Air-sea CO_2 fluxes in the Southern Ocean: Lessons learned from the comparison between CMIP5 models and SOCCOM data

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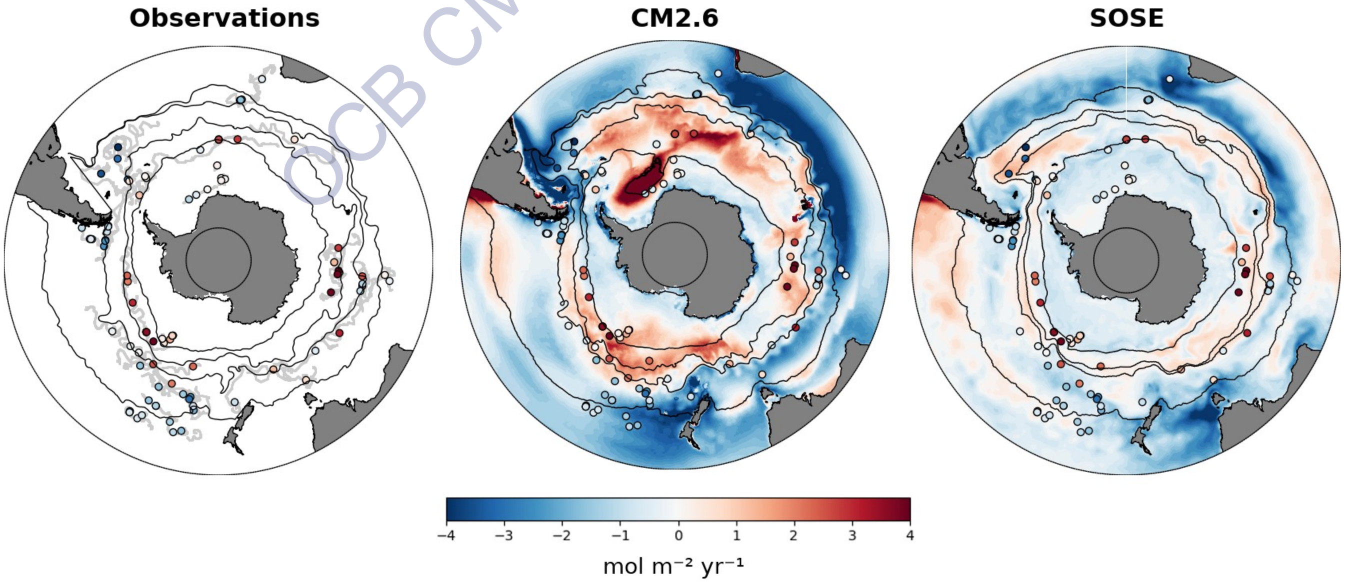
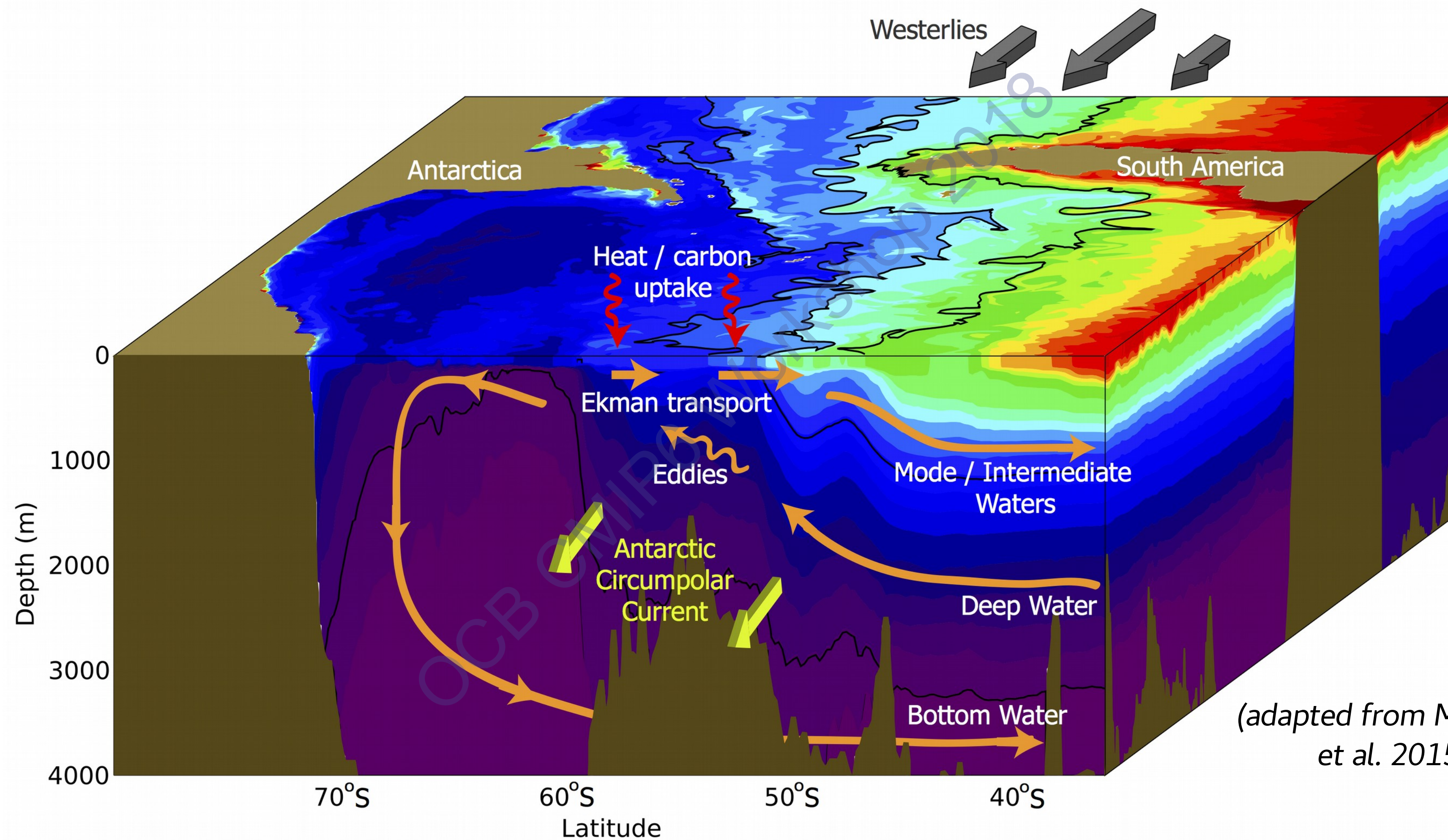
Thanks to Matt Mazloff and Ariane Verdy



Introduction

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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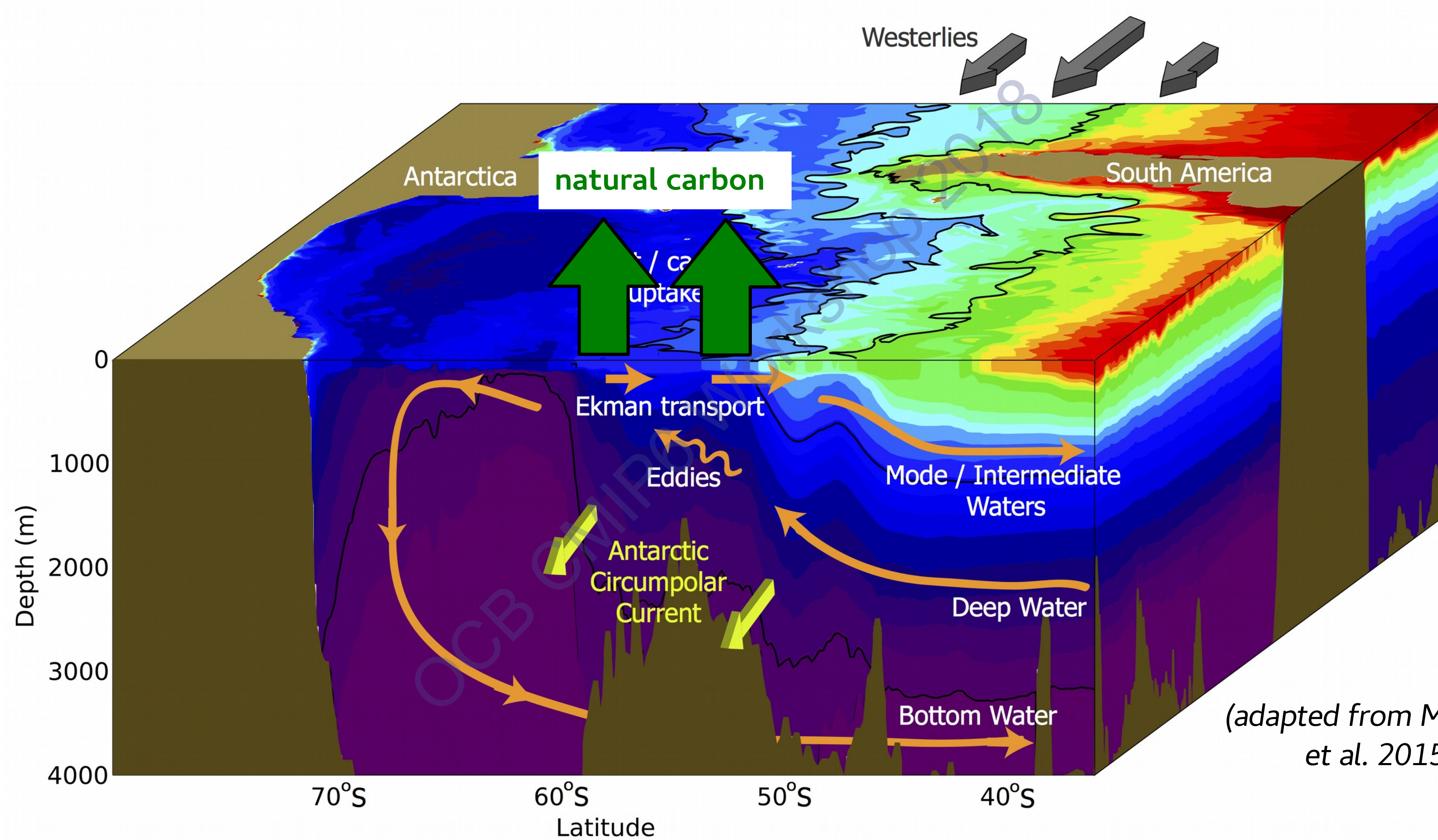

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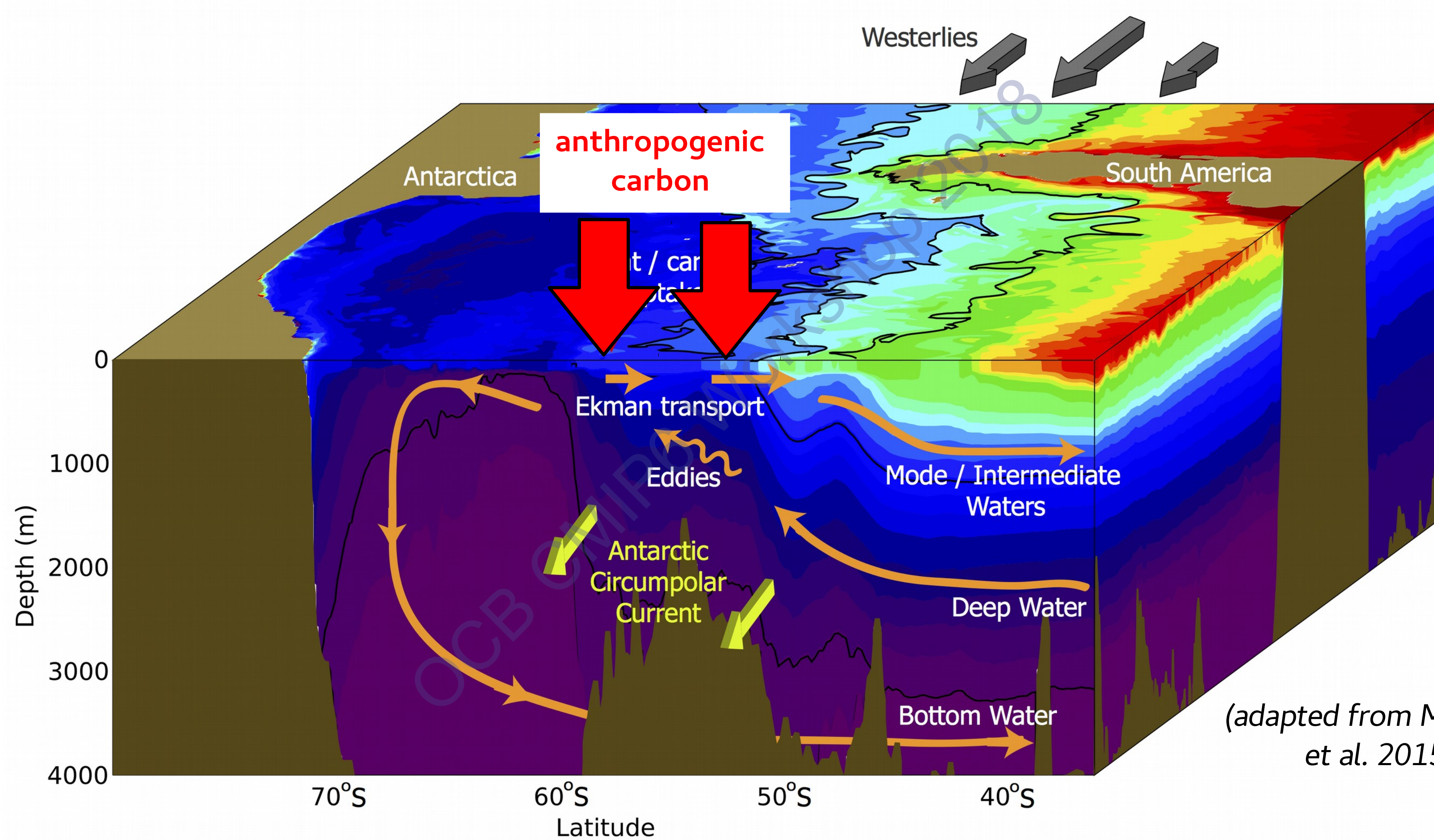

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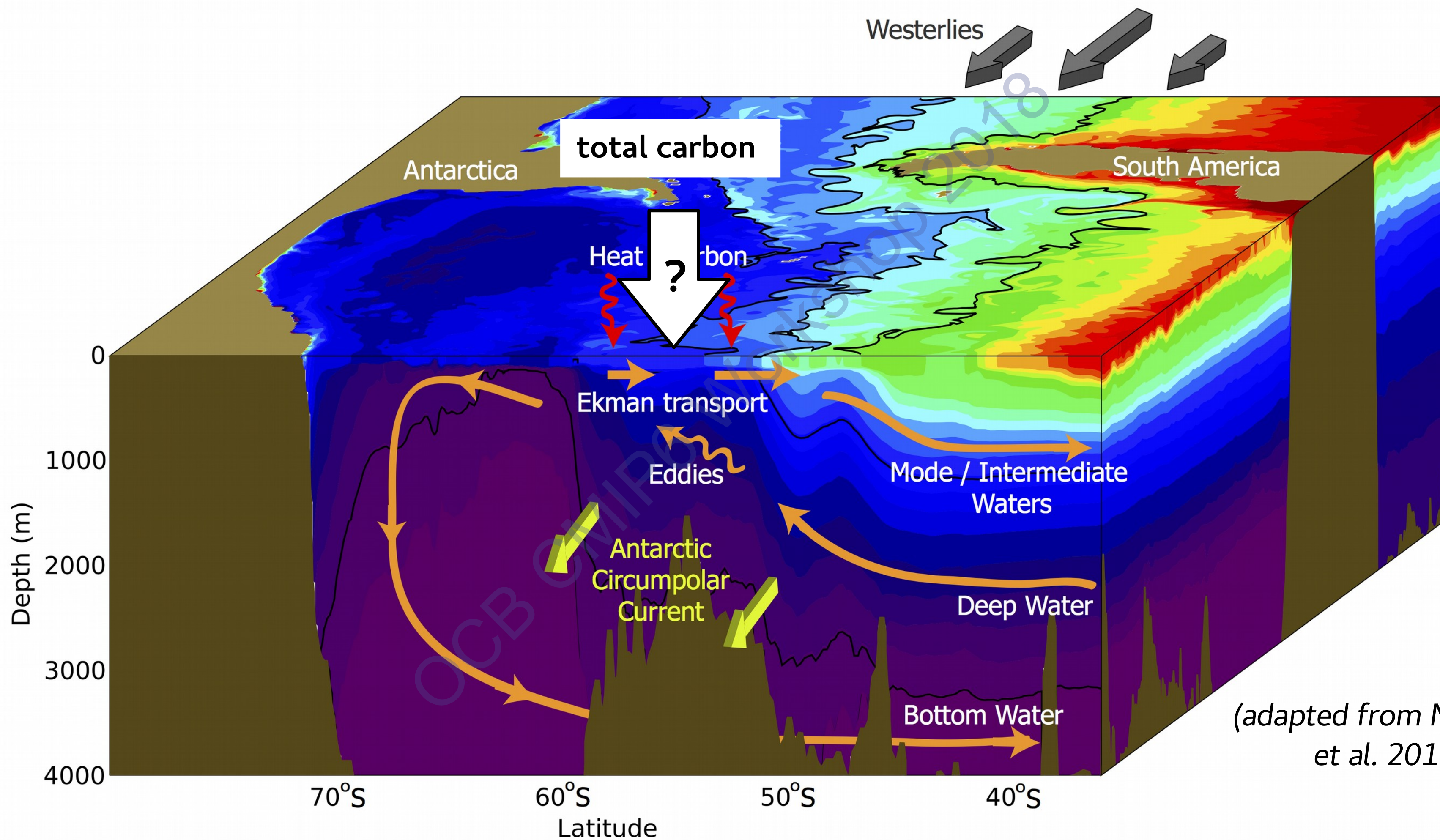

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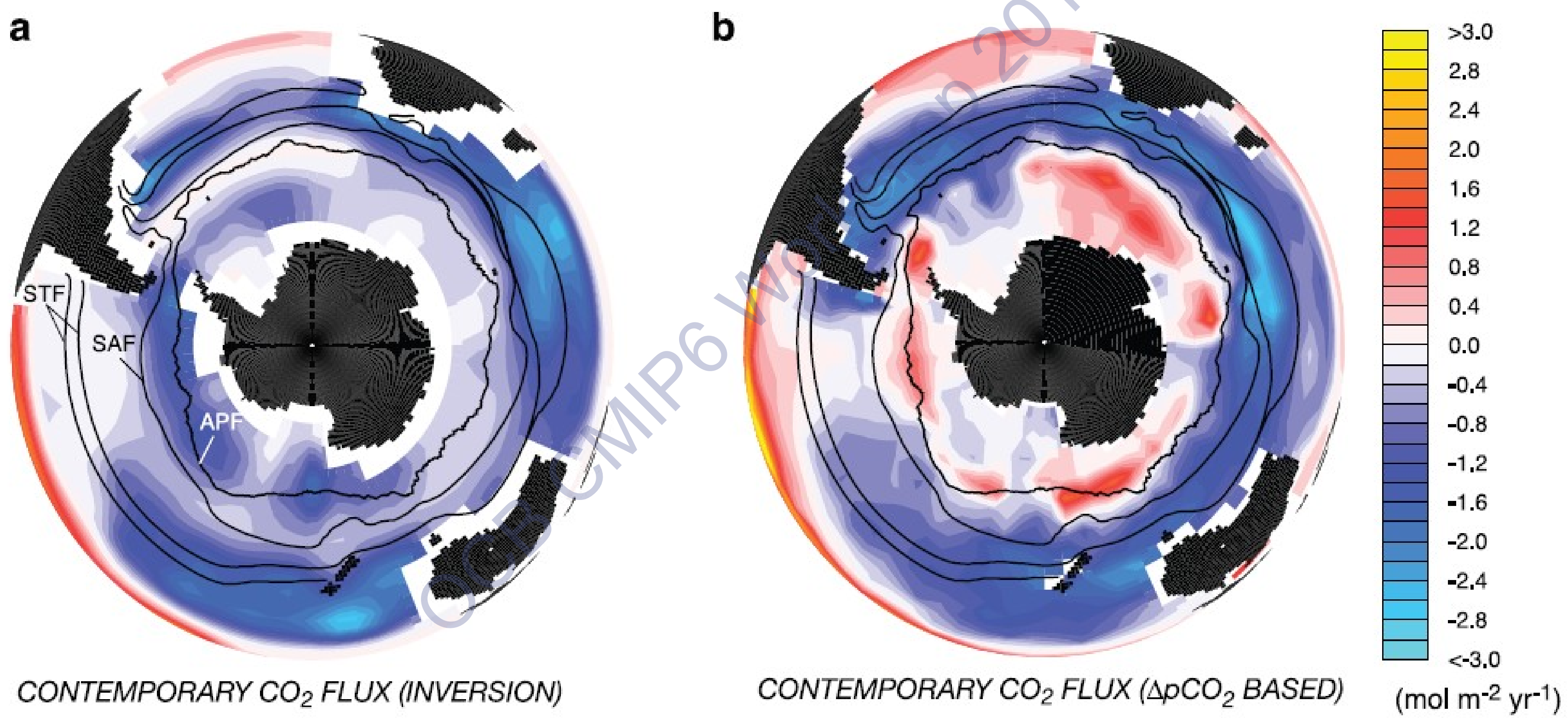
The sign and strength of the total carbon sink remains uncertain

Introduction

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



(Gruber et al. 2009)

The Southern Ocean is the region of strongest disagreement

Introduction

Overarching goal

Better quantify and understand the contemporary carbon sink in the Southern Ocean
to improve future projections

<u>Previous studies have identified issues with models</u>

- 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*

<u>This study</u>

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

	Modelling center	Name	Vertical coordinate	Ocean resolution	Radiative/atm. forcing (time period)
CMIP5 models	CERFACS	CNRM-CM5	z	0.4° to 2°	historical (1996-2005)
	IPSL	IPSL-CM5A-LR	z		
	IPSL	IPSL-CM5A-MR	z		
	MPI-M	MPI-ESM-LR	z		
	MPI-M	MPI-ESM-MR	z		
	NCC	NorESM1-ME	z		
	NOAA-GFDL	GFDL-ESM2G	isopycnal		
	NOAA-GFDL	GFDL-ESM2M	z		
	CMCC	CMCC-CESM	z		
	NSF-DOE-NCAR	NCAR-CESM1	z		
	NOAA-GFDL	CM2.6	z	0.1°	idealized 1%/yr (years 21-30)
	Scripps	SOSE	z	1/3°	historical (2008-2012)

→ All models are climate models or Earth System Models
→ SOSE is an ocean-sea ice data assimilating model forced by atmospheric reanalyses

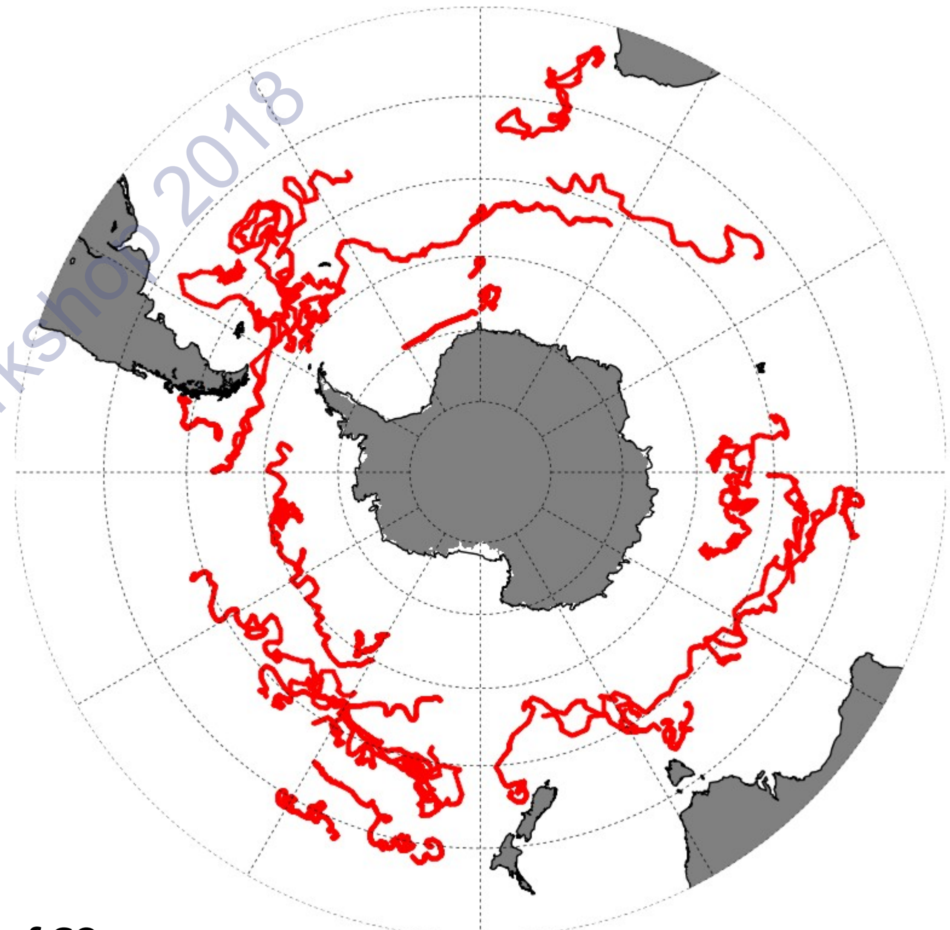
Method – Observations

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)*

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)

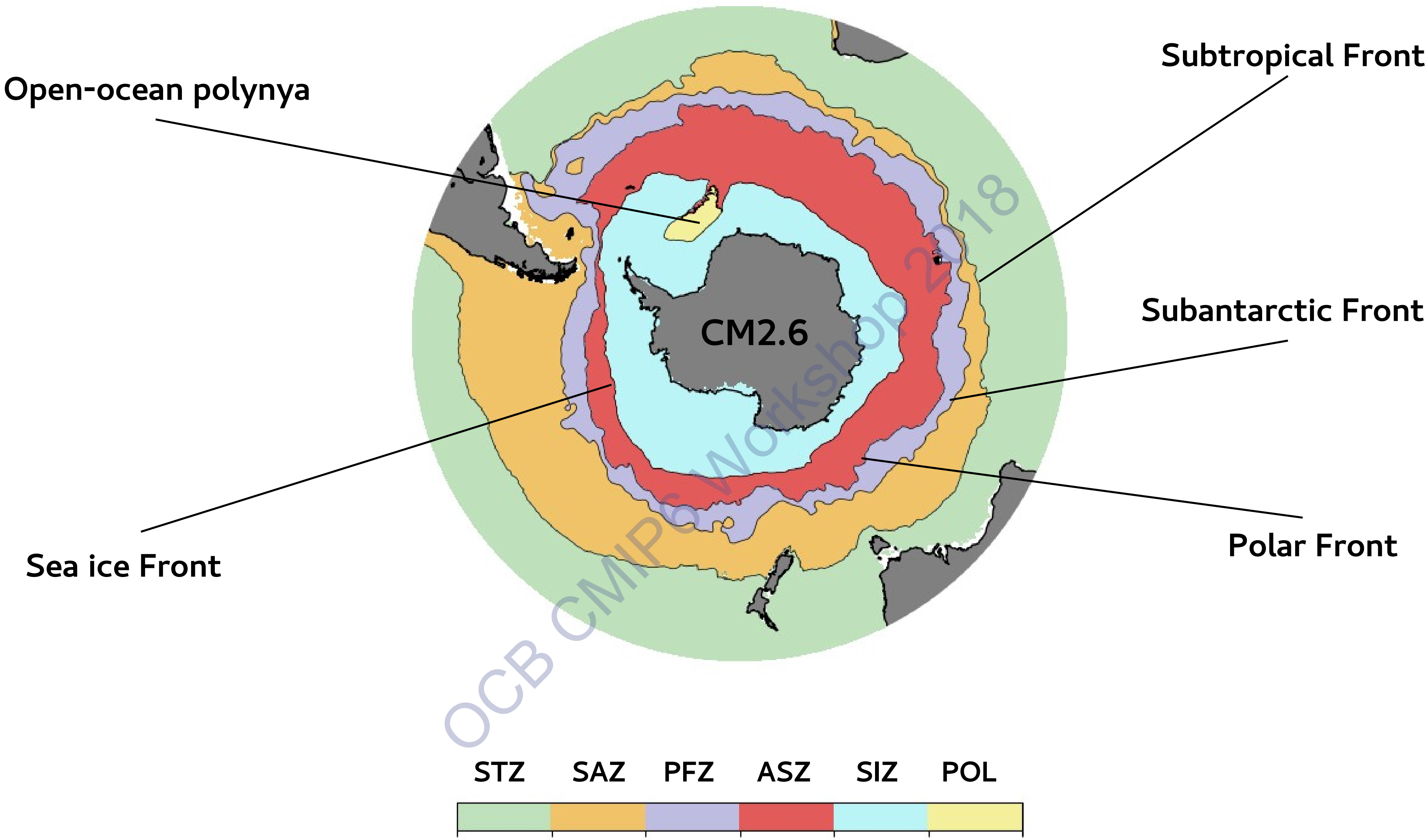
$$F = k K_0 \left(pCO_2^{oc} - pCO_2^{atm} \right)$$

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

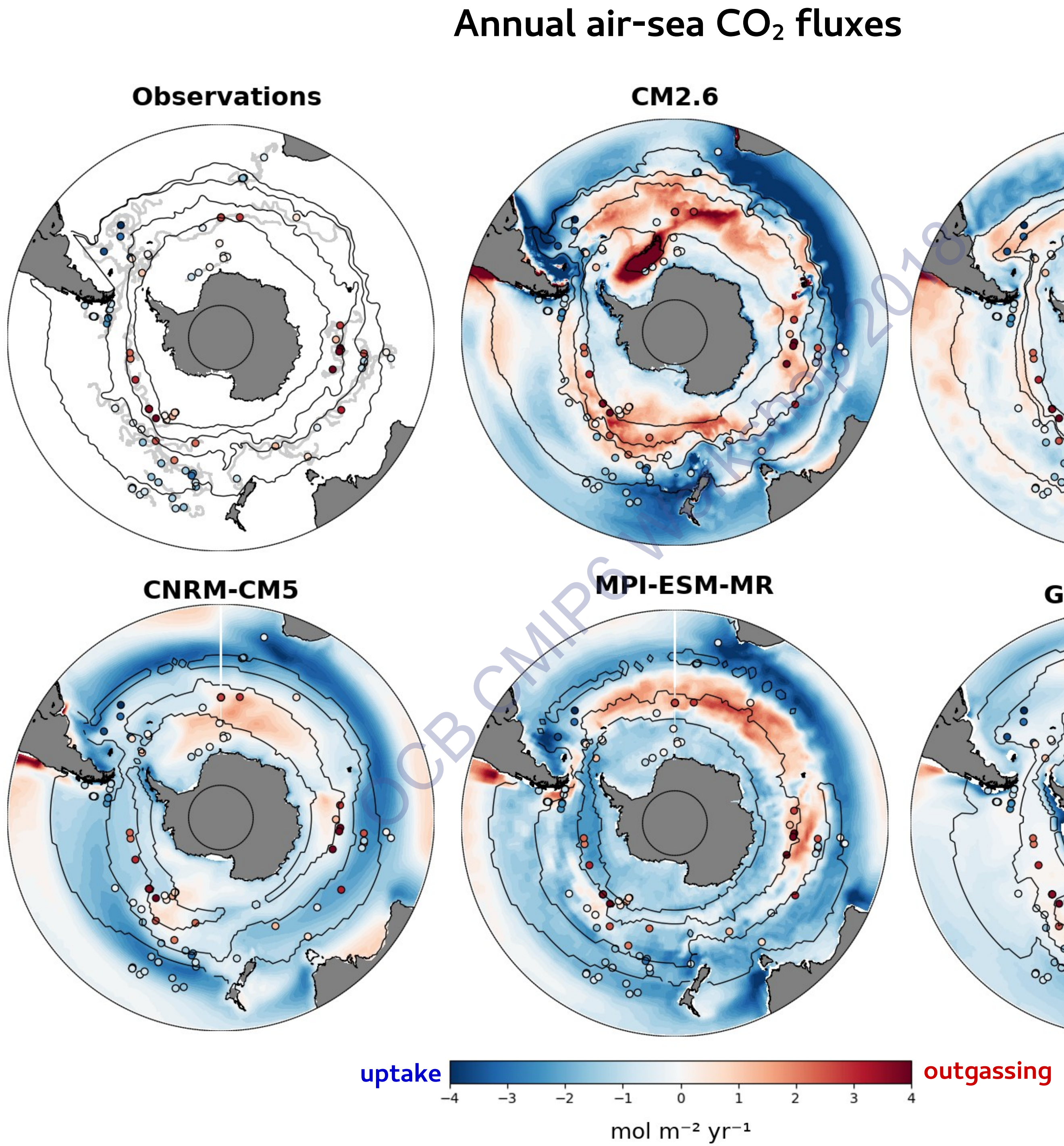
Unprecedented coverage, year round measurements, possibility of reconstructing CO_2 fluxes

Method – Provinces

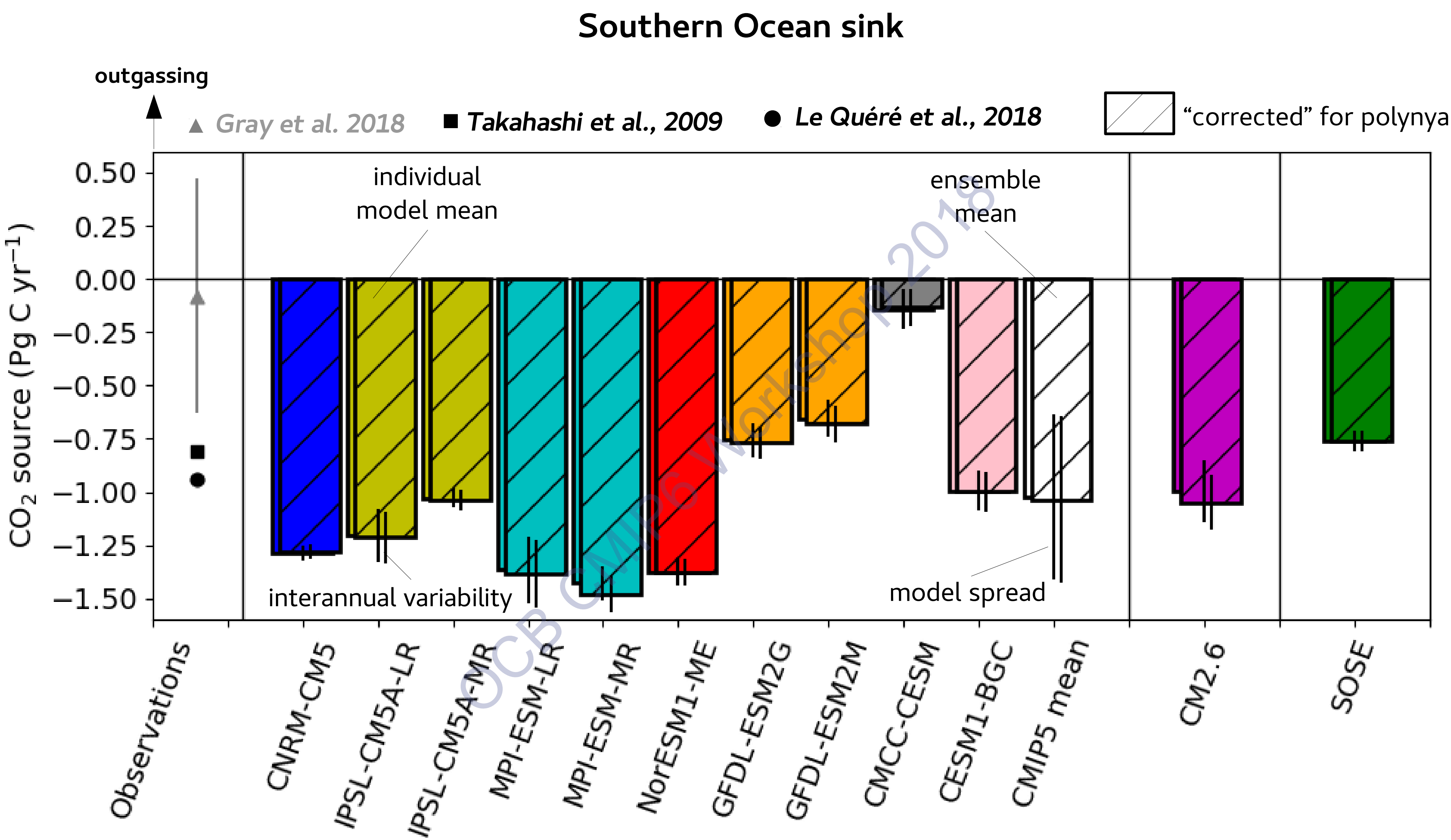


6 provinces
- physical and biogeochemical regions
- detected from an automated method for models and observations

Results – Comparison with observations

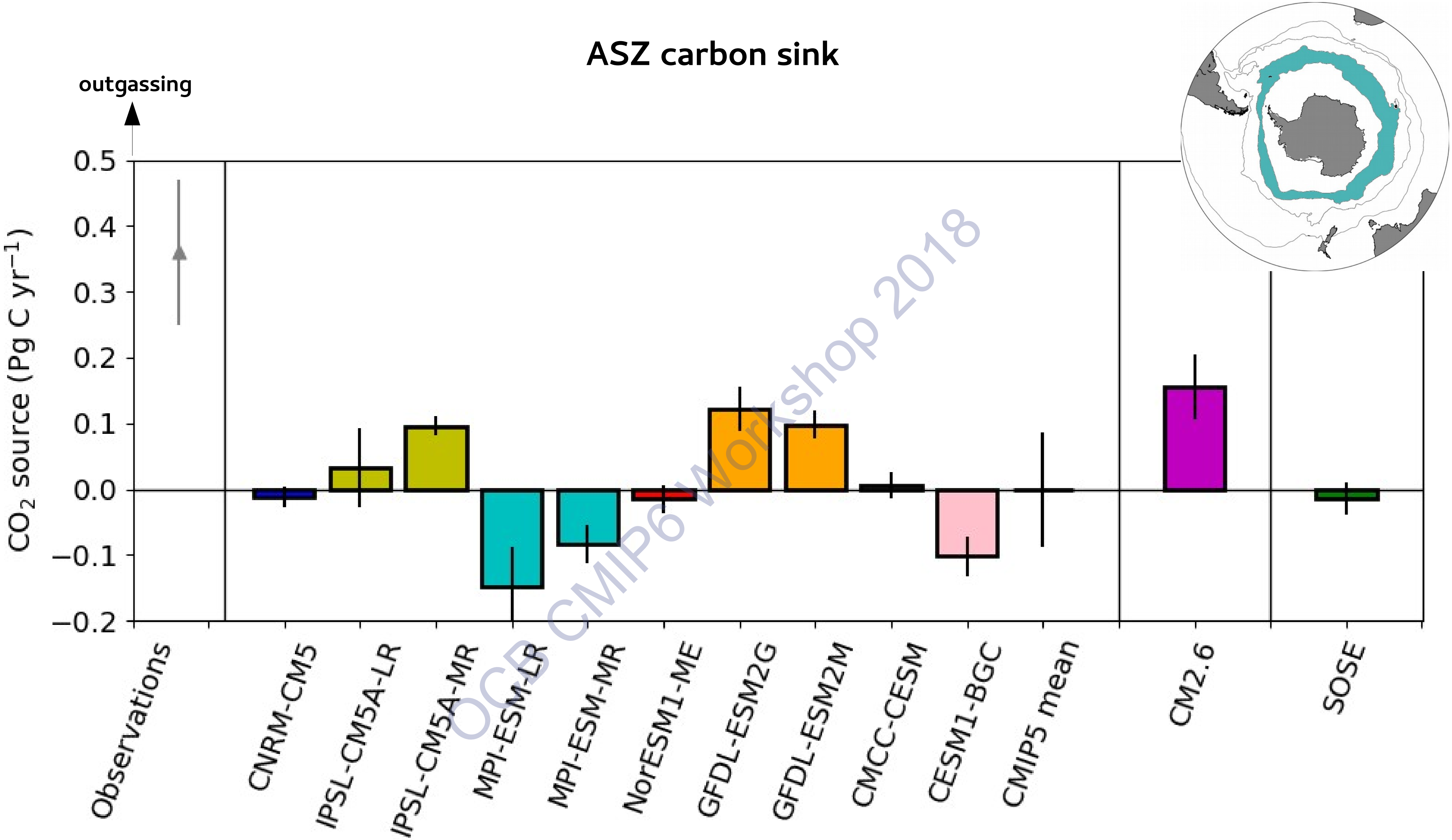


Results – Comparison with observations



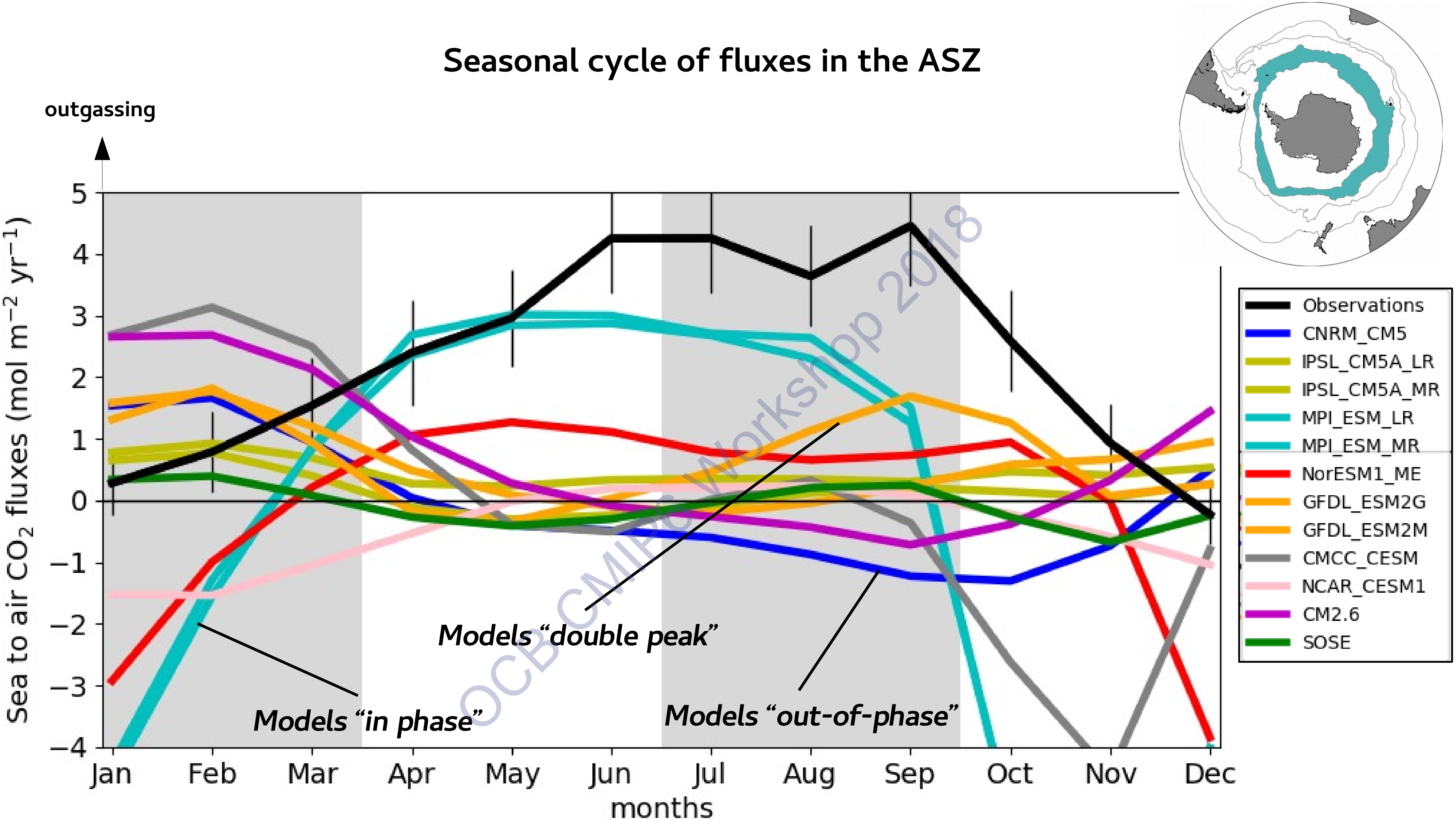
- Almost all models simulate a sink in agreement with pCO_2 based estimates
- Estimates from SOCCOM floats show a very weak sink

Results – Causes for the disagreement



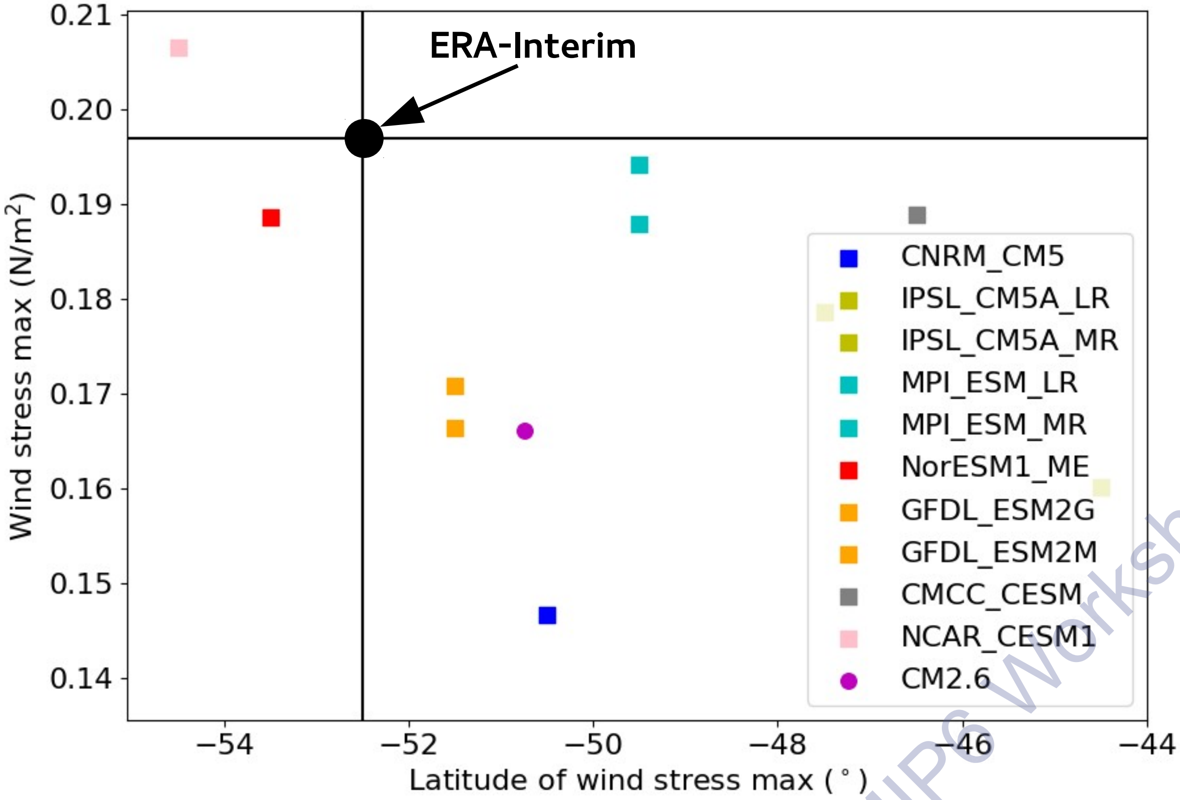
- Largest model spread of all the provinces and strong interannual variability
- Disagreement on the flux sign and magnitude between models and observations
- None of the models capture the strong outgassing observed in the ASZ

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

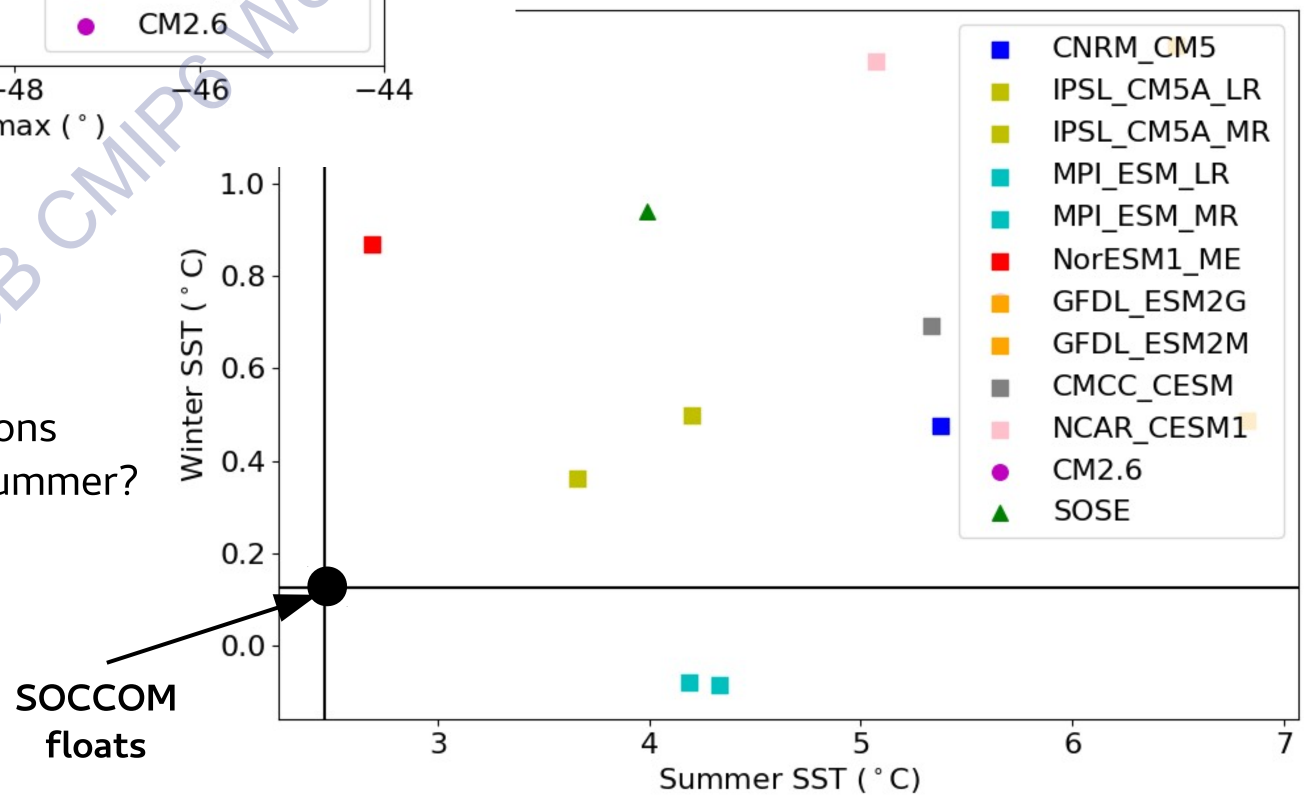


Wind stress

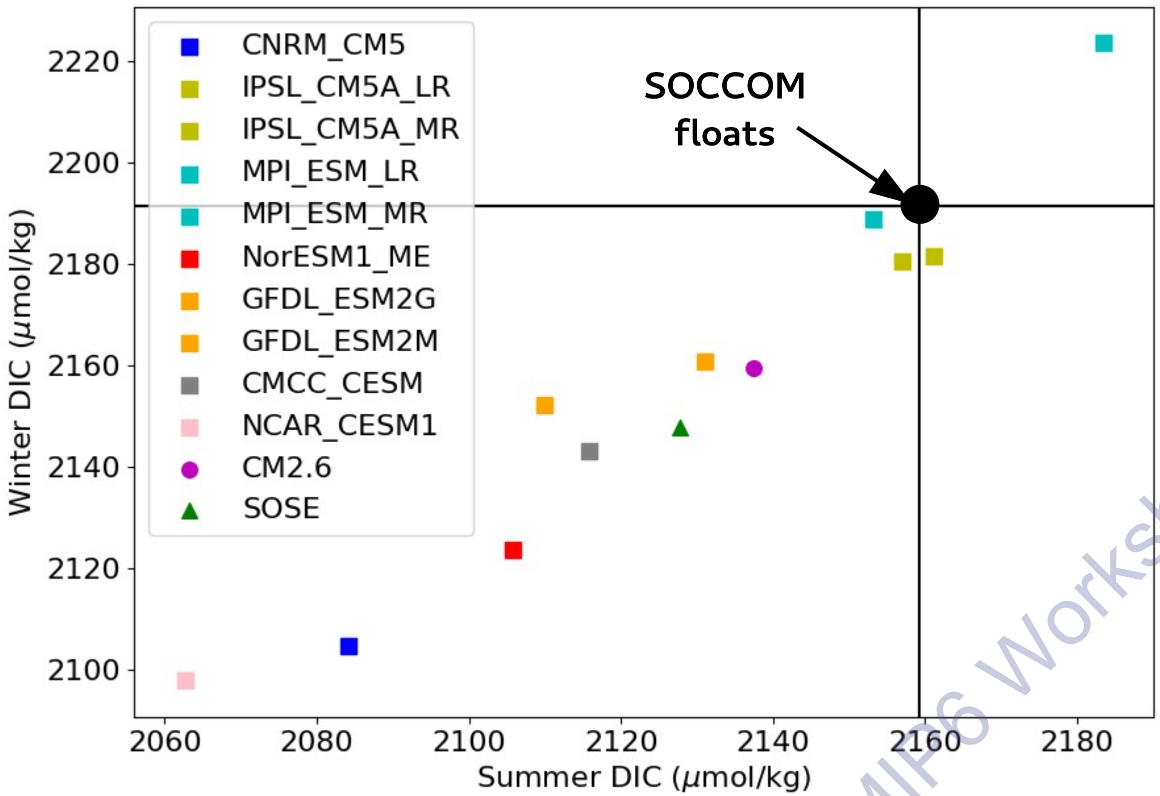
- Max of zonal wind stress too equatorward
- Models "in-phase": strongest wind stress
- Models "out-of-phase": weakest wind stress

Temperature in the ASZ

- Models generally too warm in all seasons
- Models "out-of-phase": too warm in summer?



Results – Causes for the disagreement

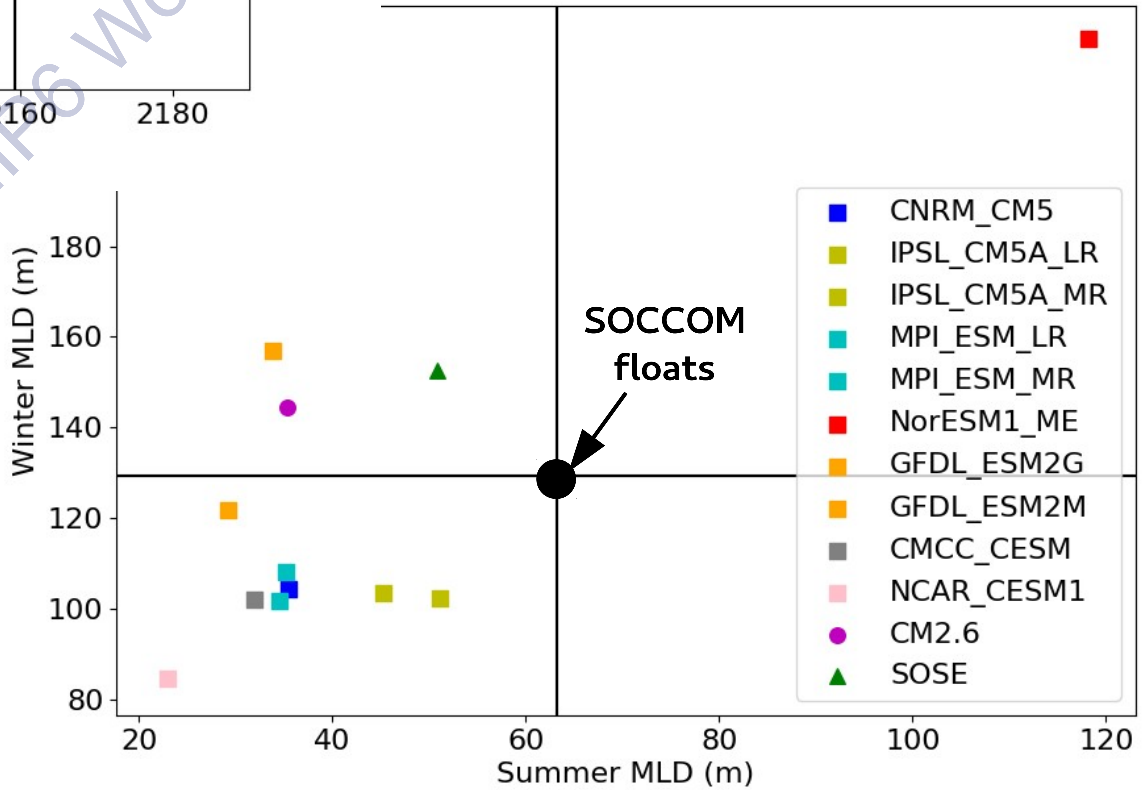


DIC in the ASZ

Models underestimate DIC in all seasons

MLD in the ASZ

- Too shallow in summer for most models
- Too shallow in winter for many models



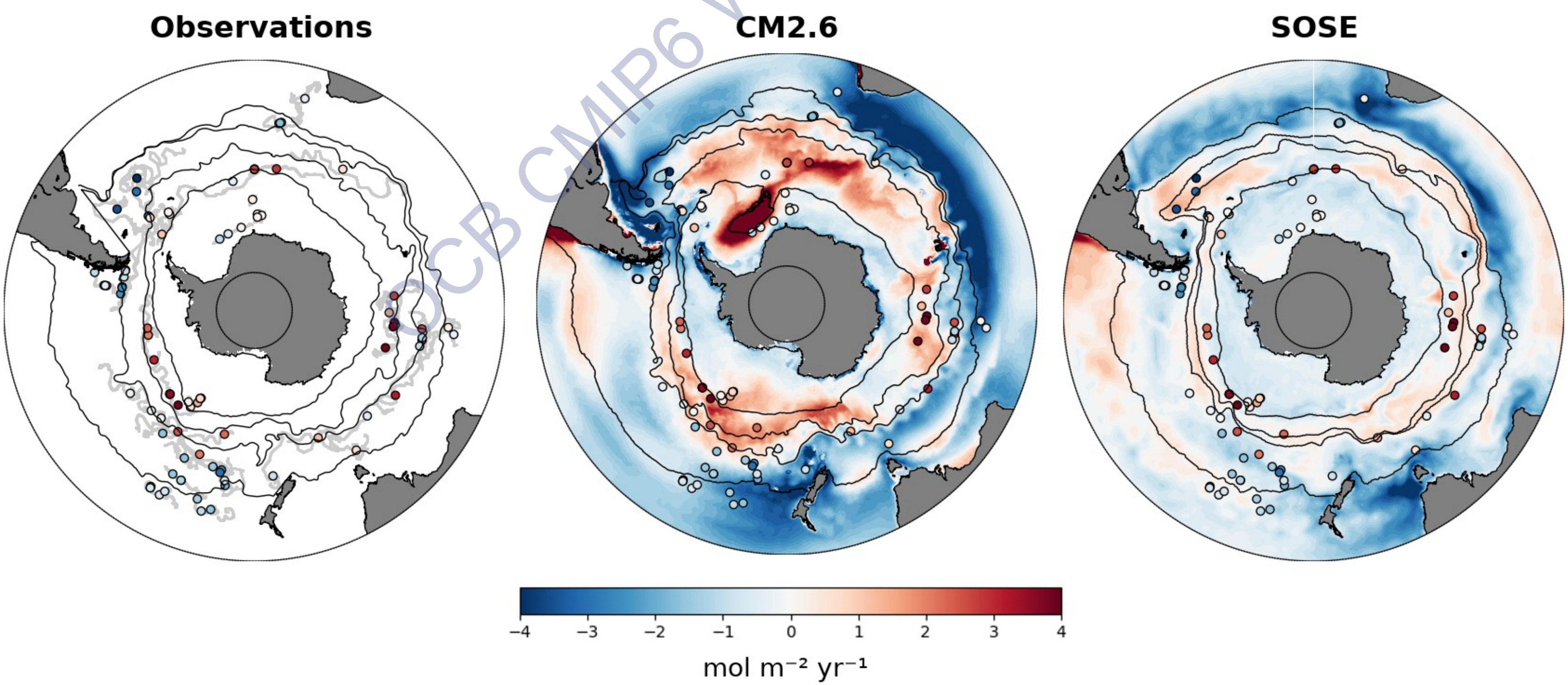
Conclusions

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

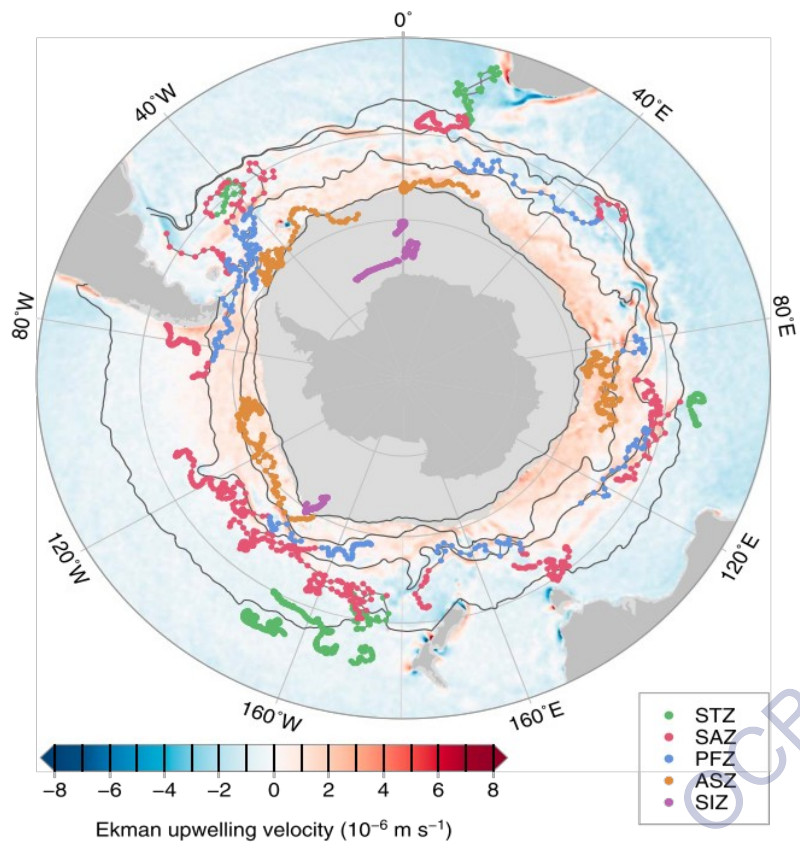
- Refine the flux estimates
- Increase the spatial coverage
- Give some insights into the interannual variability

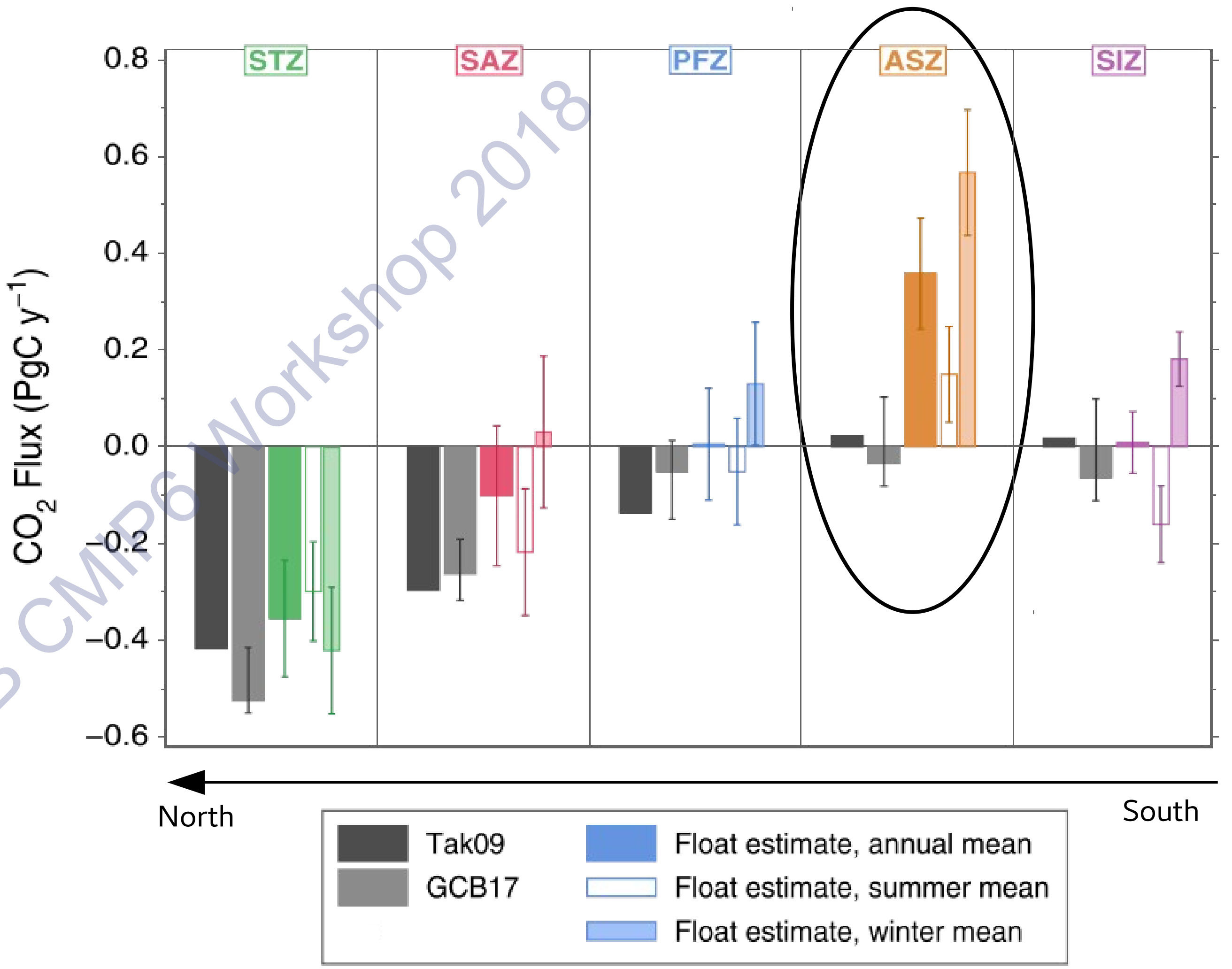
Models: looking towards CMIP6

- 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

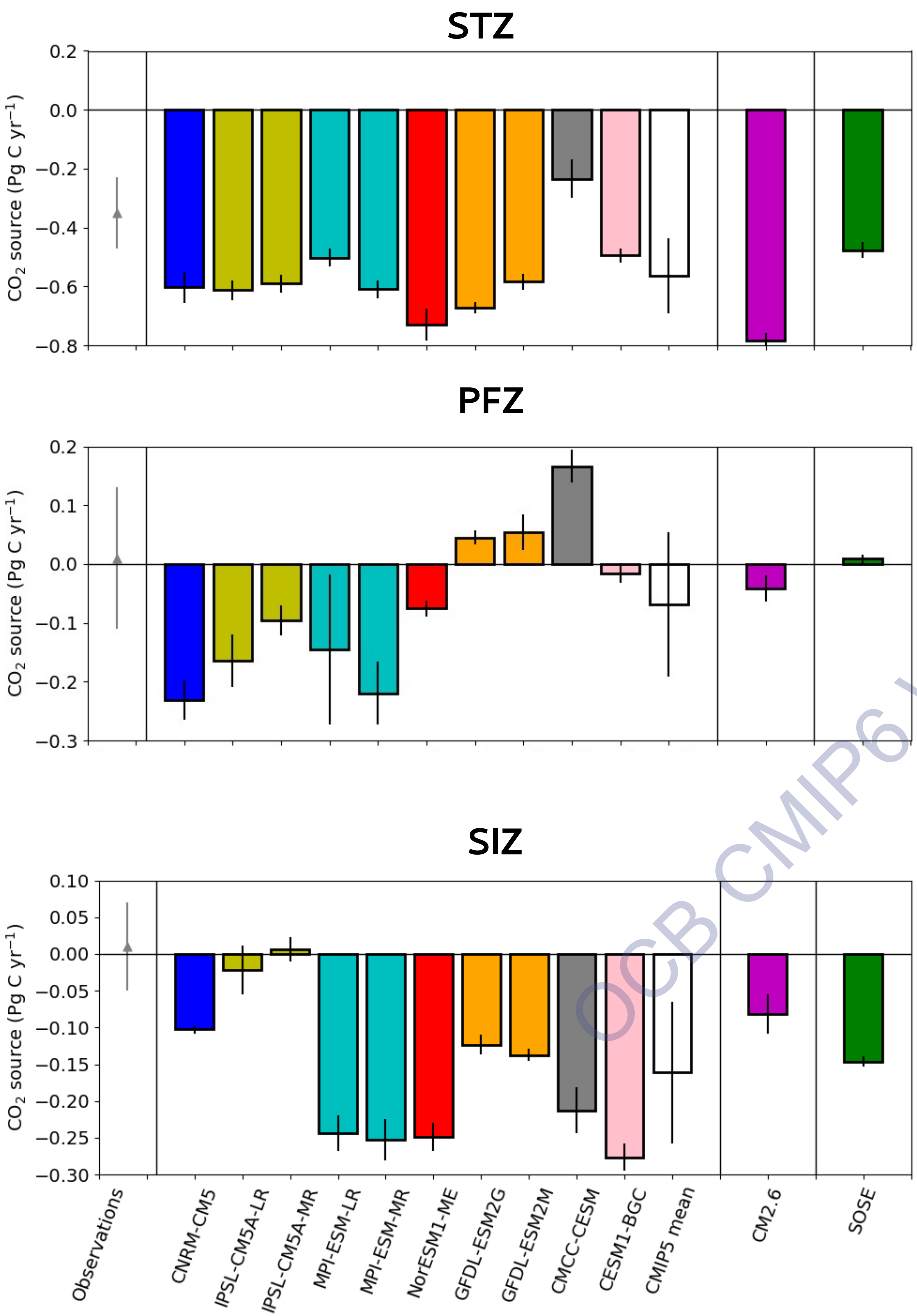


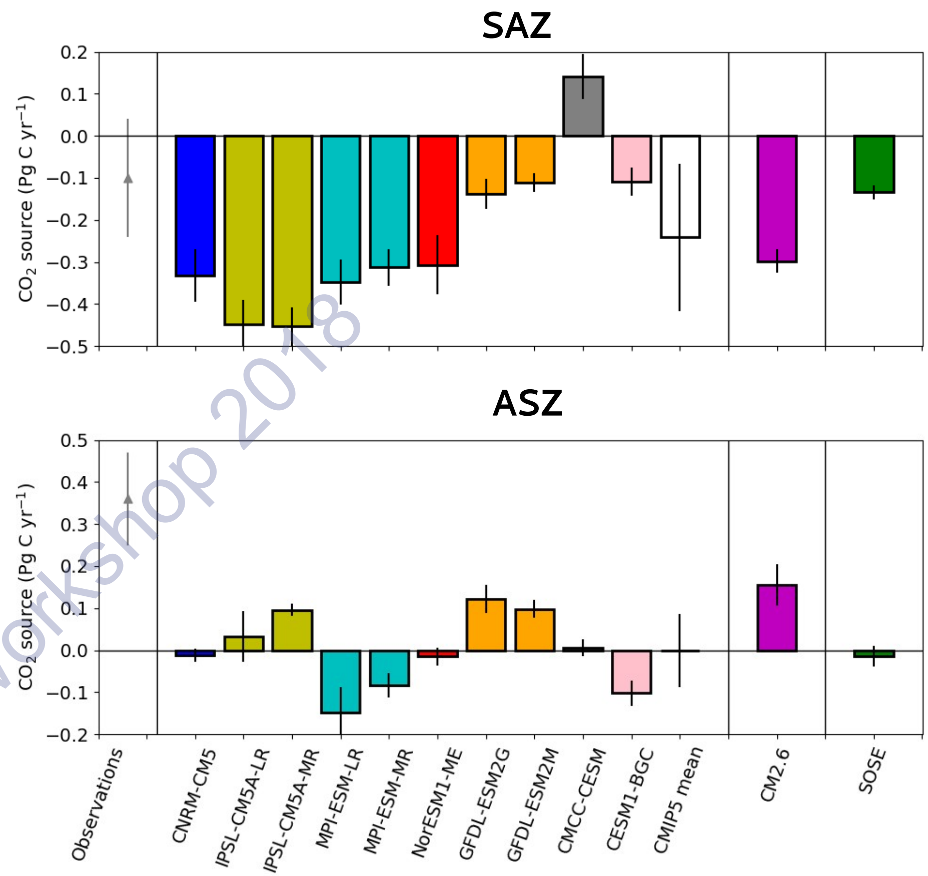


Major uncertainties in estimating the carbon sink
- Summer bias
- Interannual variability

(Gray et al. 2018)

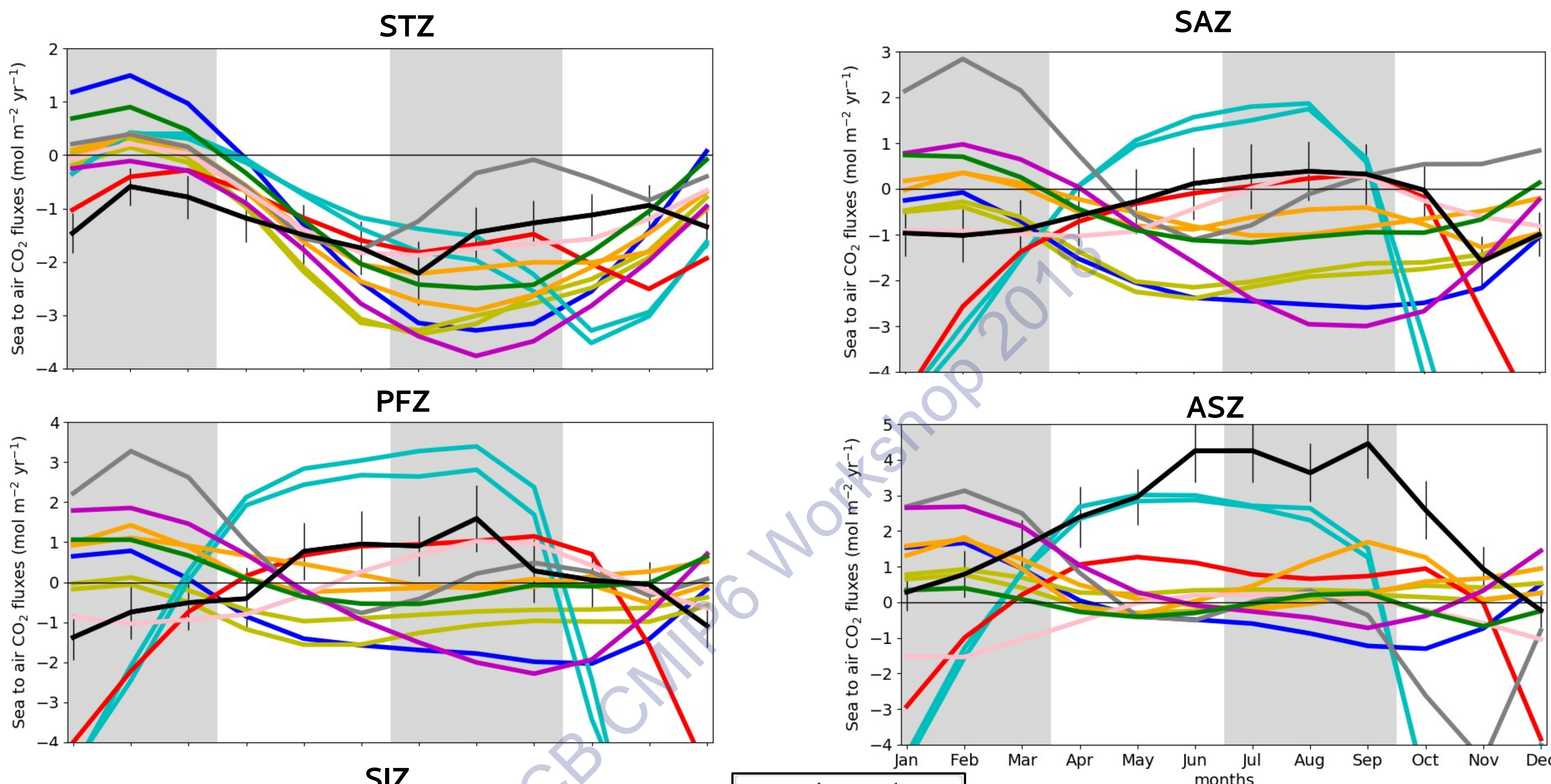
Results

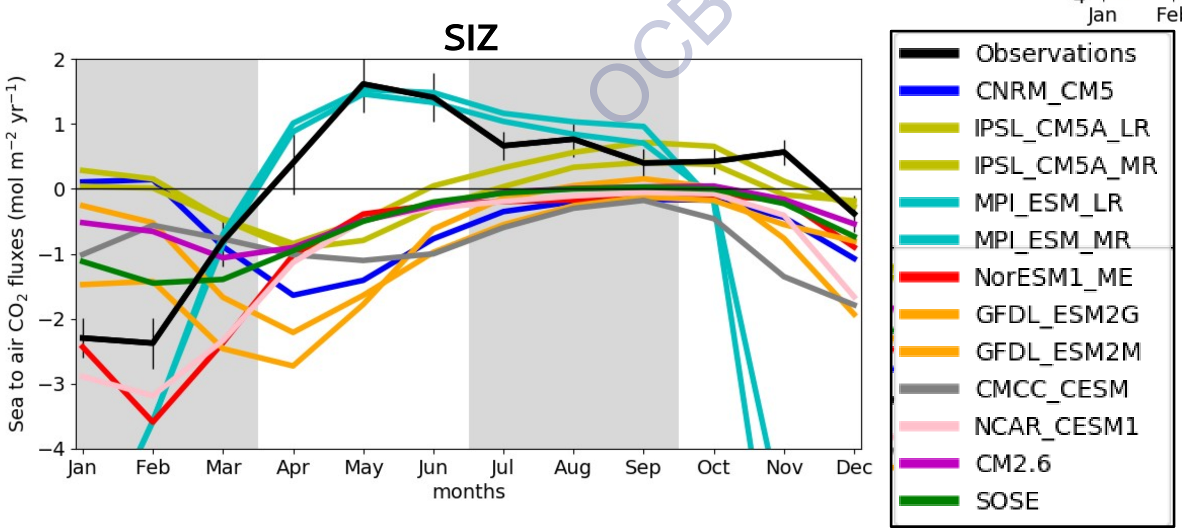




The strongest disagreement between models and obs, and among models is found in the ASZ for flux magnitude and sign

Results

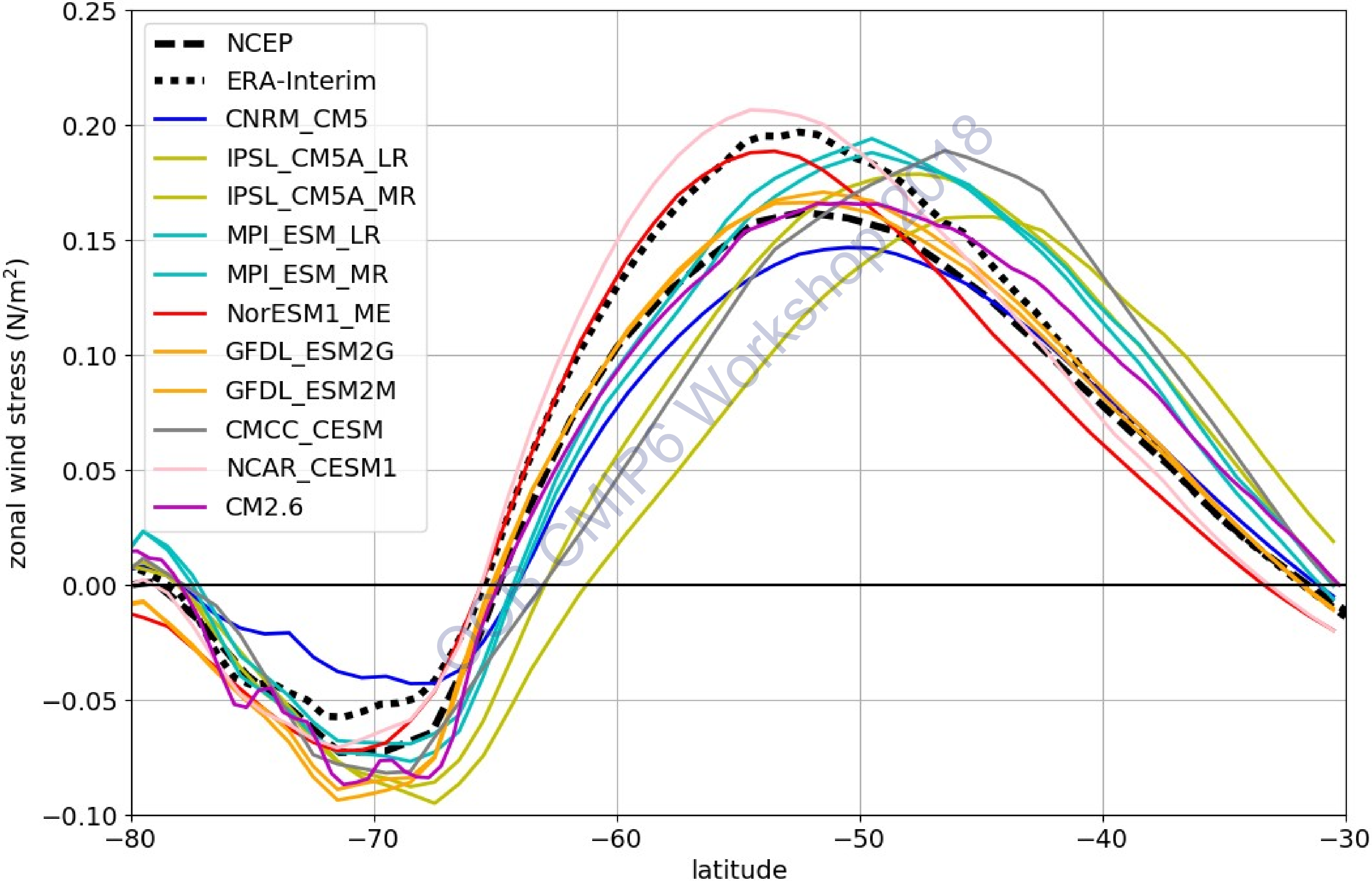




- Most models are out-of-phase with observations in the SAZ, PFZ and ASZ
- This seasonal disagreement averages out at annual scale for some models

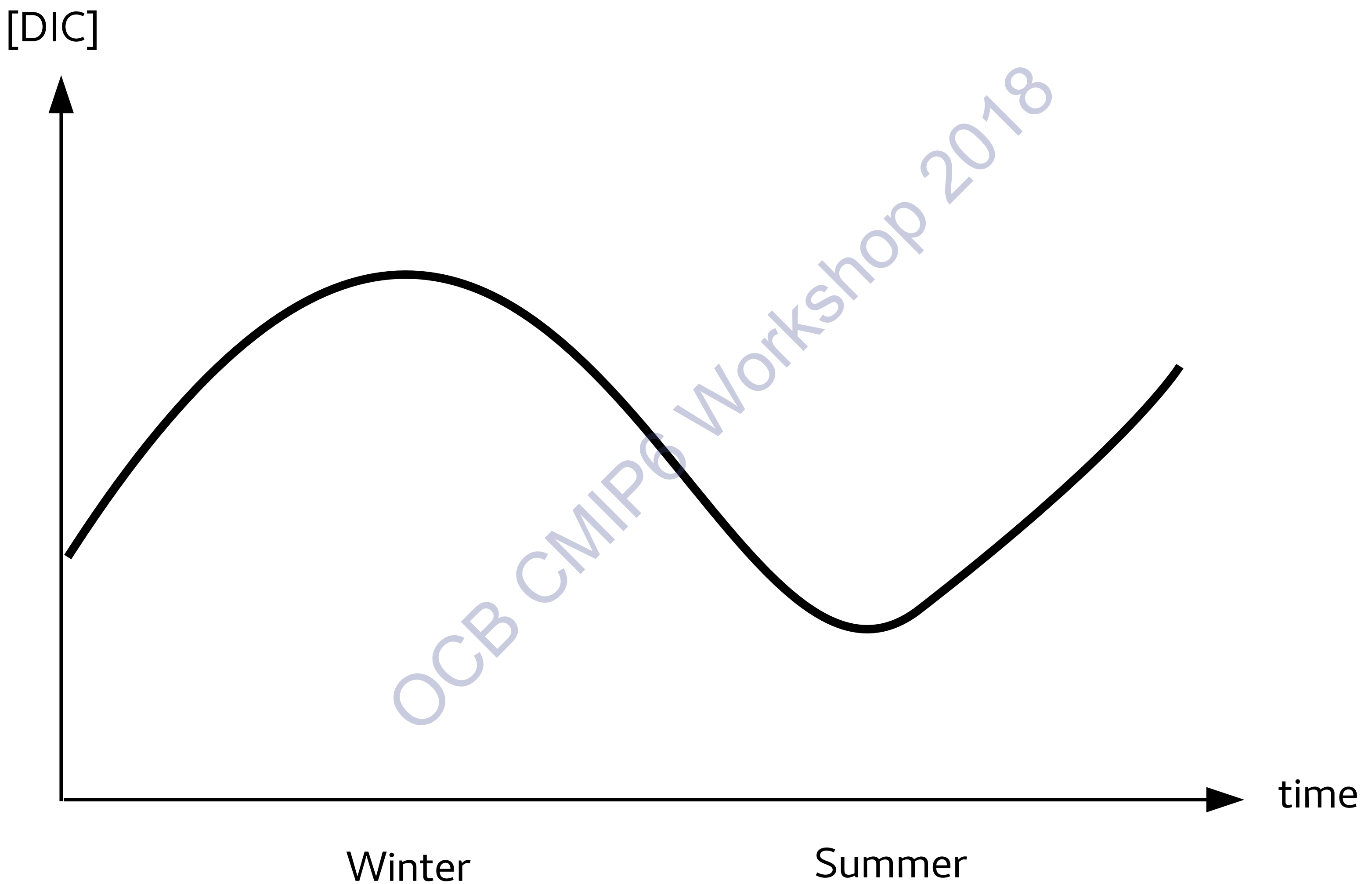
Results

Comparison of wind stress



Hypothesis

Seasonal cycle out-of-phase



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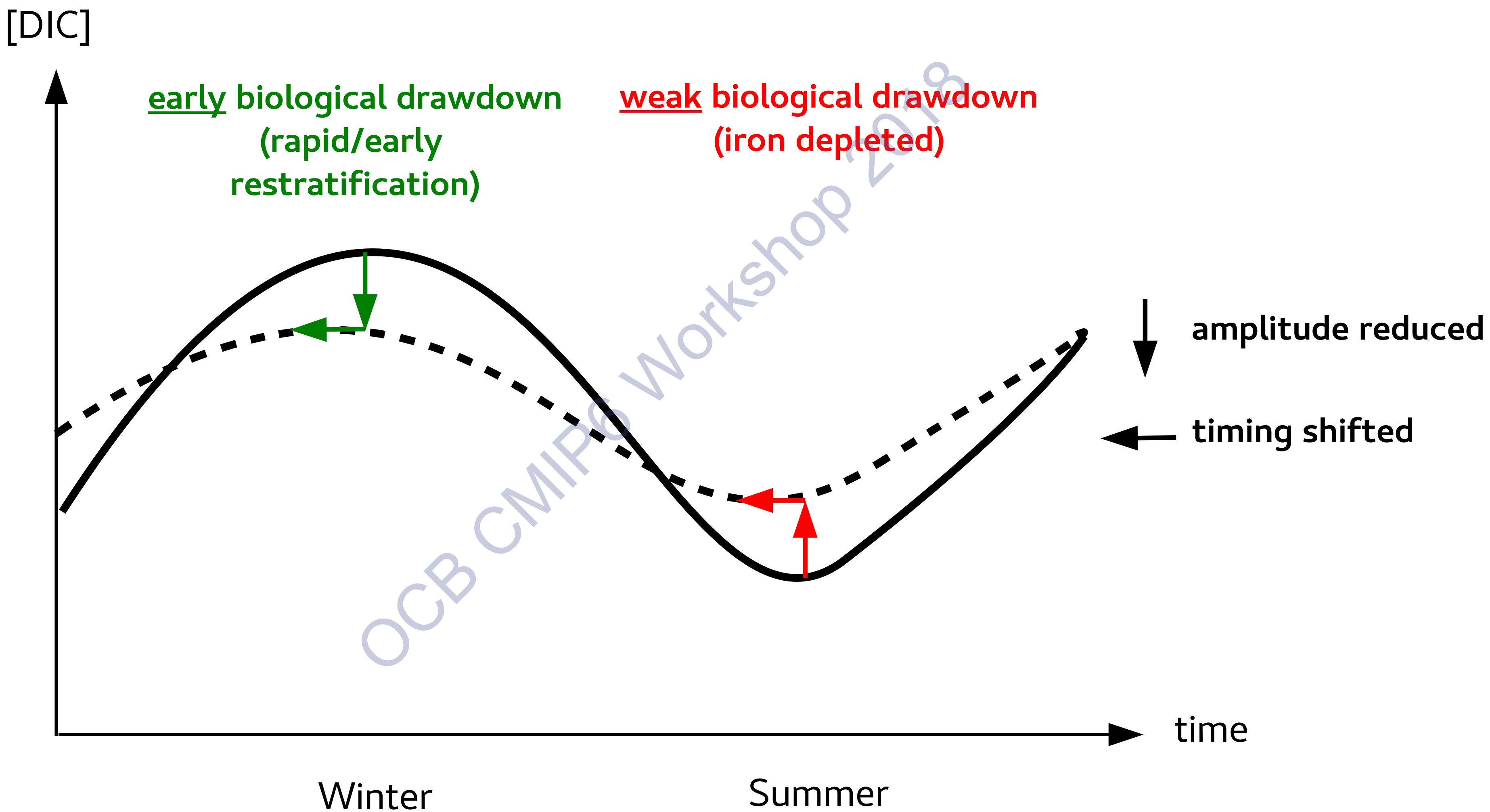
Seasonal cycle out-of-phase



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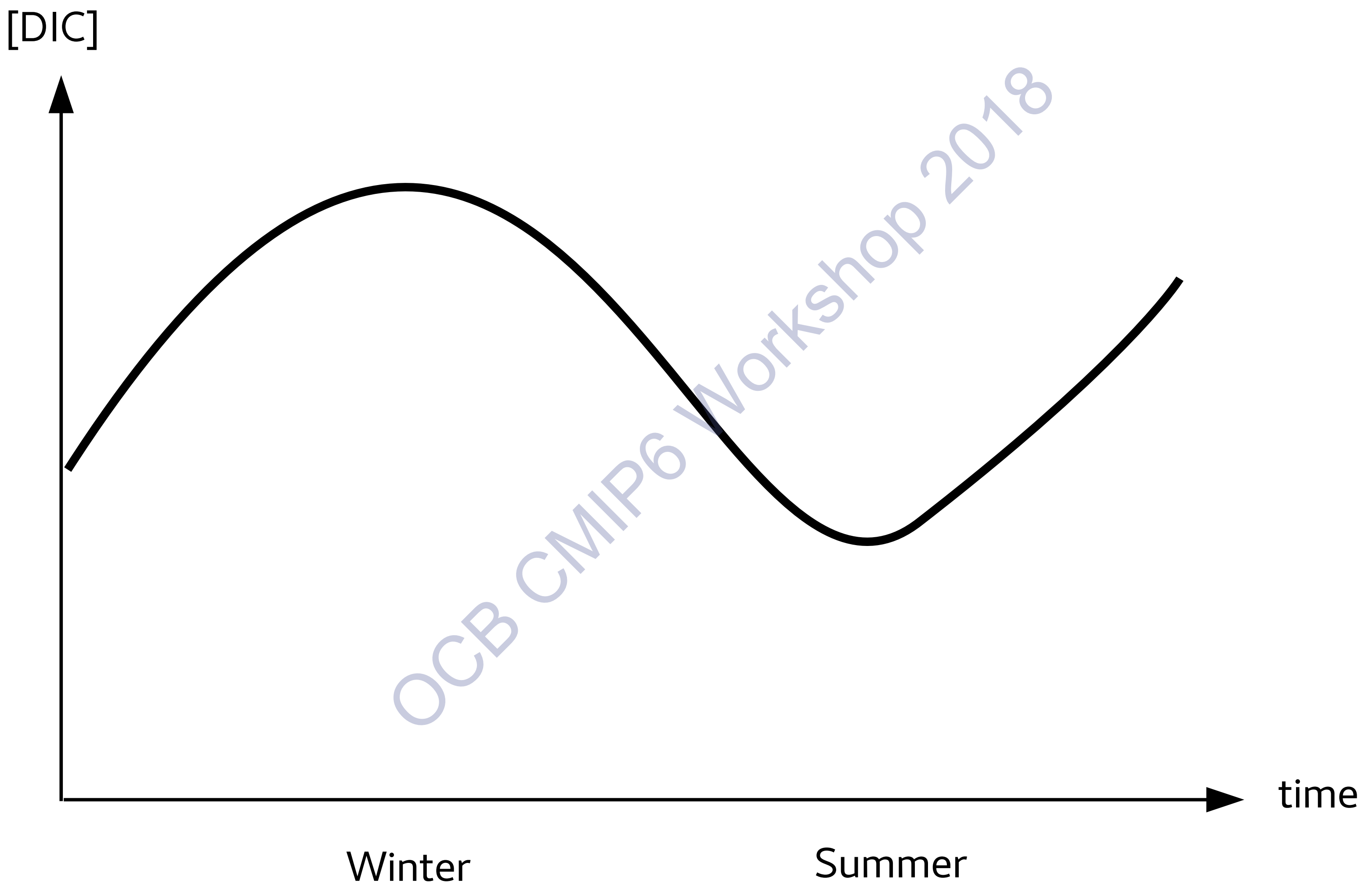
Seasonal cycle out-of-phase



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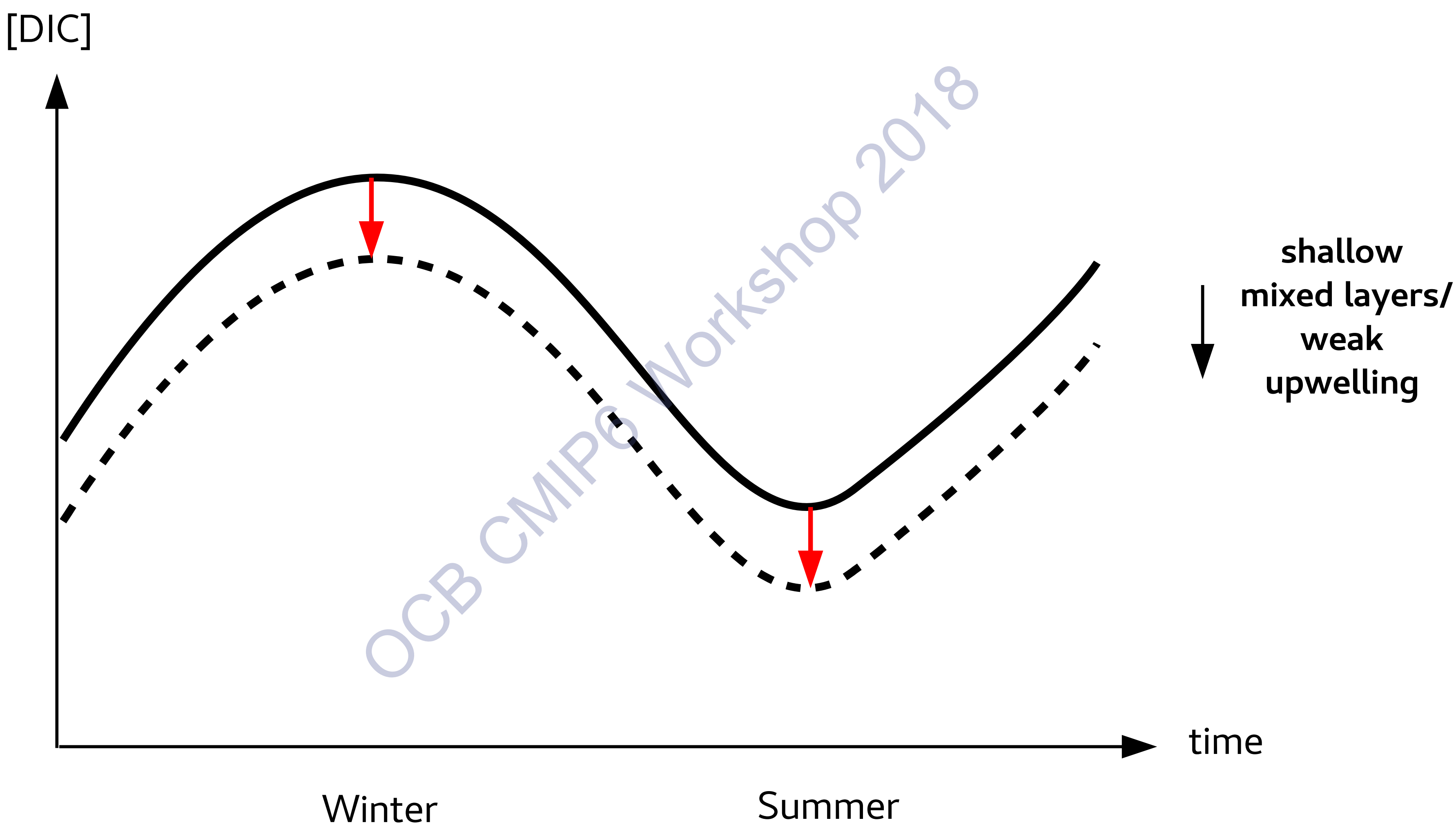
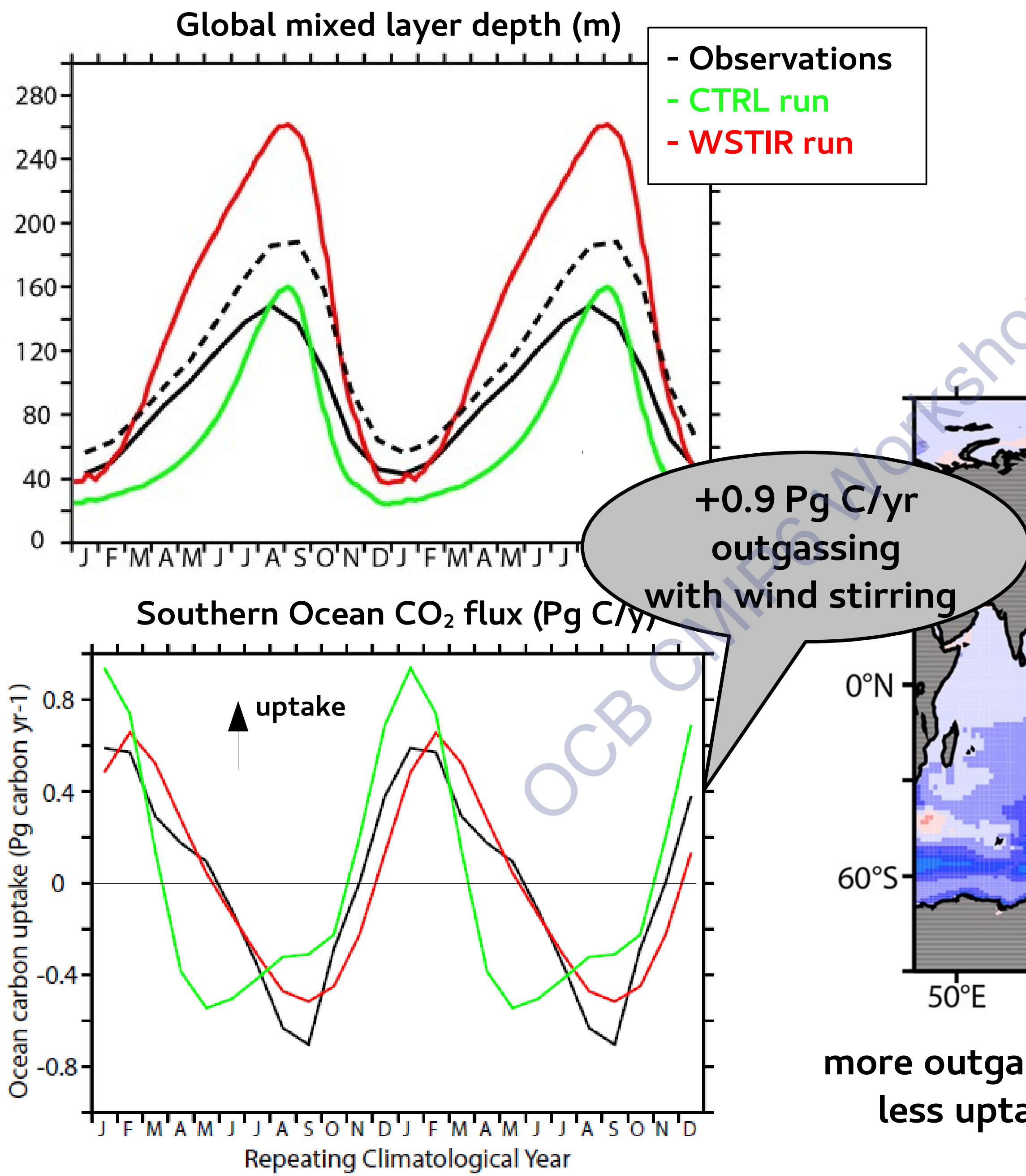
Seasonal cycle out-of-phase

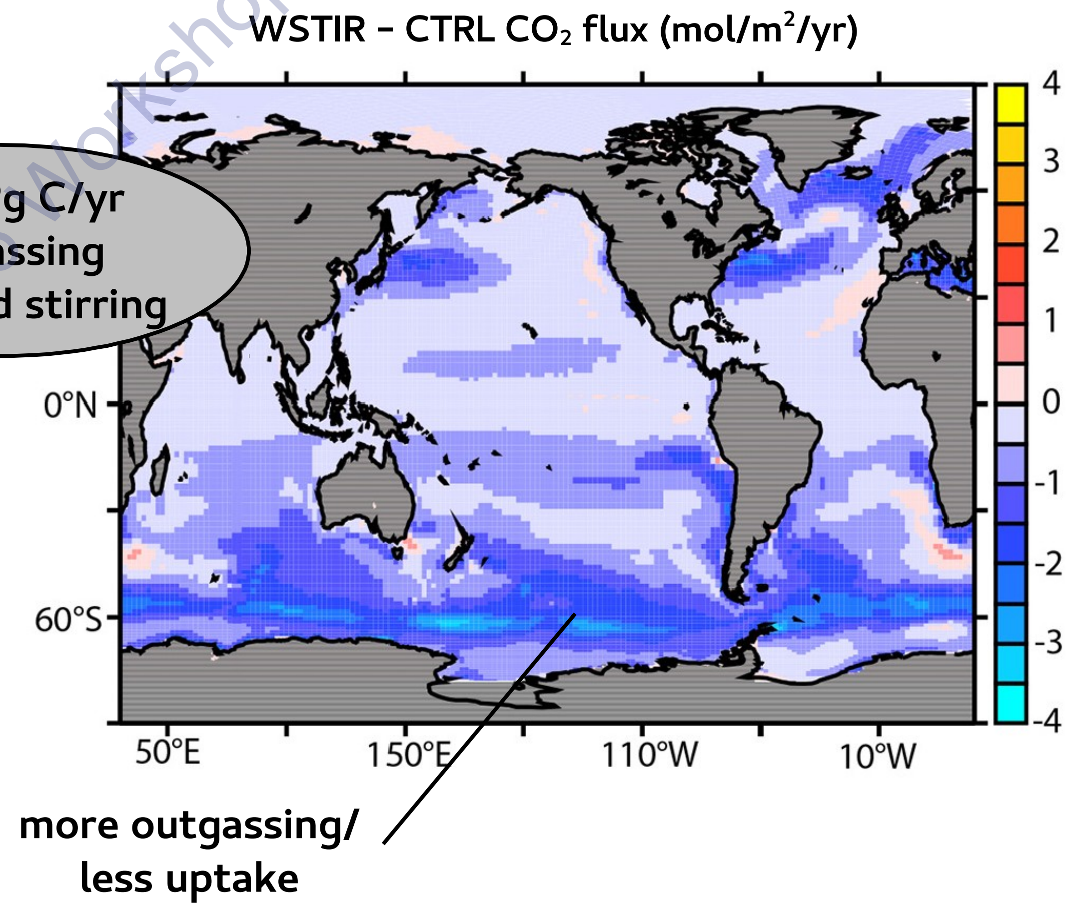


Effect of wind stirring



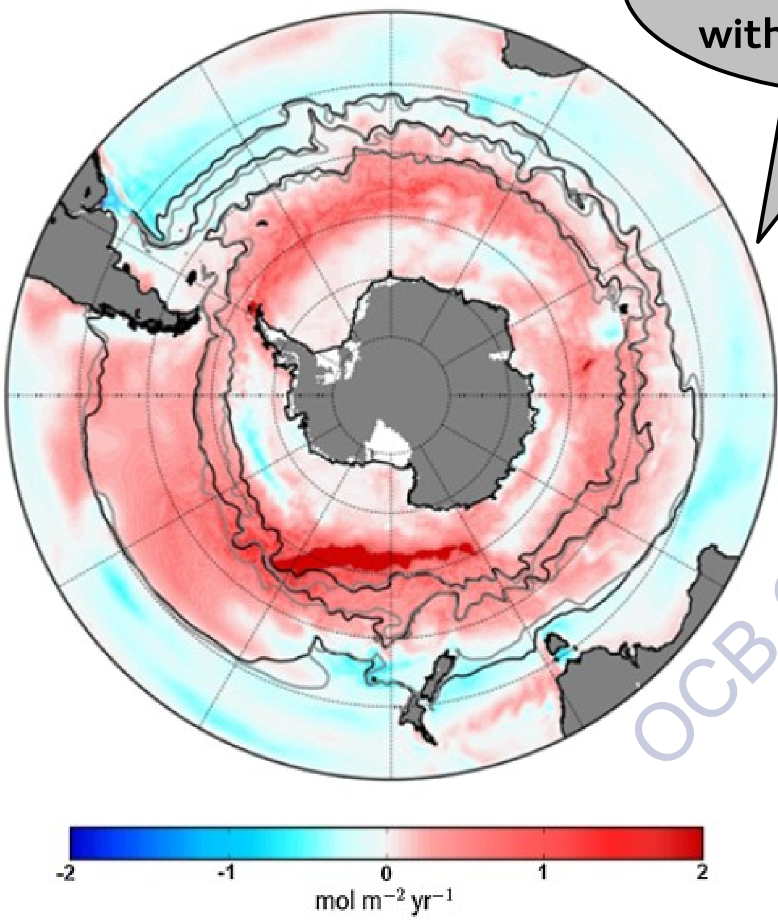
Rodgers et al. (2014)

Sensitivity experiments to wind stirring parameterization in a 2° global model (NEMO-PISCES)



Effect of wind intensification

SAM anomaly



+0.1 Pg C/yr
outgassing
with positive SAM

Dufour et al. (2013)

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

Weak and equatorward bias in westerlies