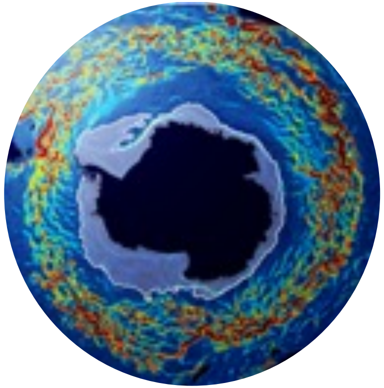


EDDY-INDUCED CARBON TRANSPORT IN THE SOUTHERN OCEAN

Lydi Keppler (she/her)

Matthew Mazloff, Ariane Verdy, Sarah Gille, Lynne Talley,
Nancy Williams, Veronica Tamsitt, Don Chambers

THE SOUTHERN OCEAN CARBON SINK

The Southern Ocean is an important carbon sink (~half of the oceanic uptake of carbon occurs in the Southern Ocean (Friedlingstein et al., 2022)

But this uptake is highly variable (e.g., Le Quéré et al., 2007; Landschützer et al., 2015; Keppler & Landschützer, 2019)

And observational estimates and models disagree on the magnitude and variability of the Southern Ocean carbon sink (e.g., Mongwe et al. 2018, Gray et al., 2018; Bushinski et al., 2019)

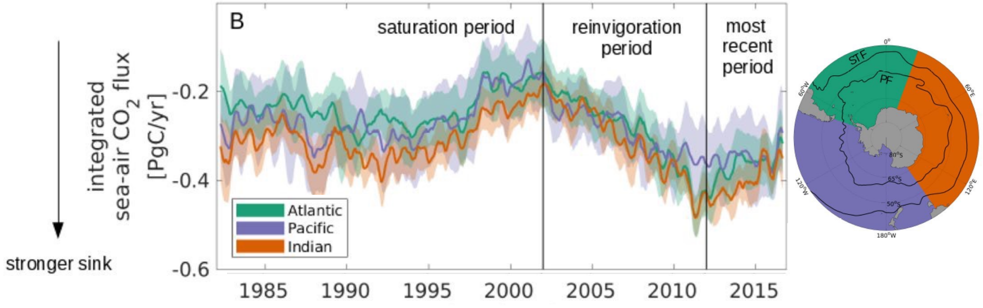


Figure adapted from Keppler & Landschützer (2019)

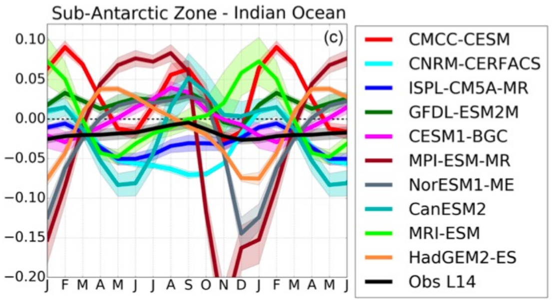
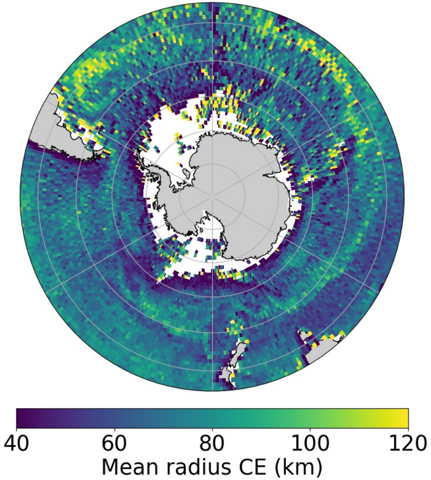


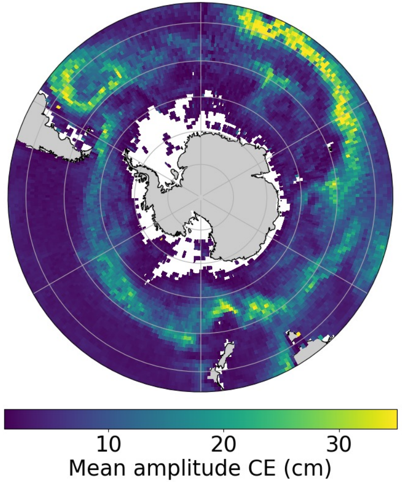
Figure adapted from Mongwe et al. 2018)

MESOSCALE EDDY PROPERTIES IN THE SOUTHERN OCEAN

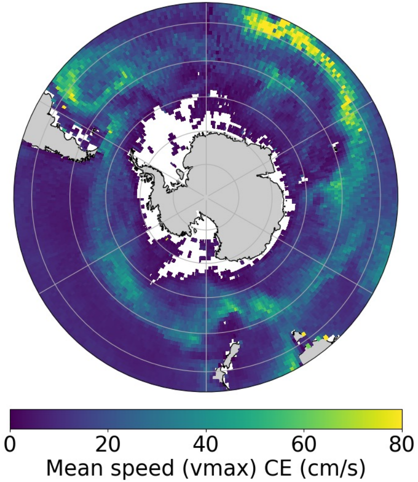
Small radius
due to small Rossby radius
mean S.O. radius ~ 70 km,
up to ~200 km
(global mean ~ 80 km)



Large amplitude
in hot spots
mean S.O. amplitude ~8 cm,
up to ~50 cm
(global mean ~8 cm)



High swirl velocity
in hot spots
mean S.O. velocity ~18 cm/s,
up to ~180 cm/s
(global mean ~18 cm/s)



Note: displaying for cyclonic eddies (CE) only here.
Looks approximately the same for anticyclonic eddies (AE)

Figures adapted from Keppler et al. (in prep.)

EDDY-INDUCED TRANSPORT

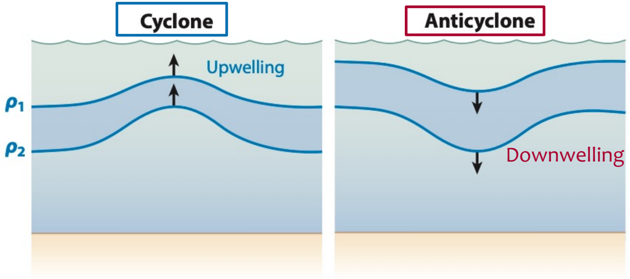
Horizontal

Eddy-stirring (turbulent advection)

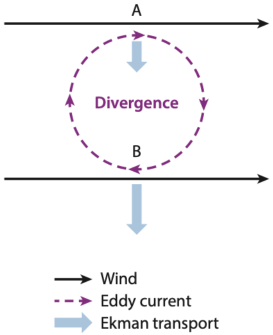
Eddy-trapping (eddies trap and transport properties along their trajectories)

Vertical

Eddy-pumping (vertical displacement of the isopycnal)



Eddy-wind interaction
(eddy-induced Ekman pumping)



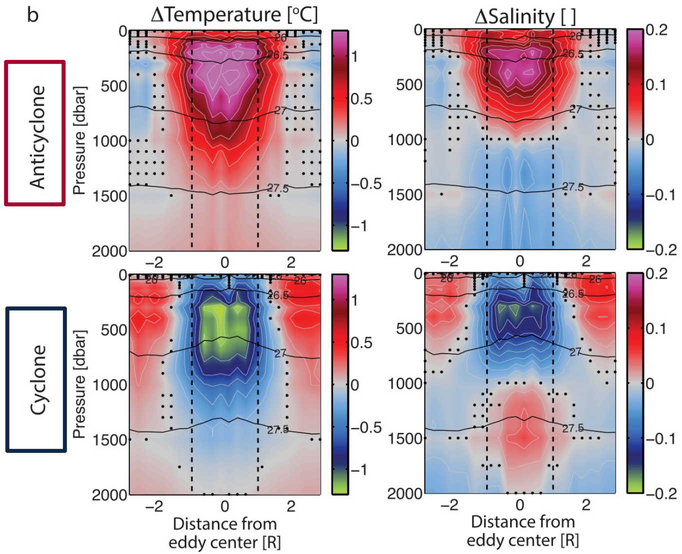
Net result: downwelling in cyclonic, upwelling in anticyclonic eddies (opposite sign as eddy-pumping)

Usually small effect but may be significant in the S.O., esp. in small and intense eddies combined with high wind speeds

Figures adapted from McGillicuddy (2016)
See also Gaube et al. (2015) and Song et al. (2020)

S.O. EDDY EFFECTS ON PHYSICS

Vertical composites, north of the ACC

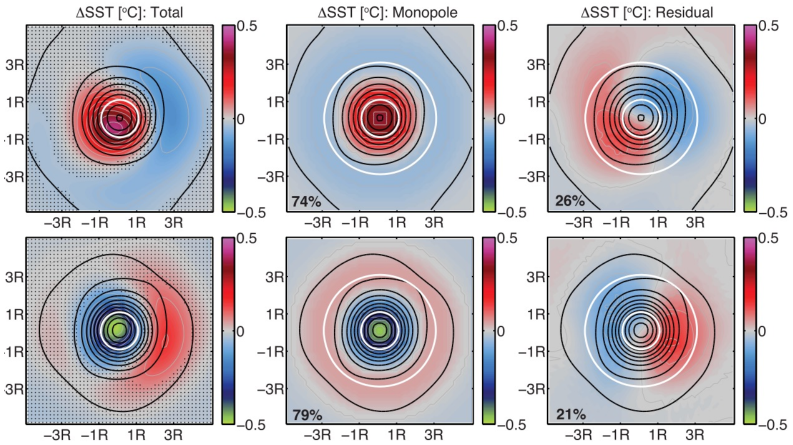


Warmer, saltier water near the eddy core (downwelling)

Colder, less salty water near the eddy core (upwelling)

→ Eddy pumping dominates over eddy-induced Ekman pumping

Horizontal composites at the surface, north of the ACC



→ Dipole pattern (superimposed on the monopole) indicates effect from eddy stirring

Figures adapted from Frenger et al. (2015)

S.O. EDDY EFFECTS ON BIOGEOCHEMISTRY

Eddies trap and transport nutrients across S.O. fronts (Patel et al., 2019)

Eddy-induced Ekman pumping and deep vertical mixing drives high chlorophyll in SO. anticyclones, while eddy pumping drives high chlorophyll in S.O. cyclones (Su et al., 2021)

Eddy stirring, trapping, and pumping contribute to physical and biological anomalies in the S.O., **depending on the region and season** (Dawson et al., 2018)

North of the ACC, cyclonic eddies (CE) have increased chlorophyll, while in the ACC, CE have less chlorophyll, and vice versa for anticyclonic eddies. In the ACC, there is a seasonal sign switch in the anomalies, associated with an eddy-induced modification of the winter mixed layer depth (Frenger et al., 2018)

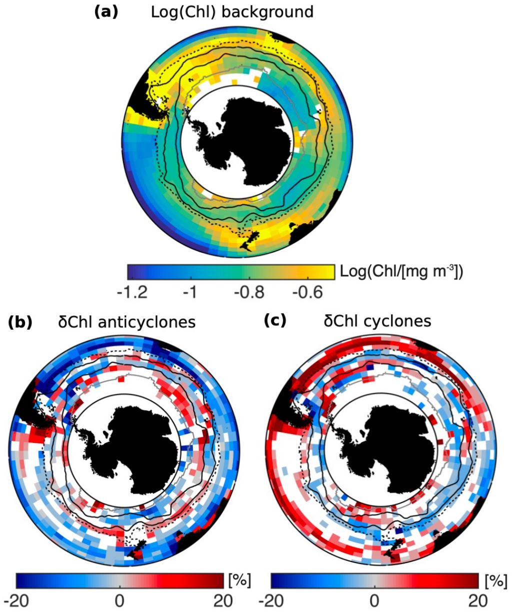


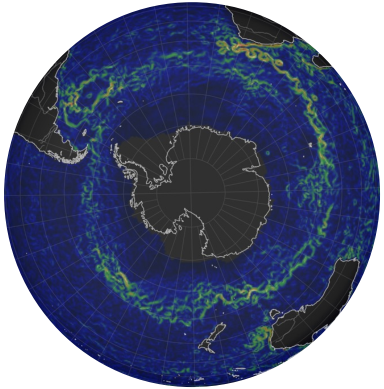
Figure adapted from Frenger et al. (2018)

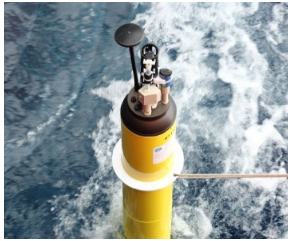
THE EFFECT OF EDDY-INDUCED TRANSPORT ON THE NET S.O. CARBON SINK IS STILL UNKNOWN

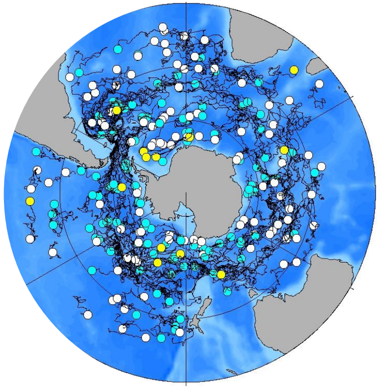
→ LET'S FIND OUT!

(PRELIMINARY RESULTS)

CO-LOCATION OF EDDIES WITH BGC FLOATS







Satellite-detected eddies from AVISO
(currently using META2.0, will soon update to
META3.1exp)

Only keeping eddies with amplitude > 2 cm,
and radius > 40 km

Chelton et al. (2011)
Pegliasco et al. (2022)

Dissolved inorganic carbon (DIC) estimated from pH
measurements from BGC Argo floats
and Alkalinity from LIAR algorithm

Only keeping floats with good quality control, and not in
seasonally-ice-covered region

https://soccom.princeton.edu/
Carter et al. (2017)

CO-LOCATED EDDIES & FLOATS

i.e., Argo float measurements when they are inside cyclonic or anticyclonic eddies*, anomalies relative to the mean seasonal field**

→ Allow us to investigate the **mean vertical structure** of eddies wrt carbon (how deep do the eddies have an effect, how large are the anomalies…)

→ With enough data, we can **quantify the role of eddies** on the Southern Ocean carbon sink

→ We can determine the **dominant processes** (eddy stirring, trapping, pumping, eddy-induced Ekman pumping)

* Currently, the eddy edge is defined as the distance of two times the radius from the eddy center using AVSIO version META2.0. We will soon use the new AVISO version META3.1exp. This will allow us to use the provided contour lines, which are based on the outermost closed SLA contour, as the eddy edge.

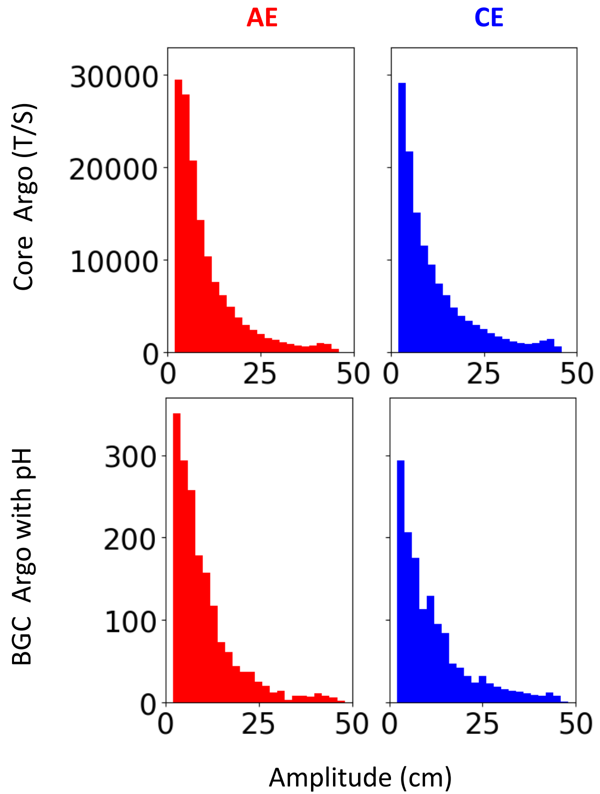
** DIC monthly climatology from MOBO-DIC (Keppler et al., 2020), temperature climatology from Argo (Roemmich & Gilson, 2009)

WORKING WITH SPARSE DATA

We still don’t have excessive amounts of pH measurements in the Southern Ocean (~8,000 good pH profiles from SOCCOM floats since 2012), even less when looking at subregions and seasons

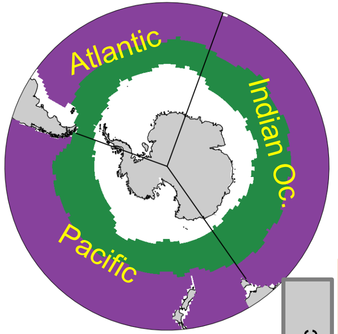
But: we have lots of data from the Core Argo program of temperature and salinity (~500,000 good T/S profiles in the S.O. since 1999)

→ We use the **Core Argo data as a testbed**, where we compare the T/S profiles from all Core Argo floats with the T/S profiles on the floats with pH sensors to inform us how representative/robust the pH data is



Figures adapted from Keppler et al. (in prep.)

VERTICAL TEMPERATURE ANOMALIES IN THE ACC



Summer & fall*

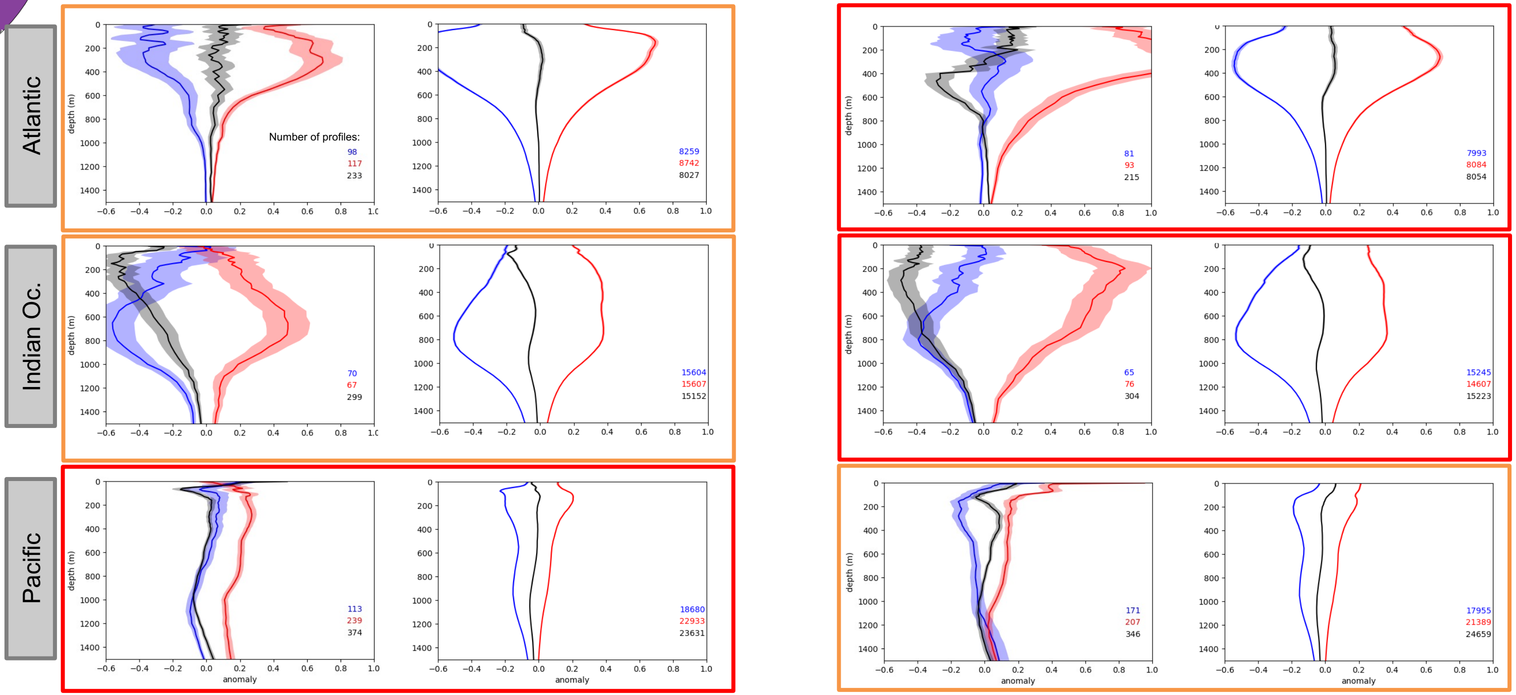
Temp. anomaly (pH floats only)

Temp. anomaly (all core Argo)

Winter & spring*

Temp. anomaly (pH floats only)

Temp. anomaly (all core Argo)



Agree quantitatively

Agree qualitatively

Don't agree

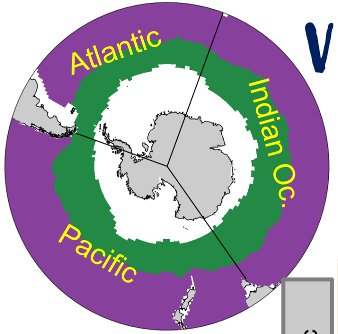
Mean±st.error

Cyclonic eddies (CE)
Anticyclonic eddies (AE)
Outside of eddies (OE)

* Summer & fall : December through May
Winter & spring: June through November

Figures from Keppler et al. (in prep.)

VERTICAL TEMPERATURE ANOMALIES NORTH OF THE ACC

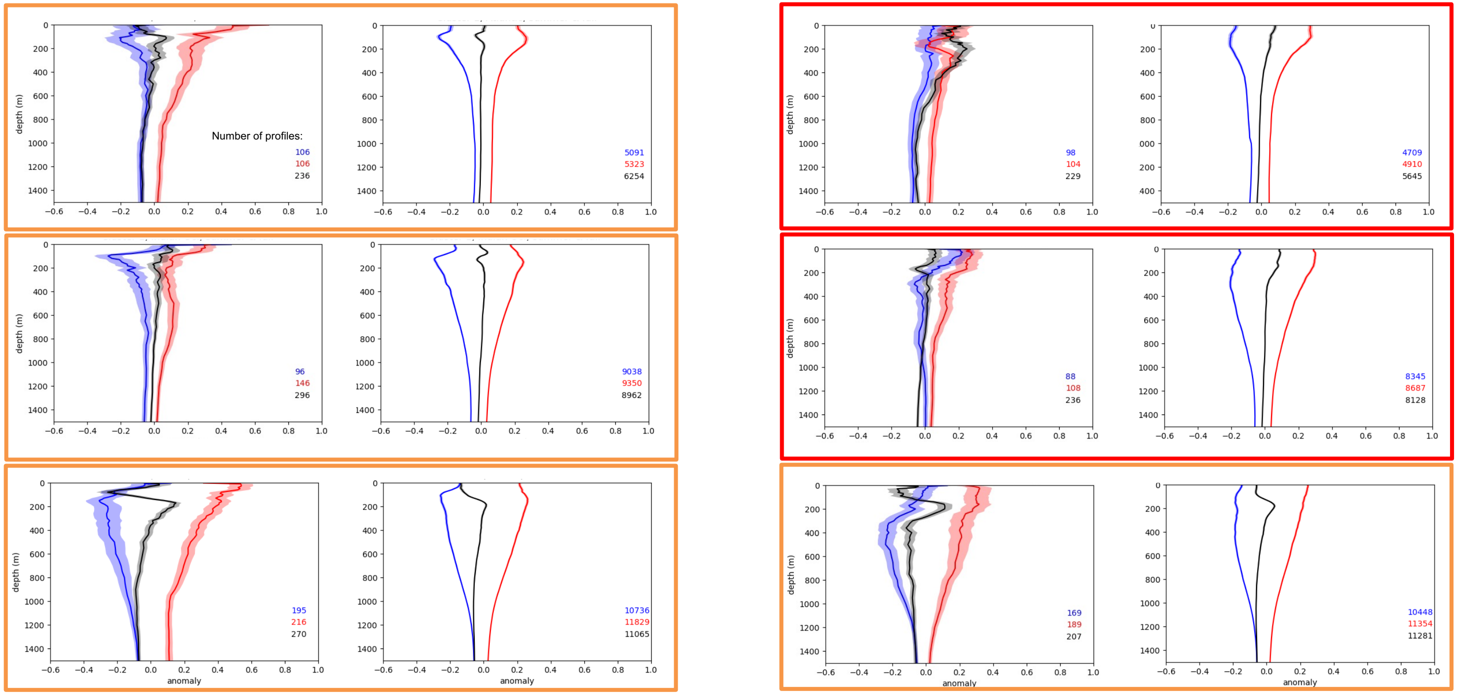


Summer & fall*		Winter & spring*	
Temp. anomaly (pH floats only)	Temp. anomaly (all core Argo)	Temp. anomaly (pH floats only)	Temp. anomaly (all core Argo)

Atlantic

Indian Oc.

Pacific



Agree quantitatively

Agree qualitatively

Don't agree

Mean±st.error

Cyclonic eddies (CE)
Anticyclonic eddies (AE)
Outside of eddies (OE)

* Summer & fall : December through May
Winter & spring: June through November

Figures from Keppler et al. (in prep.)

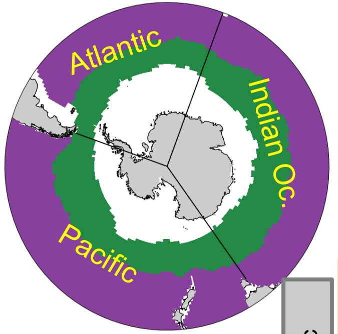
In some regions, the temperature anomalies from floats with pH sensors are qualitatively similar as the temperature anomalies from all core Argo floats.
In other regions, they disagree.
In none of the regions, they agree quantitatively.

Note: the profiles outside of eddies should be centered around 0, but this is not always the case. This might be due to our definition of the eddy edge, which we are working on improving with the new AVISO version (see slide 9).

→ We will need a lot more BGC float data before we can **quantify** the impact of eddies on the Southern Ocean carbon sink

→ But we can investigate the DIC anomalies **qualitatively** (in the regions where the temperature testbeds were similar)

VERTICAL DIC ANOMALIES



In the ACC

Summer & fall* | Winter & spring*

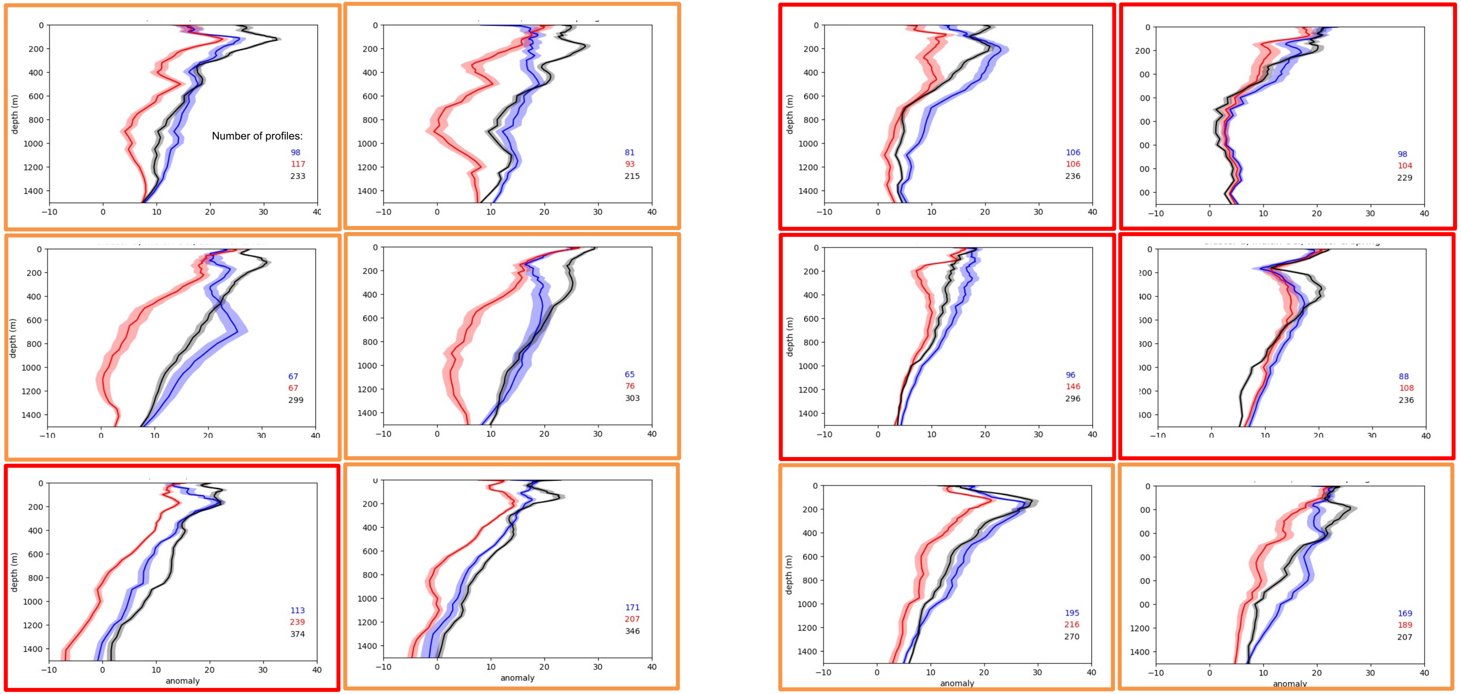
North of the ACC

Summer & fall* | Winter & spring*

Atlantic

Indian Oc.

Pacific



From temperature testbed:

We trust the DIC qualitatively

We don't trust the DIC profiles

Mean±st.error

Cyclonic eddies (CE)
Anticyclonic eddies (AE)
Outside of eddies (OE)

* Summer & fall : December through May
Winter & spring: June through November

Figures from Keppler et al. (in prep.)

The DIC anomalies are not centered around zero, because the reference DIC (MOBO-DIC) is based on the period 2004 through 2018, and the float data is from 2012 through 2020. We might normalize the reference DIC to our period.

Similar as for the temperature anomalies, the profiles outside of eddies (OE) are not always in the middle. This might be due to the definition of the eddy edge, which we are working on improving with the new AVISO version (see slide 9).

We observe clear differences between anticyclonic (AE) and cyclonic (CE) profiles:
Tendency of AE to have less DIC (downwelling) and CE to have more DIC (upwelling).

→ **the eddy induced pumping of carbon seems to be more dominant** than the effect of nutrient pumping (i.e., upwelling of nutrients in CE would lead to enhanced biological production and thus, less DIC)

→ Investigating the horizonal composite eddies will provide more insights into processes (stirring, trapping, pumping, eddy-induced Ekman transport)

PRELIMINARY CONCLUSIONS AND OUTLOOK

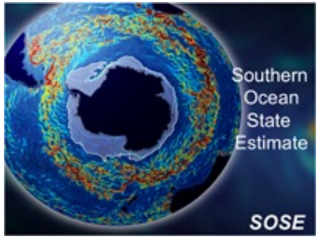
We need a lot more BGC float data in order to quantify the impact of eddies on the Southern Ocean carbon sink

DIC tends to be higher in CE (upwelling), and lower in AE (downwelling), indicating that **eddy pumping of carbon is the dominant process affecting the vertical DIC profiles**

Eddy-induced DIC anomalies are still significant at 1500 m depth

Still many things to refine and do

Outlook: once this analysis is completed, we will investigate the eddies in the Biogeochemical Southern Ocean State Estimate (B-SOSE) with the aim to improve the carbon cycle in B-SOSE



SOCCOM