>	<b>-7(±11)</b>	<b>-27(±11)</b>	<b>-20</b>	<b>+6 (0.4°C)</b>	<b>-26</b>
<b>HNLC (upstream)</b>	<b>-3(±12)</b>				
<b>North PF</b>	<b>+18(±12)</b>	<b>-77(±23)</b>	<b>-95</b>	<b>+3 (0.2°C)</b>	<b>-98</b>
<b>Plateau &lt;500m</b>	<b>+4(±15)</b>	<b>-33(±33)</b>	<b>(-37)</b>	<b>+12 (0.8°C)</b>	<b>(-49)</b>

Drawdown of  $\text{CO}_2$  at the onset of the bloom is 3 times larger above the Plateau (iron source) than in the Middle zone (recirculation)

Maximum  $\text{CO}_2$  drawdown north of the PF, large variability in shallow waters

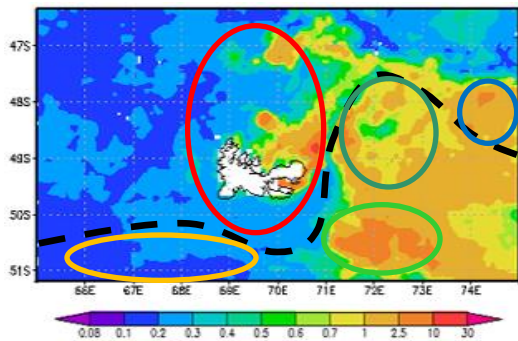
Small effect of surface warming on  $\text{fCO}_2$

$\Delta\text{CO}_2$  (sea-air,  $\mu\text{atm}$ ) Changes in surface  $\text{CO}_2$  ( $\mu\text{atm}$ )

October November Nov-Oct Warming Bio/Mix

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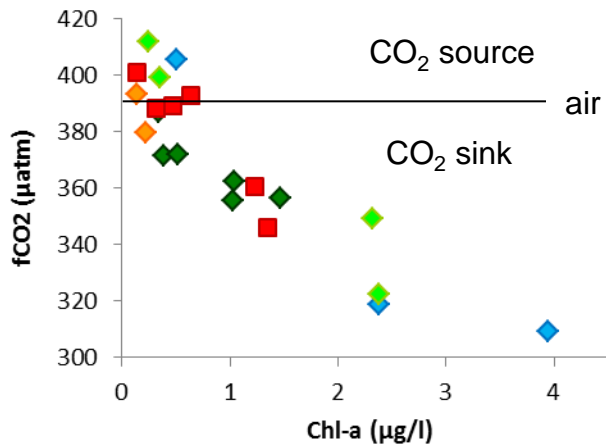
Chl-a November 2011



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Maximum  $\text{CO}_2$  drawdown north of the PF, large variability in shallow waters

Small effect of surface warming on  $f\text{CO}_2$



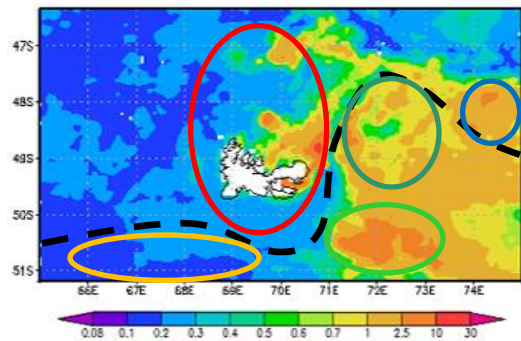
Changes in surface  $f\text{CO}_2$  are closely related to changes in Chl-a (spatial+temporal)

Chl-a is related to iron (lateral and vertical mixing)

→ larger  $\text{CO}_2$  sink above the Plateau South of Kerguelen (iron source) than in the Middle zone (recirculation)

$\Delta\text{CO}_2$  (sea-air,  $\mu\text{atm}$ ) Changes in surface  $\text{CO}_2$  ( $\mu\text{atm}$ )

Chl-a November 2011



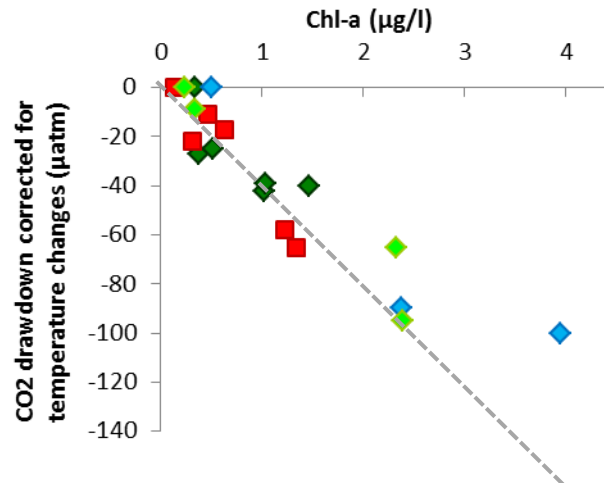
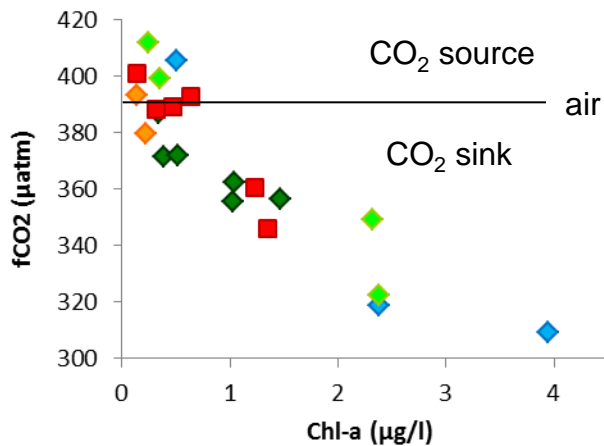
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**HNLC (upstream)**  
**North PF**  
**Plateau <500m**

October	November	Nov-Oct	Warming	Bio/Mix
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-7(±11)	-27(±11)	-20	+6 (0.4°C)	-26
-3(±12)				
+18(±12)	-77(±23)	-95	+3 (0.2°C)	-98
+4(±15)	-33(±33)	(-37)	+12 (0.8°C)	(-49)

Drawdown of  $\text{CO}_2$  at the onset of the bloom is 3 times larger above the Plateau (iron source) than in the Middle zone (recirculation)

Maximum  $\text{CO}_2$  drawdown north of the PF, large variability in shallow waters

Small effect of surface warming on  $f\text{CO}_2$



Most of the change is attributed to biological activity  
 + changes in MLD  
 + remineralization ?

# Synthesis of CO<sub>2</sub> data around Kerguelen

## Air-sea CO<sub>2</sub> fluxes (climatological winds)

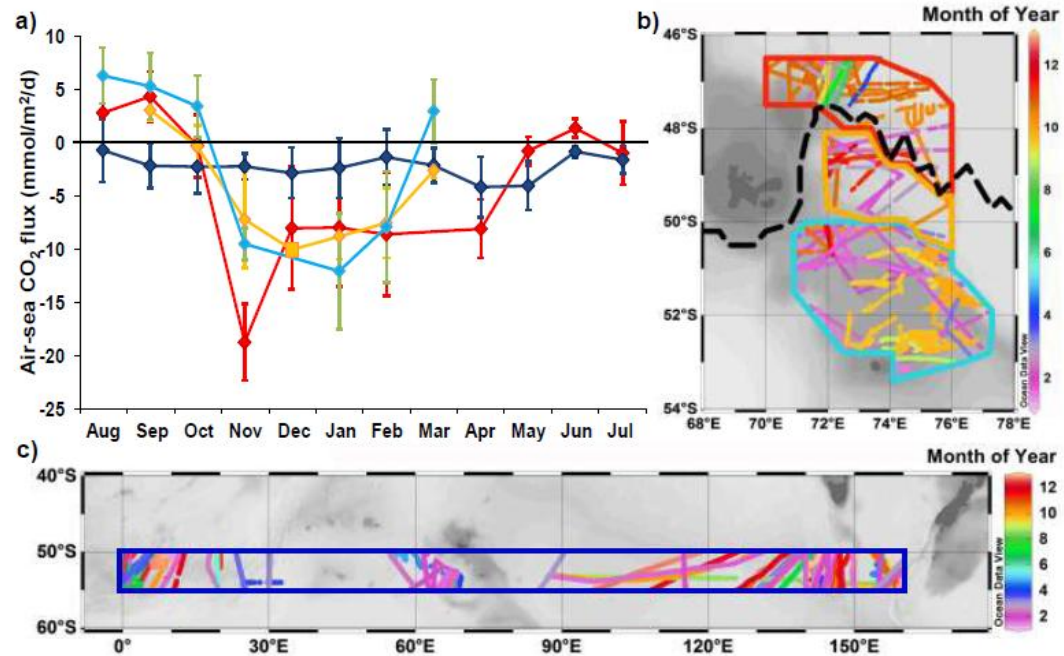
- ◇ Ship observation (SOCATdatabase, incl. OISO/KEOPS)
- CARIOCA buoy (Déc.)

- Onset of the bloom (KEOPS2):
- large spatial variability in the bloom (iron transport)
- Maximum uptake between November and January (N-S gradient related to MLD and SiOH<sub>4</sub>)
- Interannual variability ? (MLD, iron transport)

### CO<sub>2</sub> uptake from September to March :

(close to annual uptake since winter CO<sub>2</sub> flux is ~0)

- HNLC (iron limited):**  $-0.4 \pm 0.2 \text{ molC/m}^2$
- Plateau S-E (iron source) :**  $-1.1 \pm 0.2 \text{ molC/m}^2$
- Middle zone (iron transport) :**  $-1.0 \pm 0.2 \text{ molC/m}^2$
- PF zone (jets, SiOH<sub>4</sub> limitation) :**  $-1.5 \pm 0.2 \text{ molC/m}^2$



→ iron fertilization of the whole ice-free SO (~50-60°S) would increase the global uptake of atmospheric CO<sub>2</sub> by **less than 0.1 GtC** (<1% of current CO<sub>2</sub> emissions)

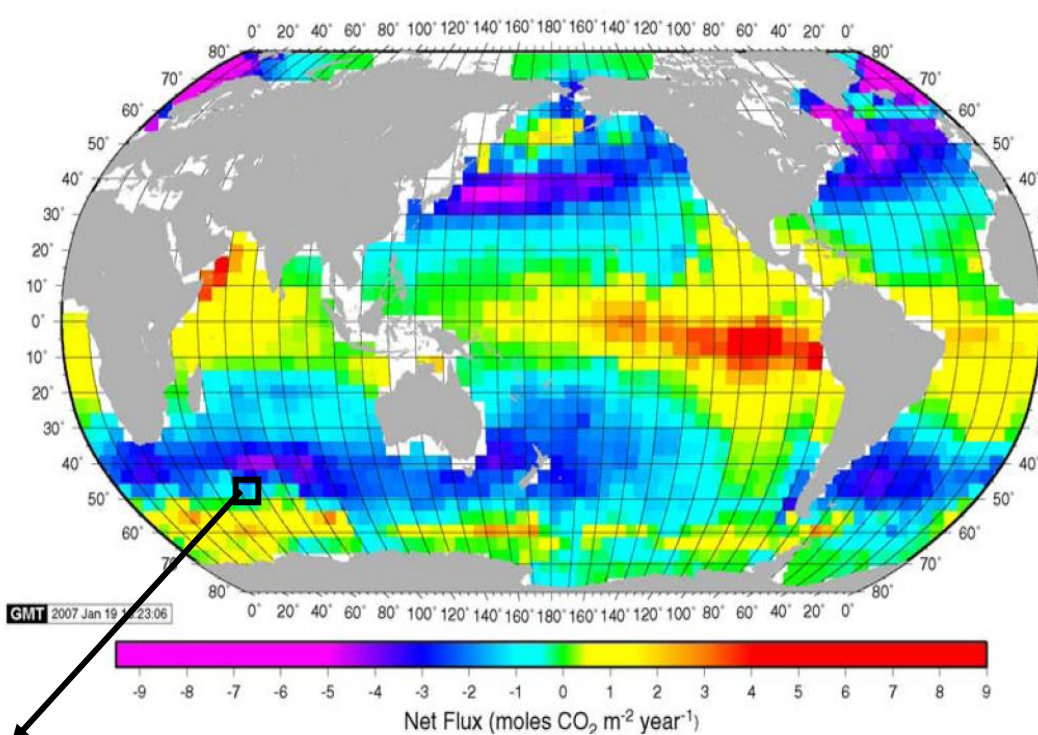
- Limitation by silicate after 1 to 3 months of intense biological activity (delayed to the South)
- The magnitude of the CO<sub>2</sub> sink depends on iron transport
- The start and duration of the CO<sub>2</sub> sink depends on MLD (rapid establishment and rapid decay over the Plateau)
- Impact of remineralization on air-sea fluxes? change in the structure of the bloom?

# Air-sea CO<sub>2</sub> fluxes

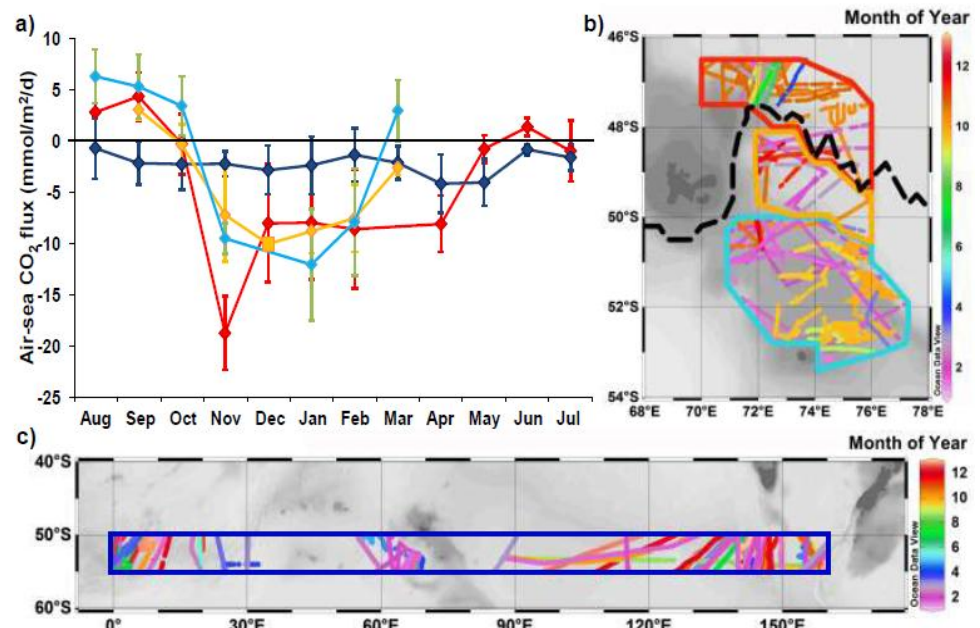
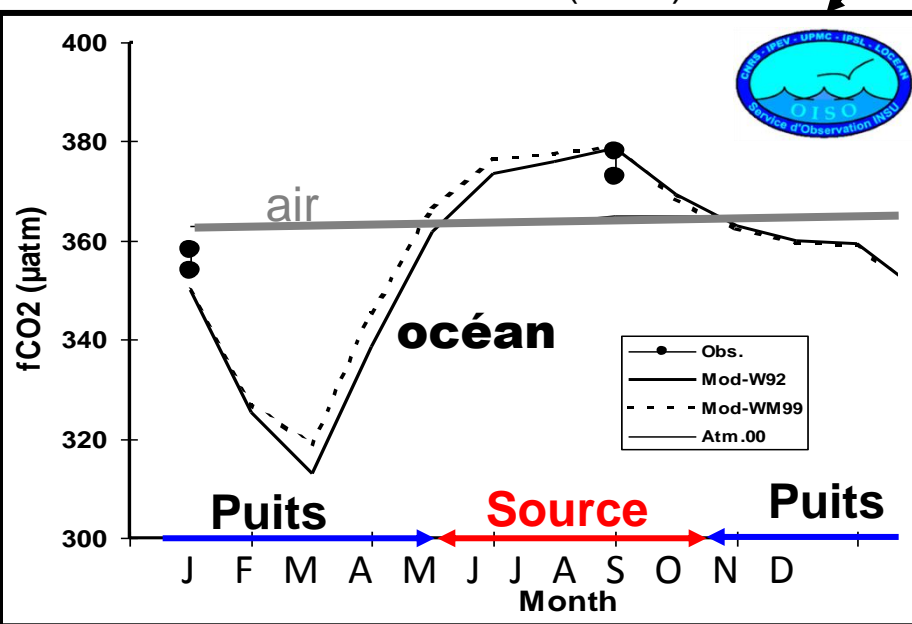
## Variabilité saisonnière du CO<sub>2</sub> dans les eaux de surface Antarctiques

Puits de CO<sub>2</sub> important en été  
 Petite source de CO<sub>2</sub> en hiver  
 → Flux net annuel négatif (puits)

*Metzl et al., (2001, 2003)*



Site KERFIX (50°S)



## Conclusions

Low uptake of atmospheric CO<sub>2</sub> south of 50°S due to deep mixing (light limitation in winter) and iron limitation (HNLC)

→ natural iron fertilization allows for the establishment of a large CO<sub>2</sub> sink above and downstream Kerguelen Plateau as soon as MLD is reduced (Oct/Nov)

Large spatial variability in the uptake of CO<sub>2</sub> within the bloom in November related to iron transport from the Plateau

Spatial variability in the CO<sub>2</sub> sink is reduced in January and February → silicate limitation?

Globally (over the productive season), the uptake of atmospheric CO<sub>2</sub> in the bloom does not depend much on the level of iron fertilization

→ iron fertilization of the whole ice-free SO (~50-60°S) would increase the global uptake of atmospheric CO<sub>2</sub> by less than 0.1 GtC (<1% of CO<sub>2</sub> emissions)

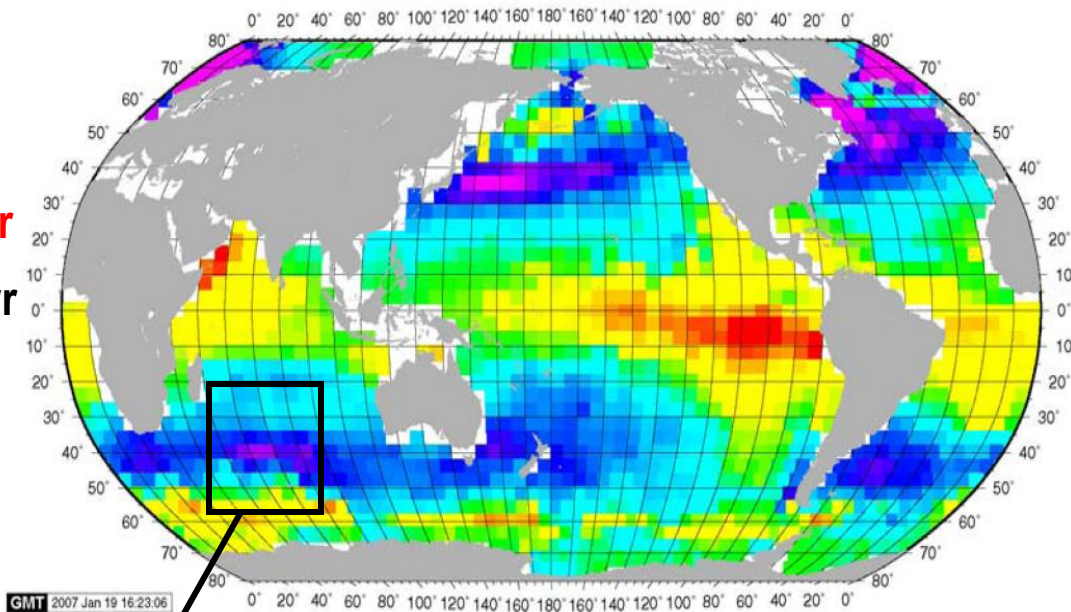
# Air-sea CO<sub>2</sub> fluxes

## Évolution décennale

CO<sub>2</sub> atmosphérique : **+1.7 μatm/yr**

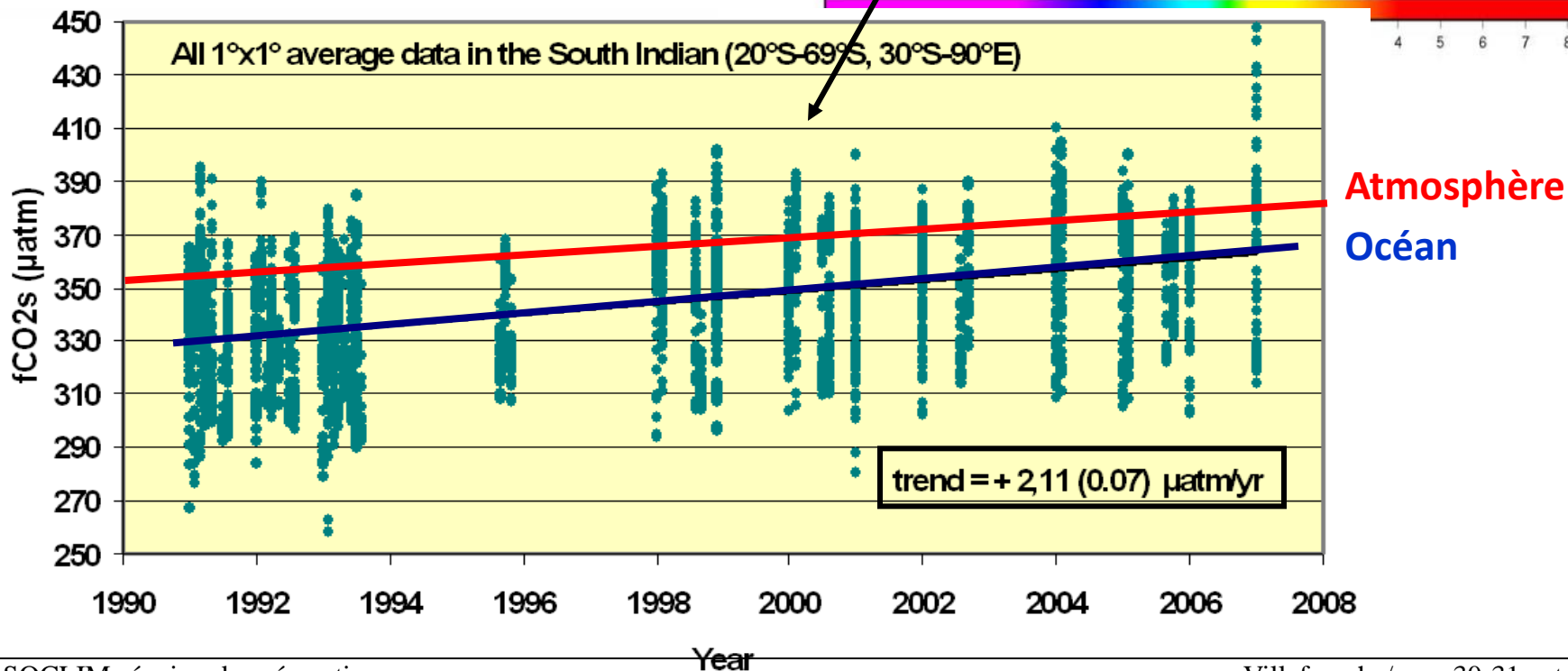
CO<sub>2</sub> océanique : **+2.1 μatm/yr**

Réduction du puits de CO<sub>2</sub> : **-0.4 μatm/yr**



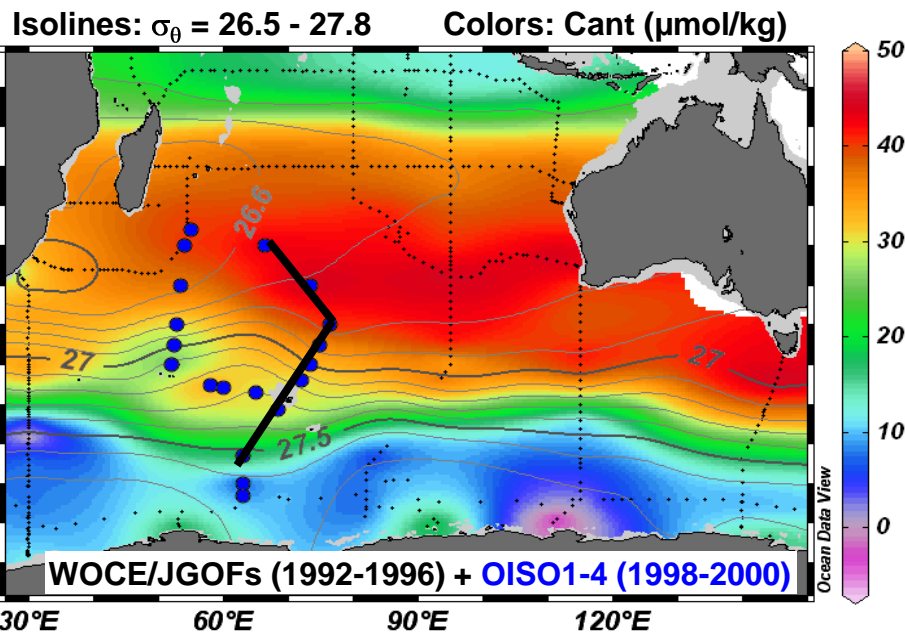
Metzl, 2009 Communiqué de Presse CNRS

GMT 2007 Jan 19 16:23:06

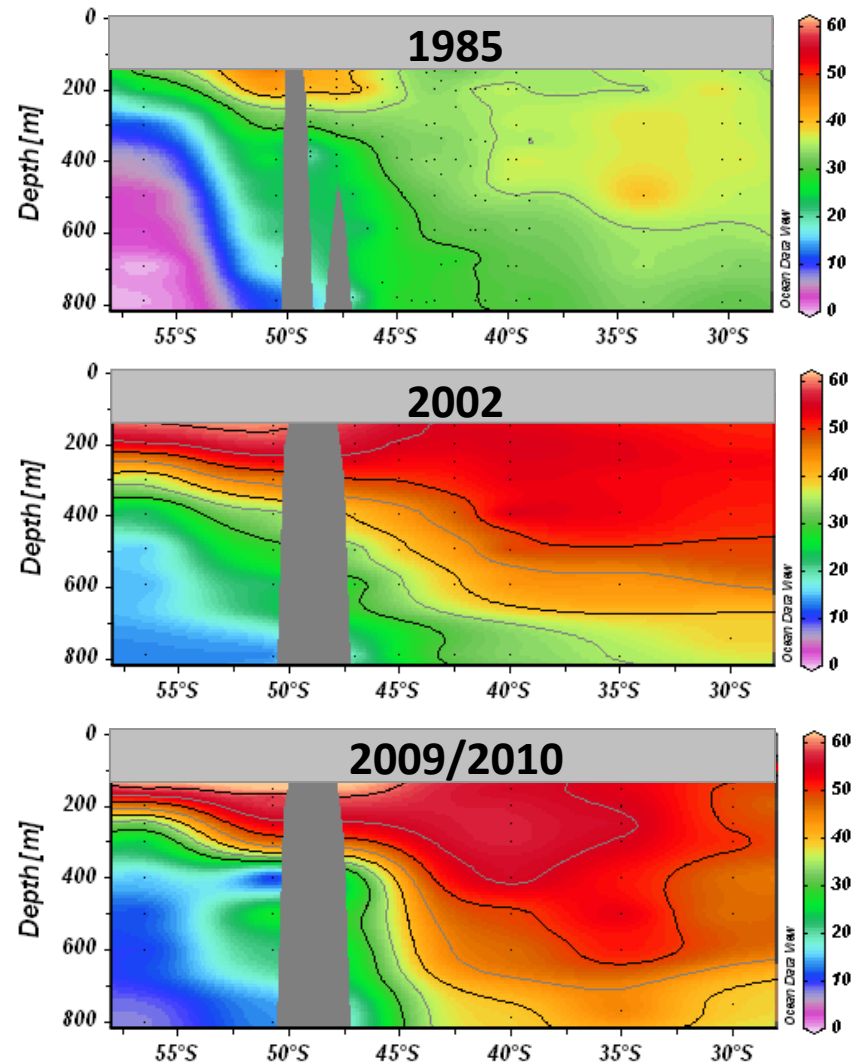


# Storage of anthropogenic CO<sub>2</sub>

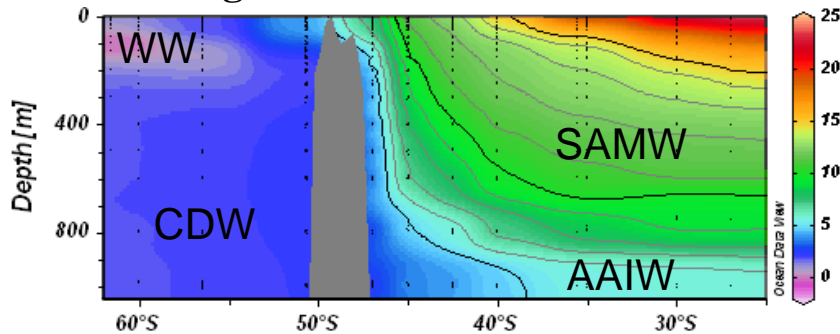
Anthropogenic CO<sub>2</sub> concentrations at 400m estimated from observations in the 1990's



Evolution of anthropogenic CO<sub>2</sub> ( $\mu\text{mol/kg}$ ) in mode waters (200-1000m)



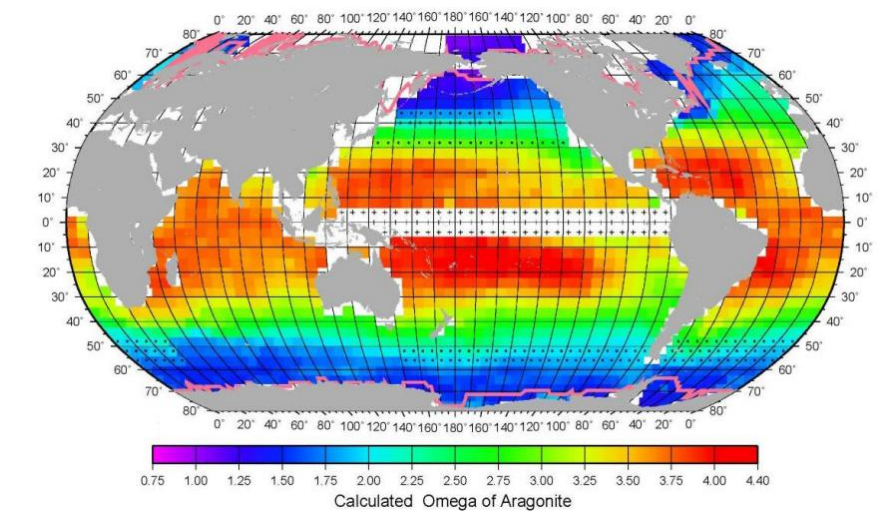
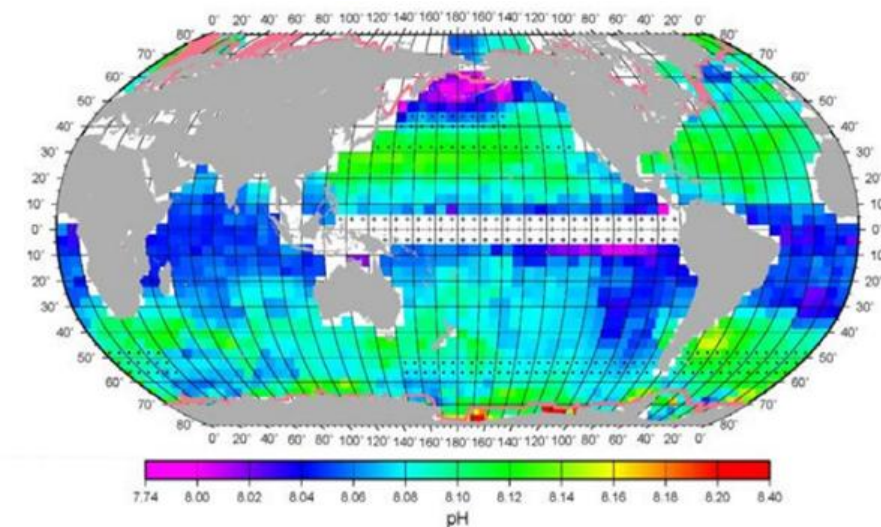
Temperature ( C ) of the upper ocean (0-1000m) along the eastern OISO transect



*Lo Monaco et al. (in prep.)*

# Ocean Acidification

## Distribution of surface pH and $\Omega_{\text{aragonite}}$



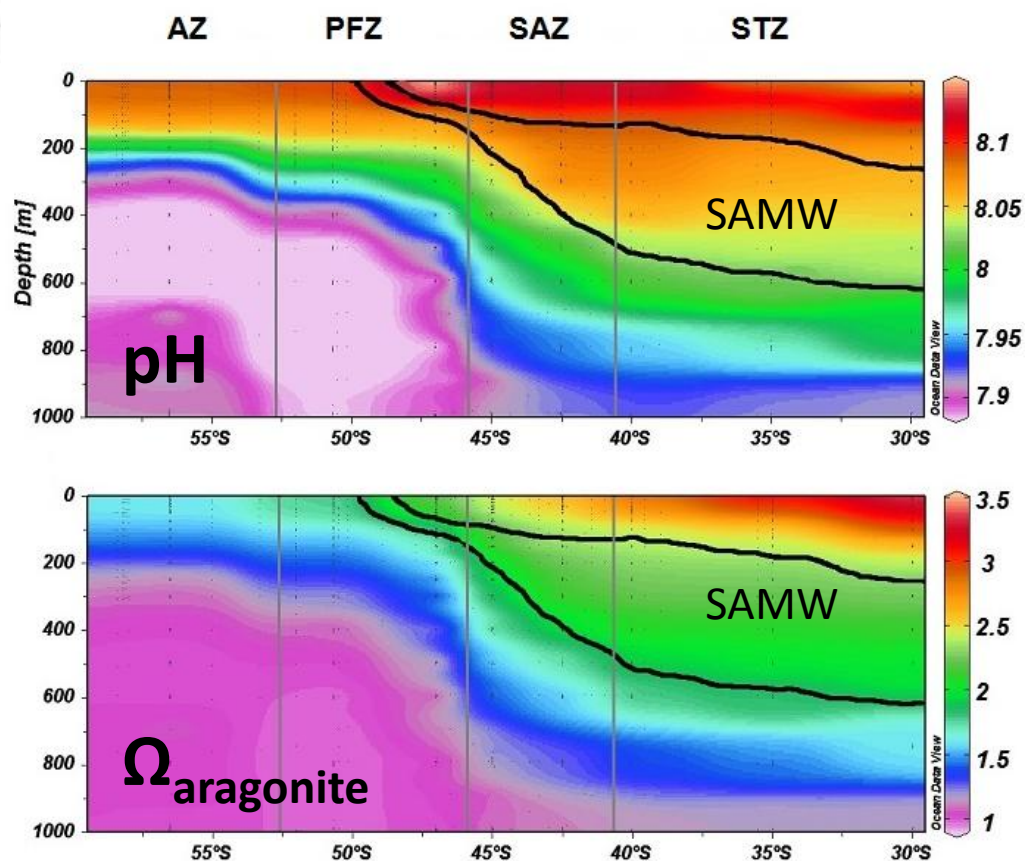
Surface pH and  $\Omega_{\text{aragonite}}$  climatology for February 2005 (from Takahashi et al., 2014)

### Subantarctic Zone (SAZ):

- Major CO<sub>2</sub> sink
- Subantarctic Mode Water (SAMW) formation

### Antarctic zone (AZ):

- Upwelling → low values of pH and  $\Omega_{\text{aragonite}}$



# Ocean Acidification

## Evolution of Cant and pH in the upper Southern Ocean

Subantarctic Zone (40° S):

Large uptake of atm. CO<sub>2</sub> + Mode water formation

→ large accumulation of Cant → large reduction in pH (and CO<sub>3</sub><sup>2-</sup>)

Antarctic Zone (56° S):

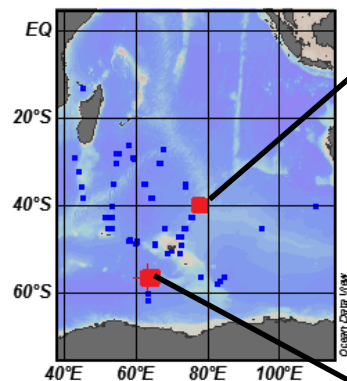
Upwelling of old deep waters (with no Cant), Vertical diffusion

→ lower accumulation of Cant → lower acidification rate ?

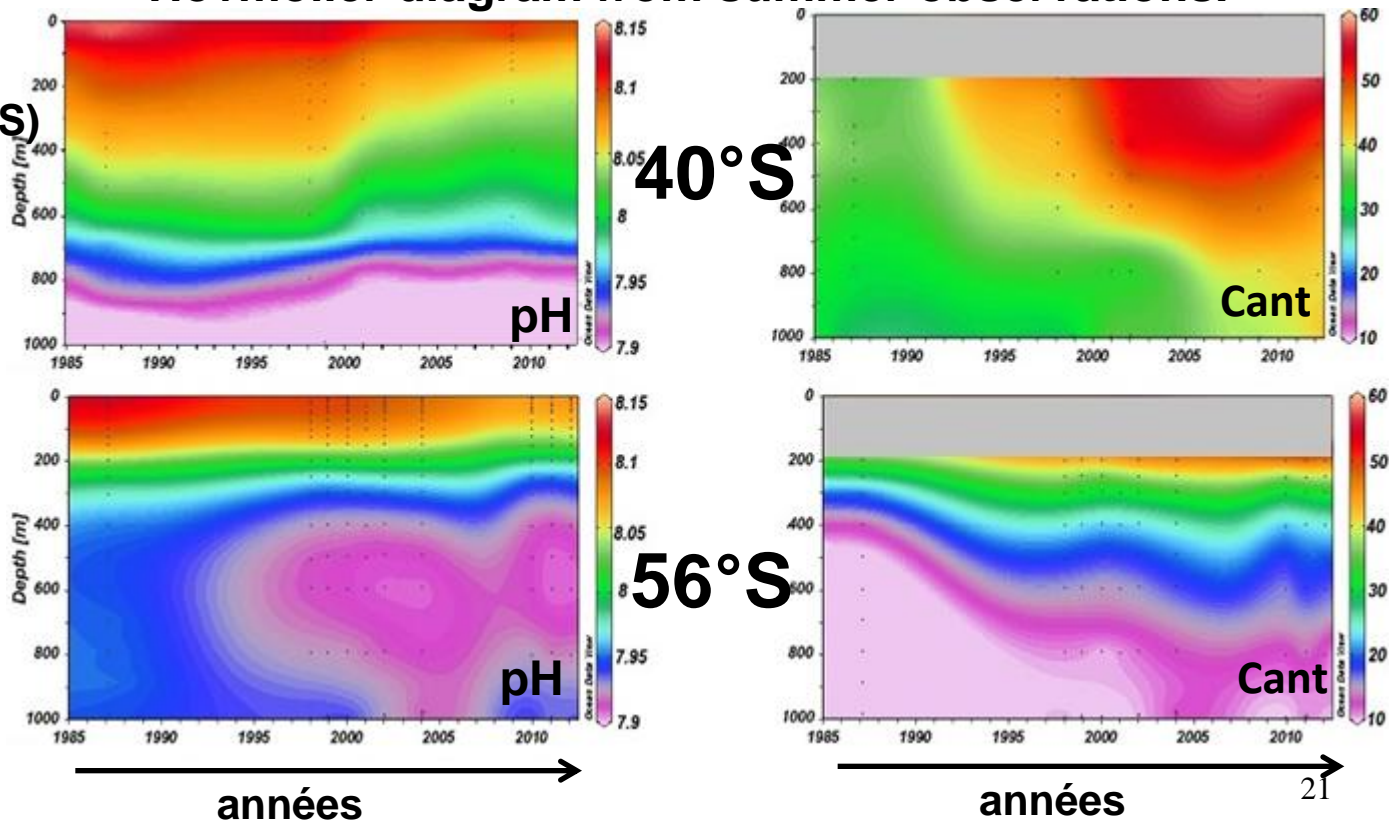
*Thèse R. Gomez (2013-2016)*

### Hovmoller diagram from summer observations.

Subantarctic Zone (40°S)



Antarctic Zone (56°S)



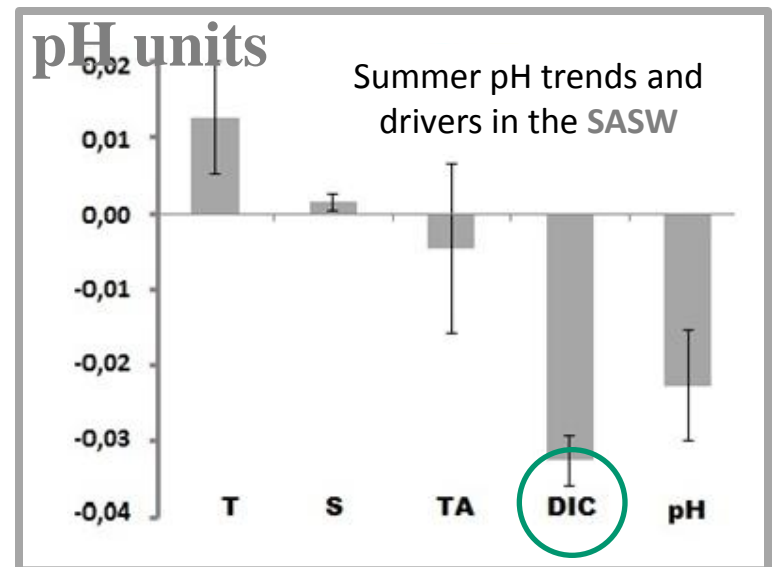
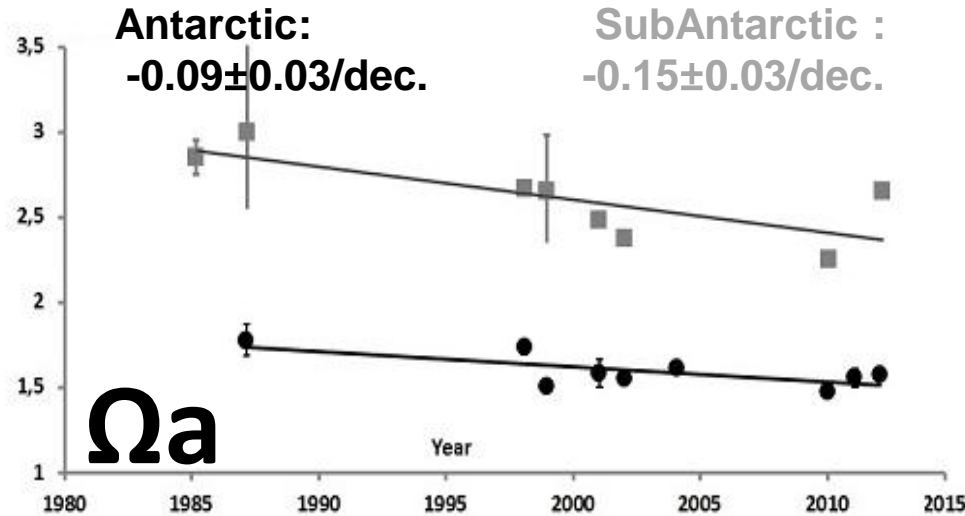
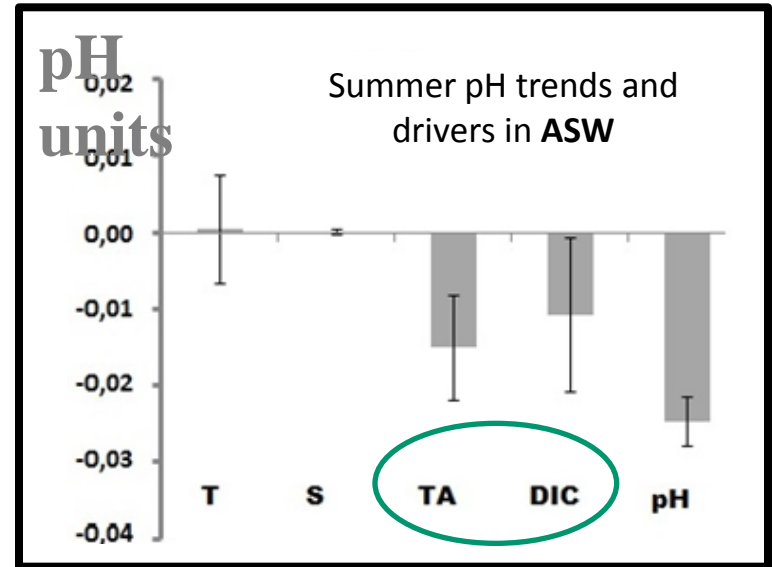
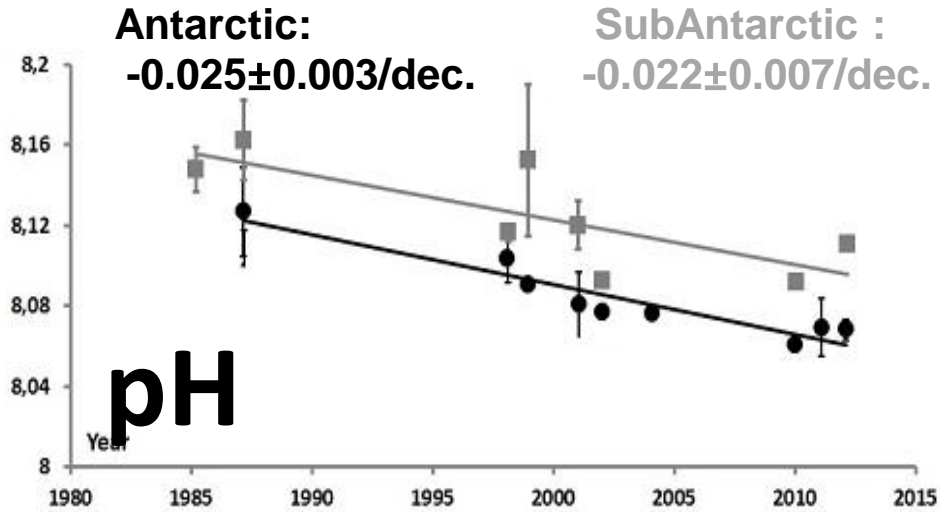
années

années

21

# Ocean Acidification

## Acidification of Antarctic and Subantarctic surface waters



pH and  $\Omega_{\text{aragonite}}$  evolution in summer in the Antarctic Surface Waters (black dots and black solid line) and in the SubAntarctic Surface Waters (grey squares and grey solid line).

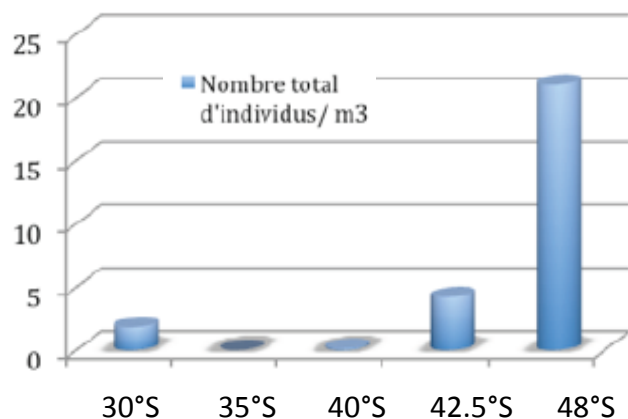
## SOforCO<sub>2</sub>



Filet à plancton

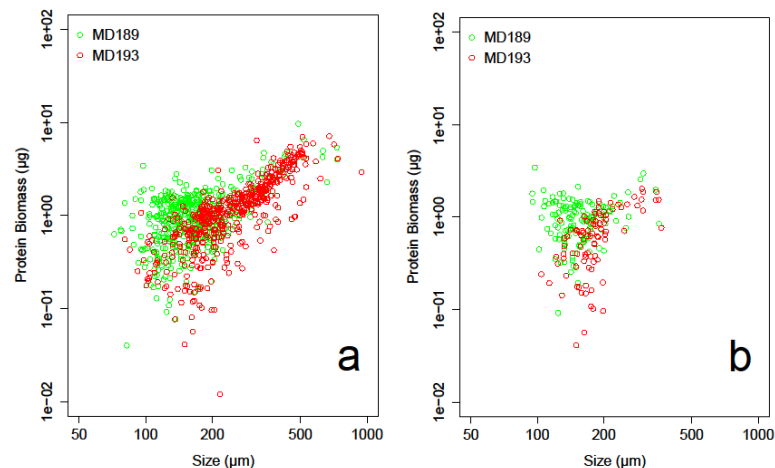
R. Schiebel (Univ. Angers), projet LEFE/INSU (2013-2016)

Rôle des foraminifères planctoniques dans la séquestration de CO<sub>2</sub> dans l'Océan Austral



Abondance des foraminifères planctoniques dans l'Océan Indien Sud-Ouest

(J. Meilland, 2011, rapport de stage, UBO)



Relation taille-biomasse des foraminifères planctoniques au cours des missions MD189 et MD193: a) espèces indifférenciées, b) cas de *Négloboquadrina pachyderma*

(J. Meilland et al., in prep., Thèse 2012-2015)

## MD-CPR

+

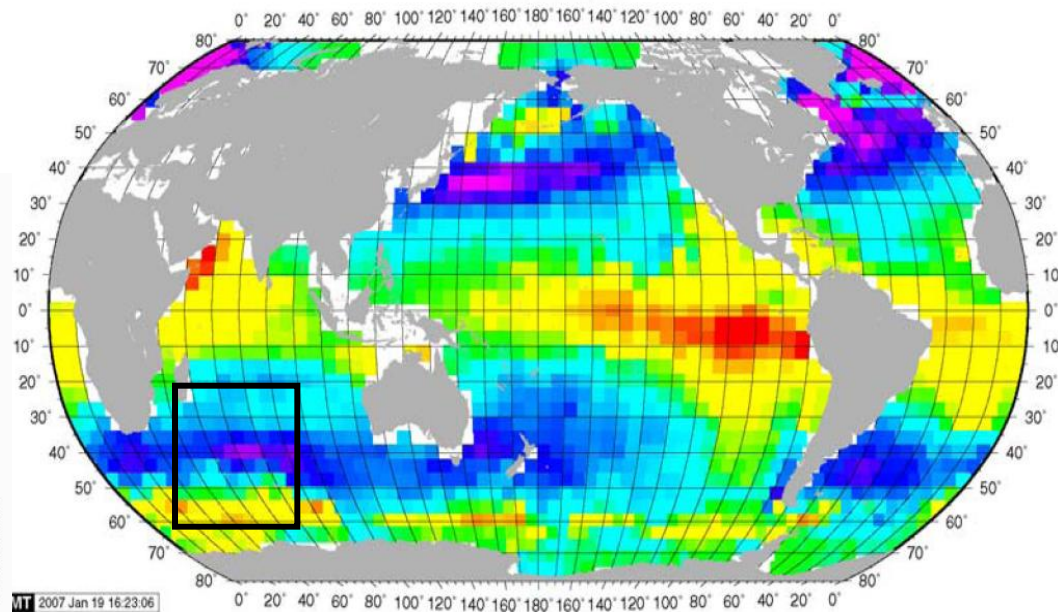
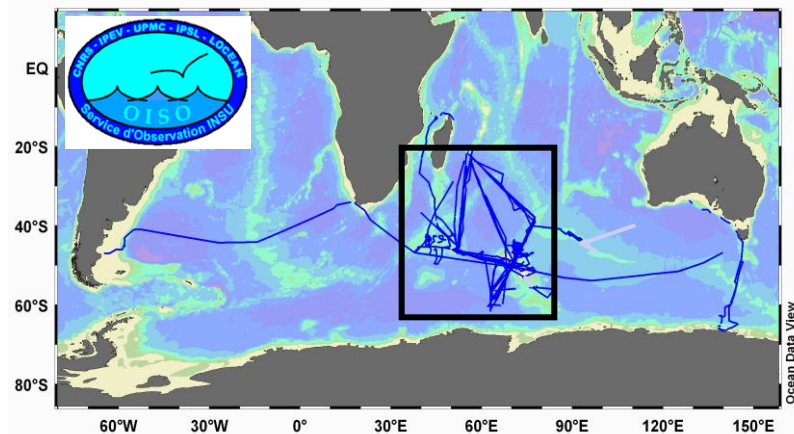
## Echosondage

P. Koubbi (UPMC) + C. Cotté (LOCEAN/MNHN)

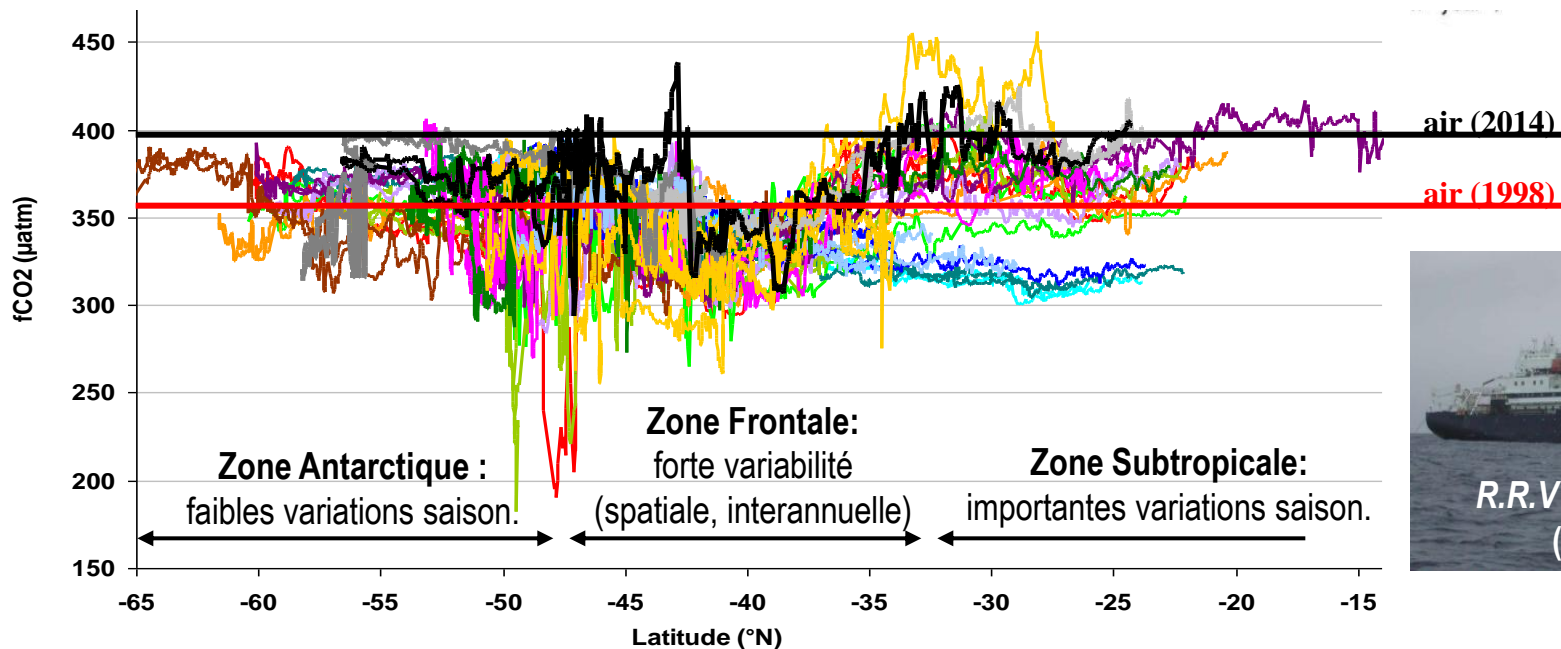
Impact des variations de paramètres environnementaux (SST, pH, O<sub>2</sub>, ...) sur les écosystèmes planctoniques et les prédateurs supérieurs (mammifères et oiseaux marins)

# Air-sea CO<sub>2</sub> fluxes

## Service d'Observation OISO (Océan Indien Service d'Observation)



## Mesures de CO<sub>2</sub> dans les eaux de surface depuis 1998

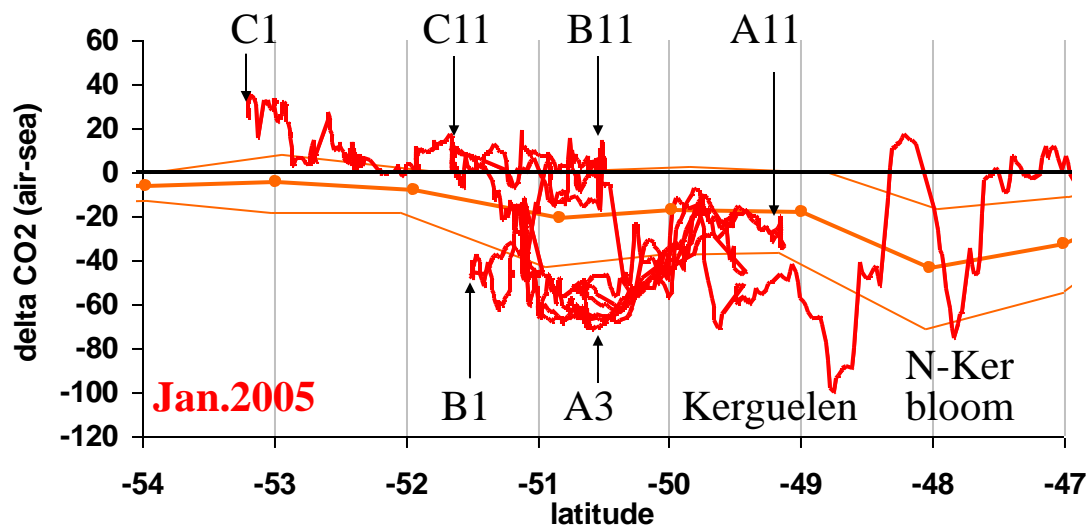


*R.R.V Marion Dufresne  
(IPEV/TAAF)*

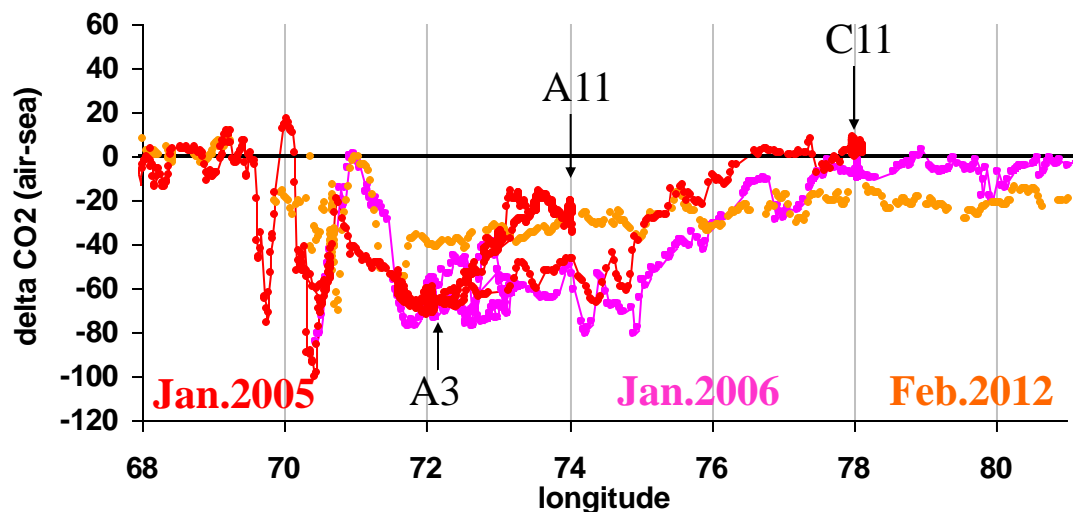
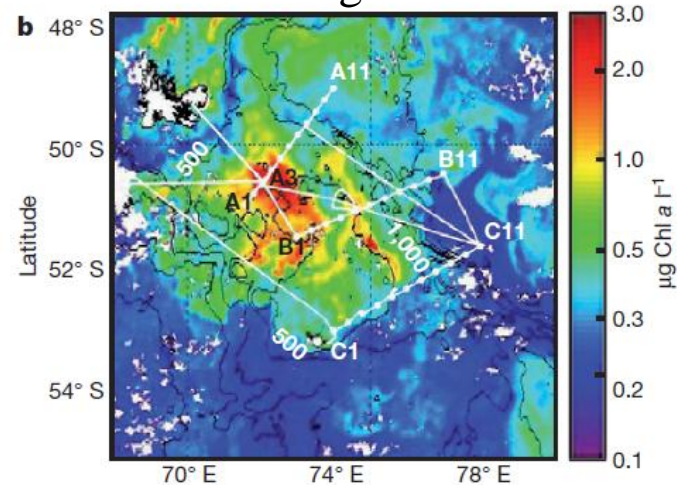
# Summer $\Delta p\text{CO}_2$ around Kerguelen

Mean  $\Delta p\text{CO}_2$  in Jan/Feb (1998-2012)

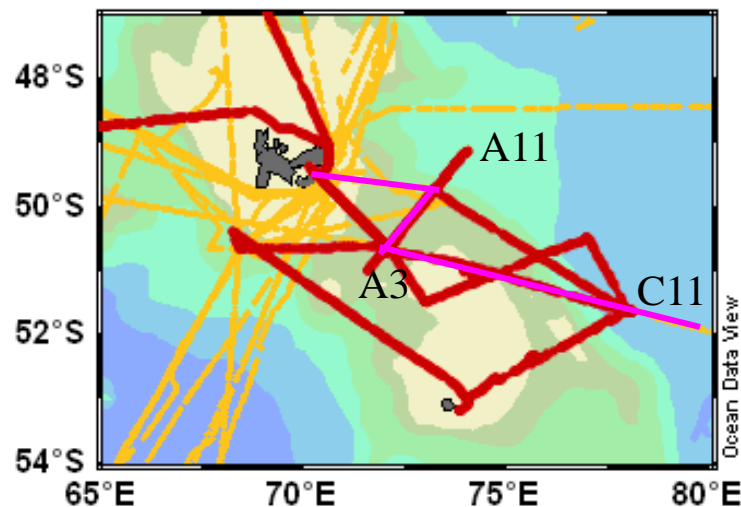
KEOPS-1 (Jan/Feb 2005)



Chl *a* during KEOPS-1



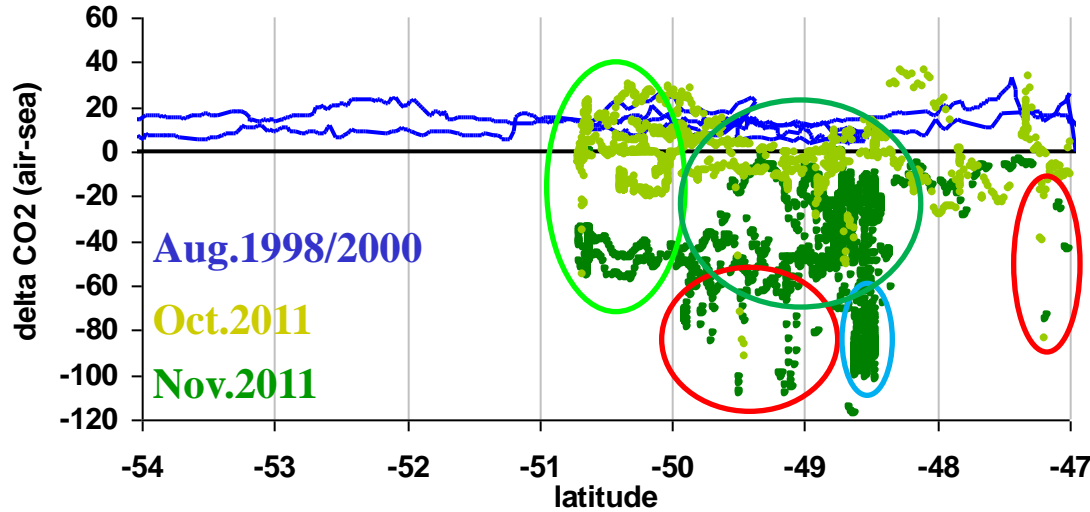
OISO and KEOPS summer cruises



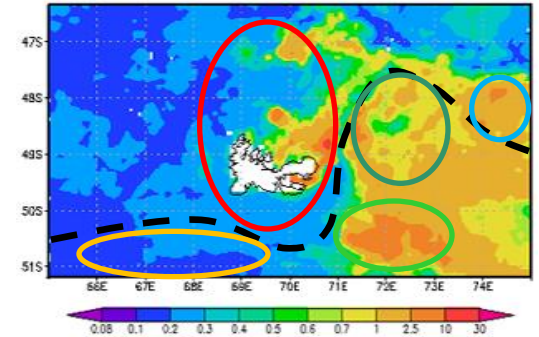
# KEOPS2 / OISO20

Near-equilibrium or CO<sub>2</sub> outgassing in October = winter conditions (deep mixing, low Chl-a)

Rapid decrease in surface fCO<sub>2</sub> early in November (stratification)



Chl-a November 2011

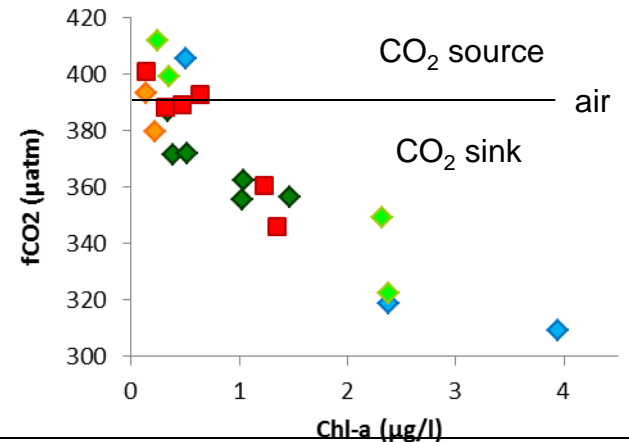


Changes in surface fCO<sub>2</sub> are closely related to changes in Chl-a (spatial+temporal)

Chl-a concentration is related to iron (water age)

→ larger CO<sub>2</sub> sink above the Plateau South of Kerguelen than in the Middle zone

	October	November	CO <sub>2</sub> drawdown
Plateau	+17(±9)	-44(±13)	-61 μatm
Middle zone	-7(±11)	-27(±11)	-20 μatm

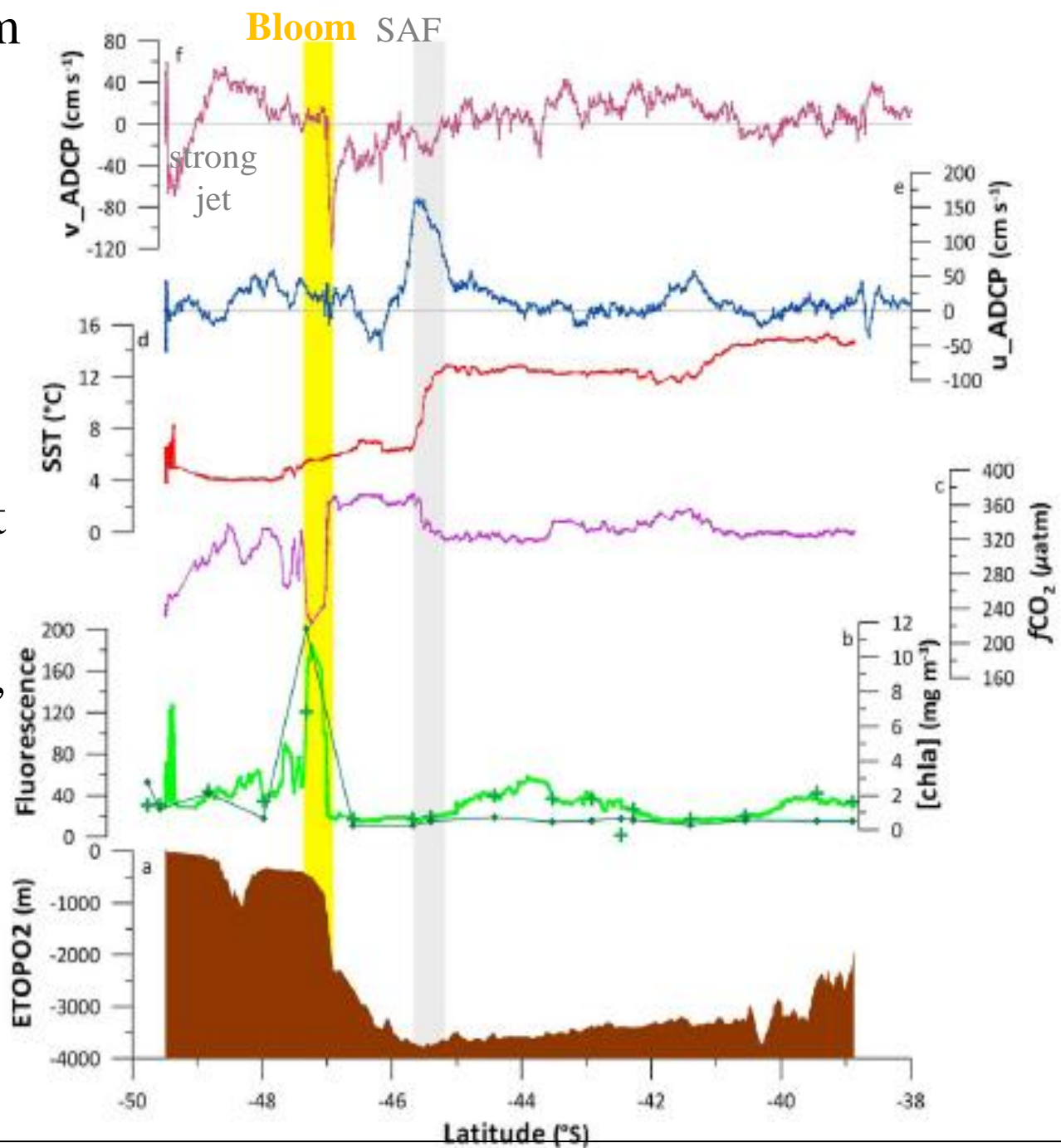


# North Kerguelen bloom

Observed every year,  
earlier than the bloom  
to the South

situated above the  
Plateau just south of  
the strong eastward jet  
(AAC)

(Lourantou and Metzl,  
2011, GRL)



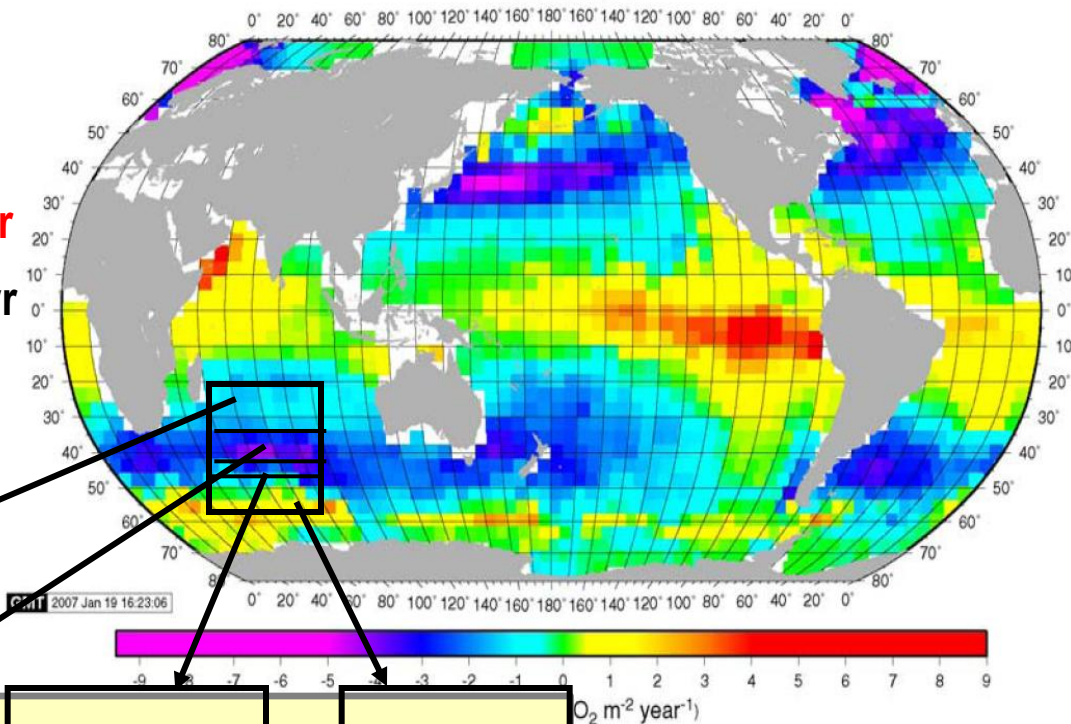
# Air-sea CO<sub>2</sub> fluxes

## Évolution décennale

CO<sub>2</sub> atmosphérique : **+1.7  $\mu\text{atm/yr}$**

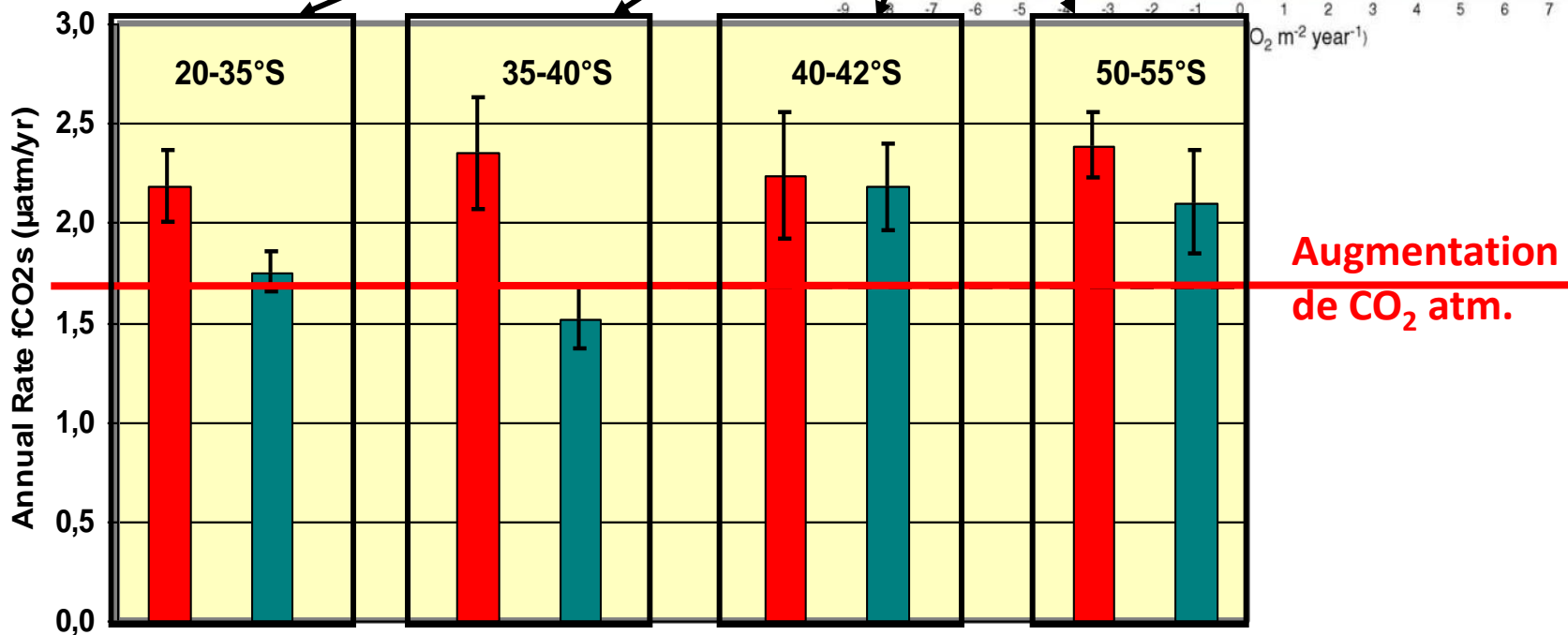
CO<sub>2</sub> océanique : **+2.1  $\mu\text{atm/yr}$**

Réduction du puits de CO<sub>2</sub> : **-0.4  $\mu\text{atm/yr}$**



Metzl, 2009

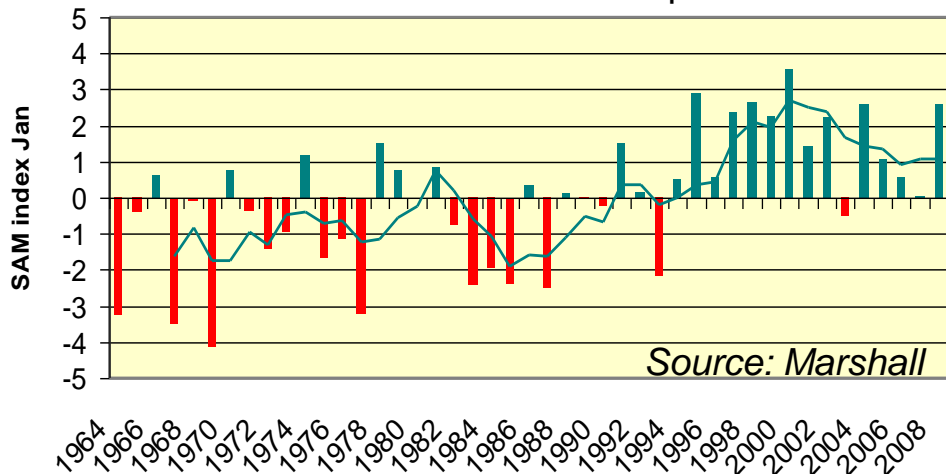
Communiqué de  
Presse CNRS



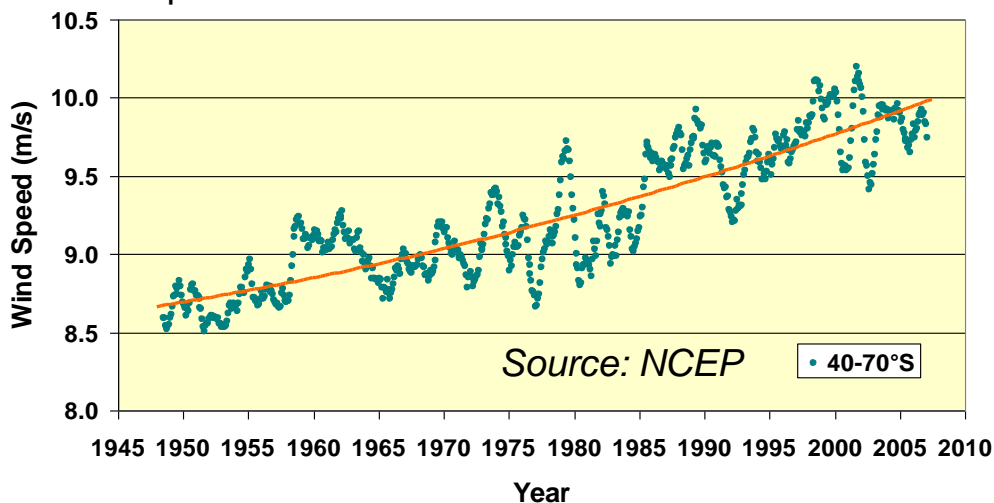
# Air-sea CO<sub>2</sub> fluxes

## Évolution décennale

Évolution de la SAM observée depuis 50 ans



Accélération des vents dans l'Océan Austral en réponse à l'évolution de la SAM



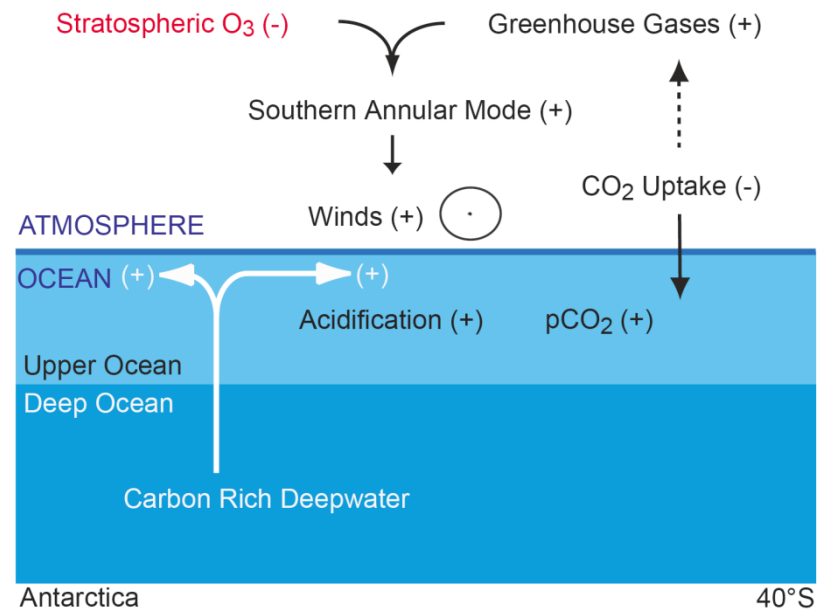
## Couplage Climat / CO<sub>2</sub> Océanique

Southern Annular Mode (SAM) index = différence de pression atm. entre 40°S et 60°S

Tendance décennale de la SAM vers les valeurs positives

due à diminution de O<sub>3</sub> stratosphérique  
+ augmentation des gaz à effet de serre

→ Accélération des vents dans l'Austral  
→ Renforcement de l'upwelling ?



(Lenton et al, 2009, GRL)

Villefranche/mer, 30-31 octobre 2014

# Storage of anthropogenic CO<sub>2</sub>

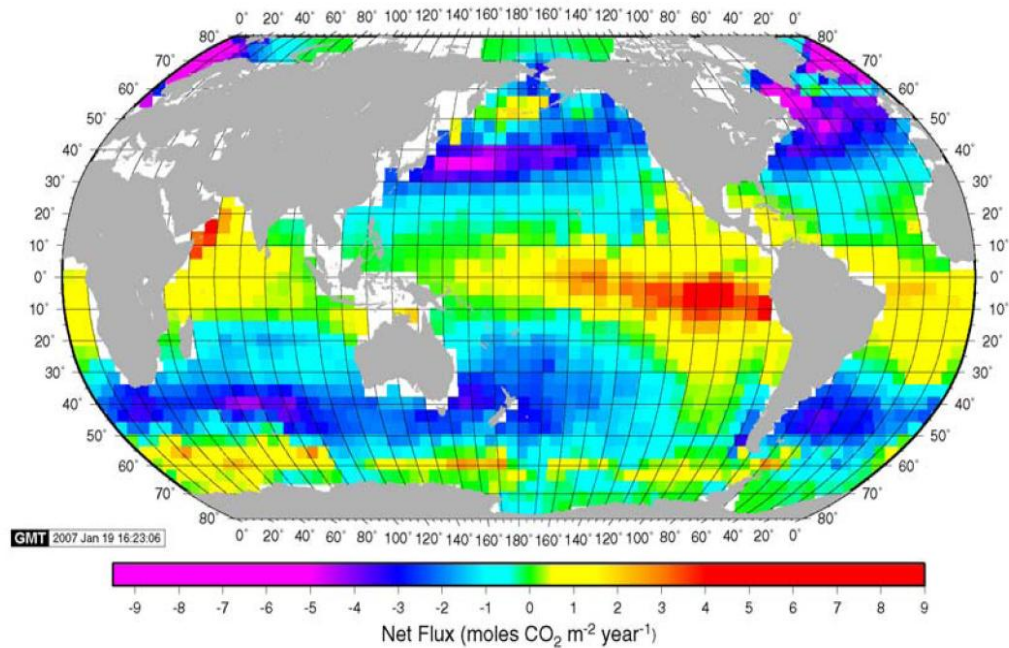
## Flux de CO<sub>2</sub> à l'interface air-mer, moyenne annuelle (année 2000)

flux net global : -2 GtC/an

*Takahashi et al. (2009)*

l'océan agit globalement comme un puits de CO<sub>2</sub> atmosphérique

→ Absorption de CO<sub>2</sub> anthropique



## Accumulation de CO<sub>2</sub> anthropique dans l'océan (année 1995)

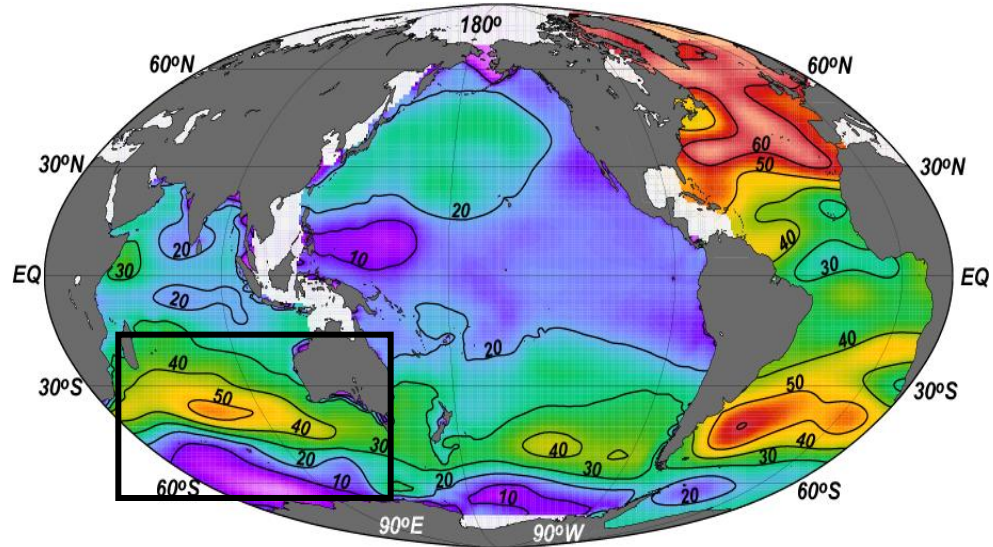
accumulation totale : 118 GtC

*Sabine et al. (2004)*

= CO<sub>2</sub> en excès dans l'océan

→ Acidification des eaux

Propagation dans l'océan intérieur (eaux de mode, eaux profondes)



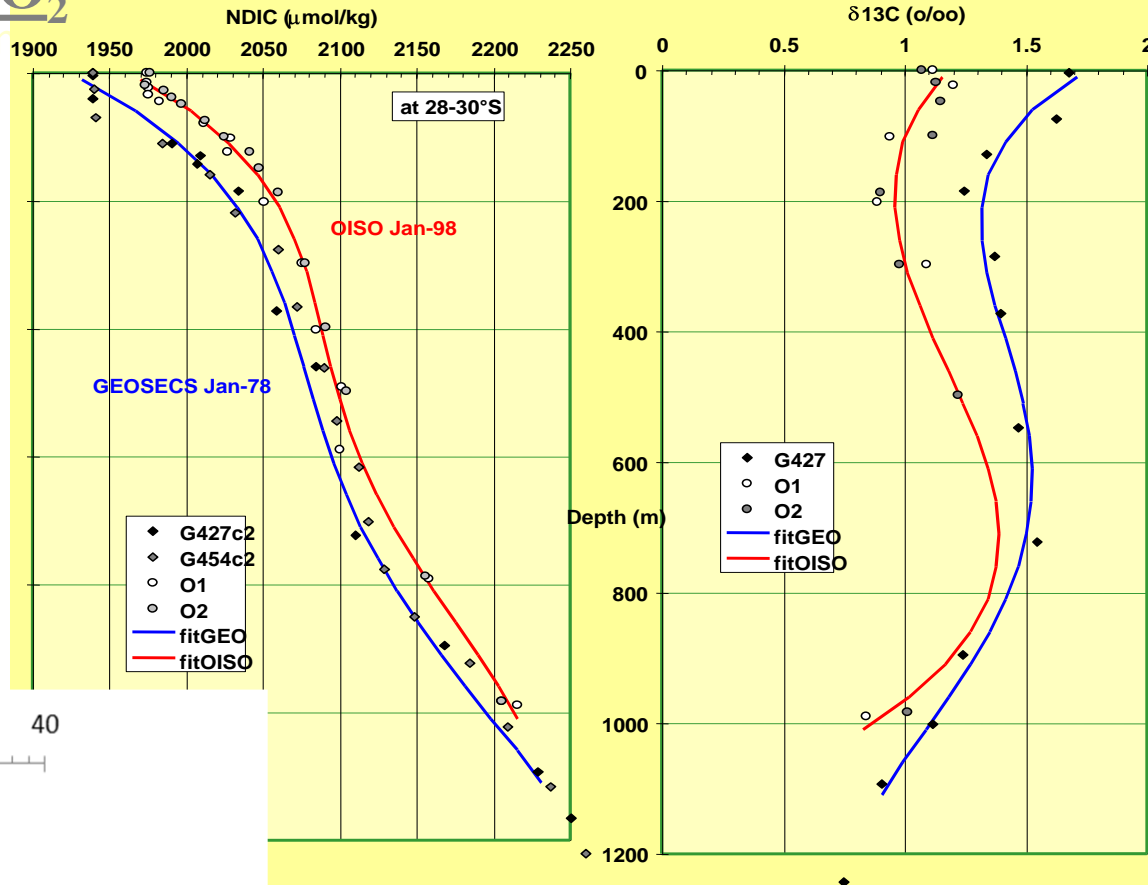
# Storage of anthropogenic CO<sub>2</sub> in the ocean

(e.g. détection du carbone anthropique)

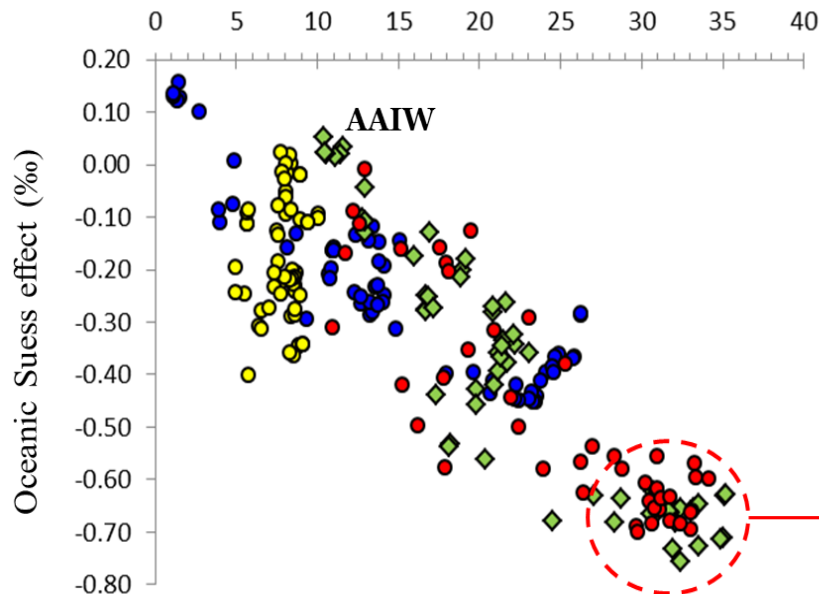
The storage of anthropogenic CO<sub>2</sub> in the ocean is revealed by

- increase in Total CO<sub>2</sub> (DIC)
- decrease in <sup>13</sup>C (Suess effet)

Thèse V. Racapé (2010-2013)



Anthropogenic carbon change (μmol/kg)



$\delta^{13}\text{C}_{\text{DIC}} \searrow \sim -0.020\text{‰/year}$

$[\text{CO}_2]_{\text{ocean}} \nearrow \sim 1\mu\text{mol/kg/year}$

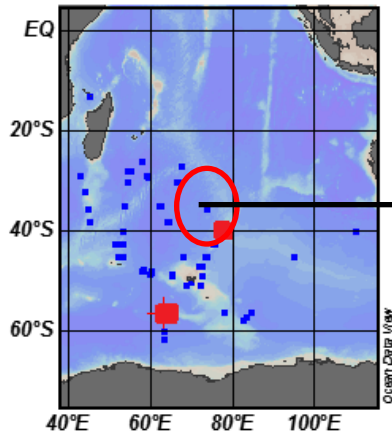
MODE WATERS

# Ocean Acidification

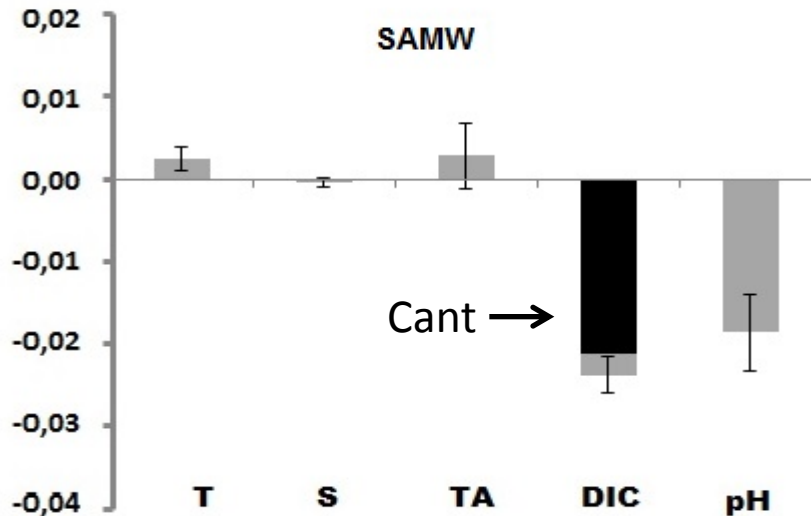
## Surface Waters

Antarctic:  
 $-0.025 \pm 0.003/\text{dec.}$

SubAntarctic :  
 $-0.022 \pm 0.007/\text{dec.}$

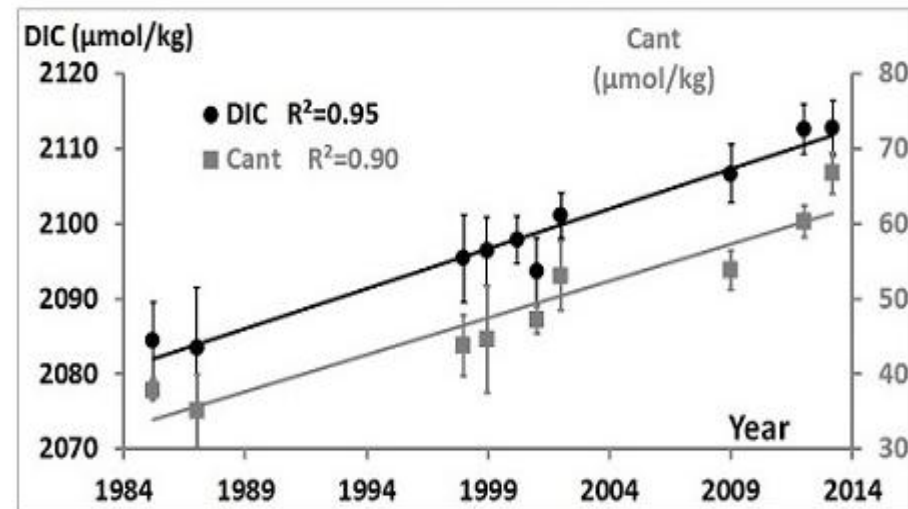
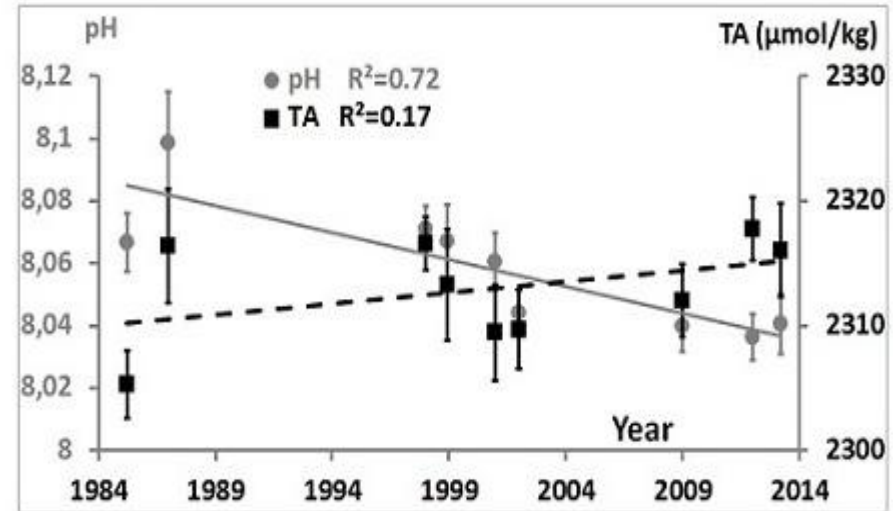


Subantarctic Mode Waters:  
 $-0.018 \pm 0.005/\text{dec.}$



Summer pH trends and its drivers in the SAMW

## Subantarctic Mode Waters (~300m)



pH,  $\Omega_{\text{aragonite}}$ , DIC and TA evolution in summer in the SubAntarctic Mode Waters