Air-sea CO$_2$ fluxes in the Southern Ocean: Lessons learned from the comparison between CMIP5 models and SOCCOM data

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Thanks to Matt Mazloff and Ariane Verdy
The Southern Ocean plays a key role in the global carbon cycle (adapted from Morrison et al. 2015).

The sign and strength of the total carbon sink remains uncertain.

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Estimating the Southern Ocean carbon sink is challenging

- **Observations**: no direct measurements, low spatial coverage, Summer bias
- **Models**: lack of observational constraints, complex processes to simulate

The Southern Ocean is the region of strongest disagreement
Overarching goal
Better quantify and understand the contemporary carbon sink in the Southern Ocean to improve future projections

Previous studies have identified issues with models
- Seasonal phasing of the fluxes
  → e.g. Lenton et al., 2013; Anav et al., 2013; Jiang et al., 2013; Kessler and Tjiputra, 2016; Nevison et al., 2016; Mongwe et al., 2018
- Inaccurate representation of flux intensity
  → e.g. Kessler and Tjiputra, 2016
- Physics would be the main driver
  → Orr et al., 2001; Ito et al., 2004; Lachkar et al., 2007; Pilcher et al., 2015; Galbraith et al. 2015

This study

1/ Revisit models' performance in light of new observational estimates
2/ Investigate the cause(s) of the disagreement between models and observations
### Method - Models and simulations

<table>
<thead>
<tr>
<th>Modelling center</th>
<th>Name</th>
<th>Vertical coordinate</th>
<th>Ocean resolution</th>
<th>Radiative/atm. forcing (time period)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CERFACS</td>
<td>CNRM-CM5</td>
<td>z</td>
<td>0.4° to 2°</td>
<td>historical (1996-2005)</td>
</tr>
<tr>
<td>IPSL</td>
<td>IPSL-CM5A-LR</td>
<td>z</td>
<td></td>
<td></td>
</tr>
<tr>
<td>IPSL</td>
<td>IPSL-CM5A-MR</td>
<td>z</td>
<td></td>
<td></td>
</tr>
<tr>
<td>MPI-M</td>
<td>MPI-ESM-LR</td>
<td>z</td>
<td></td>
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<tr>
<td>MPI-M</td>
<td>MPI-ESM-MR</td>
<td>z</td>
<td></td>
<td></td>
</tr>
<tr>
<td>NCC</td>
<td>NorESM1-ME</td>
<td>z</td>
<td></td>
<td></td>
</tr>
<tr>
<td>NOAA-GFDL</td>
<td>GFDL-ESM2G</td>
<td>isopycnal</td>
<td></td>
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<tr>
<td>NOAA-GFDL</td>
<td>GFDL-ESM2M</td>
<td>z</td>
<td></td>
<td></td>
</tr>
<tr>
<td>CMCC</td>
<td>CMCC-CESM</td>
<td>z</td>
<td></td>
<td></td>
</tr>
<tr>
<td>NSF-DOE-NCAR</td>
<td>NCAR-CESM1</td>
<td>z</td>
<td></td>
<td></td>
</tr>
<tr>
<td>NOAA-GFDL</td>
<td>CM2.6</td>
<td>z</td>
<td>0.1°</td>
<td>idealized 1%/yr (years 21-30)</td>
</tr>
<tr>
<td>Scripps</td>
<td>SOSE</td>
<td>z</td>
<td>1/3°</td>
<td>historical (2008-2012)</td>
</tr>
</tbody>
</table>

→ All models are climate models or Earth System Models
→ SOSE is an ocean-sea ice data assimilating model forced by atmospheric reanalyses
The Southern Ocean Carbon and Climate Observations and Modeling project (SOCCOM)
https://soccom.princeton.edu/

Autonomous biogeochemical profiling floats
- Deployment: Southern Ocean
- Time period: May 2014 – May 2018
- Number of floats studied: 35 (out of 114)
- Variables measured: pressure, temperature, salinity, pH, dissolved oxygen ($O_2$), nitrate ($NO_3$)

Air-sea CO$_2$ flux estimate (Gray et al., 2018)

\[ F = k K_0 (pCO_{2}^{oc} - pCO_{2}^{atm}) \]

- Solubility from measured $T$ and $S$ (Weiss, 1974)
- Oceanic partial pressure of CO$_2$ $f(T,S,pH,Alk)$ calculated from measured $T$, $S$, $pH$ and estimated $Alk$ (Carter et al. 2016)
- Gas transfer velocity from measured $T$ and $S$ and wind reanalysis products (Wanninkhof, 2014)
- Atmospheric partial pressure of CO$_2$ from observations at Cape Grim, Australia

Unprecedented coverage, year round measurements, possibility of reconstructing CO$_2$ fluxes
Subtropical Front
Subantarctic Front
Open-ocean polynya
Sea ice Front

Method - Provinces

6 provinces
- physical and biogeochemical regions
- detected from an automated method for models and observations
Results – Comparison with observations

Annual air-sea CO$_2$ fluxes

Observations
CM2.6
SOSE
CNRM-CM5
MPI-ESM-MR
GFDL-ESM2M

uptake
outgassing
mol m$^{-2}$ yr$^{-1}$
- Almost all models simulate a sink in agreement with pCO$_2$ based estimates
- Estimates from SOCCOM floats show a very weak sink
Results - Causes for the disagreement

- Largest model spread of all the provinces and strong interannual variability
- Disagreement on the flux sign and magnitude between models and observations
- None of the models capture the strong outgassing observed in the ASZ
Seasonal cycle of fluxes in the ASZ

Results - Causes for the disagreement

- Many models are out-of-phase with observations: outgassing (summer), uptake/weak outgassing (winter)
- None of the models reproduce the outgassing observed in winter
- Models producing a significant outgassing in winter show strong uptake in summer
Results – Causes for the disagreement

Wind stress
- Max of zonal wind stress too equatorward
- Models “in-phase”: strongest wind stress
- Models “out-of-phase”: weakest wind stress

Temperature in the ASZ
- Models generally too warm in all seasons
- Models “out-of-phase”: too warm in summer?
Results – Causes for the disagreement

DIC in the ASZ
Models underestimate DIC in all seasons

MLD in the ASZ
- Too shallow in summer for most models
- Too shallow in winter for many models
Conclusions

How do models compare to recent observational estimates of CO$_2$ fluxes in the Southern Ocean?

- Strongest disagreement in the ASZ (sign and intensity), and in the Pacific sector
- Models do not reproduce the observed outgassing at the right time nor with the right magnitude
- Neither CM2.6 nor SOSE show significant improvement compared to the CMIP5 models

Why do models disagree with observations in the ASZ?

- Winds: Westerly winds too equatorward and/or too weak (weak upwelling)
- Temperature: Surface is too warm (shallow mixed layer)
- DIC: concentrations are too low (shallow mixed layer)
What is next?

**Observations: more data in the next years**
- Refine the flux estimates
- Increase the spatial coverage
- Give some insights into the interannual variability

**Models: looking towards CMIP6**
- Compare with CMIP5 models and identify the similarities and differences
- Focus analyses on the main drivers (wind, temperature, DIC, etc) of the fluxes
- Use SOSE to help identify the causes for the misrepresentation of fluxes
**Results**

**Large disagreement across observational products**

Major uncertainties in estimating the carbon sink
- Summer bias
- Interannual variability

(Gray et al. 2018)
The strongest disagreement between models and obs, and among models is found in the ASZ for flux magnitude and sign.
Results

- Most models are out-of-phase with observations in the SAZ, PFZ and ASZ
- This seasonal disagreement averages out at annual scale for some models
Comparison of wind stress

- NCEP
- ERA-Interim
- CNRM_CM5
- IPSL_CM5A_LR
- IPSL_CM5A_MR
- MPI_ESM_LR
- MPI_ESM_MR
- NorESM1_ME
- GFDL_ESM2G
- GFDL_ESM2M
- CMCC_CESM
- NCAR_CESM1
- CM2.6
**Hypothesis**

Seasonal cycle out-of-phase

![Graph showing seasonal cycle out-of-phase](image_url)
Hypothesis
Seasonal cycle out-of-phase

[DIC]

- **early biological drawdown** (rapid/early restratification)
- **weak biological drawdown** (iron depleted)

- amplitude reduced
- timing shifted

Winter

Summer

time
Hypothesis
Seasonal cycle out-of-phase
Hypothesis
Seasonal cycle out-of-phase

[DIIC]

Winter Summer

shallow
mixed layers/
weak
upwelling
Effect of wind stirring

Rodgers et al. (2014)
Sensitivity experiments to wind stirring parameterization in a 2° global model (NEMO-PISCES)

WSTIR – CTRL CO₂ flux (mol/m²/yr)
+0.9 Pg C/yr outgassing with wind stirring

Global mixed layer depth (m)
- Observations
- CTRL run
- WSTIR run

Southern Ocean CO₂ flux (Pg C/yr)

Ocean carbon uptake (Pg carbon yr⁻¹)
uptake

more outgassing/less uptake
Effect of wind intensification

Dufour et al. (2013)
Sensitivity experiments to intensification and poleward shift in winds (positive SAM) in a 0.5° regional model (NEMO-PISCES)

+0.1 Pg C/yr outgassing with positive SAM

Weak and equatorward bias in westerlies

OCB CMIP6 Workshop 2018