Eddy compensation of the enhanced sea-to-air CO$_2$ flux during positive phases of the SAM

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**SAM**: Southern Annular Mode

Dominant atmospheric mode of variability in the Southern Hemisphere

**Temporal evolution of the SAM**

*Observed SAM index*


**Positive trend in the SAM**

Intensification and poleward shift of zonal winds

**Impact on the Southern Ocean carbon sink?**
Introduction

Hypothesis 1
Saturation of the Southern Ocean CO$_2$ sink
(Le Quéré et al. 2007)

Antarctic Divergence

zonal winds

F$_{\text{natural}}$

ICE

Ekman transport

DIC

ACC

ANTARCTICA

70°S 60°S 50°S 40°S

DIC

DIC
Hypothesis 1: Saturation of the Southern Ocean CO$_2$ sink
(Le Quéré et al. 2007)

Introduction

- zonal winds
- Antarctic Divergence
- ICE
- DIC
- Ekman transport
- ACC
- ANTARCTICA

$F_{natural}$
Hypothesis 1

Saturation of the Southern Ocean CO$_2$ sink
(Le Quéré et al. 2007)

Introduction

zonal winds

Antarctic Divergence

F$_{natural}$

ICE

DIC

ACC

upper cell

Ekman transport

ANTARCTICA

70°S 50°S 40°S

60°S
Hypothesis 2

Eddy compensation
(Böning et al. 2008)

zonal winds

South North

Ekman transport
Hypothesis 2

Eddy compensation
(Böning et al. 2008)

zonal winds

Ekman transport

Sud

Nord
Eddy compensation
(Böning et al. 2008)
Hypothesis 2

Eddy compensation
(Böning et al. 2008)

\[ \Delta F_{\text{natural}} ? \]

zonal winds

Ekman transport

Eddy transport

South

North
Introduction

Hypothesis 1
Saturation of the Southern Ocean CO$_2$ sink
(Le Quéré et al. 2007)

Coarse-resolution models

Hypothesis 2
Eddy compensation
(Böning et al. 2008)

Observations

Representation of mesoscale eddies in models

Question

How do mesoscale processes impact on the response of natural air-sea CO$_2$ fluxes to the SAM?

✓ Eddy-permitting model
✓ Sensitivity experiments to the SAM
Outline

I/ Method
Modelling framework
Approach

II/ Results
Description of the response
Analysis of the response
Eddy compensation

III/ Conclusions and perspectives
Outline

I/ Method
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III/ Conclusions and perspectives
- **Modelling system:** *NEMO* (Madec, 2008)
  - **OPA:** ocean (Madec et al. 1998)
  - **LIM:** sea ice (Fichefet and Maqueda, 1997)
  - **PISCES:** biogeochemistry (Aumont and Bopp, 2006)

- **Atmospheric forcing:**
  - **DRAKKAR Forcing Set 3** (Brodeau et al. 2010)
  - ERA-40 reanalyses + satellite

- **DRAKKAR configuration:** *BIOPERIANT05*
  - regional extraction from ORCA05
  - domain: South of 30°S
  - horizontal resolution: 0.5°

- **Characteristics:**
  - no eddy transport parameterization

- **Air-sea CO\(_2\) flux:**
  \[
  F = k \alpha \left( pCO_2^{oc} - pCO_2^{atm} \right) \left(1 - f_{\text{ice}}\right)
  \]
  \[
  \begin{align*}
  k & : \text{gas transfer coefficient (Whanninkhof, 1992)} \\
  \alpha & : \text{CO}_2 \text{ solubility (Weiss and Price, 1980)} \\
  pCO_2^{oc} & : \text{oceanic partial pressure of CO}_2 \\
  pCO_2^{atm} & : \text{atmospheric partial pressure of CO}_2, \text{278 ppm} \\
  f_{\text{ice}} & : \text{sea ice concentration}
  \end{align*}
  \]
$\vec{U}(x, y, t) = \vec{U}_{DFS3}(x, y, t) + (\beta \vec{P}(x, y))$

$\{ \vec{U} : $ wind velocity at 10 m 
\beta : +2$ \text{std}$ of the SAM index (NCEP) 
$\vec{P} : $ regression pattern of $\vec{U}_{DFS3}$ onto the SAM index

<table>
<thead>
<tr>
<th>Name</th>
<th>Type</th>
<th>Wind forcing</th>
</tr>
</thead>
<tbody>
<tr>
<td>REF05</td>
<td>control</td>
<td>DFS3</td>
</tr>
<tr>
<td>SAM05</td>
<td>sensitivity</td>
<td>DFS3 + perturbation</td>
</tr>
</tbody>
</table>

**Experiments:**

- **Method**: model
- **Approach**: approach

**Response of natural CO$_2$ fluxes to the SAM:** anomaly over 1995-2004: $\Delta = \text{SAM05} - \text{REF05}$
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Response of natural CO$_2$ fluxes to the SAM

**Intensity**
- $\Delta F = 0.09 \text{ Pg C yr}^{-1}\text{std}^{-1}(\text{SAM})$

**Spatial distribution**
- Zonally inhomogeneous

**Conclusions**
- Inhomogeneous spatial distribution
Response of natural CO₂ fluxes to the SAM

Results

- Intensification of outgassing
- Intensification of uptake

Intensity
- ΔF = 0.09 Pg C yr⁻¹ std⁻¹ (SAM)
- AZ: 83% of the SO response

Spatial distribution
- Zonally inhomogeneous
- 3 sectors of intensified outgassing

Conclusions
- Inhomogeneous spatial distribution
- Dominance of high latitudes (AZ)
\[ F = k\alpha\left(pCO_2^{oc} - pCO_2^{atm}\right)\left(1 - f_{ice}\right) \]

- \( f(SST,SSS,Wr) \)
- \( f(SST,SSS) \)
- \( f(SST,SSS,DIC,Alk) \)
\[ F = k(pCO_{2}^{oc} - pCO_{2}^{atm})(1 - f_{\text{co}}) \]

\( f(T, S, Wr) \)  \( f(T, S) \)  \( f(SST, SSS, DIC, Alk) \)

\[ \rightarrow \text{Wr, DIC, Alk, SST and SSS} \]
Results

**Response**: F = k \(\Delta pCO_2^o - \Delta pCO_2^{atm}\) \((1 - f)\)

**Analysis**: \(f(SST,SSS,Alk)\)

**Compensation**: \(f(SST,SSS)\)

### Major Drivers
- \(\Delta DIC\) and \(\Delta Alk\)

### Minor Drivers
- \(\Delta SST\), \(\Delta SSS\), \(\Delta Wr\)

### Conclusions
- Major drivers: \(\Delta DIC\) and \(\Delta Alk\)
- Minor drivers: \(\Delta SST\), \(\Delta SSS\), \(\Delta Wr\)
Meridional transport of DIC by density classes:

\[ \Gamma_{tot}(y, \sigma_2) = \iint_{-H} z(x, y, \sigma_2) \cdot v \times DIC \, d\tilde{z} \, dx \]

where:
- \( v \): meridional velocity
- \( \sigma_2 \): potential density referenced at 2000m
- \( \tilde{z} \): depth of \( \sigma_2 \) isopycnal
- \( H \): bottom depth

Integration:
- **zonally**: along isopycnals
- **vertically**: from bottom to top

Results response analysis compensation
Meridional transport of DIC by density classes:

\[ \Gamma_{tot}(y,\sigma_2) = \oint \oint_{-H} z(x,y,\sigma_2) \times \mathbf{v} \times \text{DIC} \, d\tilde{z}' \, dx \]

- \( \mathbf{v} \): meridional velocity
- \( \sigma_2 \): potential density referenced at 2000m
- \( \tilde{z} \): depth of \( \sigma_2 \) isopycnal
- \( H \): bottom depth

Integration:
- zonally: along isopycnals
- vertically: from bottom to top

Antarctic Divergence

REF05

Potential density \( \sigma_2 \) (kg m\(^{-3}\))

\( \Delta T \): thickness of ice

\( \Delta T \) (upper cell)

\( \Delta T \) (upper cell)
Results

ΔΓ

$\Delta \Gamma_{tot}$

total

anomaly

$P_{GC \ yr^{-1}}$

potential density $\sigma^2 (kg \ m^{-3})$

AZ

latitude
Results
response
analysis
compensation

\[ \Delta \Gamma_{\text{tot}} \text{ total} \]

\[ \Delta \Gamma = \Delta \Gamma_{\text{mean}} + \Delta \tilde{\Gamma}_{\text{standing}} + \Delta \Gamma^*_{\text{transient}} \]
Results

**ΔΓ**

**total**

\[
\Delta \Gamma_{\text{tot}} = \Delta \Gamma_{\text{mean}} + \Delta \Gamma_{\text{standing}} + \Delta \Gamma_{\text{transient}}
\]

potential density \(\sigma_2\) (kg m\(^{-3}\))

anomaly

PgC yr\(^{-1}\)

-10
-6
0
6
10

latitude

AZ

mean standing transient
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How do mesoscale processes impact on the response of natural air-sea CO$_2$ fluxes to the SAM?

- Distribution and intensity
  - Inhomogeneous spatial distribution
  - Domination of high latitudes (AZ)
How do mesoscale processes impact on the response of natural air-sea CO$_2$ fluxes to the SAM?

**Mechanisms**
- **Surface**: DIC increase compensated by alkalinity increase
- **Ocean interior**: partial eddy compensation dominated by standing eddies
How do mesoscale processes impact on the response of natural air-sea CO₂ fluxes to the SAM?

**Mechanisms**

- **Surface**: DIC increase compensated by alkalinity increase
- **Ocean interior**: partial eddy compensation dominated by standing eddies
Role of the mixed layer (ML) in the response
Which processes are responsible for the DIC increase into the ML?
Conclusions and perspectives

Role of the mixed layer (ML) in the response

Which processes are responsible for the DIC increase into the ML?

Perspectives

\[
\Delta F_{\text{natural}} \quad \text{surface} \quad \text{mixed layer} \quad \text{ocean interior}
\]

South \quad AZ \quad North

\[
\Gamma \quad \Gamma^* \quad <\Gamma> \quad \tilde{\Gamma}
\]

Tendency of DIC into the time-varying ML:

\[
\partial_t DIC_{ML} = \text{adv}_x + \text{adv}_y + \text{adv}_z + \text{ent} + \text{dif}_{xy} + \text{dif}_z + \text{flw} + \text{bio} + \text{flx}
\]
Conclusions and perspectives

Role of the mixed layer (ML) in the response
Which processes are responsible for the DIC increase into the ML?

Perspectives

Preliminary results
Vertical diffusion dominates & advection remains very small

Tendency of DIC into the time-varying ML:

$$\partial_t DIC_{ML} = \underbrace{adv_x + adv_y + adv_z}_{\text{adv}} + \underbrace{ent + dif_{xy} + dif_z}_{\text{diff}} + flw + bio + flx$$
How do mesoscale processes impact on the response of natural air-sea CO₂ fluxes to the SAM?

- **Question**

- **Distribution and intensity**
  - Inhomogeneous spatial distribution
  - Domination of high latitudes (AZ)

- **Mechanisms**
  - *Surface*: DIC increase compensated by alkalinity increase
  - *Mixed layer*: dominance of vertical diffusion
  - *Ocean interior*: partial eddy compensation dominated by standing eddies

- **Dufour et al., in preparation**: On eddy compensation of the enhanced sea-to-air CO₂ flux during positive phases of the Southern Annular Mode, *Global Biogeochemical Cycles.*