Discovery of a Southern Ocean carbon source: Implications for carbon uptake in southern hemisphere western boundary regions

Jorge L. Sarmiento
Princeton University

SOCCOM

Southern Ocean Carbon and Climate Observations and Modeling

SOCCOM Floats (so far…)

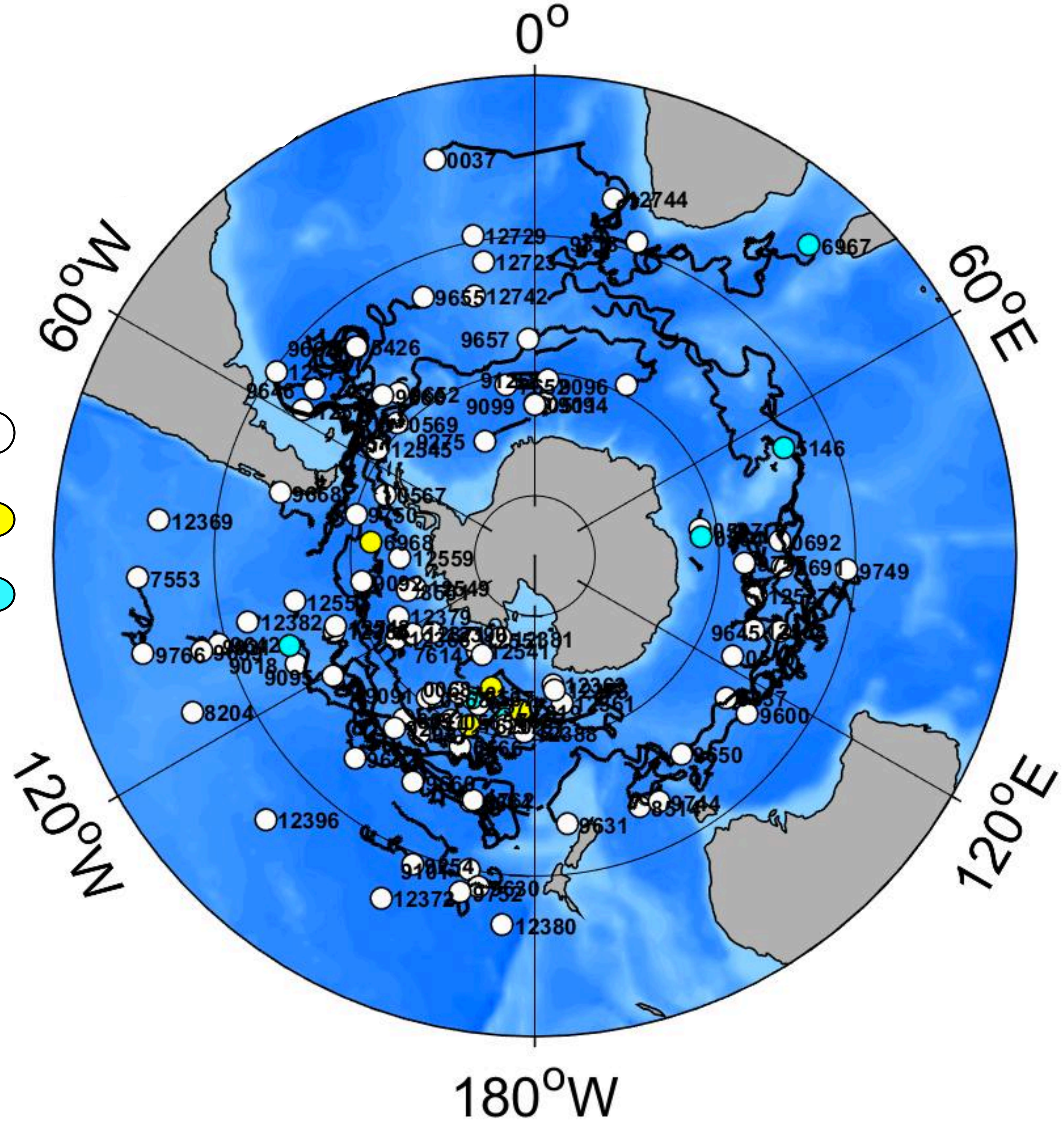
Hannahd Zanowski

SOCCOM floats

Pre-SOCCOM floats

Non-operational floats

As of 20 May, 2017



- Biogeochem sensors now developed for
  - pH
  - Nitrate,
  - oxygen, and
  - optics (FLBB) – *funded by NASA*

Estimation of pCO_2

DuraFET
pH sensor

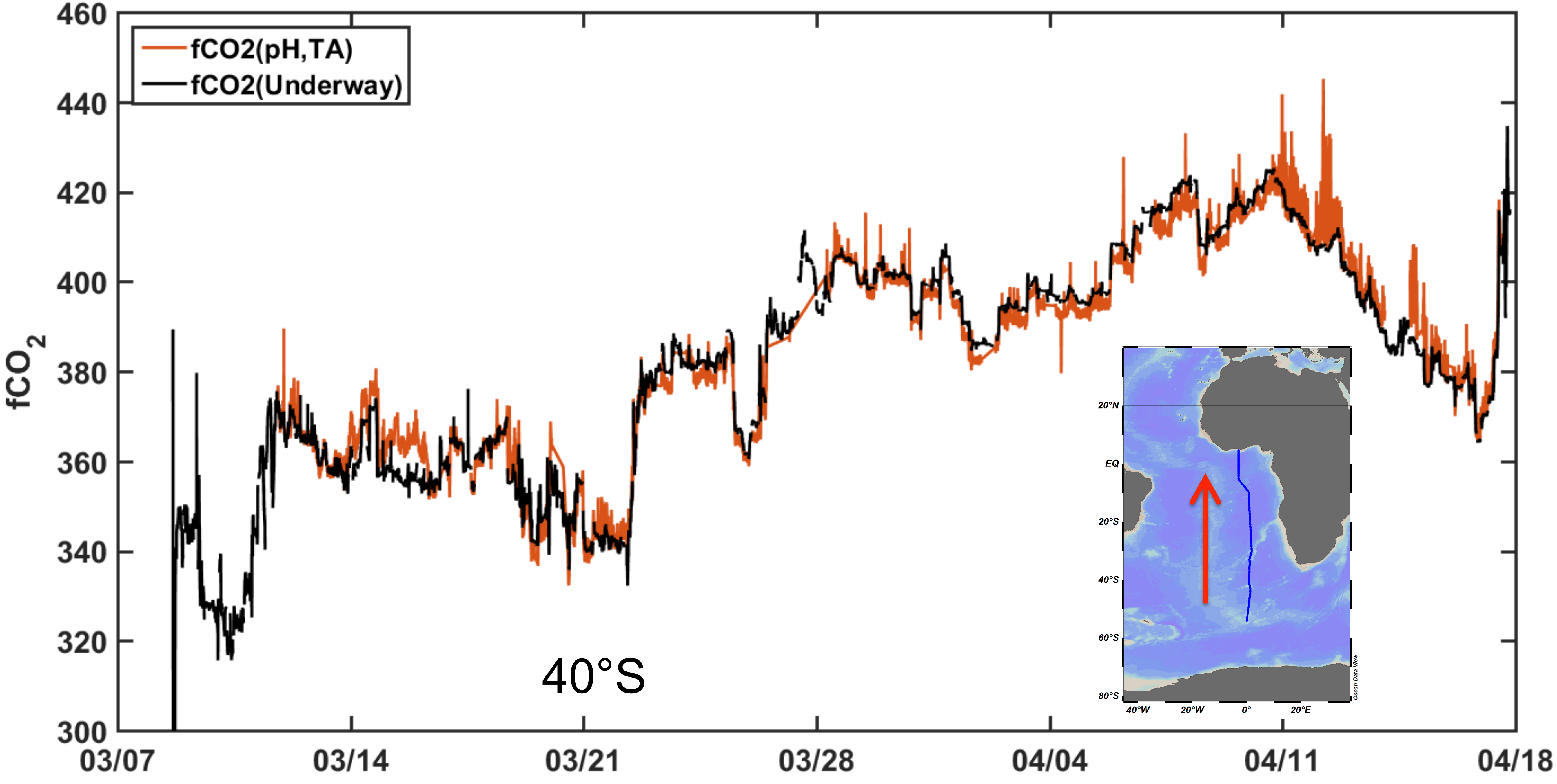
Algorithm TA
(eg., Carter
et al. 2016)

CO2SYS(**pH_{Total}**, **TA**, T, S, P) → **pCO_2**

Error analysis gives a 2.7% uncertainty in pCO_2
(11 μatm at a pCO_2 of 400 μatm)

Williams et al., 2017(*GBC*)

Comparison of underway shipboard measurements of fCO_2 (black) with calculated fCO_2 (red)



Takeshita (pers. comm.)

Deep Dive:
Air-sea carbon fluxes

A. Gray (faculty, UW),

Ken Johnson (MBARI), J. L. Sarmiento (Princeton) et al.

$F = k K_0 \Delta pCO_2$

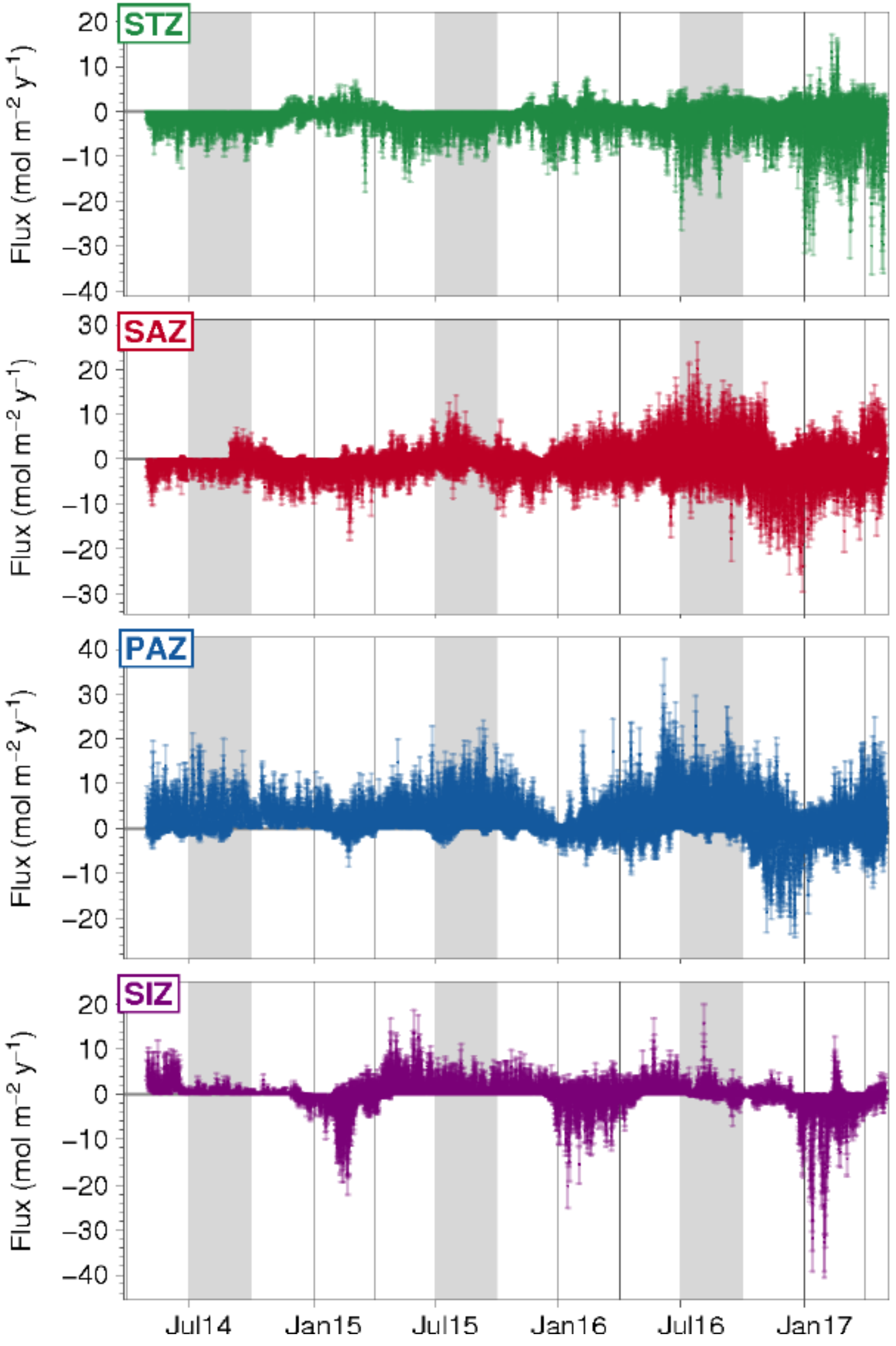
k Gas transfer velocity,
$\propto$ wind speed squared (Wanninkhof 2014)
6-hourly ERA-Interim winds

K_0 solubility constant

FLOAT-BASED AIR-SEA CO_2 FLUX

- Comes from 36 floats that have all the requisite sensors.
- Covers the period May 2014-Dec 2016
- Data from each float was binned by month and then averaged.
- There are 497 float-months (>41float years) in the data set

+ Outgassing
– Uptake



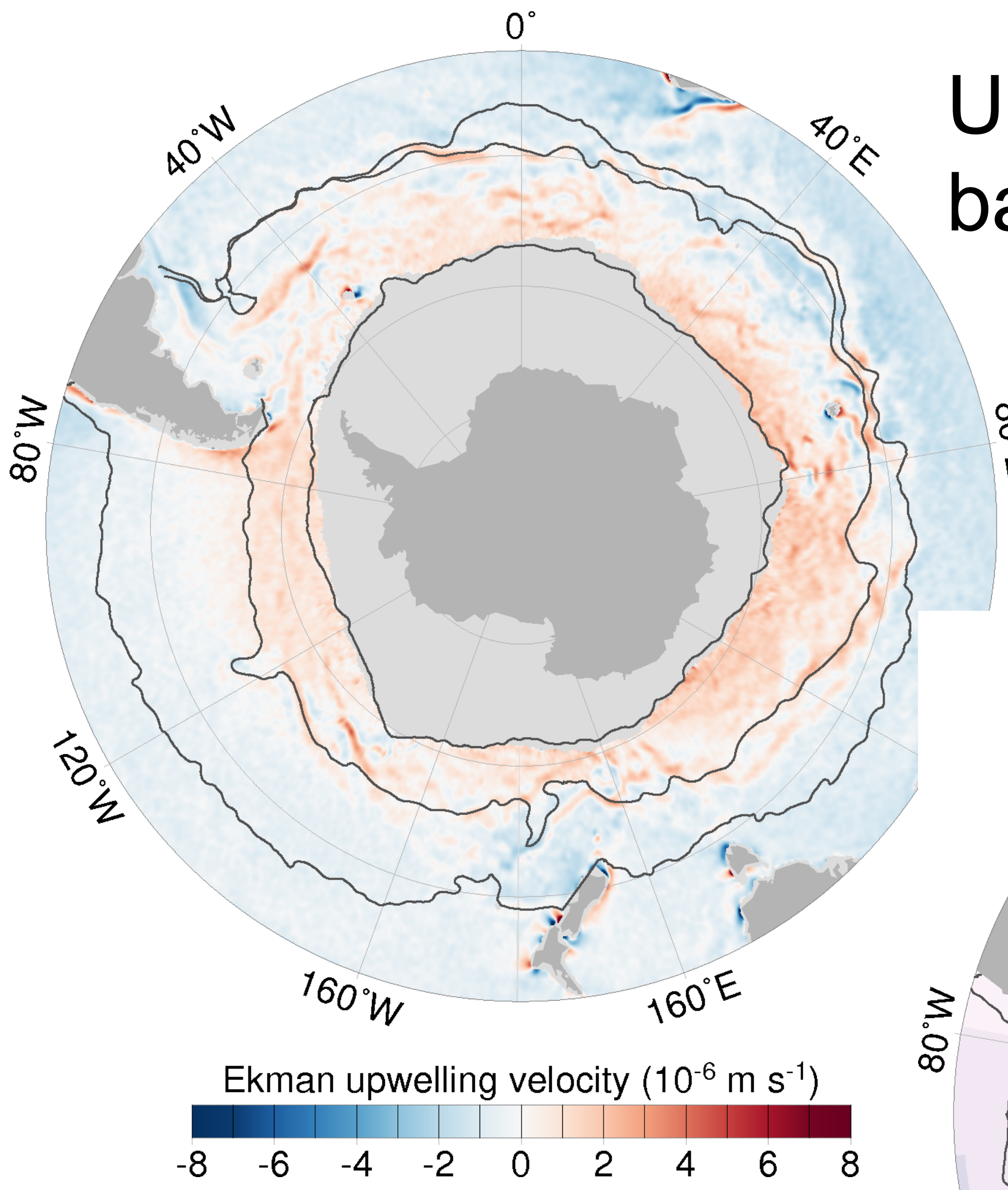
Getting oriented

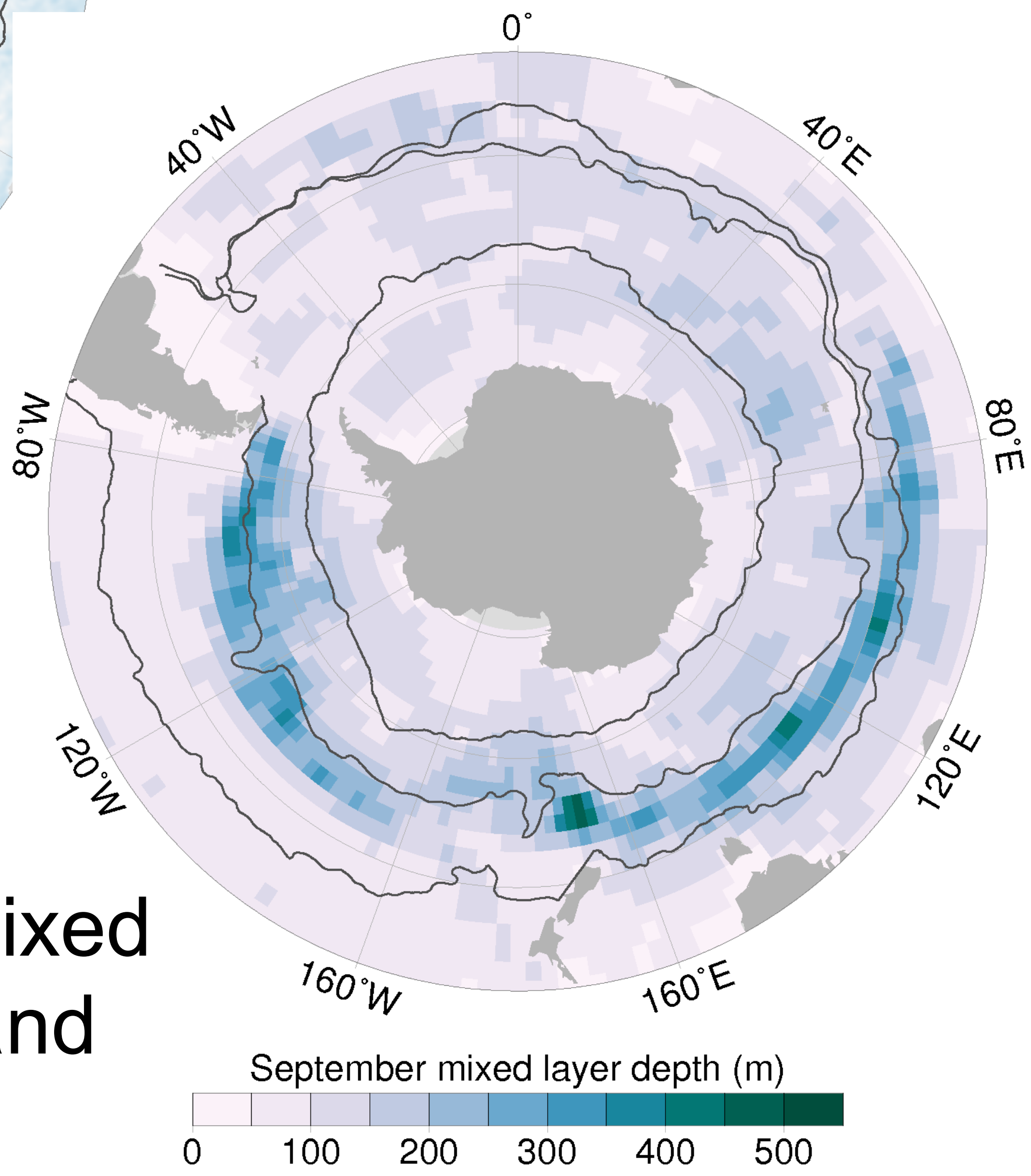
Four zones are defined by the fronts:

- GRAY – Seasonal Ice Zone (SIZ)
- PINKish – Polar Frontal-Antarctic Zone (PAZ) – upwelling & ACC
- BLUEish – Subantarctic Zone (SAZ) – deep MLDs
- Subtropical Zone (STZ) to north

- Ekman velocity is from QuikSCAT 1999-2009 winds (Risien and Chelton 2011).
- MLDs from de Boyer-Montégut et al. (2004) climatology (>250 in upper figure purple line)

Upwelling band

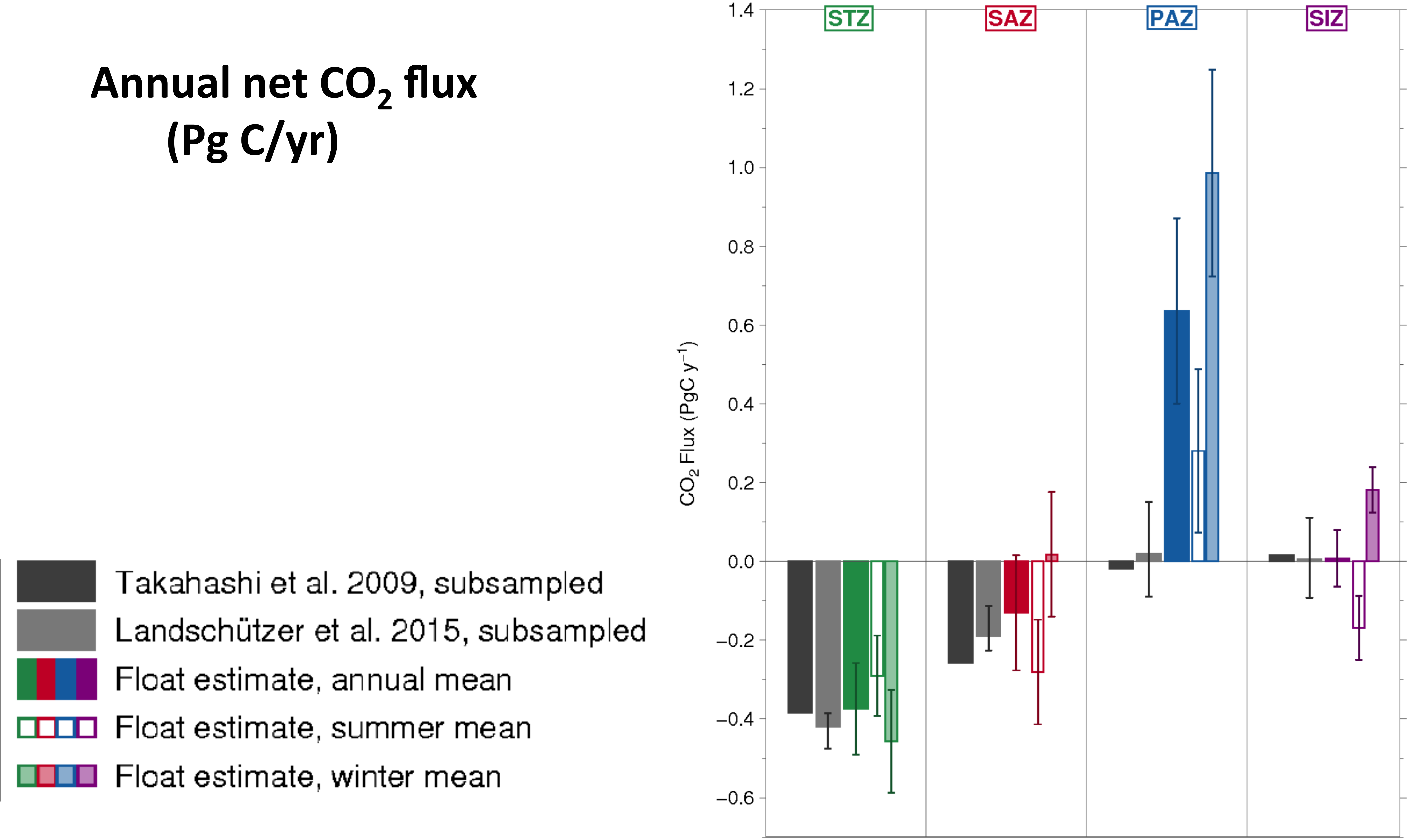




Deep mixed layer band

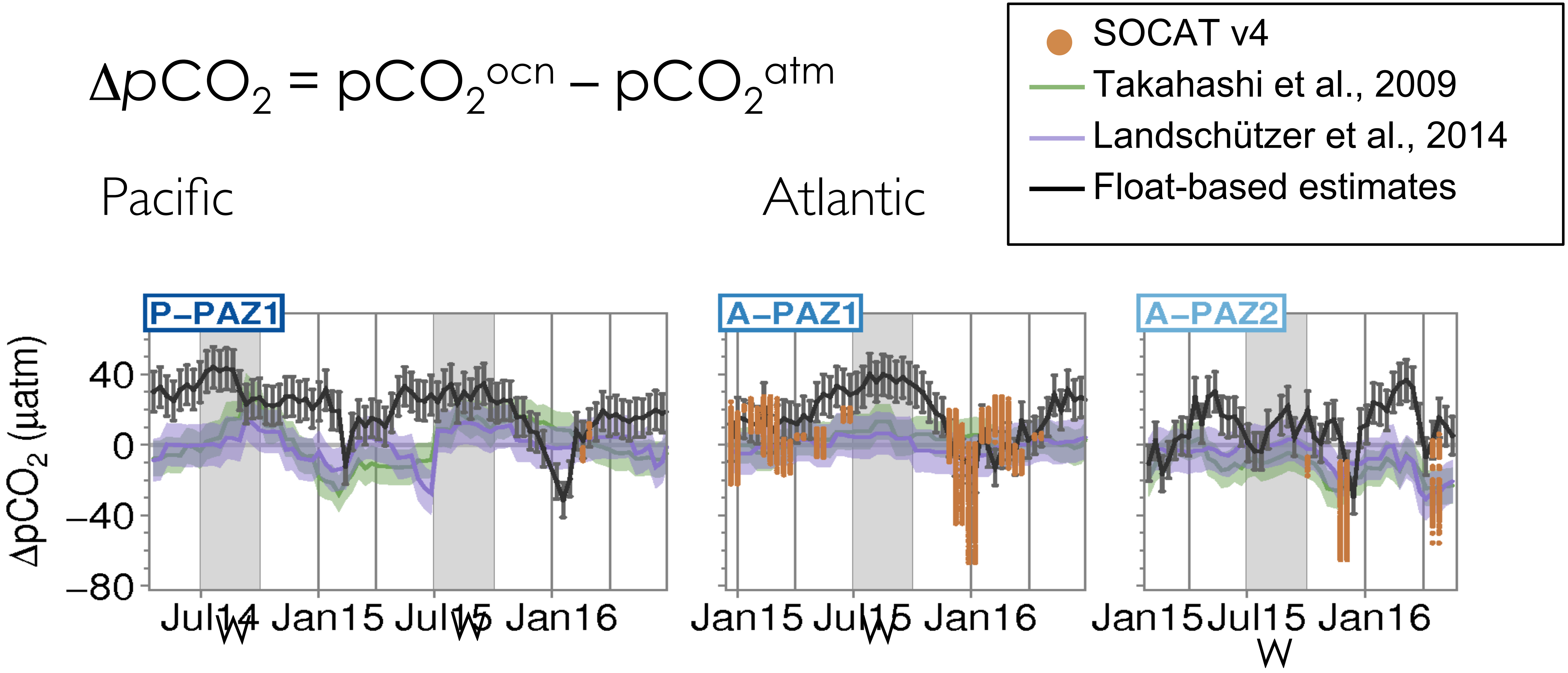
Annual mean air-sea CO_2 fluxes

Annual net CO_2 flux (Pg C/yr)



ΔpCO_2 in PAZ zone

$$\Delta pCO_2 = pCO_2^{ocn} - pCO_2^{atm}$$

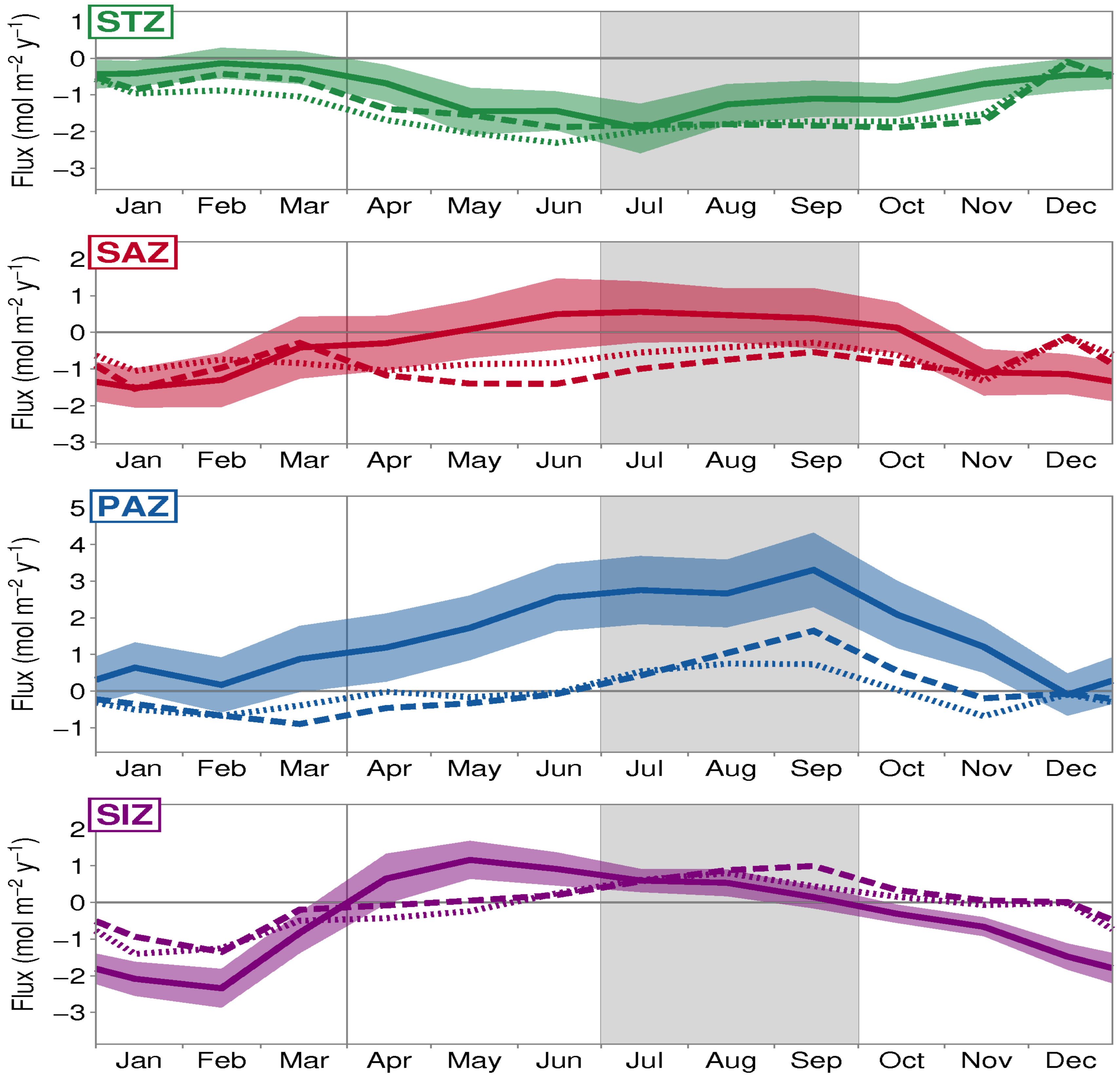


Seasonal cycle of CO_2 flux

Landschützer and Takahashi estimates miss fall and winter outgassing in PAZ

———	This estimate
- - - -	Takahashi et al. 2009
....	Landschützer et al. 2014 2002-2011 mean

+ Outgassing
– Uptake



Implications for the Southern Ocean carbon cycle

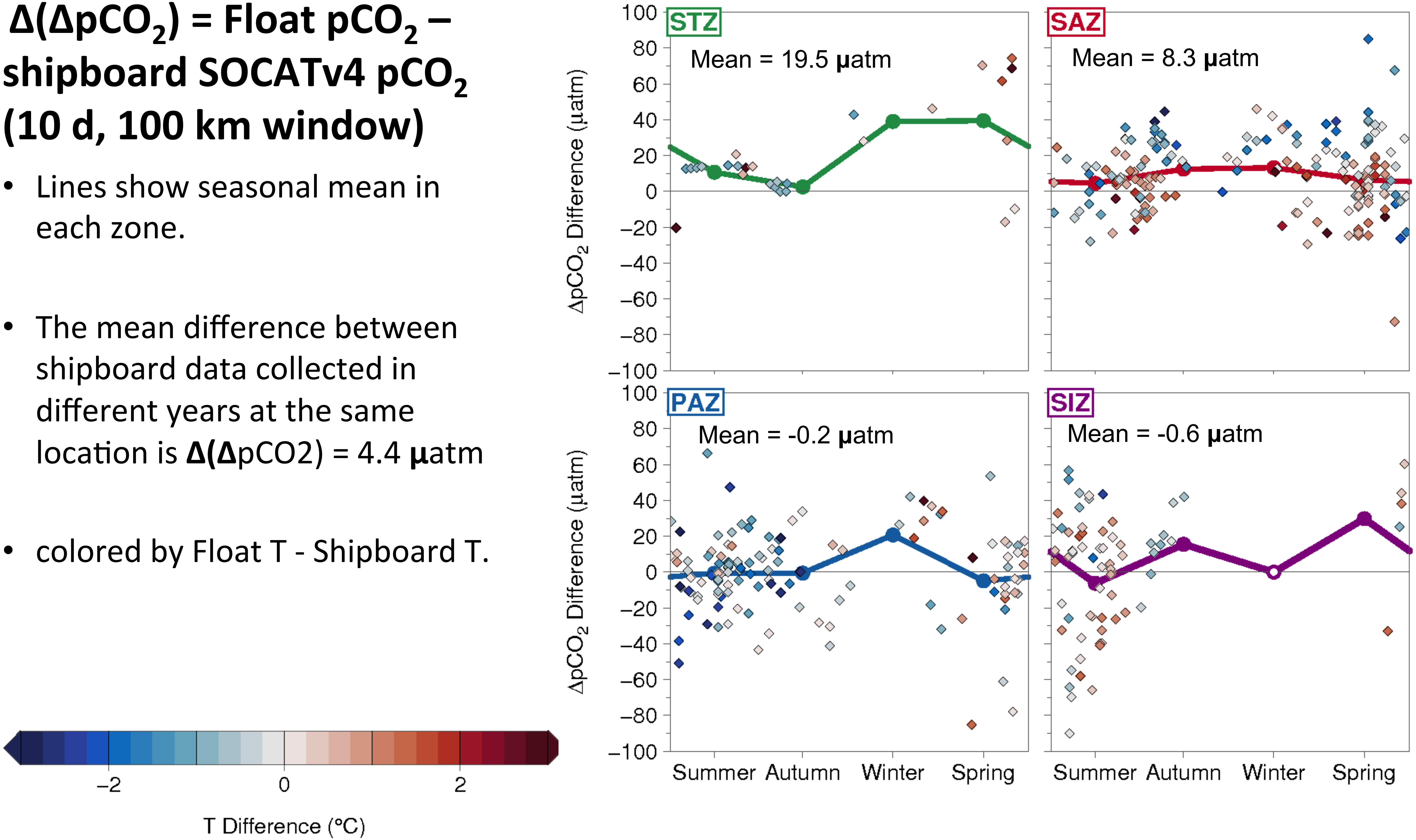
Annual net oceanic CO_2 uptake (Pg C y^{-1})

- Covers region south of 35°S
- Positive indicates net outgassing, negative is uptake.

Zone	SOCCOM floats	Takahashi et. al. (2009)	Landschützer et al. (2014)
STZ	-0.37 ± 0.12	-0.40	-0.50
SAZ	-0.13 ± 0.15	-0.24	-0.24
PAZ	0.64 ± 0.24	-0.16	-0.11
SIZ	0.01 ± 0.07	0.02	-0.04
TOTAL	0.14 ± 0.57 (0.04)	-0.77	-0.88

$\Delta(\Delta pCO_2)$ = Float pCO_2 – shipboard SOCATv4 pCO_2 (10 d, 100 km window)

- Lines show seasonal mean in each zone.
- The mean difference between shipboard data collected in different years at the same location is **Δ(Δ**pCO2) = 4.4 **µ**atm
- colored by Float T - Shipboard T.



Uncertainty analysis on total ocean carbon sink

- Based on a thorough uncertainty analysis, an estimate of 0.57 PgC y-1 was determined by stipulating that the mean error in the float-derived pCO2 ocn, due to systematic uncertainties in the pH data, was normally-distributed with a standard deviation of 1.8% (approximately 7.2 **μ**atm).

- The agreement of the float-based fluxes in three of the four regions with independent estimates, together with the agreement of both the pH data and the float- derived pCO2 ocn data with ship-based measurements, suggests that systematic biases have been minimized in our approach and are likely less than 1.8%.
- Thus a standard error of 0.57 PgC y-1 most likely represents an upper limit to the uncertainty in the total Southern Ocean CO2 flux

Annual net oceanic CO_2 uptake (Pg C y^{-1})

- Covers region south of 35°S
- Positive indicates net outgassing, negative is uptake.
- Dashes indicate fluxes less than 0.05

Zone	SOCCOM floats	Takahashi et. al. (2009) & Landschützer et al. 52014)
STZ	-0.4	-0.5
SAZ	-0.1	-0.2
PAZ	0.6	-0.1
SIZ	-	-
TOTAL	0.1 ± 0.6 (0.14 ± 0.04)	-0.8

Implications for Southern Ocean carbon

- Units Pg C y^{-1}
- Positive indicates net outgassing, negative is uptake
- region south of 35°S

	SOCCOM floats	Takahashi et. al. (2009) & Landschützer et al. (2014)
Pre-industrial (out of ocean)	1.1	0.2
Anthropogenic (half global)	-1.0	-1.0
Contemporary	0.1	-0.8

If the pre-industrial Southern Ocean source is real, where is the uptake required to keep ocean carbon in balance?

Results from David Baker 4DVar fit to atmospheric observations

David Baker global CO_2 inversion setup

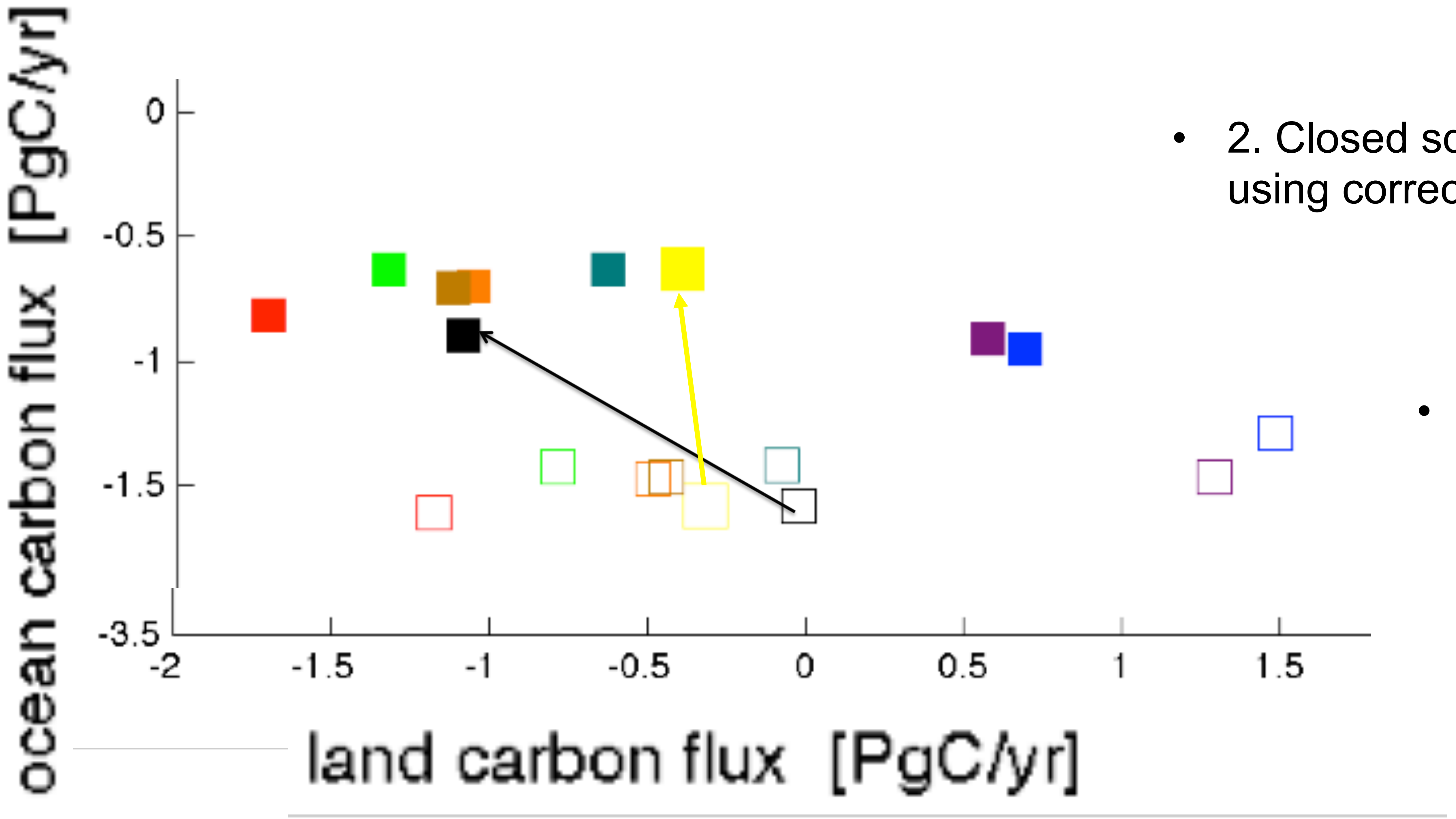
- PCTM off-line tracer transport model
- 4Dvar data assimilation scheme
- Forward runs at 2° x 2.5° (lat/lon)
- Inverse corrections at 6.7°x6.7° (lat/lon)

Priors
In situ
OCO-2 land nadir
OCO-2 land nadir + s31
OCO-2 land nadir + s31r
OCO-2 land glint
OCO-2 land glint + s31
OCO-2 ocean glint
OCO-2 OG (+airmass BC)
OCO-2 OG (airmass < 2.4)

Possible combinations:

- CO_2 data assimilated (4 possibilities)
  - In situ: surface + NOAA aircraft profiles
  - OCO-2 land nadir
  - OCO-2 land glint
  - OCO-2 ocean glint
- Prior estimates (4 possibilities):
  - CASA + NOBM ocean + ODIAC FF
  - CASA + Takahashi ocean + ODIAC FF
  - CASA + Landschutzer ocean + ODIAC FF
  - CASA + Lands. + ODIAC + 0.95 PgC/yr So. Ocean (In situ)

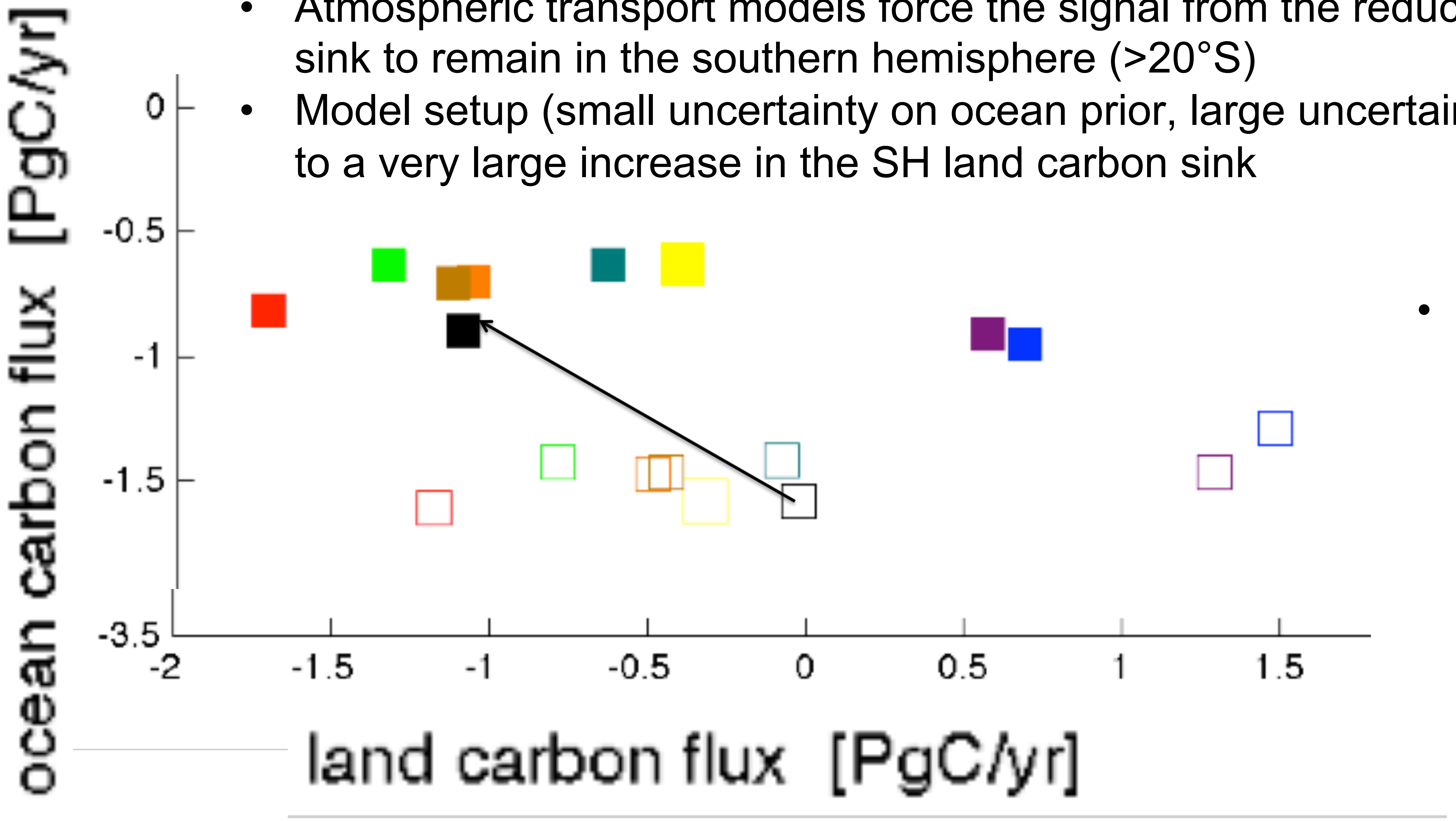
Southern hemisphere land-ocean trade offs



- 2. Closed squares are solutions using corrected ocean prior
- 1. Open squares are solutions using uncorrected ocean prior

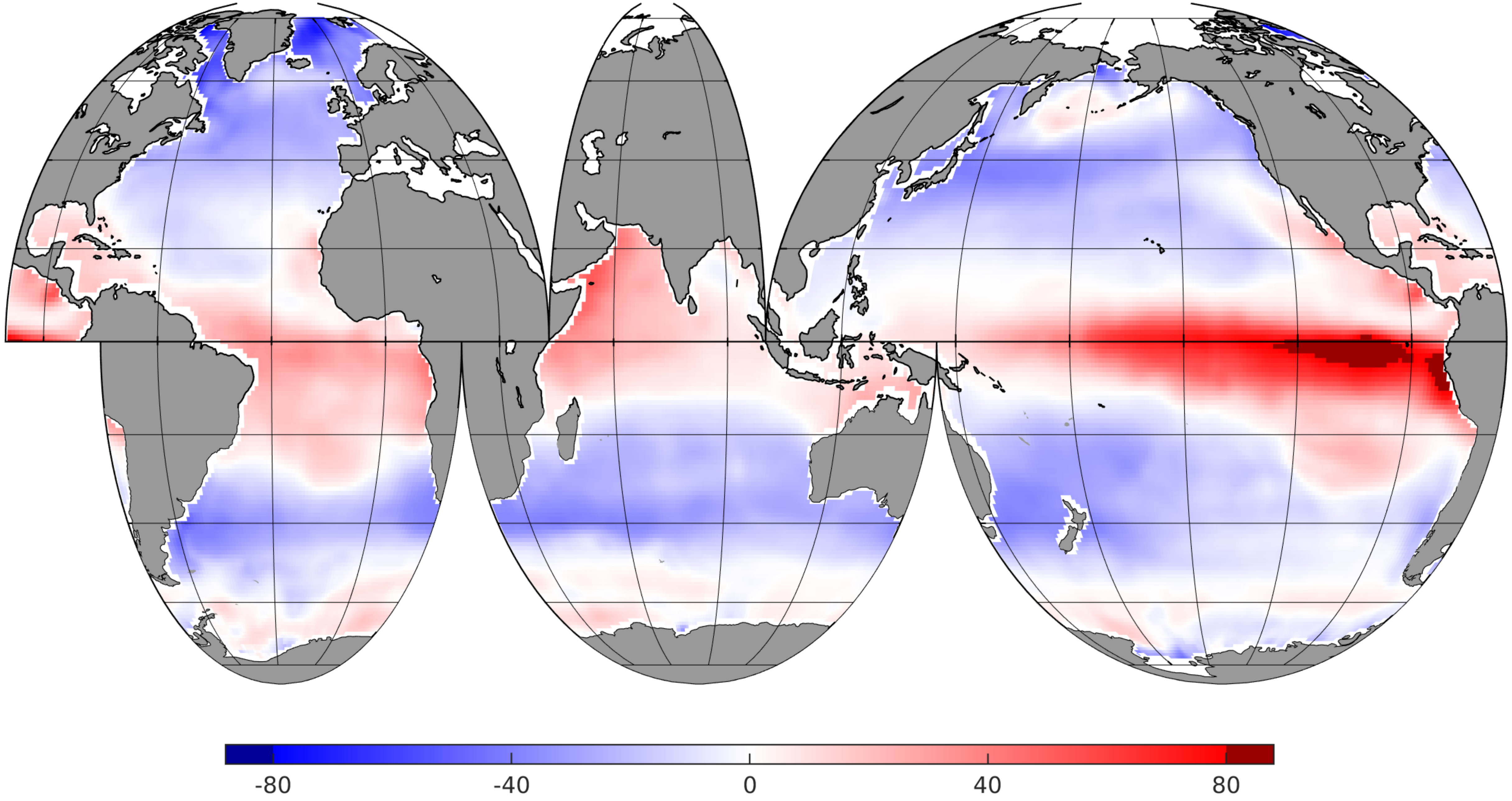
Southern hemisphere land-ocean trade offs

- The reduced Southern Ocean carbon sink requires increased uptake elsewhere to re-balance the carbon budget
- Atmospheric transport models force the signal from the reduced ocean carbon sink to remain in the southern hemisphere (>20°S)
- Model setup (small uncertainty on ocean prior, large uncertainty on land) leads to a very large increase in the SH land carbon sink



- Alternative would be for temperate ocean to become a larger sink by relaxing or modifying the SH ocean prior

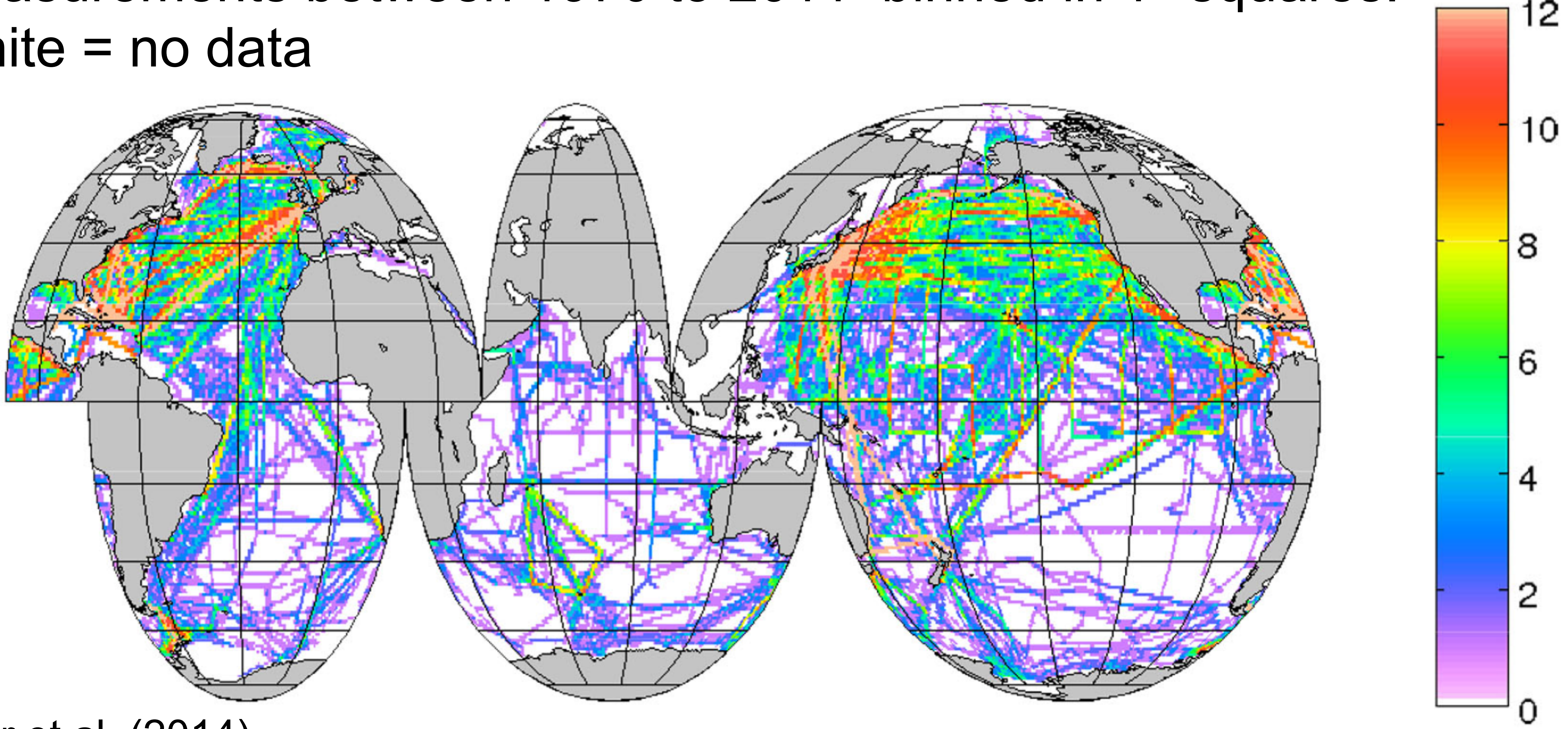
Sea-air CO_2 difference (μatm)



Landschützer (pers. comm. Nov, 2016)

Undersampling of pCO_2

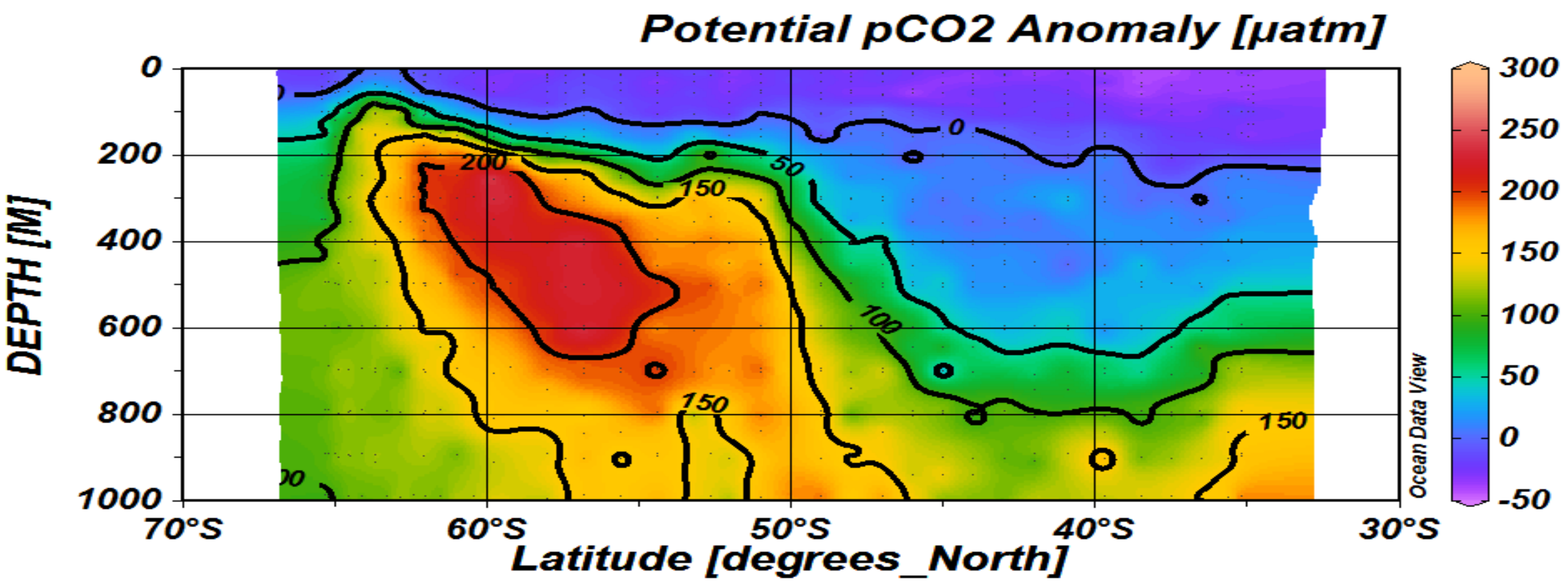
Months of year with surface pCO_2 measurements based on all measurements between 1970 to 2011 binned in 1° squares. White = no data



Bakker et al. (2014)

Oceanographic consistency: Where does the upwelling CO_2 plume come from?

Figures by Ken Johnson and Haidi Chen


Potential pCO2 Anomaly [µatm]
DEPTH [M]
0
200
400
600
800
1000
70°S
60°S
50°S
40°S
30°S
Latitude [degrees_North]
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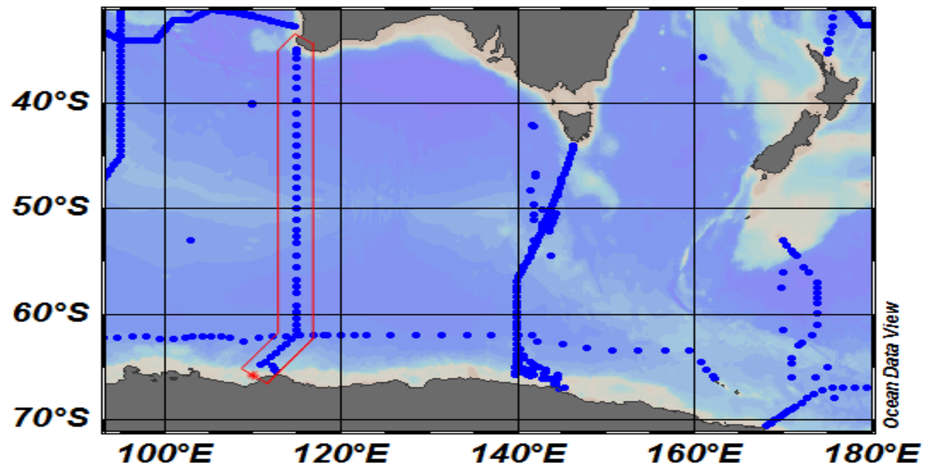
Ocean Data View

40°S
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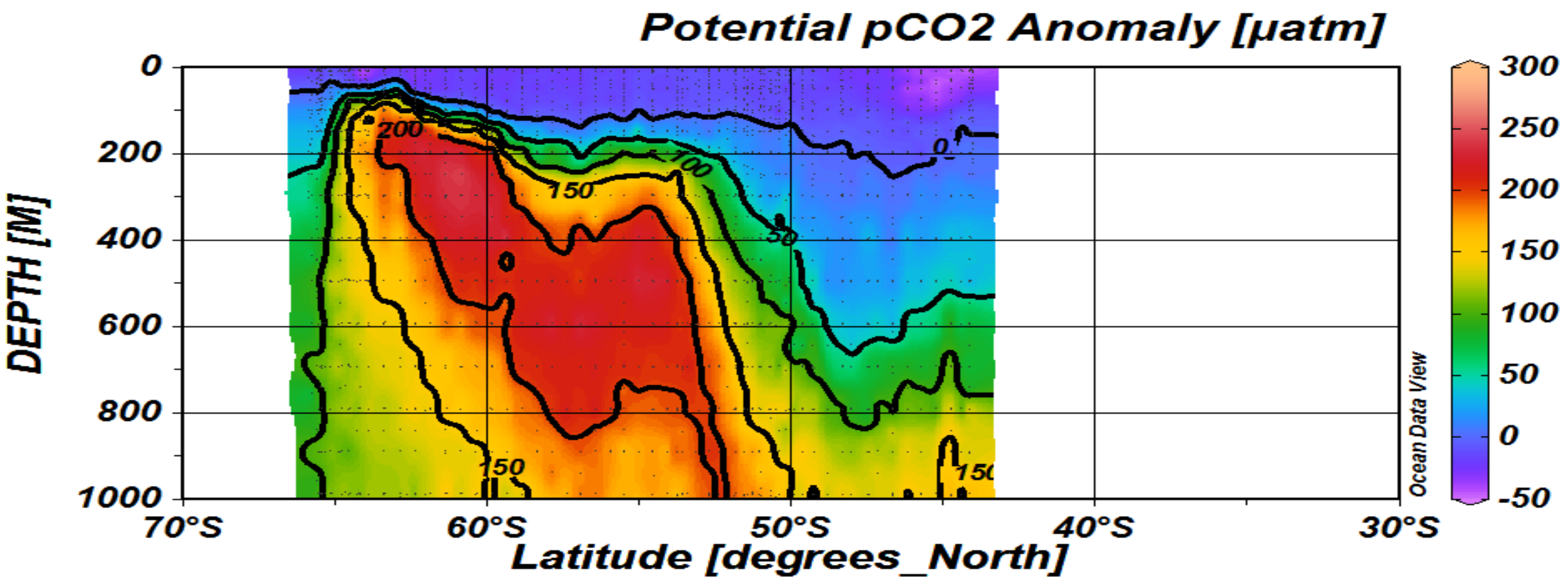
Ocean Data View

Potential pCO2 Anomaly [µatm]
DEPTH [M]
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Latitude [degrees_North]
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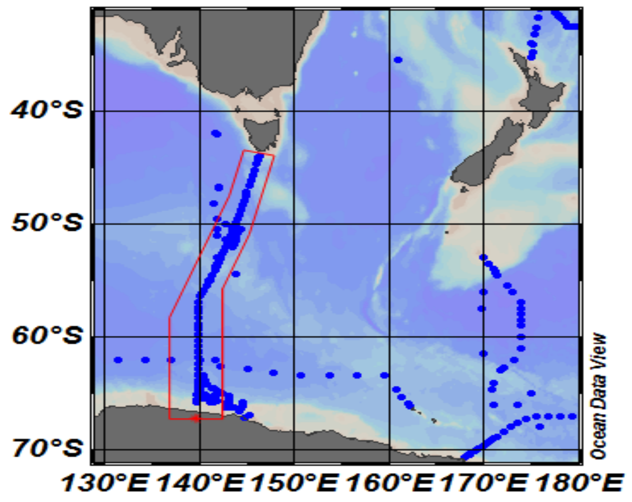
Ocean Data View

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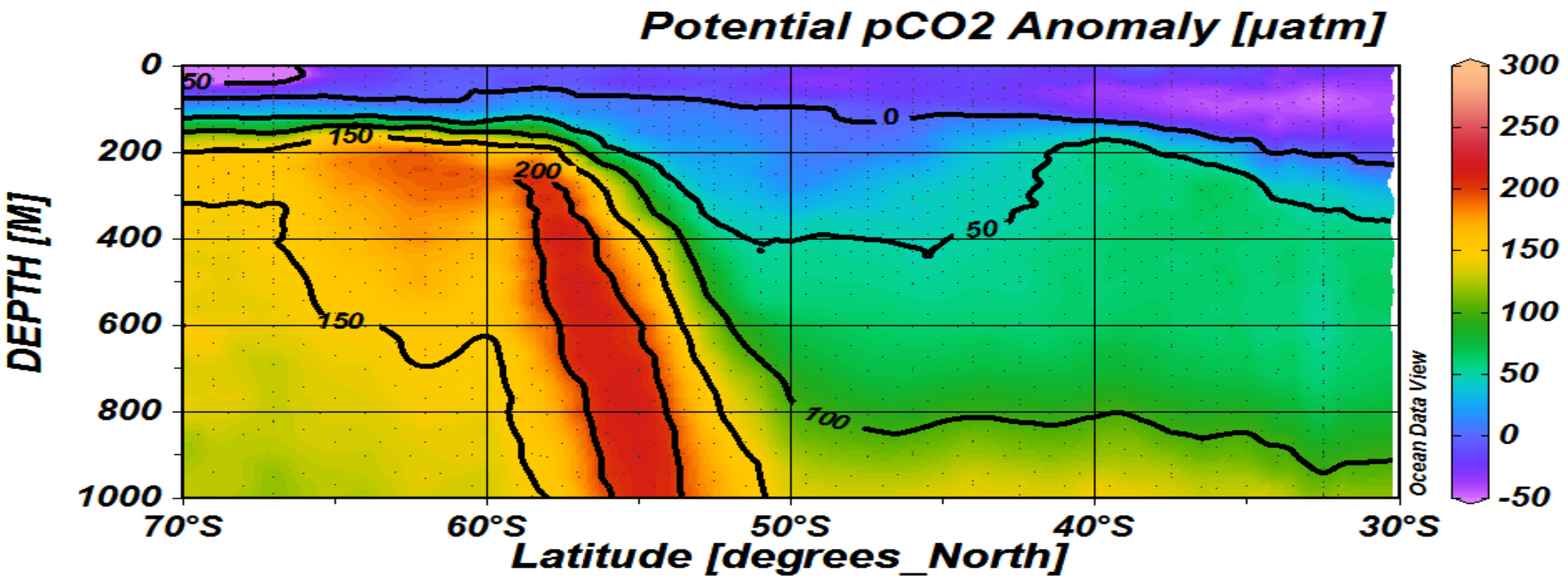
Ocean Data View

Potential pCO2 Anomaly [µatm]
DEPTH [M]
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Latitude [degrees_North]
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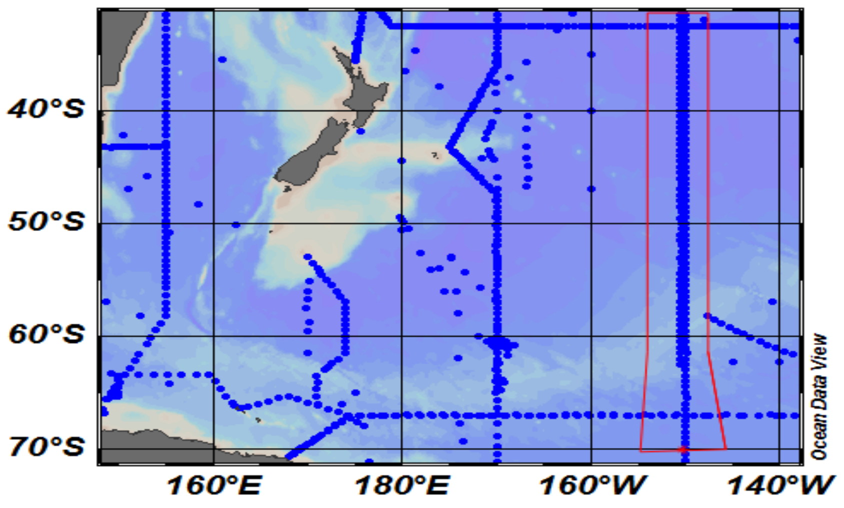
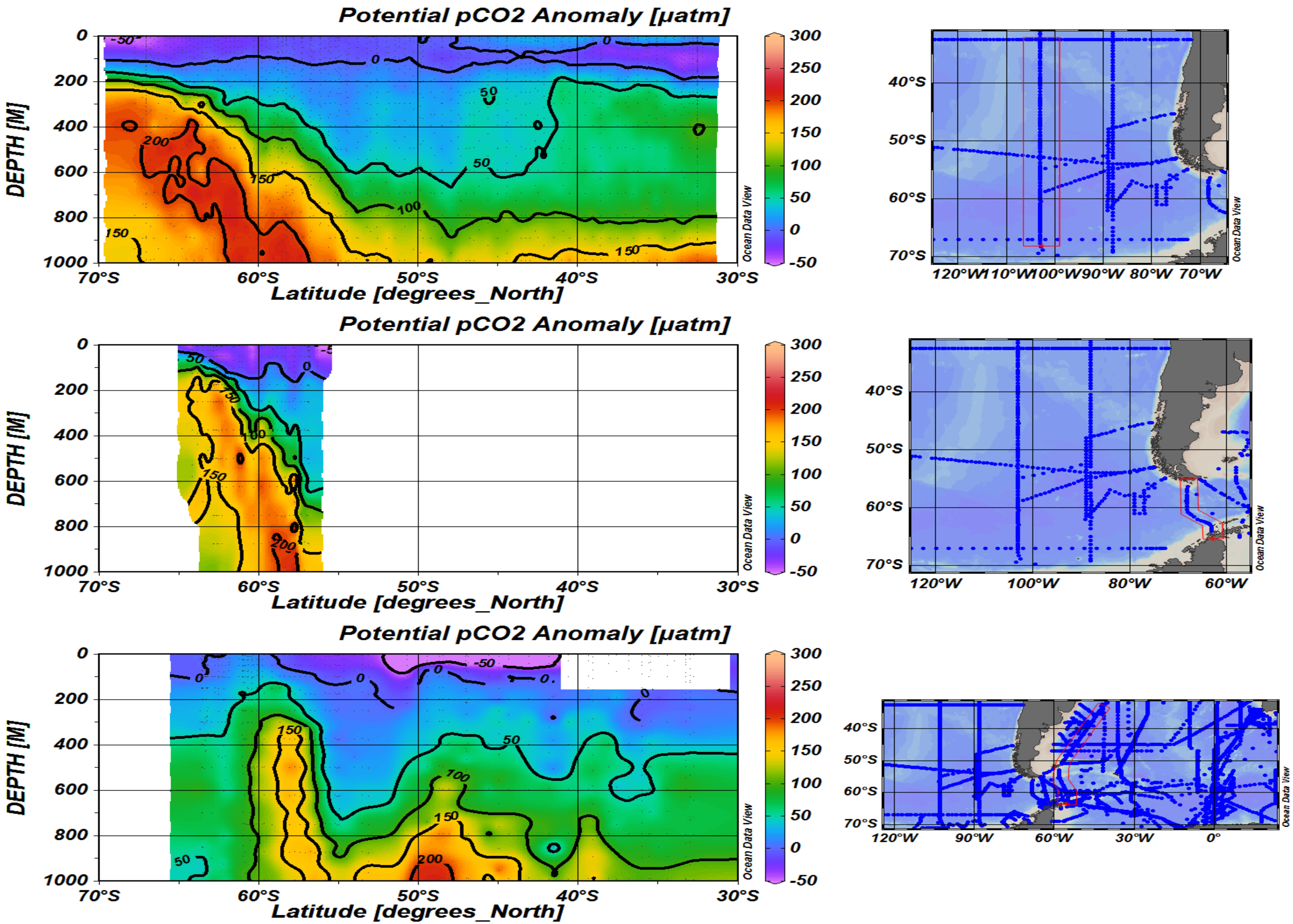
Ocean Data View

40°S
50°S
60°S
70°S
160°E
180°E
160°W
140°W
Ocean Data View


Potential pCO2 Anomaly [µatm]
DEPTH [M]
Latitude [degrees_North]
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70°S
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50°S
40°S
30°S
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0
-50
Ocean Data View
40°S
50°S
60°S
70°S
120°W
110°W
100°W
90°W
80°W
70°W
Potential pCO2 Anomaly [µatm]
DEPTH [M]
Latitude [degrees_North]
100°W
60°W
Potential pCO2 Anomaly [µatm]
DEPTH [M]
Latitude [degrees_North]
90°W
30°W
0°

How do models do?

Dufour et al. (in prep.)

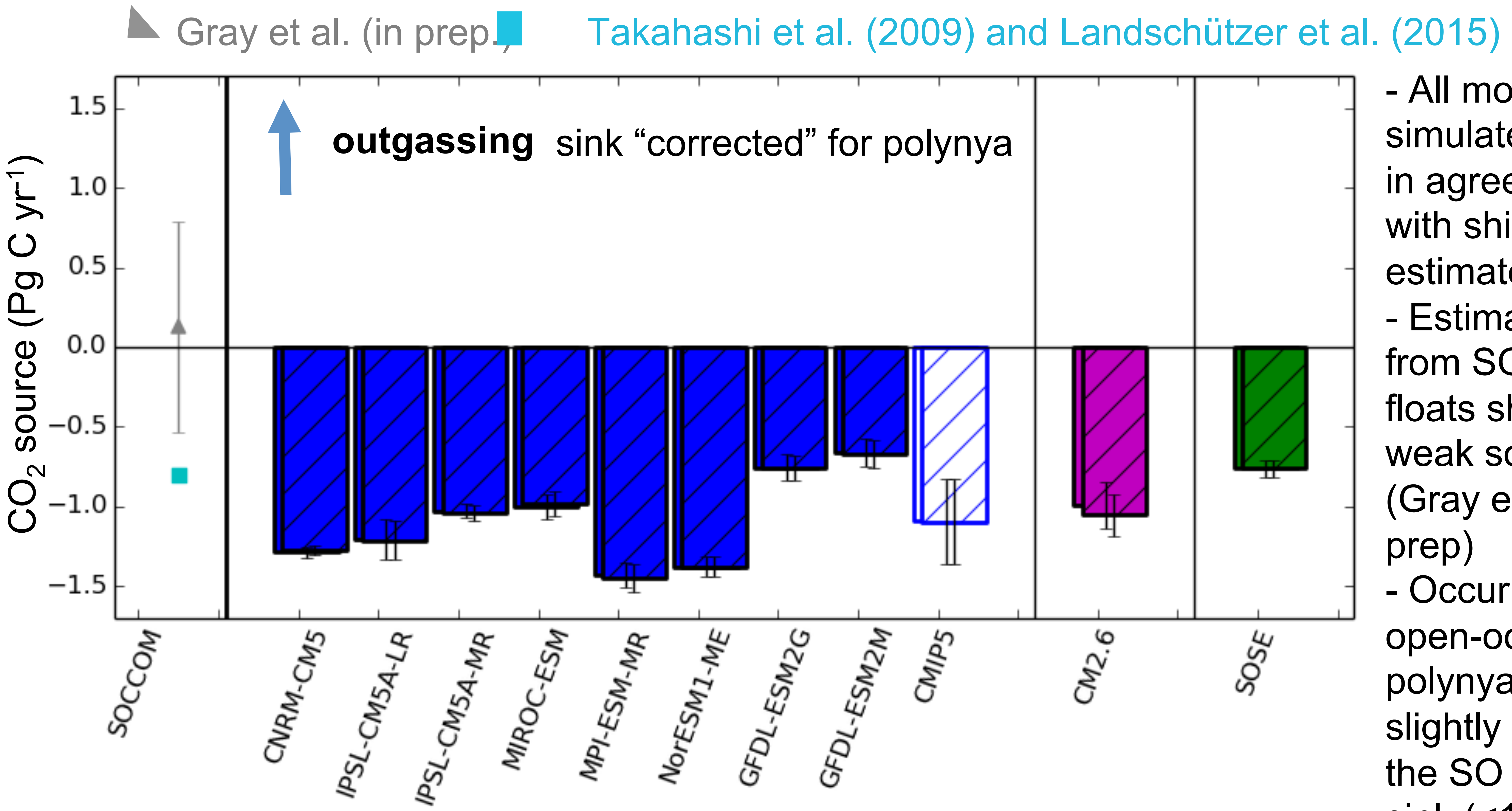
cf. also Gloor et al. (2003)

Models & simulations used in analysis

	center	name	vertical coordinate	ocean resolution	scenario (time period)
CMIP5 models	CERFACS	CNRM–CM5	z	0.4° to 2°	historical (1996–2005)
	NOAA–GFDL	GFDL–ESM2G	isopycnal		
	NOAA–GFDL	GFDL–ESM2M	z		
	IPSL	IPSL–CM5A–LR	z		
	IPSL	IPSL–CM5A–MR	z		
	MIROC	MIROC–ESM	isopycnal		
	MPI–M	MPI–ESM–MR	z		
	NCC	NorESM1–ME	z		
	NOAA–GFDL	CM2.6	z	0.1°	idealized 1%/yr (years 21–30)
	Scripps	SOSE*	z	1/6°	historical (2008–2012)

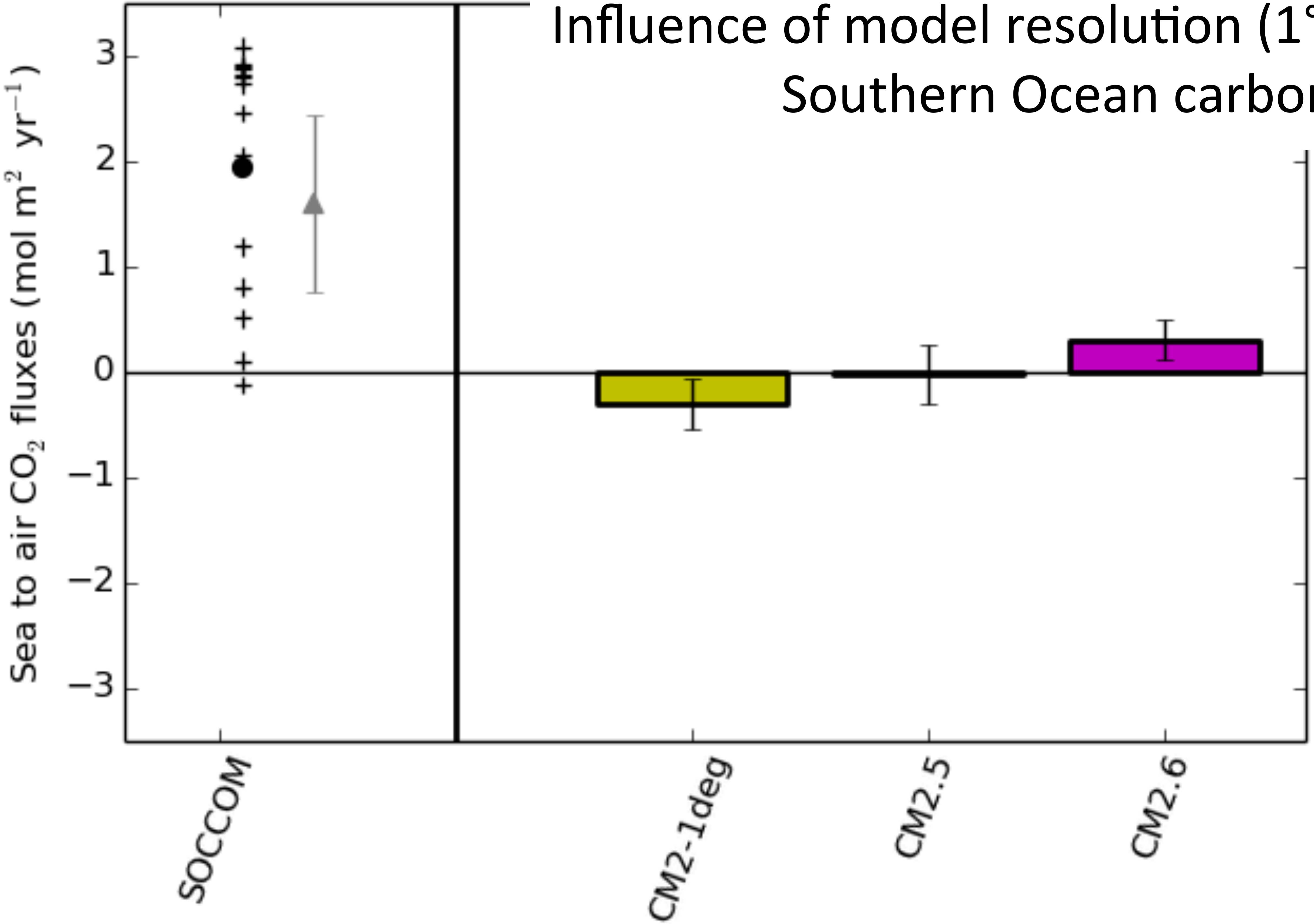
All models are climate models except SOSE which is an ocean-sea ice data assimilating model forced by atmospheric reanalyses (NCEP)

Annual CO_2 Southern Ocean sink



- All models simulate a sink in agreement with shipbased estimates
- Estimates from SOCCOM floats show a weak source (Gray et al., in prep)
- Occurrence of open-ocean polynyas slightly impact the SO carbon sink (<10%)

Influence of model resolution (1°, 0.25°, 0.1°) on Southern Ocean carbon flux)



Strong sensitivity of Southern Ocean carbon uptake and nutrient cycling to wind stirring

K. B. Rodgers[1], O. Aumont[2], S. E. Mikaloff Fletcher[3], Y. Plancherel[4], L. Bopp[5], C. de Boyer Montégut[6], D. Iudicone[7], R. F. Keeling[8], G. Madec[9,10], and R. Wanninkhof[11]

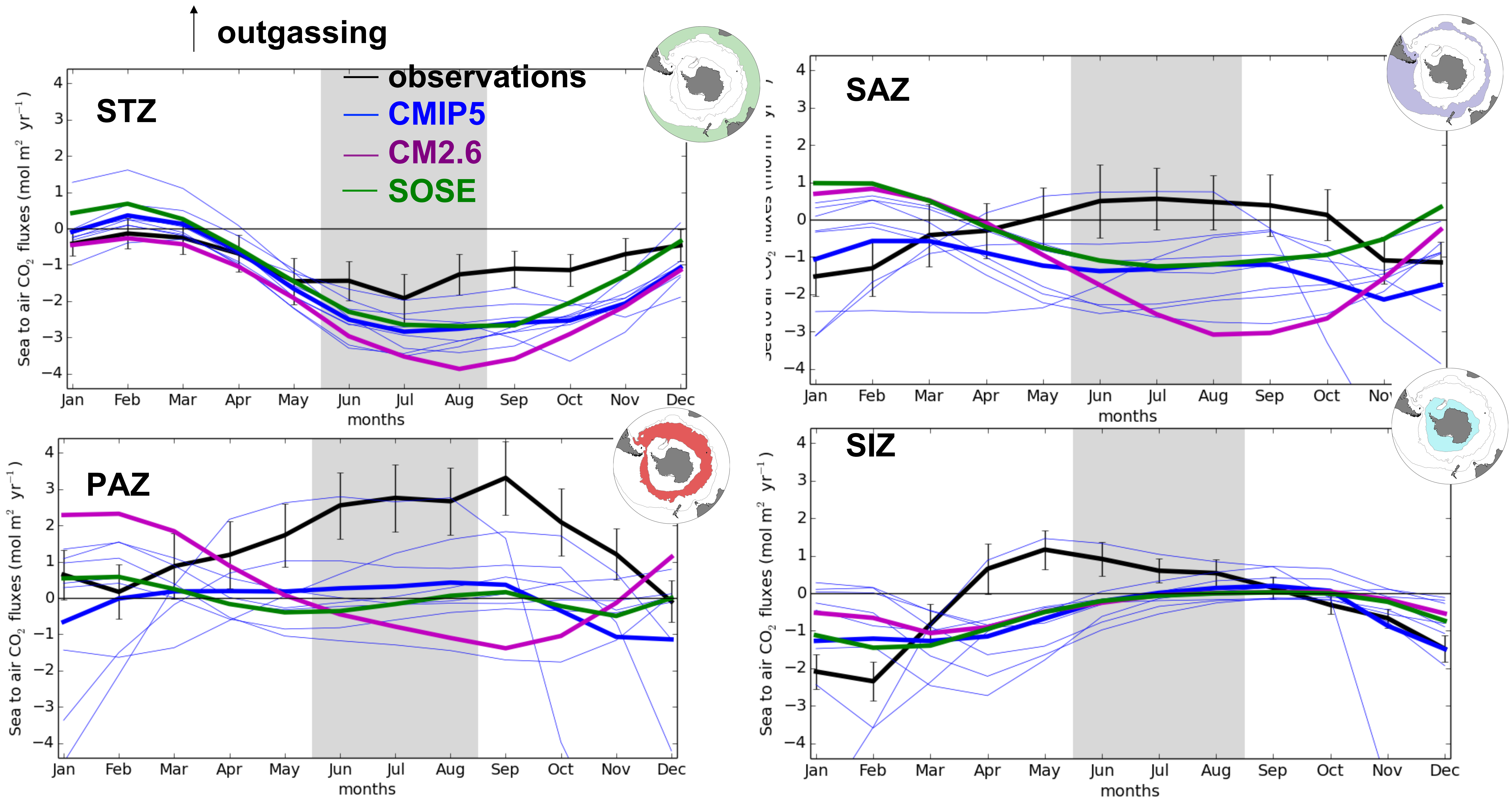
This is tested with a sensitivity study using an ad hoc parameterization of wind stirring in an ocean carbon cycle model, where the objective is to identify the way in which perturbations to the vertical density structure of the planetary boundary in the ocean impacts the carbon cycle and ocean biogeochemistry.

Wind stirring leads to reduced uptake of CO_2 by the Southern Ocean over the period 2000–2006, with a relative reduction with wind stirring on the order of 0.9 $Pg\,C\,yr^{-1}$ over the region south of 45° S. This impacts not only the mean carbon uptake, but also the phasing of the seasonal cycle of carbon and other ocean biogeochemical tracers. Enhanced wind stirring delays the seasonal onset of stratification, and this has large impacts on both entrainment and the biological pump.

Biogeosciences, 11, 4077–4098, 2014

Seasonal mean air-sea CO_2 fluxes

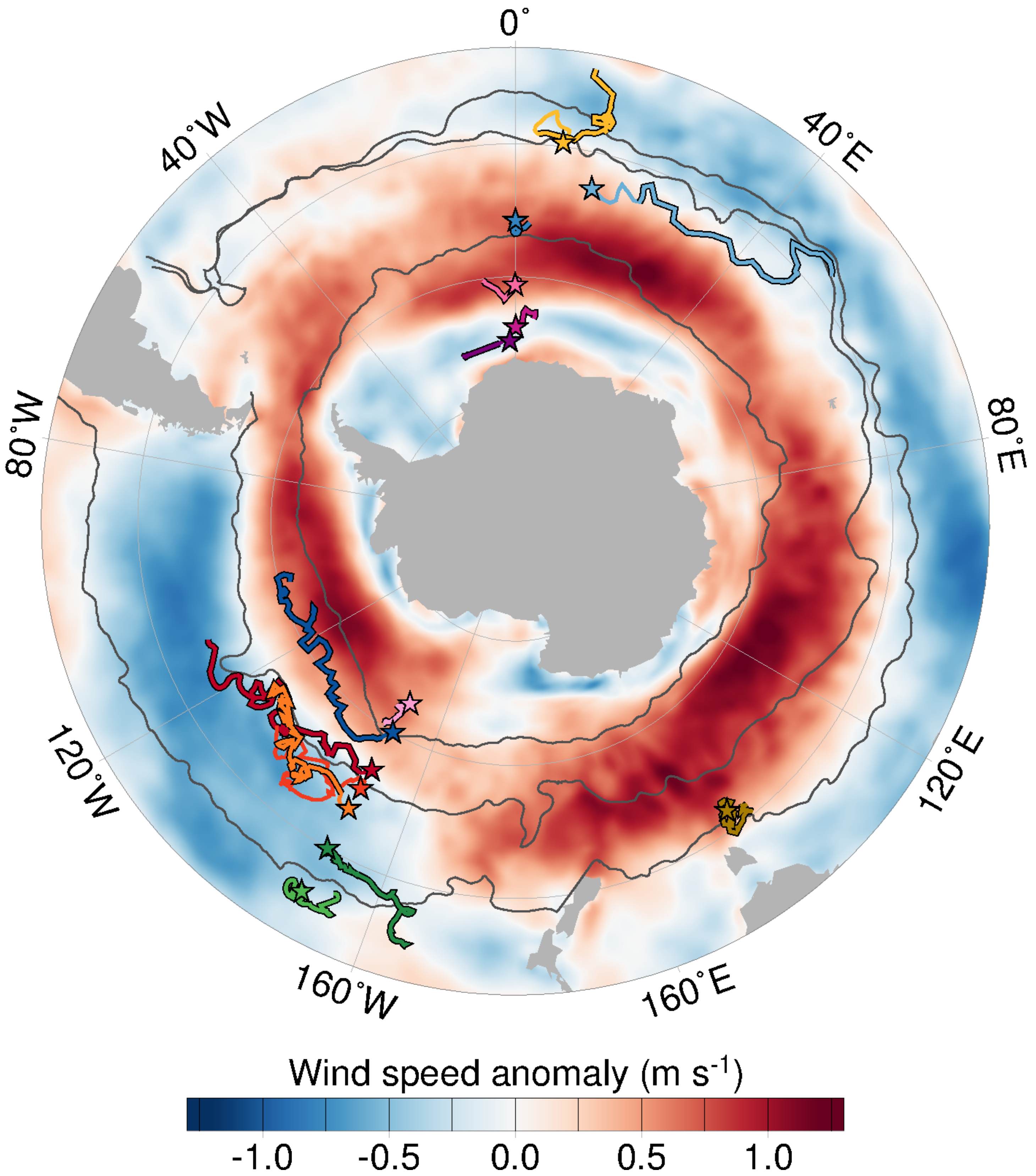
Results: seasonal CO_2 fluxes



Role of interannual variability?

Wind speed anomaly (April 2014 to 2016)

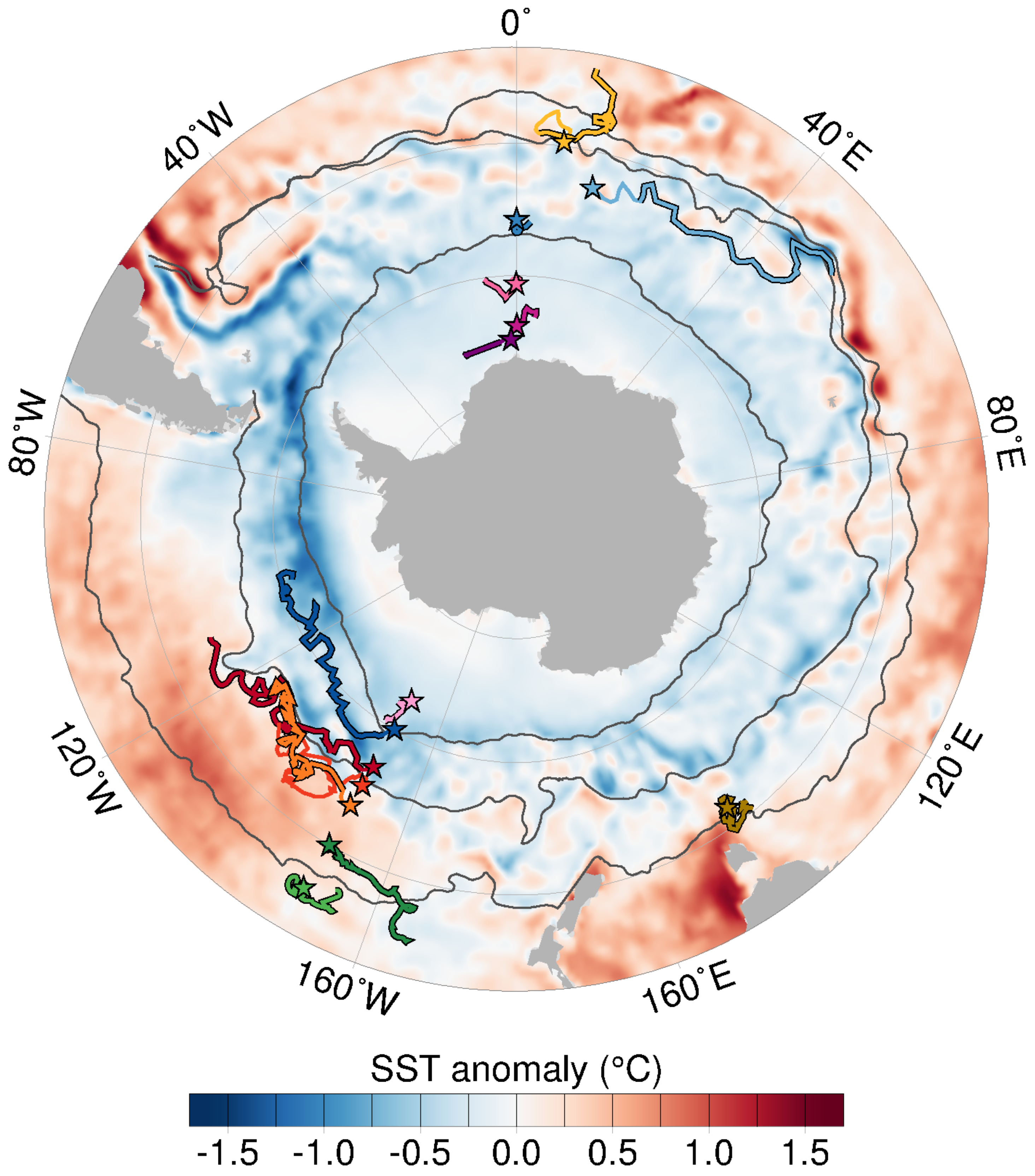
- The ACC region has increased winds which would imply more upwelling & thus outgassing.
- ERA-interim wind fields, calculated as the mean over Apr 2014 - Apr 2016 minus the mean over Apr 1979 - Apr 2016



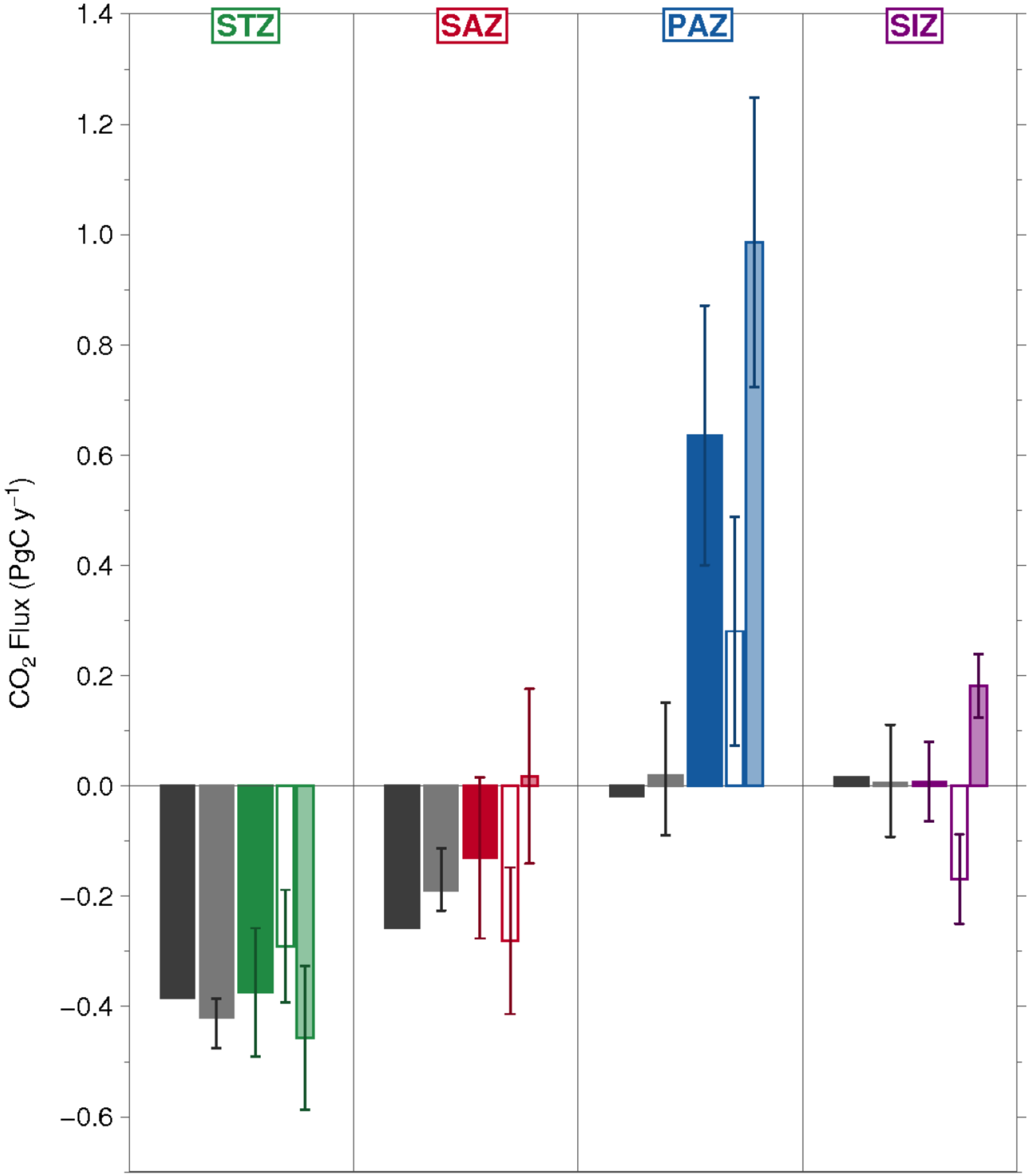
SST Anomaly
(April 2014 to 2016)

- The subtropics are warmer, consistent with increased outgassing.
- The ACC region has colder temperatures, consistent with higher upwelling.

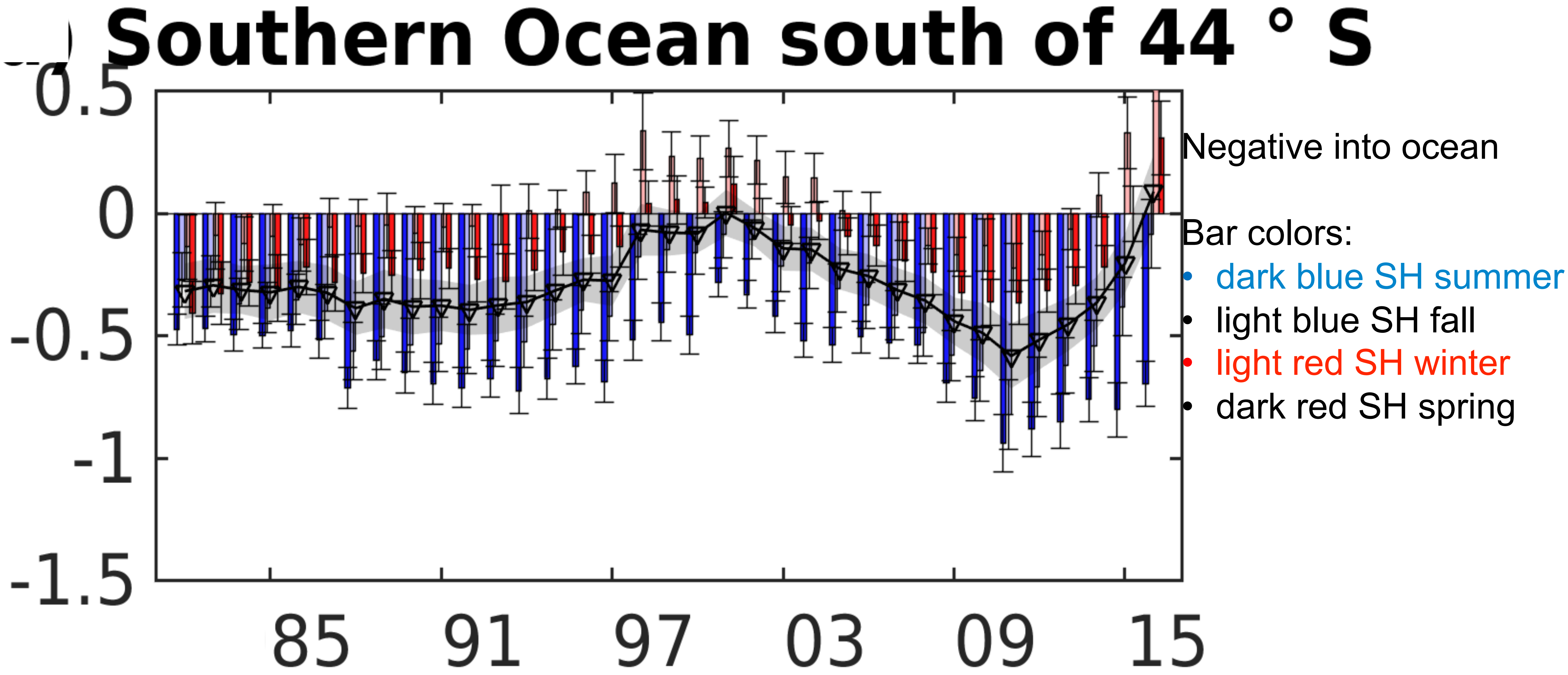
- ERA-interim SST fields, calculated as the mean over Apr 2014 - Apr 2016 minus the mean over Apr 1979 - Apr 2016



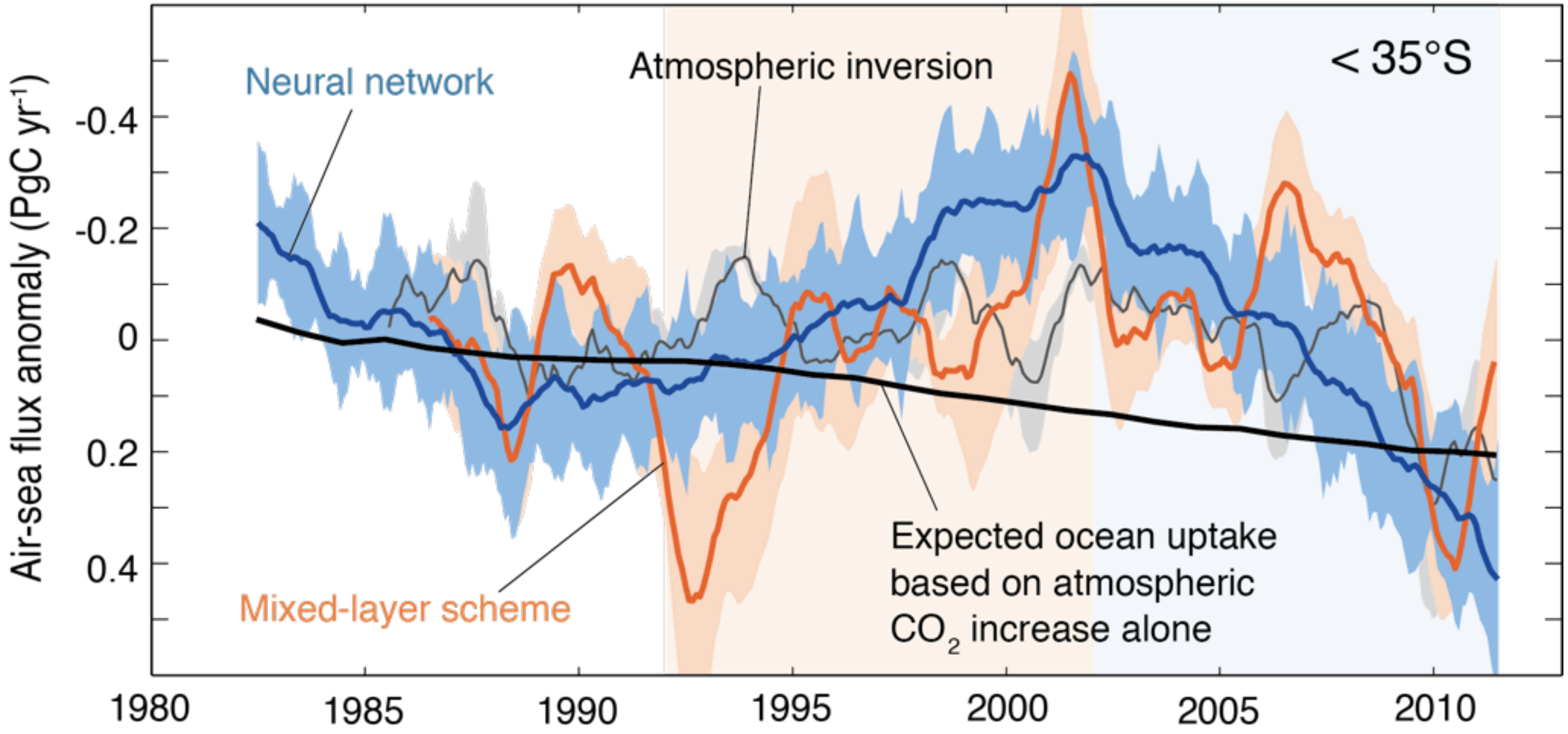
Annual net CO_2 flux (Pg C/yr)



CO_2 Flux (Pg C yr^{-1})



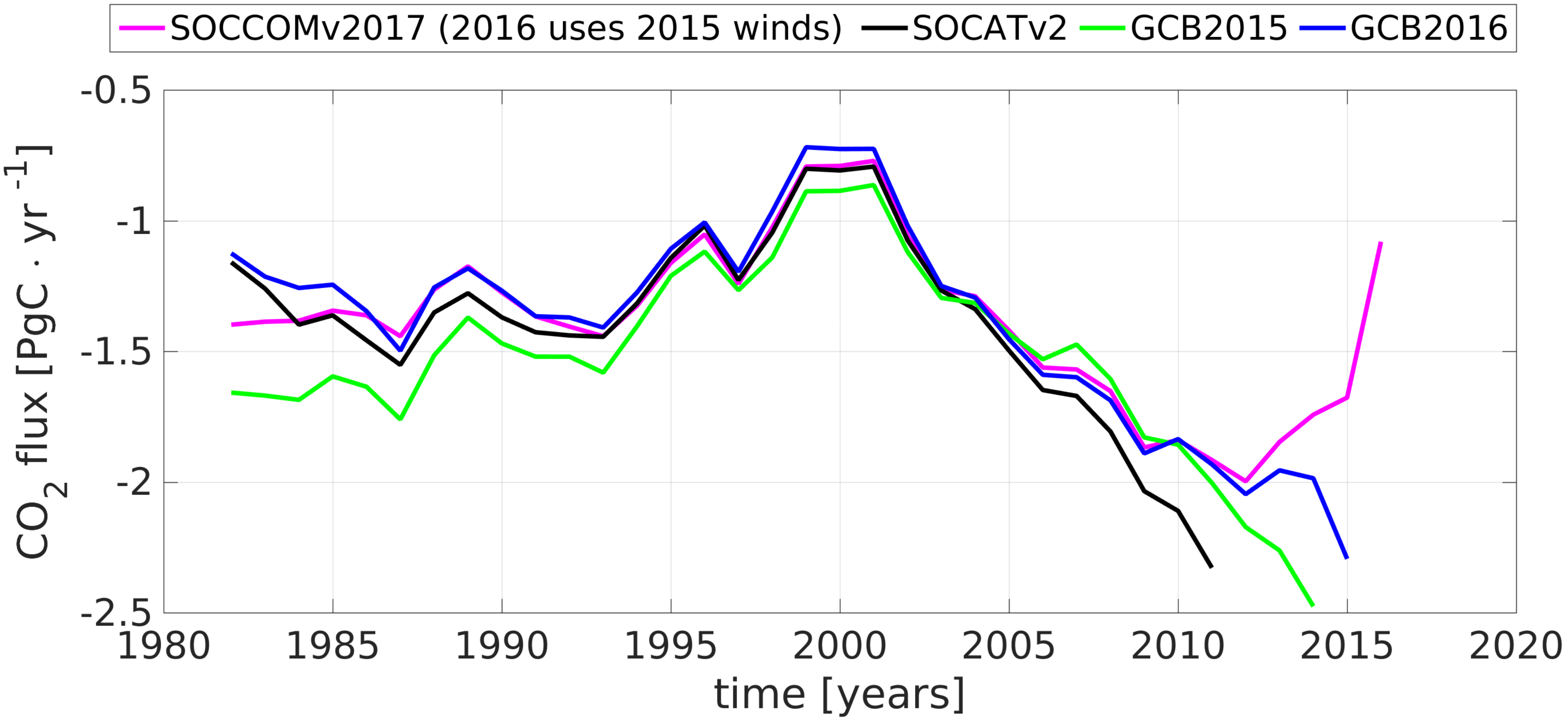
Recent CO_2 flux trend into the Southern Ocean



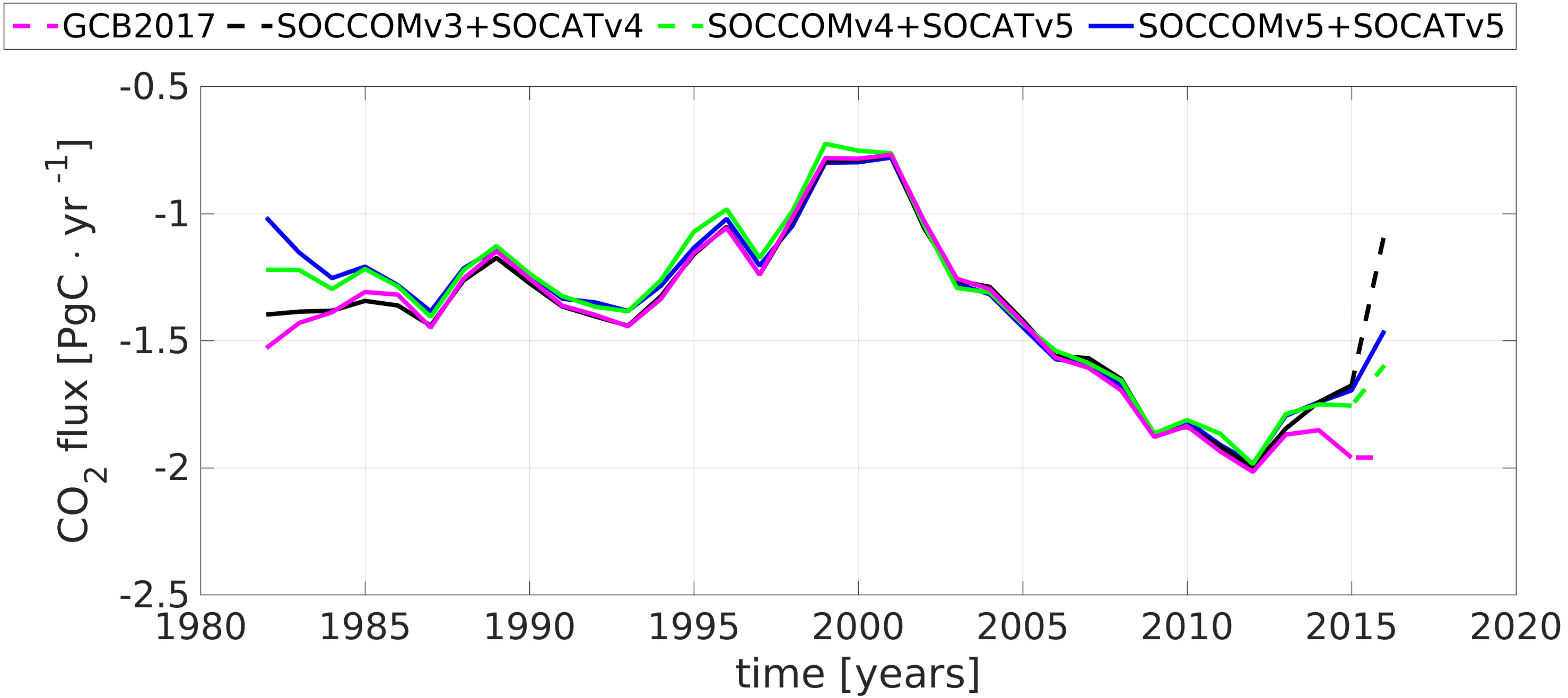
Le Quéré et al. (2007, Science): Saturation of Southern Ocean CO_2 sink?

Landschützer et al. (2015, Science): Reinvigoration of Southern Ocean carbon sink

Global ocean carbon sink



Global ocean carbon sink



Conclusion: Southern Ocean CO_2 flux to atmosphere is greater than previous estimates

- Hypothesis 1: flawed methodology
  - Small number of floats is worrisome, but
  - Good agreement when shipboard data is available is reassuring
  - Method for converting pH to pCO_2 looks good.

- Hypothesis 2: Climatological baseline should have a stronger Southern Ocean source
  - but is this due to pre-industrial component or anthropogenic component, or both?
  - Maintaining a large global ocean anthropogenic carbon sink requires a larger carbon uptake elsewhere to compensate the smaller carbon uptake in the Southern Ocean

- Hypothesis 3: Interannual variability: 2014-present is anomalous
  - This appears to be the case, but past history suggest this can only explain ~0.5 Pg C y^{-1} of 0.9 Pg C y^{-1} anomaly we find

Discovery of a Southern Ocean carbon source: Implications for carbon uptake in southern hemisphere western boundary regions

Jorge L. Sarmiento
Princeton University

- Current paradigm: the Southern Ocean (south of 35°S) accounts for half the oceanic uptake of anthropogenic carbon. The contemporary air-sea flux estimated from SOCAT shipboard underway data is ~0.8 Pg C/yr into the ocean.
- Results from SOCCOM Argo floats equipped with biogeochemical sensors give a net flux of ~0.1 out of the ocean. This implies an outgoing pre-industrial flux larger by ~0.9 Pg C/yr than current estimates.

Thank you

Alison Gray & Ken Johnson

Nancy Williams,
Seth Bushinsky, Carolina Dufour & Peter Landschützer

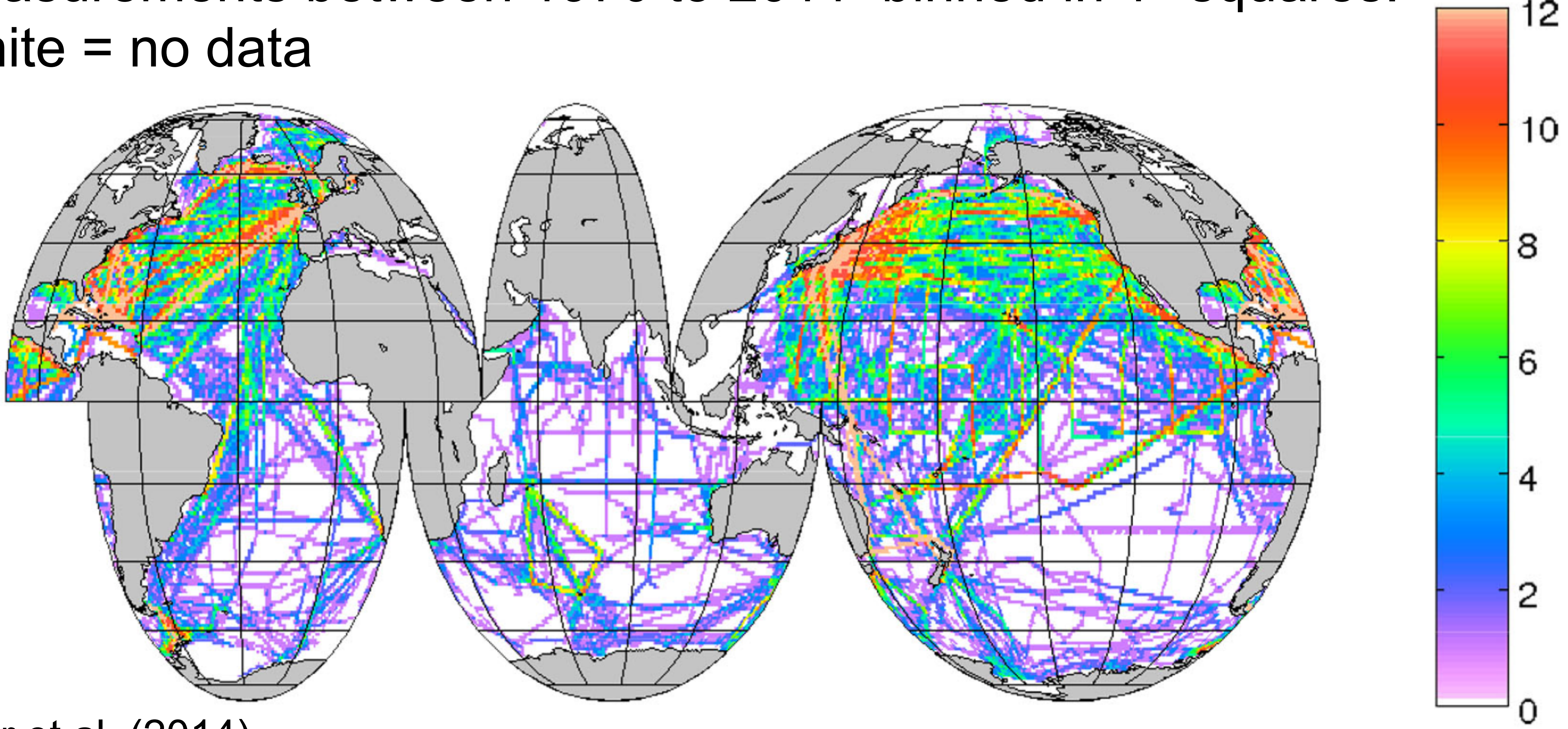
Stephen Riser, Joellen Russell, Lynne Talley,
& Rik Wanninkhof

The End

The grand challenge

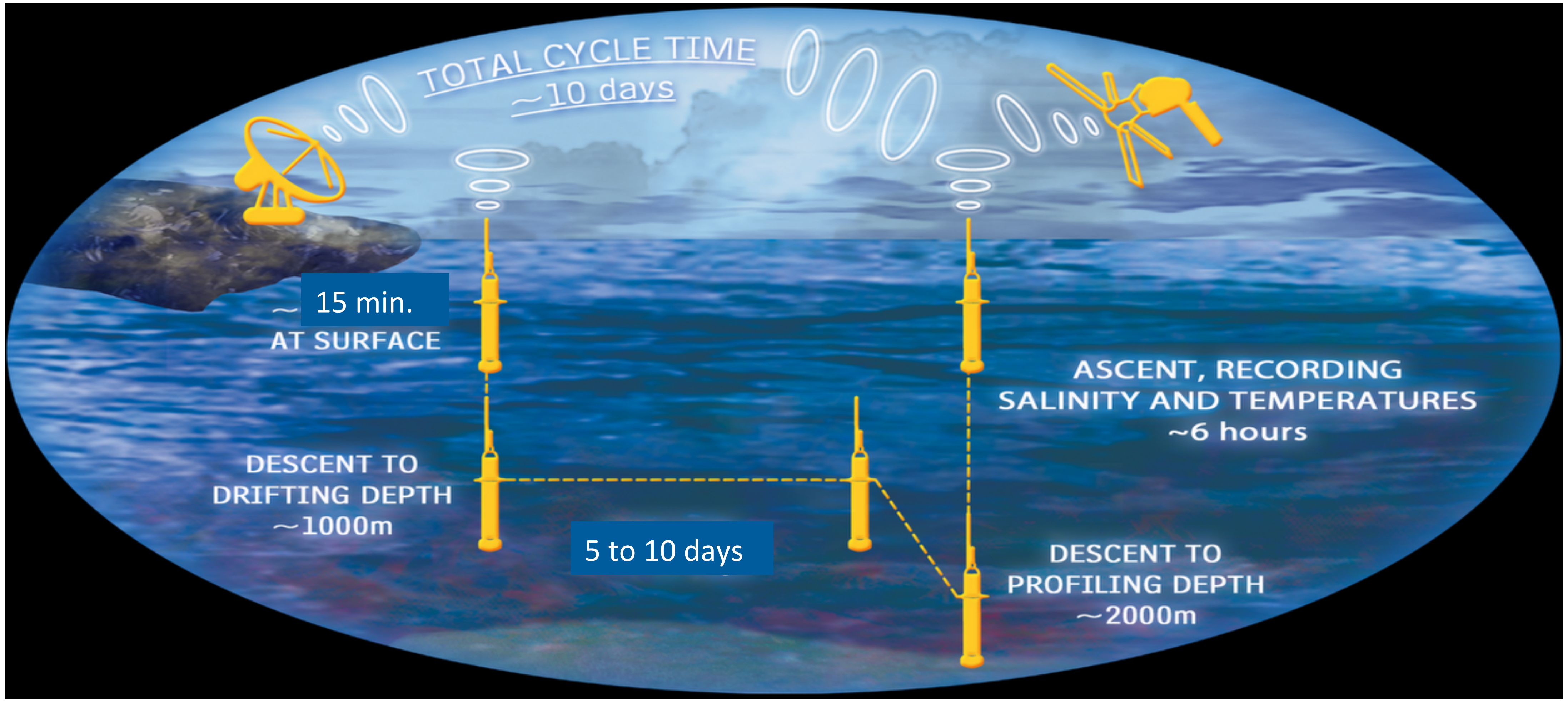
Undersampling of *p*CO_2

Months of year with surface *p*CO_2 measurements based on all measurements between 1970 to 2011 binned in 1° squares.
White = no data

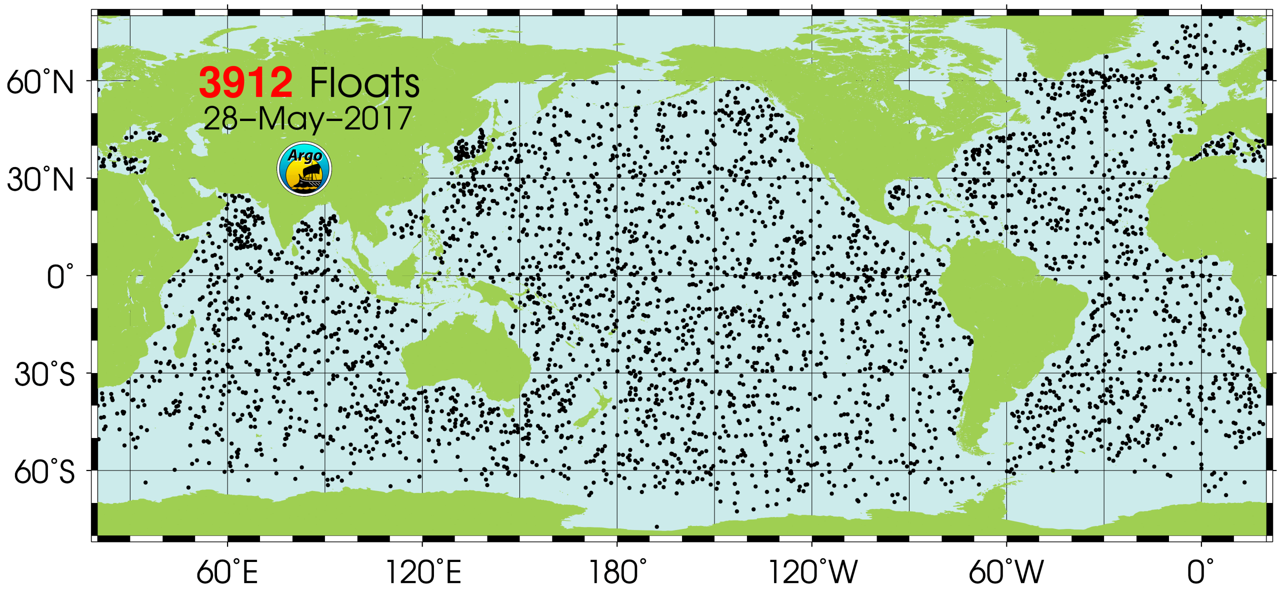


Bakker et al. (2014)

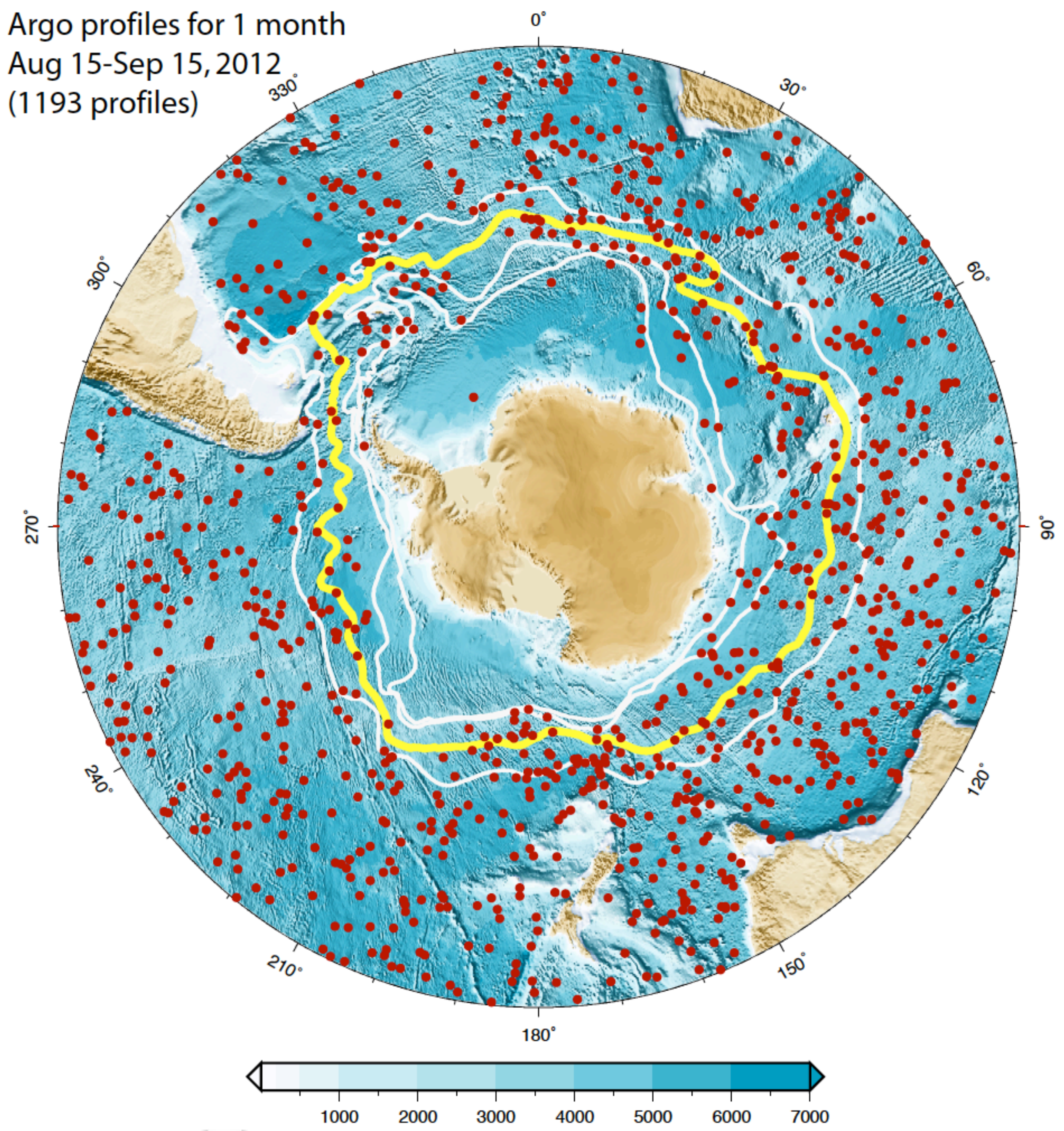
The opportunity



- Argo profiling floats
  - have a 4 to 7 year lifetime,
  - Measure T & S from ~2000 m to the surface every 5 to 10 days.
  - data direct to Internet.



The Opportunity



A paradigm shift – Transformative observing system

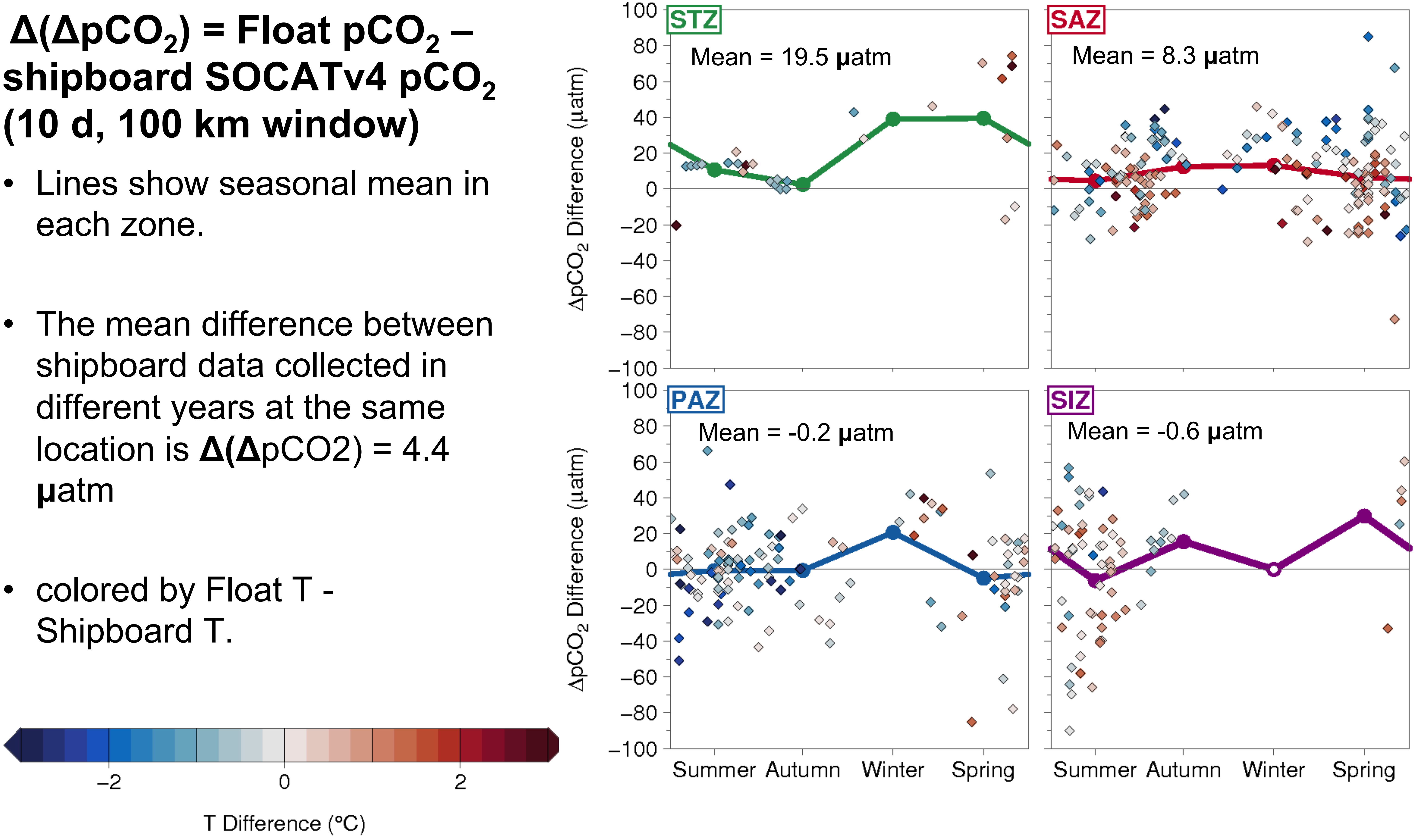
- Argo floats (currently required to measure only temperature & salinity)

- Biogeochem sensors now developed for
  - pH
  - Nitrate,
  - oxygen, and
  - optics (FLBB) – *funded by NASA*

SOCCOM

$\Delta(\Delta pCO_2)$ = Float pCO_2 – shipboard SOCATv4 pCO_2 (10 d, 100 km window)

- Lines show seasonal mean in each zone.
- The mean difference between shipboard data collected in different years at the same location is **Δ(Δ**pCO2) = 4.4 **µ**atm
- colored by Float T - Shipboard T.

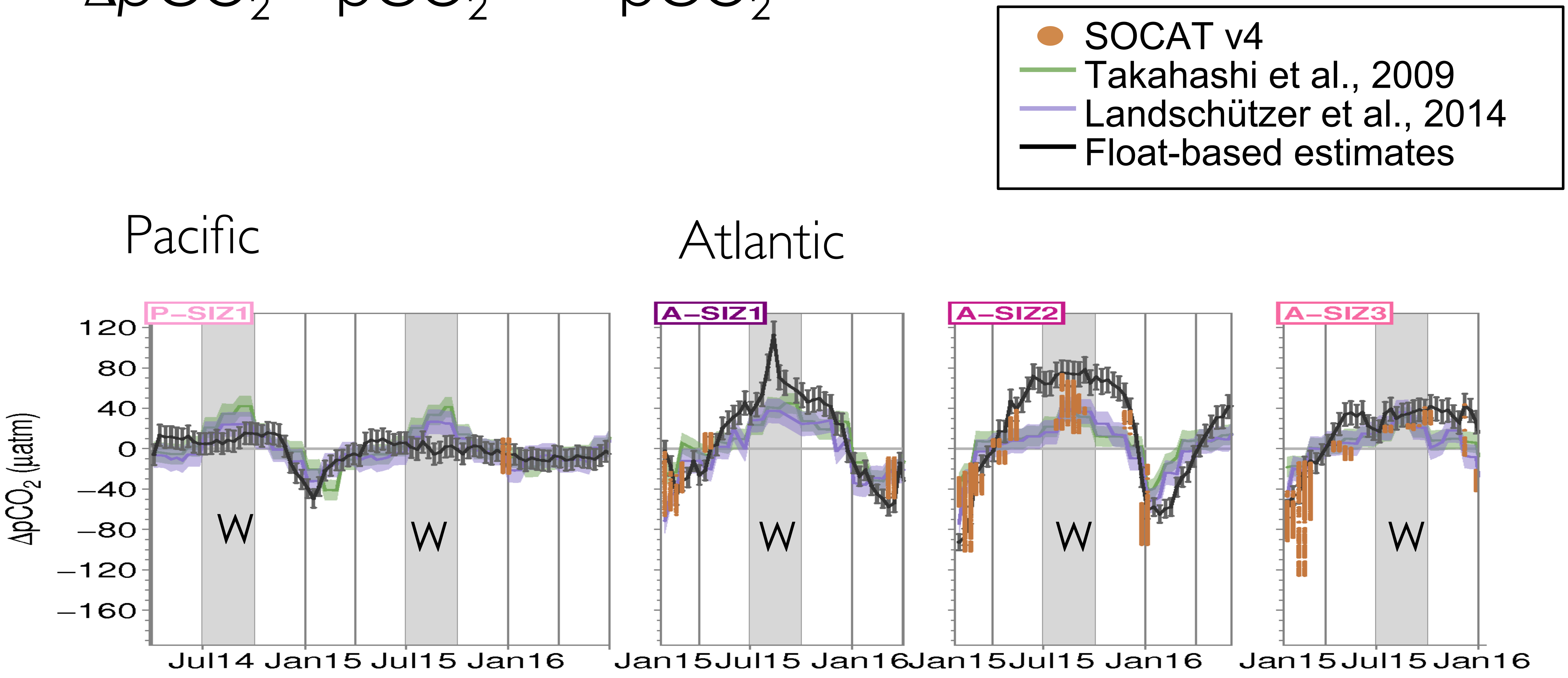


ΔpCO_2 estimate

Gray et al. (resubmitted)

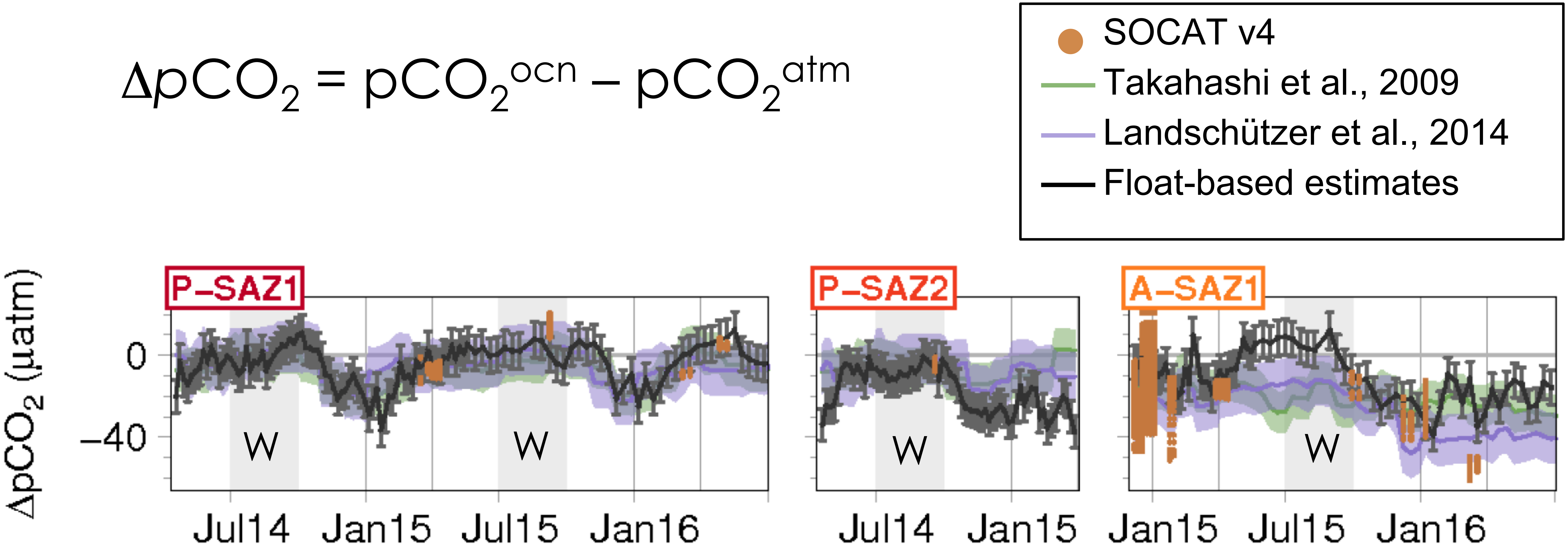
ΔpCO_2 in SIZ zone

$$\Delta pCO_2 = pCO_2^{ocn} - pCO_2^{atm}$$



ΔpCO_2 in SAZ

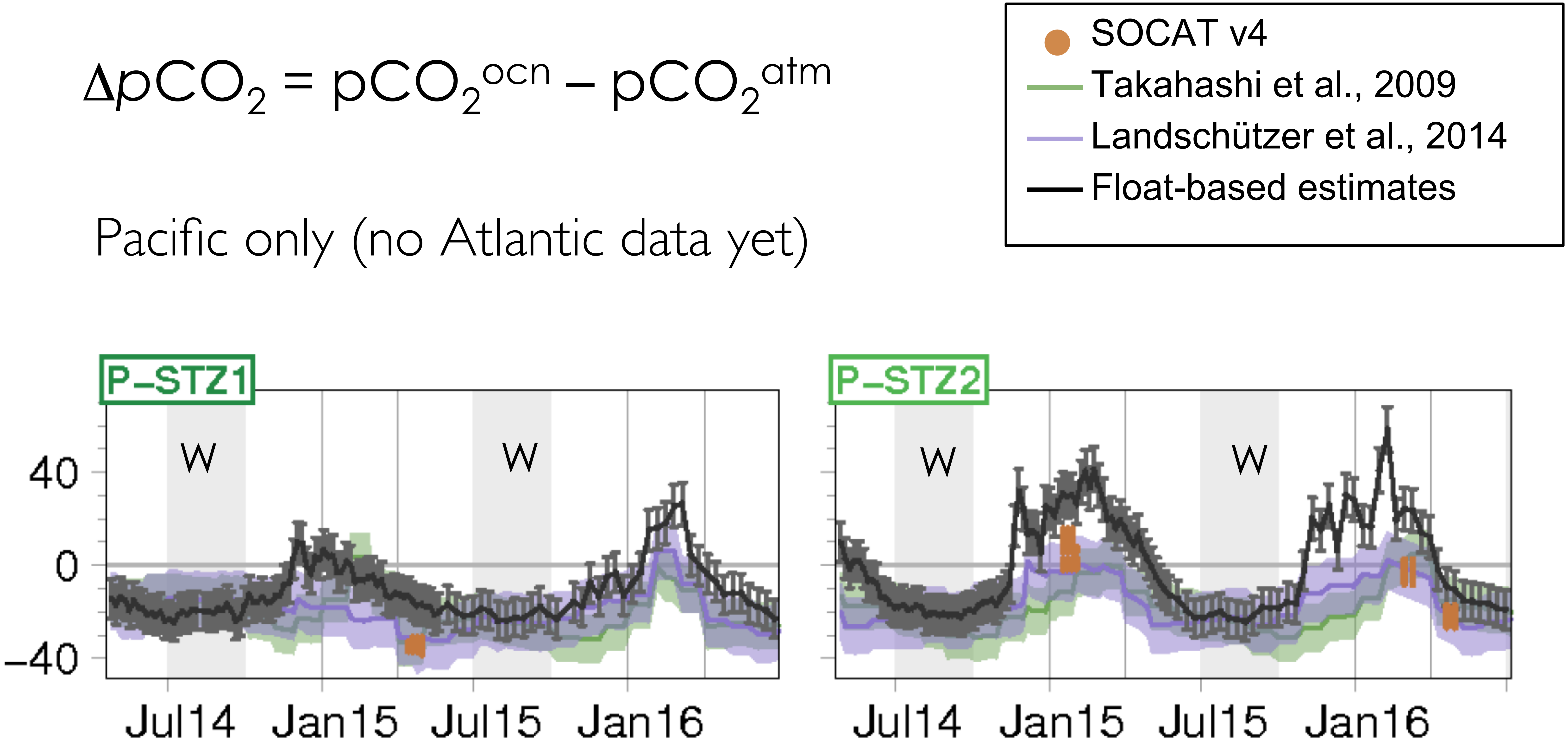
$$\Delta pCO_2 = pCO_2^{ocn} - pCO_2^{atm}$$



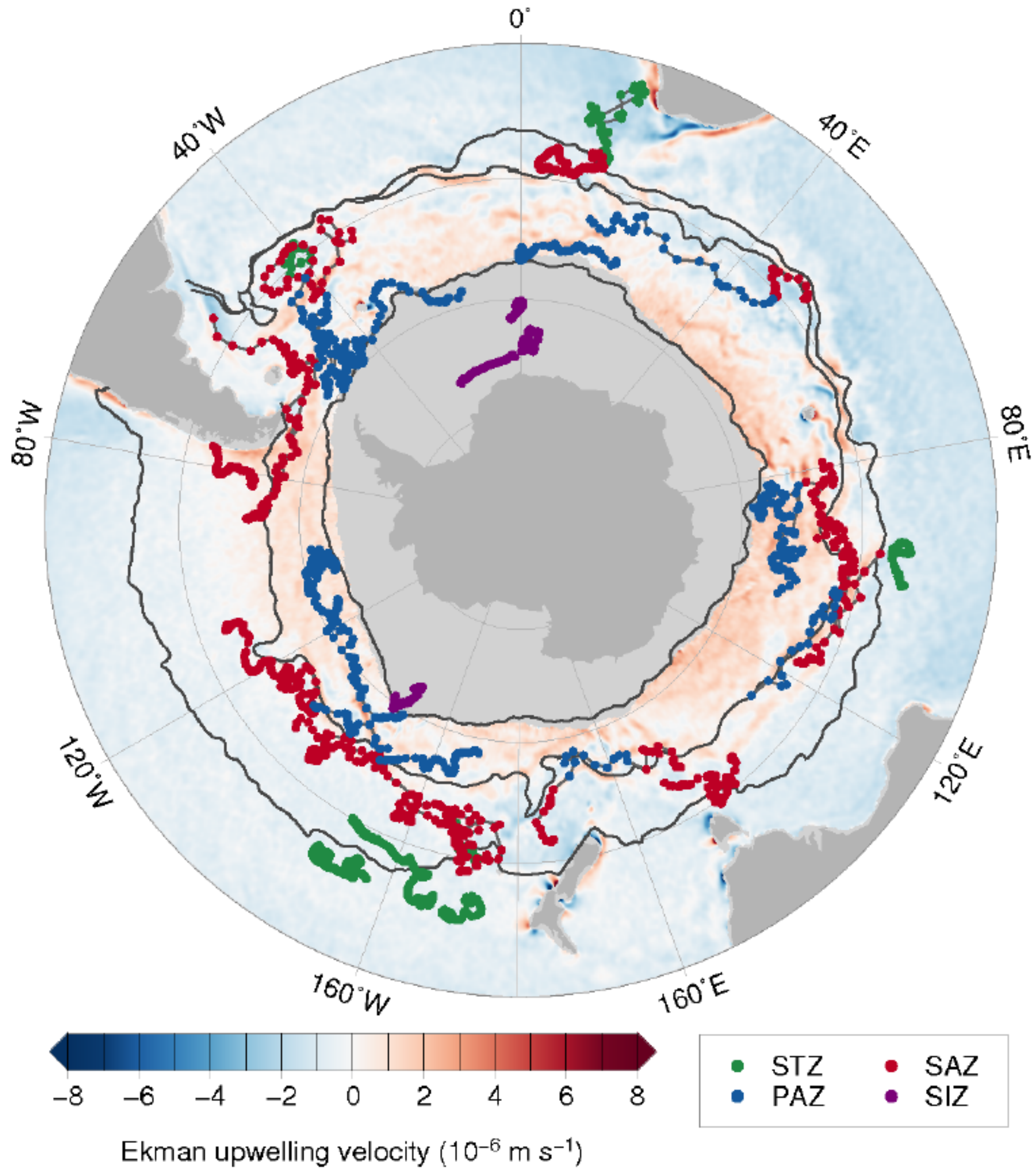
ΔpCO_2 in STZ

$$\Delta pCO_2 = pCO_2^{ocn} - pCO_2^{atm}$$

Pacific only (no Atlantic data yet)



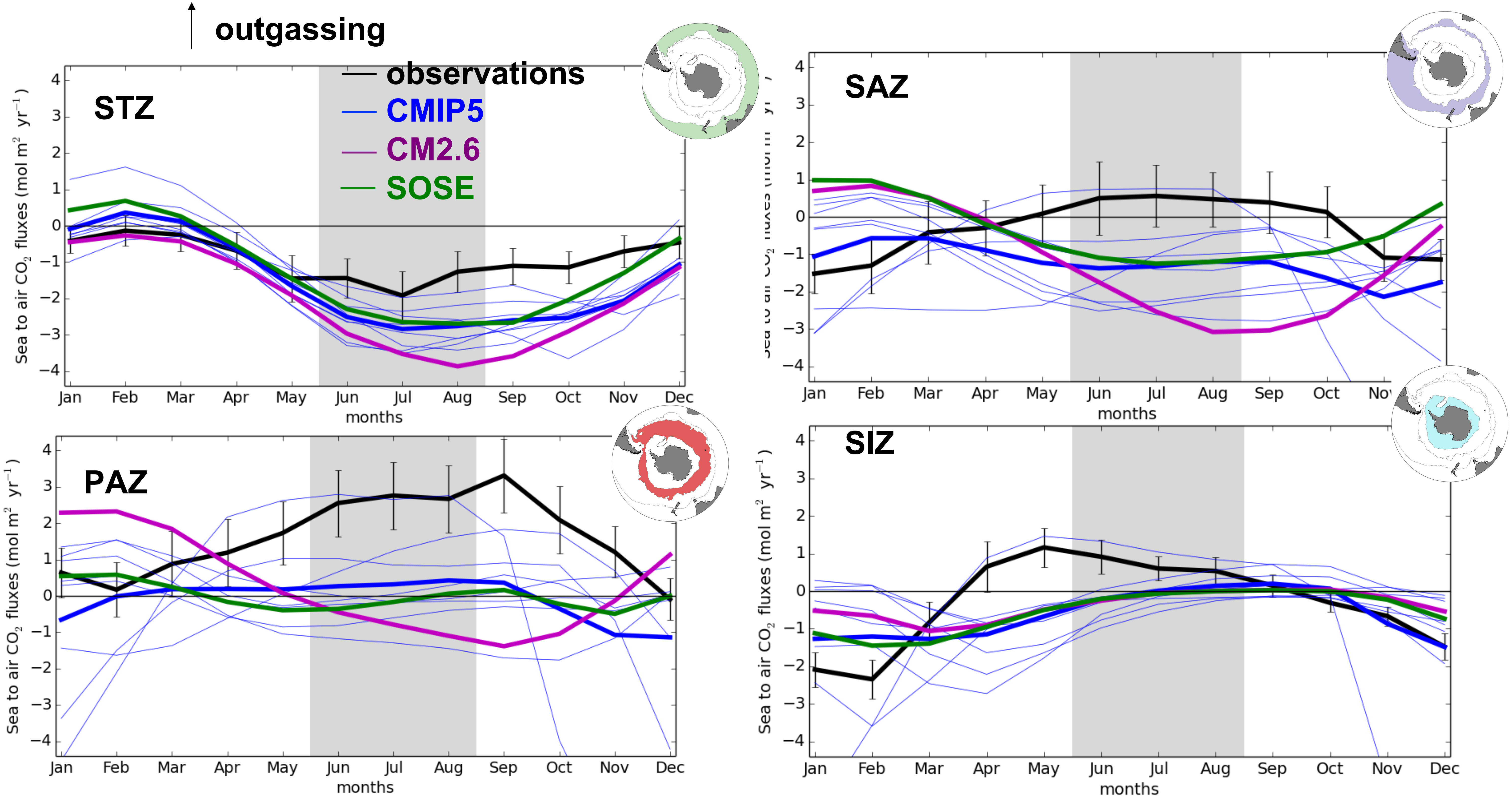
Float coverage



How do models do?

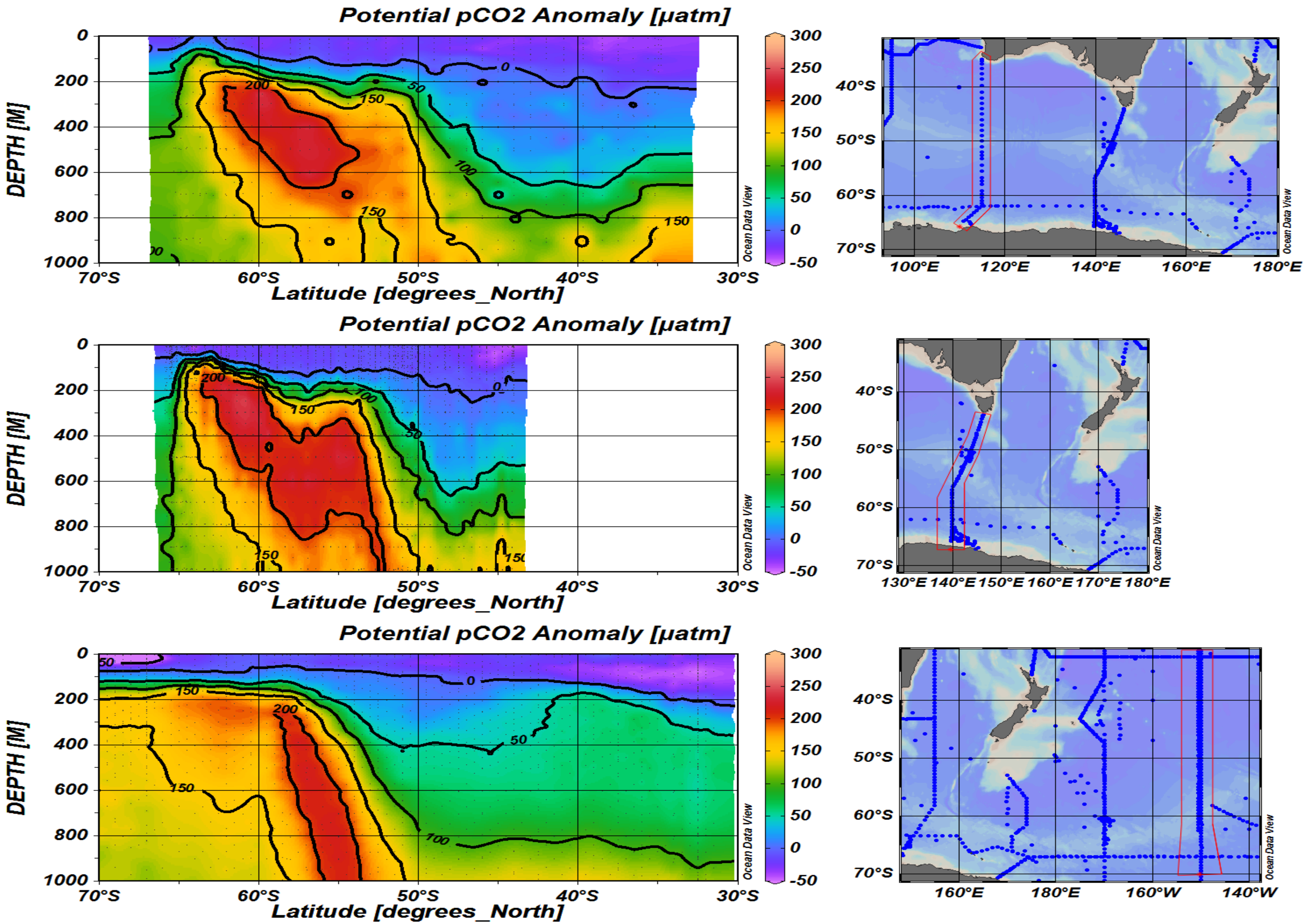
Dufour et al. (in prep.)

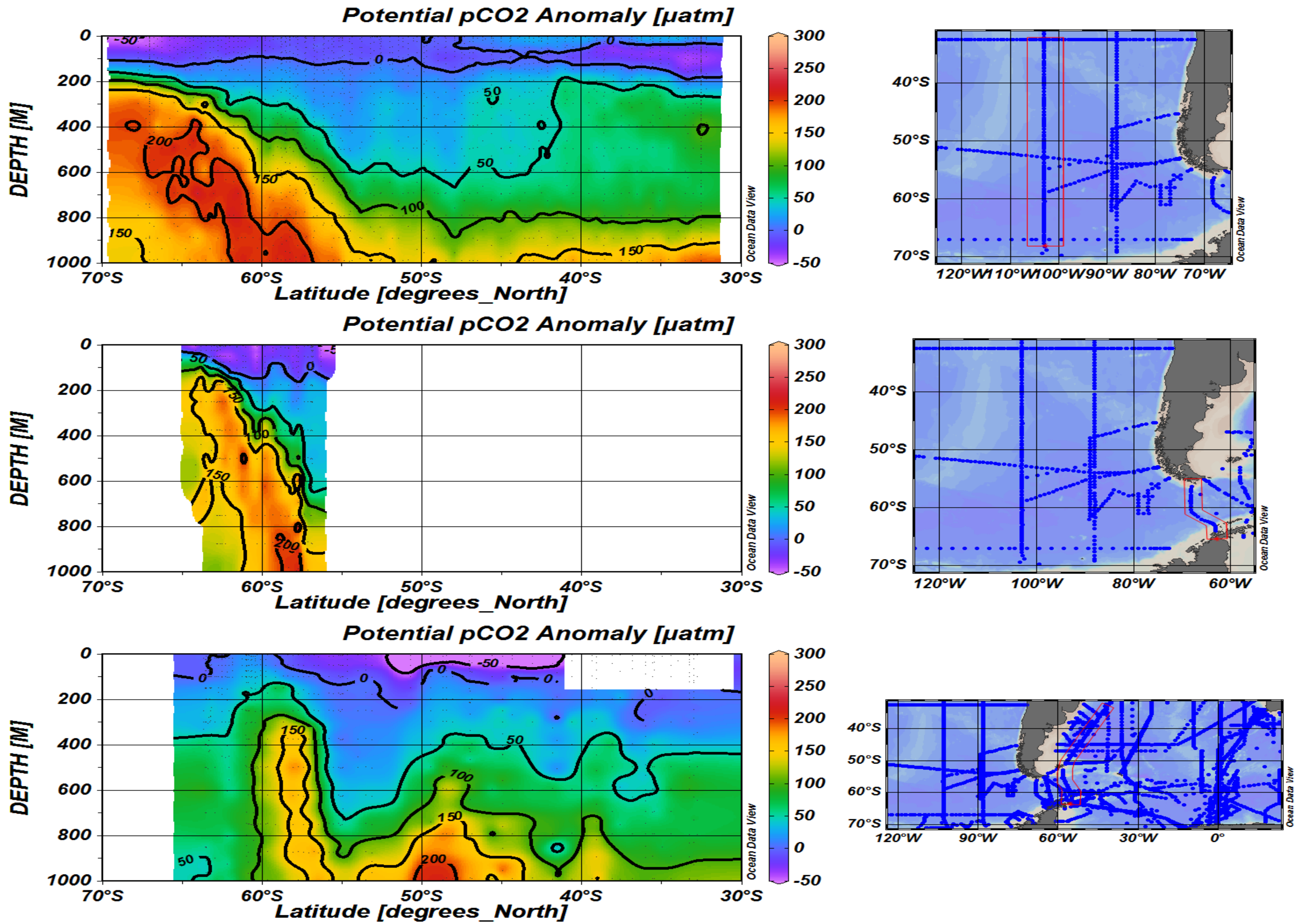
Results: seasonal CO_2 fluxes



Oceanographic consistency: Where does the upwelling CO_2 plume come from?

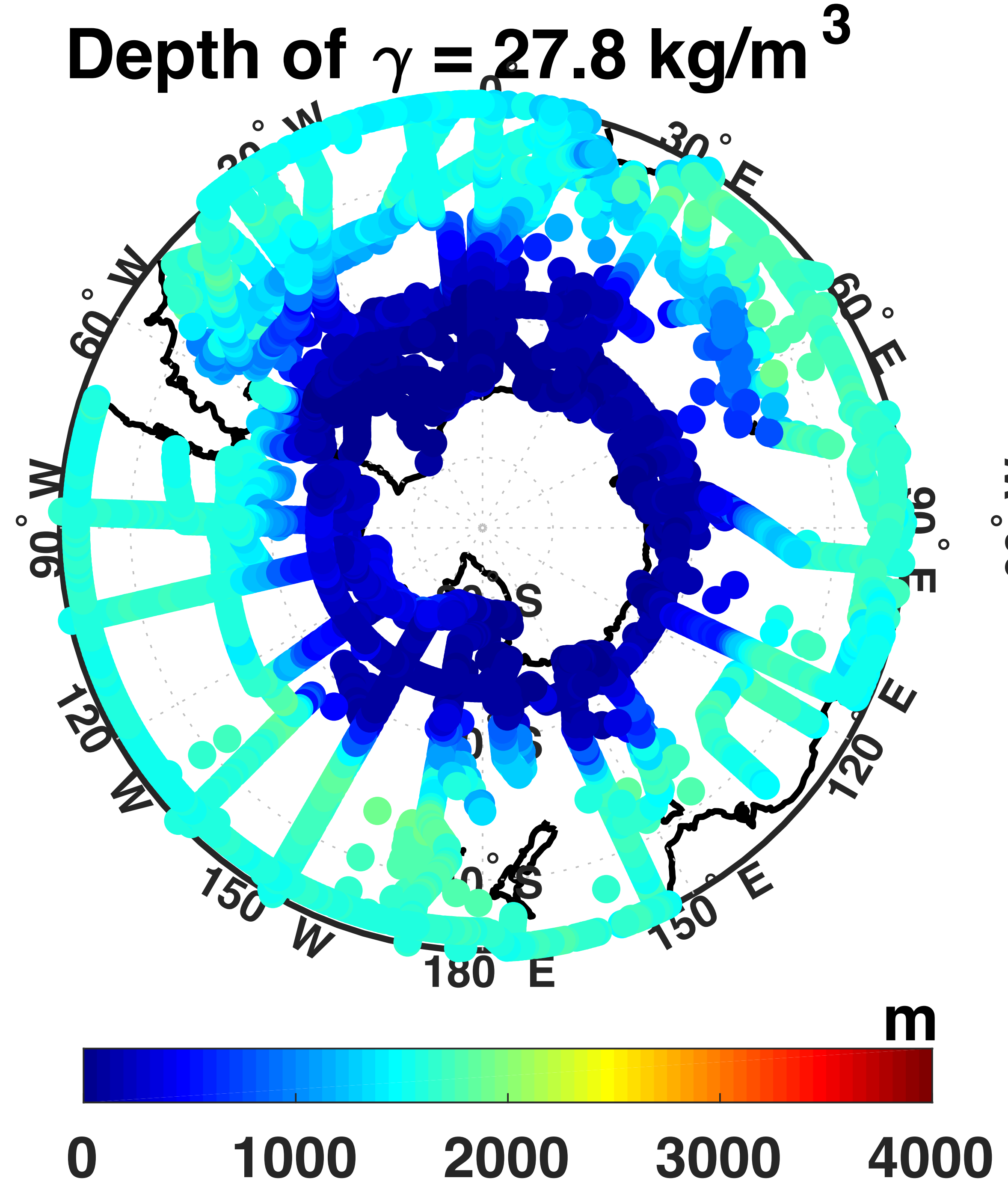
Figures by Ken Johnson and Haidi Chen

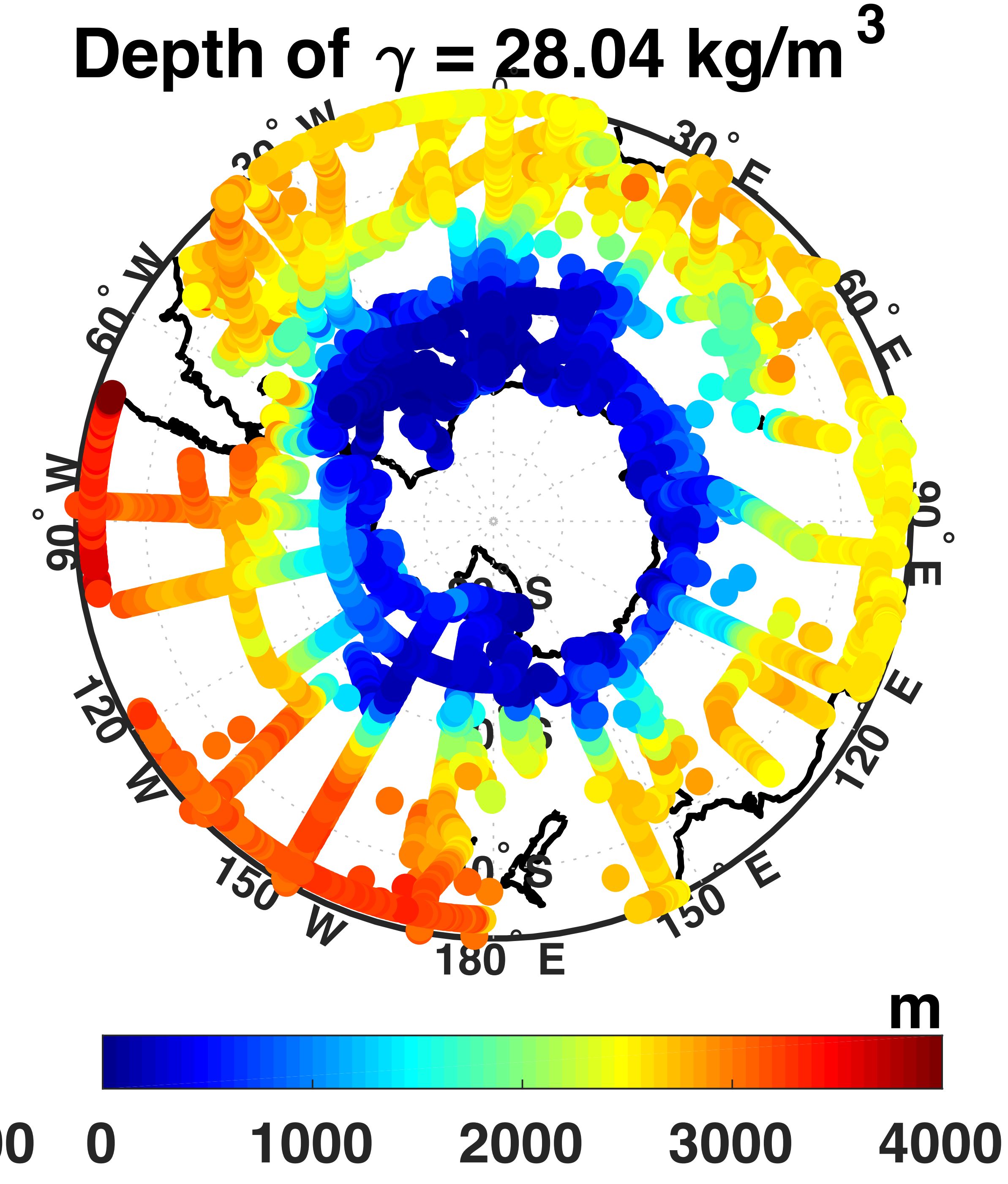

Potential pCO2 Anomaly [µatm]
DEPTH [M]
0
200
400
600
800
1000
70°S
60°S
50°S
40°S
30°S
Latitude [degrees_North]
300
250
200
150
100
50
0
-50
Ocean Data View
0
50
100
150
200
40°S
50°S
60°S
70°S
100°E
120°E
140°E
160°E
180°E
Potential pCO2 Anomaly [µatm]
DEPTH [M]
Latitude [degrees_North]
Ocean Data View
130°E
140°E
150°E
160°E
170°E
180°E
Potential pCO2 Anomaly [µatm]
DEPTH [M]
Latitude [degrees_North]
Ocean Data View
160°E
180°E
160°W
140°W



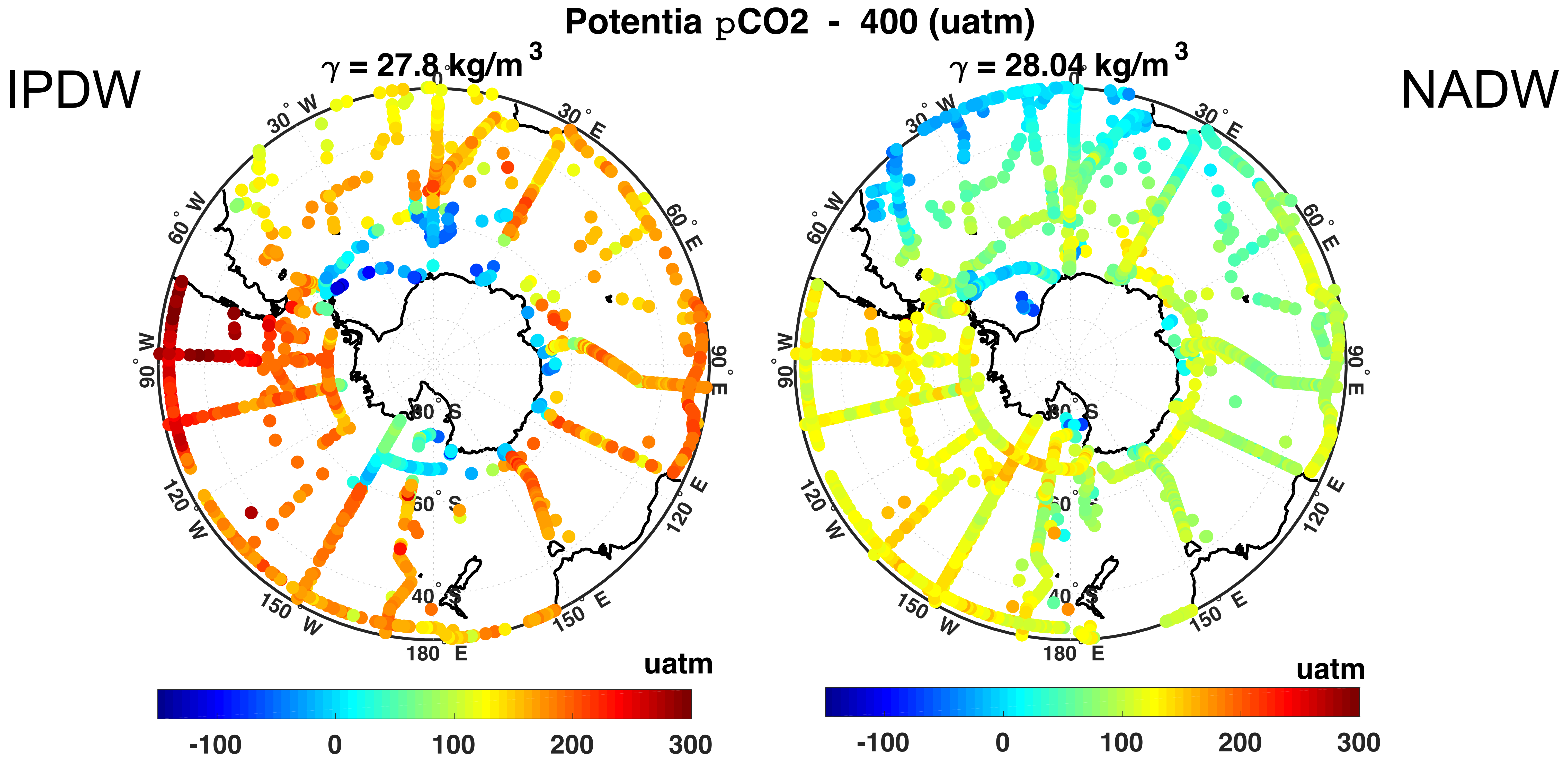
Potential pCO2 Anomaly [µatm]
DEPTH [M]
0
200
400
600
800
1000
70°S
60°S
50°S
40°S
30°S
Latitude [degrees_North]
300
250
200
150
100
50
0
-50
Ocean Data View
40°S
50°S
60°S
70°S
120°W
110°W
100°W
90°W
80°W
70°W
60°W
30°W
0°

Depth of IPDW (left) and NADW (right) neutral density surfaces





Potential CO_2 – 400 ppm



Annual net CO_2 flux (Pg C/yr)

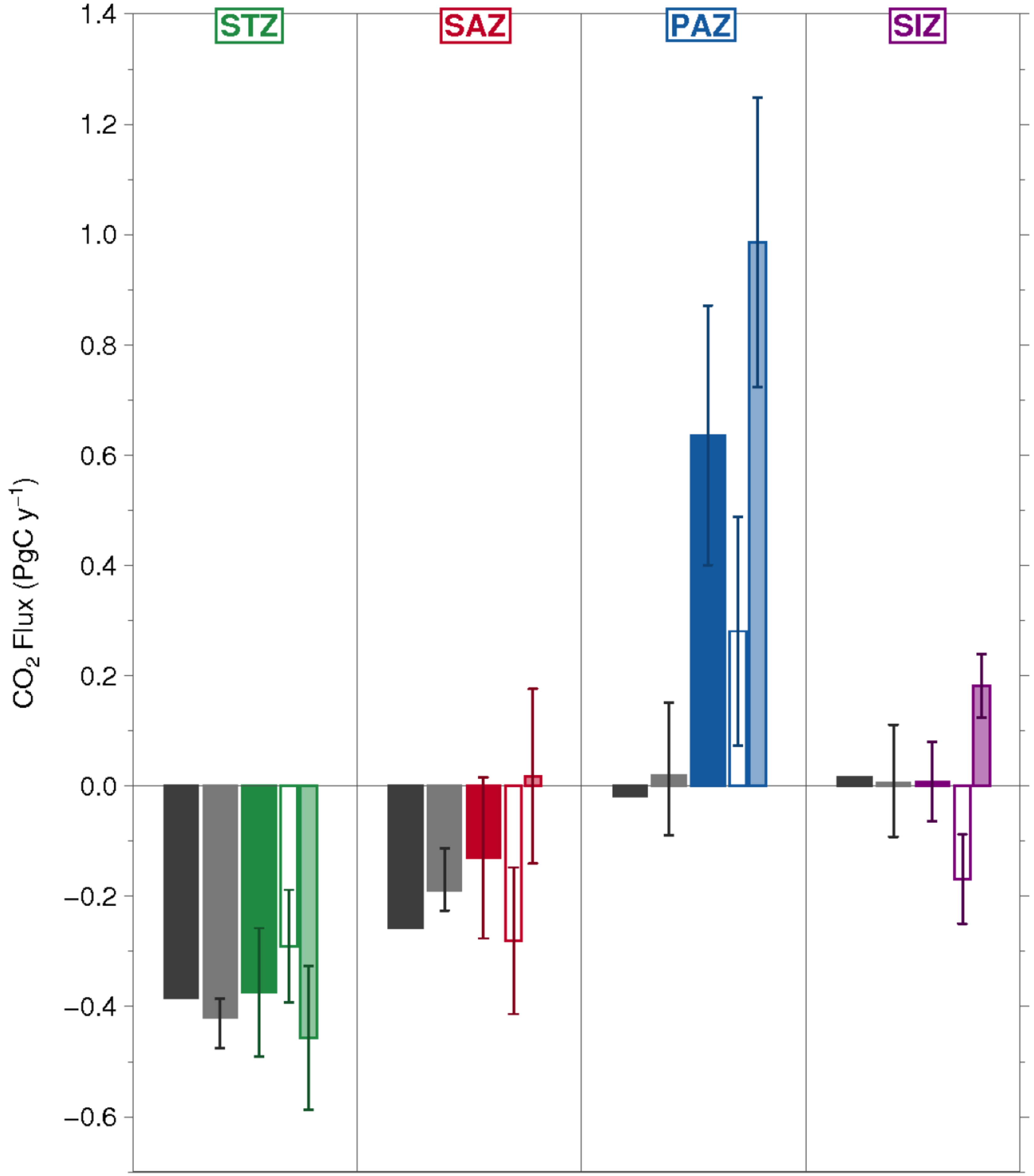
Takahashi et al. 2009, subsampled

Landschützer et al. 2015, subsampled

Float estimate, annual mean

Float estimate, summer mean

Float estimate, winter mean



Implications for the Southern Ocean carbon cycle

Annual net oceanic CO_2 uptake (Pg C y^{-1})

- Covers region south of 35°S
- Positive indicates net outgassing, negative is uptake.

Zone	SOCCOM floats	Takahashi et. al. (2009)	Landschützer et al. (2014)
STZ	-0.37 ± 0.12	-0.40	-0.50
SAZ	-0.13 ± 0.15	-0.24	-0.24
PAZ	0.64 ± 0.24	-0.16	-0.11
SIZ	0.01 ± 0.07	0.02	-0.04
TOTAL	0.14 ± 0.57 (0.04)	-0.77	-0.88

Annual net oceanic CO_2 uptake (Pg C y^{-1})

- Covers region south of 35°S
- Positive indicates net outgassing, negative is uptake.
- Dashes indicate fluxes less than 0.05

Zone	SOCCOM floats	Takahashi et. al. (2009) & Landschützer et al. 52014)
STZ	-0.4	-0.5
SAZ	-0.1	-0.2
PAZ	0.6	-0.1
SIZ	-	-
TOTAL	0.1 ± 0.6 (0.14 ± 0.04)	-0.8

Implications for Southern Ocean carbon

- Units Pg C y^{-1}
- Positive indicates net outgassing, negative is uptake
- region south of 35°S

	SOCCOM floats	Takahashi et. al. (2009) & Landschützer et al. (2014)
Pre-industrial (out of ocean)	1.1	0.2
Anthropogenic (half global)	-1.0	-1.0
Contemporary	0.1	-0.8

Annual net oceanic CO_2 uptake (Pg C y^{-1})

- Covers region south of 35°S
- Positive indicates net outgassing, negative is uptake.

Zone	SOCCOM floats	Takahashi et. al. (2009)	Landschützer et al. (2014)
STZ	-0.25 ± 0.12	-0.40	-0.50
SAZ	-0.08 ± 0.12	-0.24	-0.24
PAZ	0.50 ± 0.22	-0.16	-0.11
SIZ	-0.08 ± 0.08	0.02	-0.04
TOTAL	0.09 ± 0.53	-0.77	-0.88

Annual net oceanic CO_2 uptake (Pg C y^{-1})

- Covers region south of 35°S
- Positive indicates net outgassing, negative is uptake.
- Dashes indicate fluxes less than 0.05

Zone	SOCCOM floats	Takahashi et. al. (2009) & Landschützer et al. (2014)
STZ	-0.2	-0.4
SAZ	-0.1	-0.2
PAZ	0.5	-0.2
SIZ	-0.1	-
TOTAL	0.1 ± 0.5	-0.8

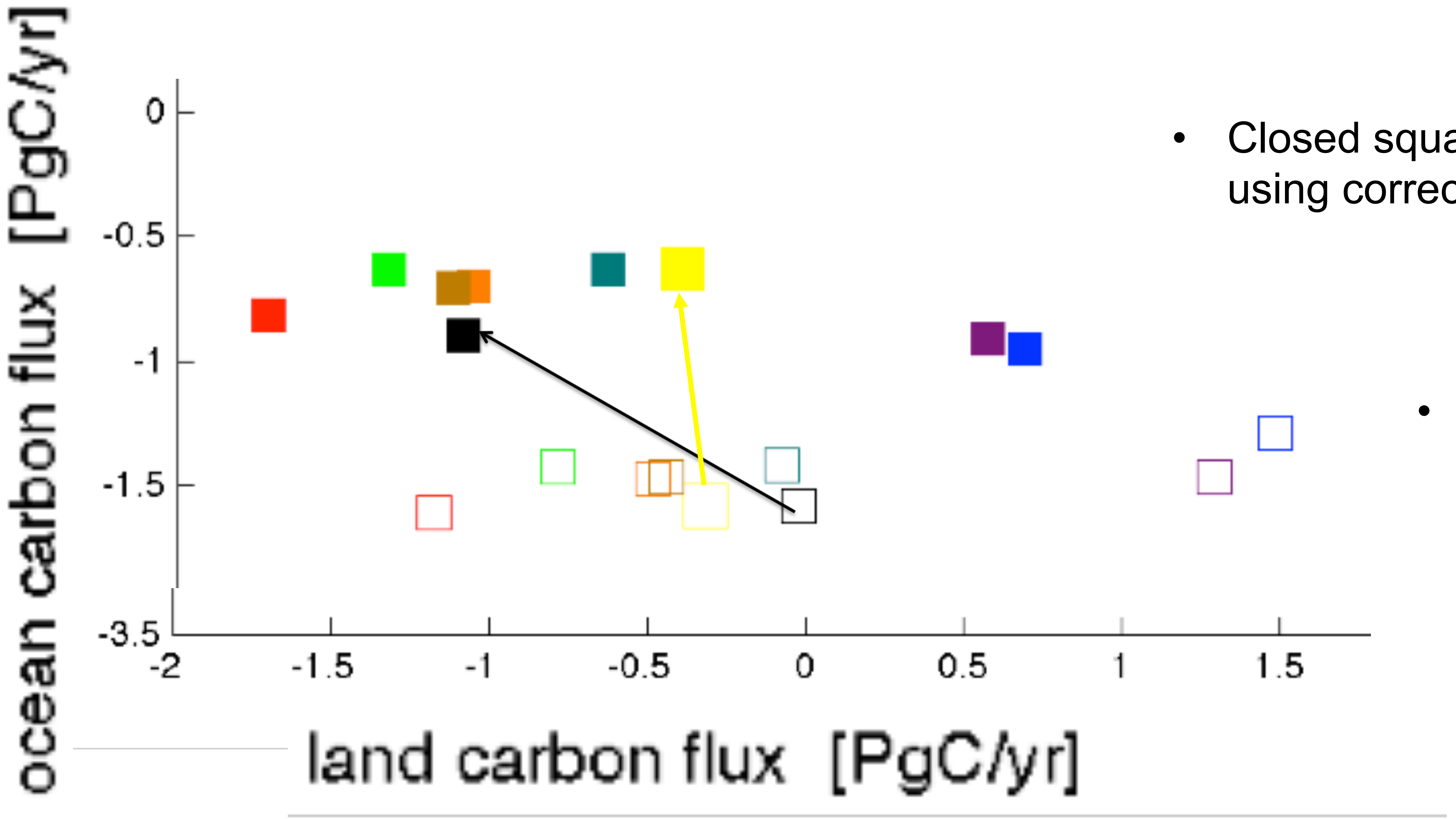
Implications for Southern Ocean carbon

- Units Pg C y^{-1}
- Positive indicates net outgassing, negative is uptake
- region south of 35°S

	SOCCOM floats	Takahashi et. al. (2009) & Landschützer et al. (2014)
Pre-industrial (out of ocean)	1.1	0.2
Anthropogenic	-1.0	-1.0
Contemporary	0.1 ± 0.5	-0.8

If the pre-industrial Southern Ocean source is real: where is the uptake?

Southern hemisphere land-ocean trade offs

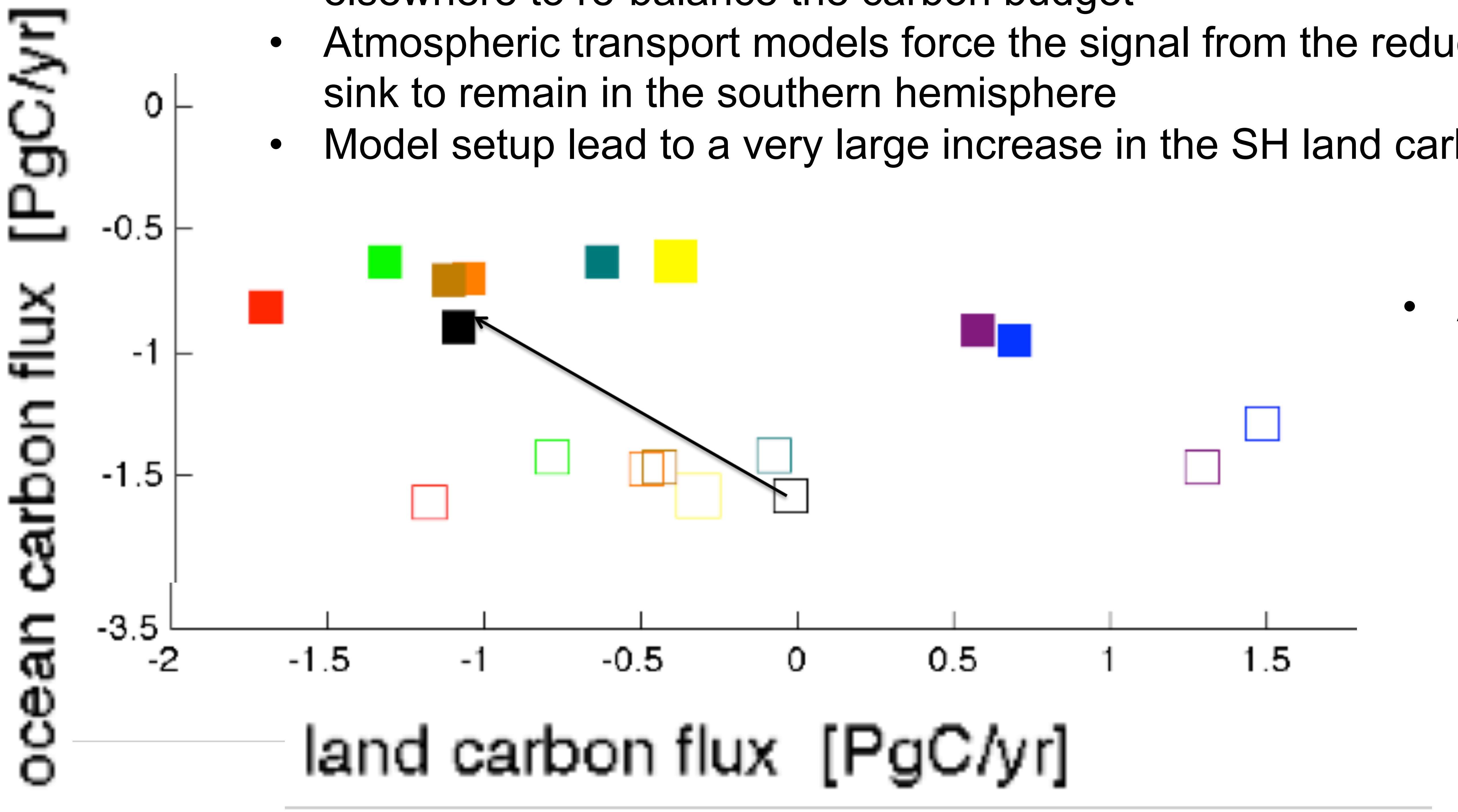


- Closed squares are solutions using corrected ocean prior

- Open squares are solutions using uncorrected ocean prior

Southern hemisphere land-ocean trade offs

- The reduced Southern Ocean carbon sink requires increased uptake elsewhere to re-balance the carbon budget
- Atmospheric transport models force the signal from the reduced ocean carbon sink to remain in the southern hemisphere
- Model setup lead to a very large increase in the SH land carbon sink



- Alternative would be for temperate ocean to become a larger sink by relaxing or modifying the SH ocean prior

David Baker global CO_2 inversion setup

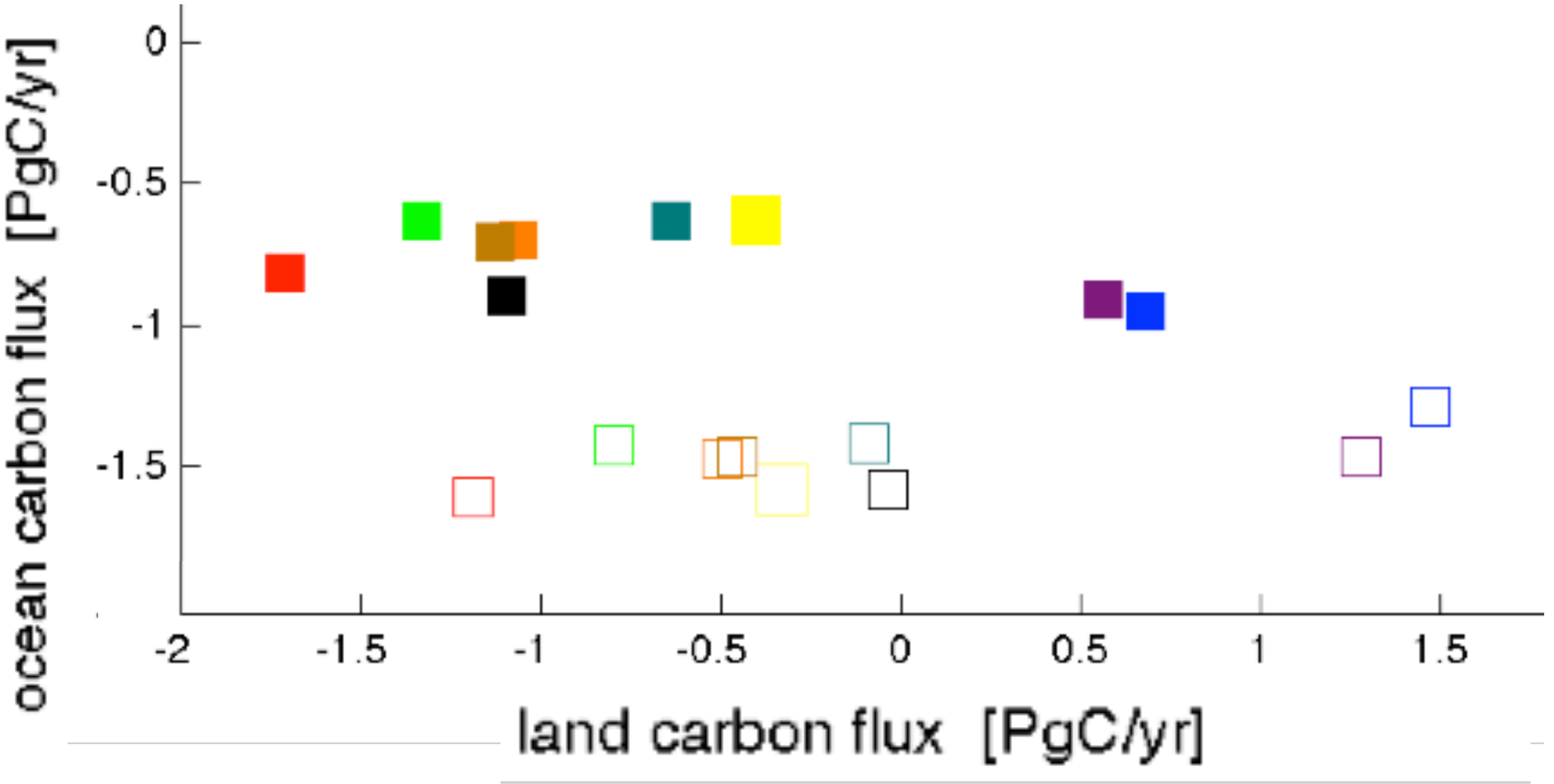
- PCTM off-line tracer transport model
- 4Dvar data assimilation scheme
- Forward runs at 2° x 2.5° (lat/lon)
- Inverse corrections at 6.7°x6.7° (lat/lon)

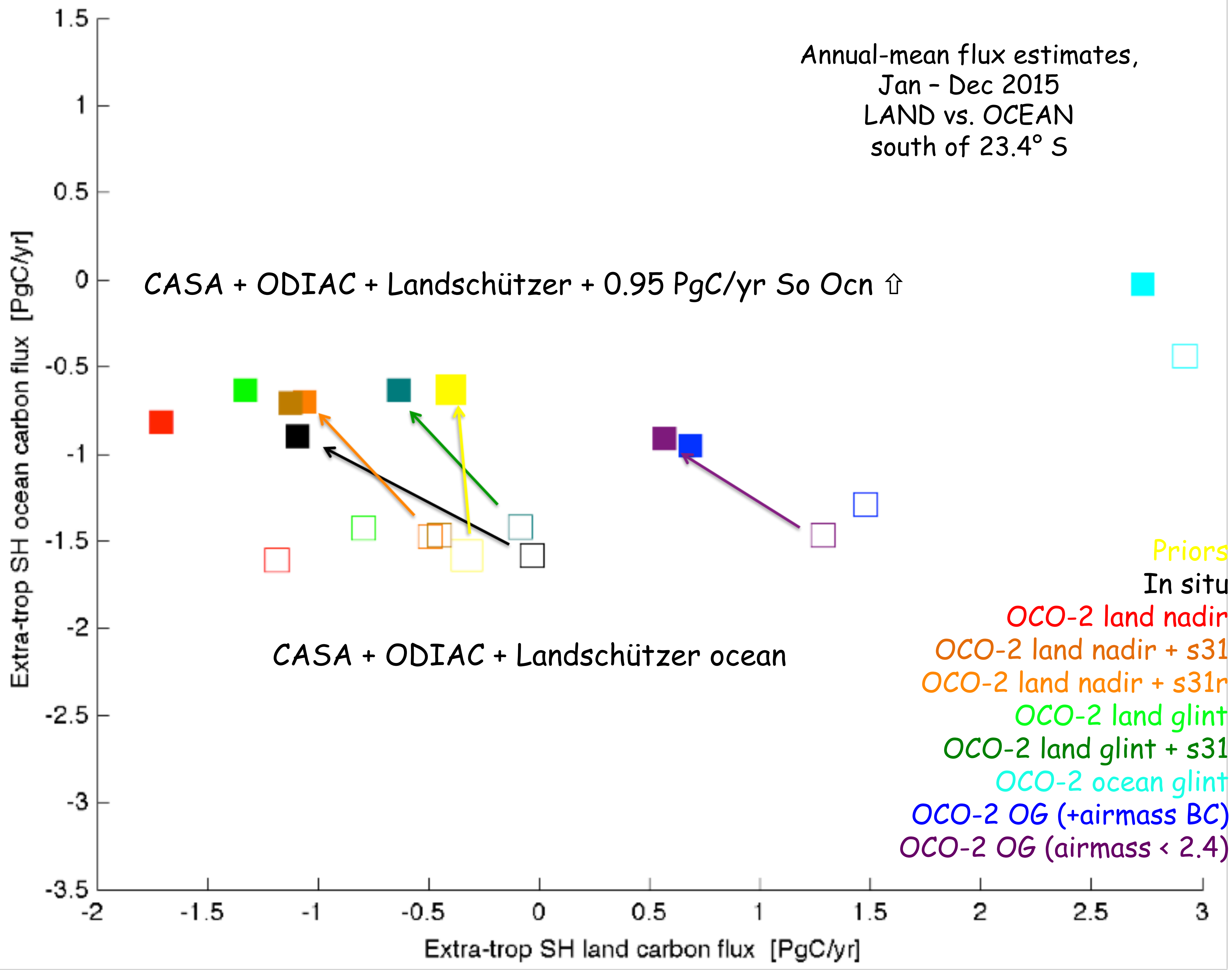
Priors
In situ
OCO-2 land nadir
OCO-2 land nadir + s31
OCO-2 land nadir + s31r
OCO-2 land glint
OCO-2 land glint + s31
OCO-2 ocean glint
OCO-2 OG (+airmass BC)
OCO-2 OG (airmass < 2.4)

Possible combinations:

- CO_2 data assimilated (4 possibilities)
  - In situ: surface + NOAA aircraft profiles
  - OCO-2 land nadir
  - OCO-2 land glint
  - OCO-2 ocean glint
- Prior estimates (4 possibilities):
  - CASA + NOBM ocean + ODIAC FF
  - CASA + Takahashi ocean + ODIAC FF
  - CASA + Landschutzer ocean + ODIAC FF
  - CASA + Lands. + ODIAC + 0.95 PgC/yr So. Ocean (In situ)

Southern hemisphere land-ocean trade off





Annual-mean flux estimates,
Jan – Dec 2015
LAND vs. OCEAN
south of 23.4° S
CASA + ODIAC + Landschützer + 0.95 PgC/yr So Ocn ⇧
CASA + ODIAC + Landschützer ocean
Priors
In situ
OCO-2 land nadir
OCO-2 land nadir + s31
OCO-2 land nadir + s31r
OCO-2 land glint
OCO-2 land glint + s31
OCO-2 ocean glint
OCO-2 OG (+airmass BC)
OCO-2 OG (airmass < 2.4)
Extra-trop SH ocean carbon flux [PgC/yr]
Extra-trop SH land carbon flux [PgC/yr]
1.5
1
0.5
0
-0.5
-1
-1.5
-2
-2.5
-3
-3.5
-2
-1.5
-1
-0.5
0
0.5
1
1.5
2
2.5
3

Immediate source: CO_2 addition by organic matter remineralization in Indo-Pacific Deep Water

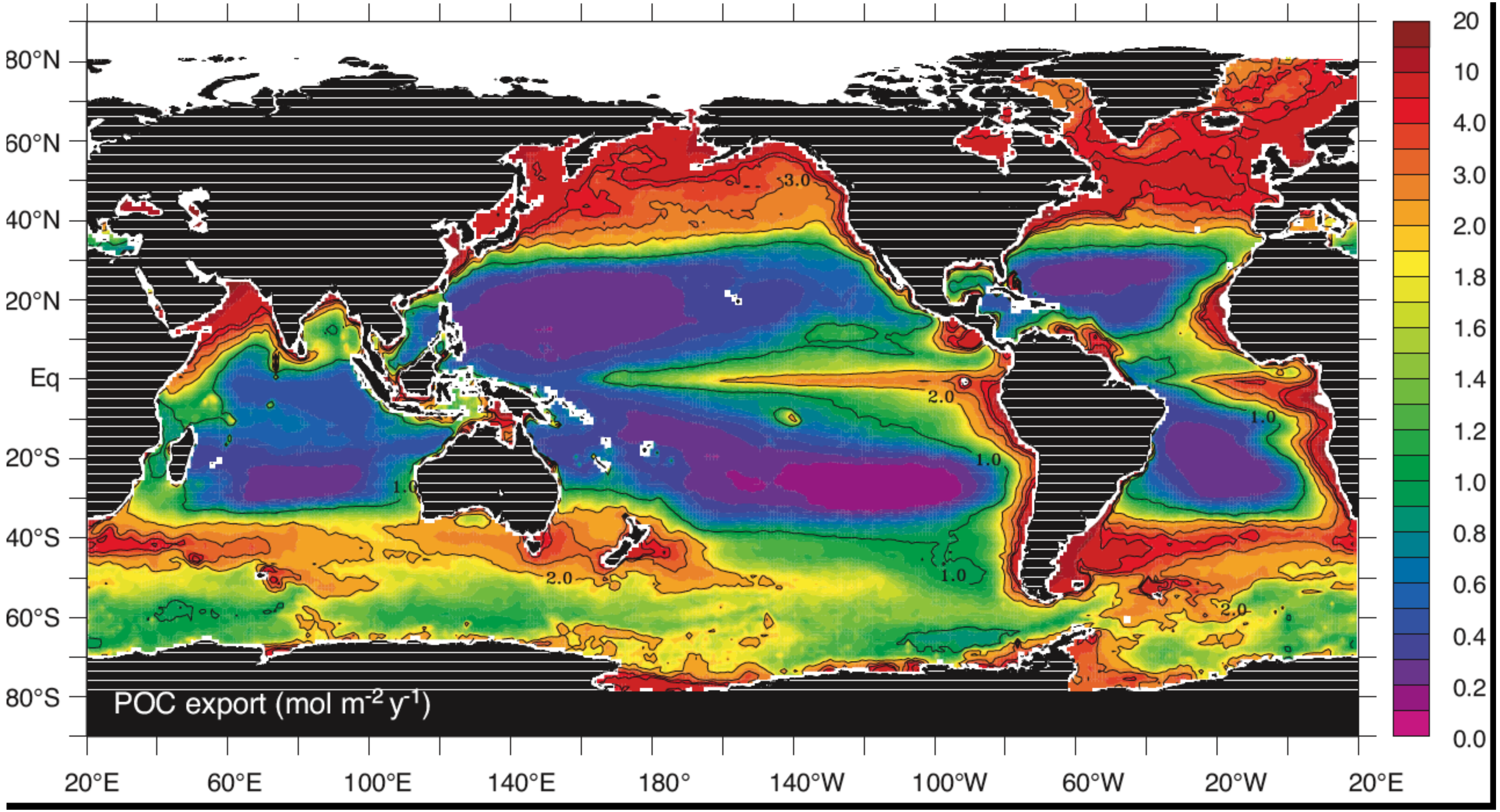
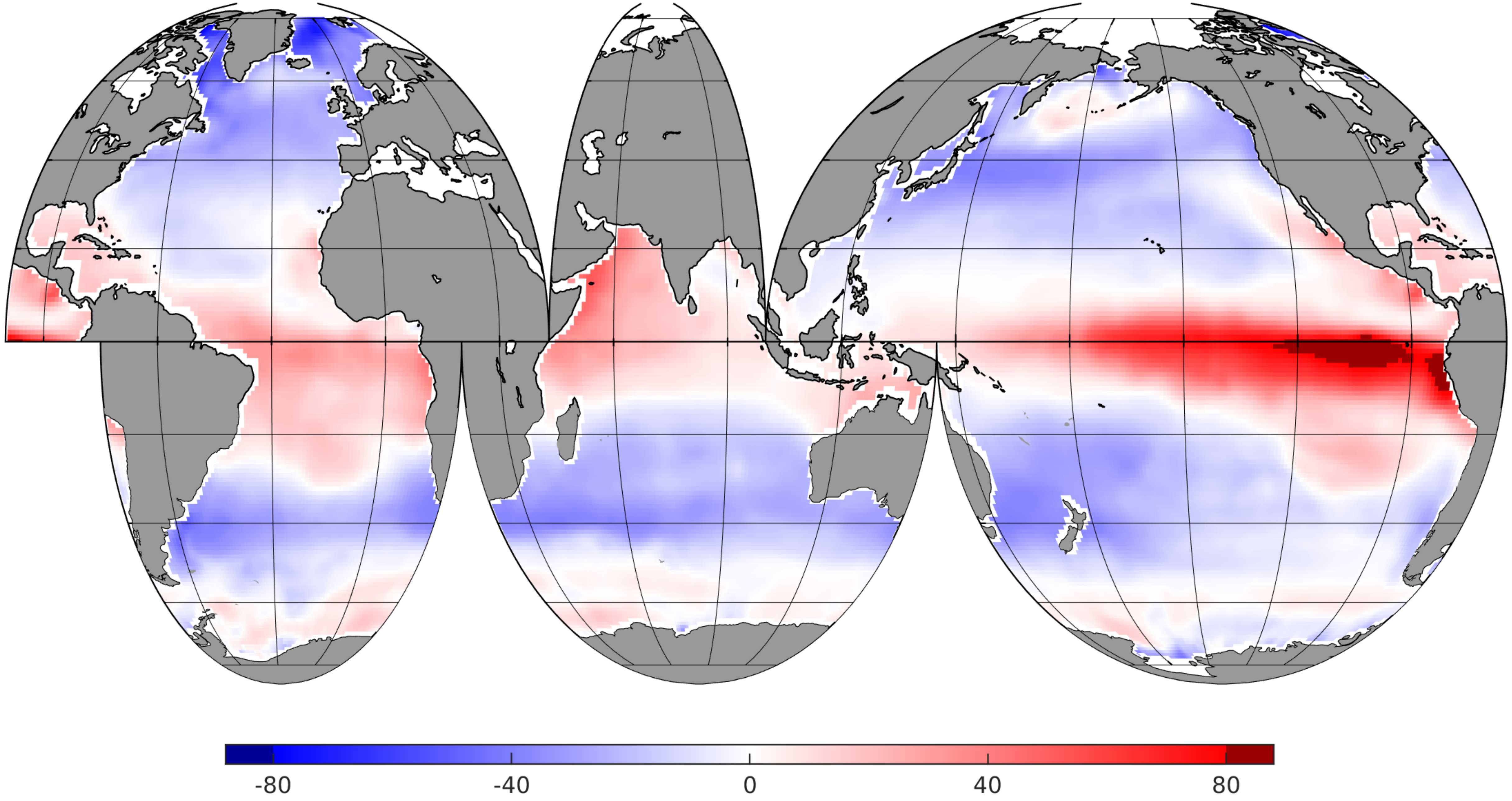


Figure shows POC export from NPP•*pe*-ratio

Sea-air CO_2 difference (μatm)



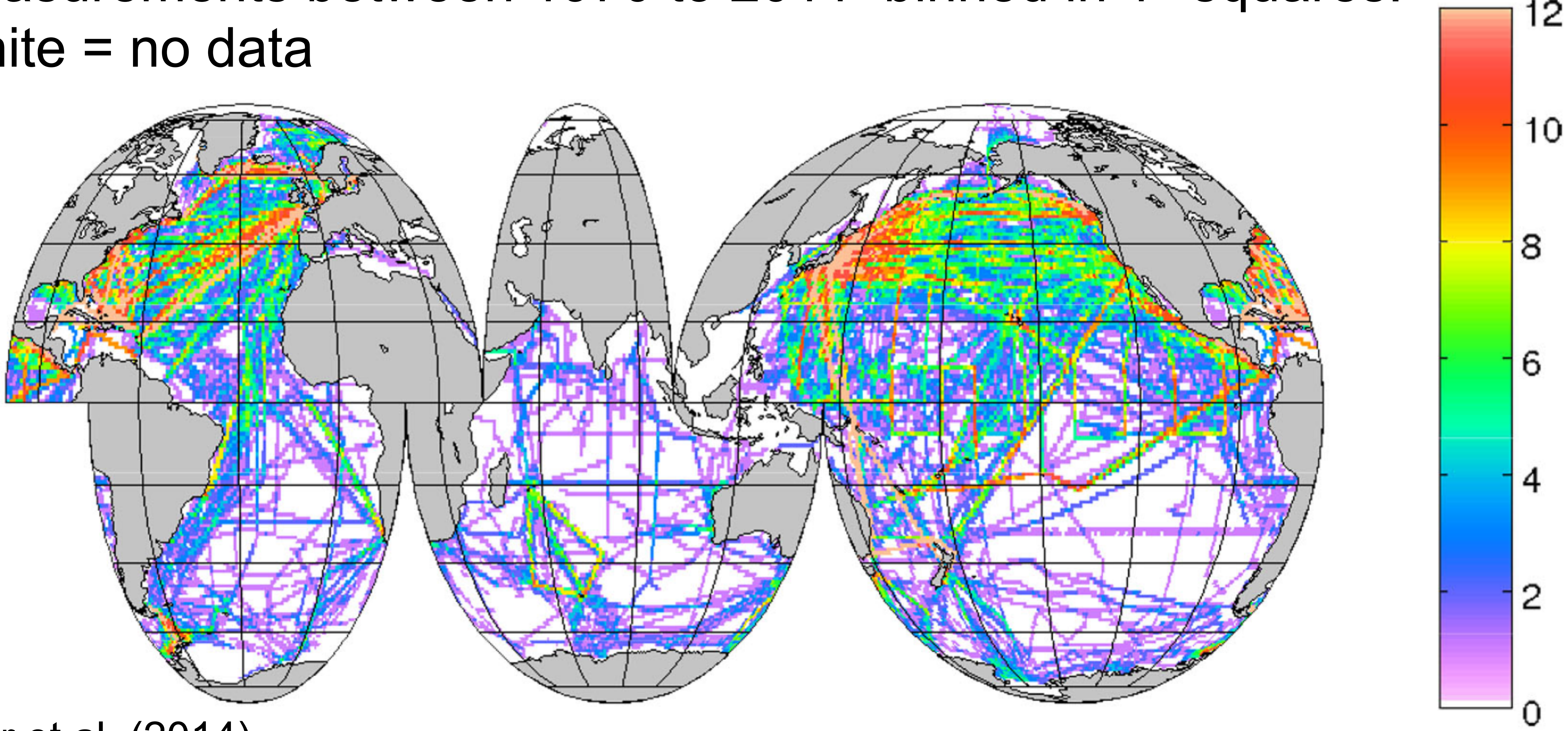
But where does uptake from the atmosphere occur?

- In high biological production regions?
- In nearby subtropical gyre regions?

Landschützer (pers. comm. Nov, 2016)

Undersampling of pCO_2

Months of year with surface pCO_2 measurements based on all measurements between 1970 to 2011 binned in 1° squares.
White = no data



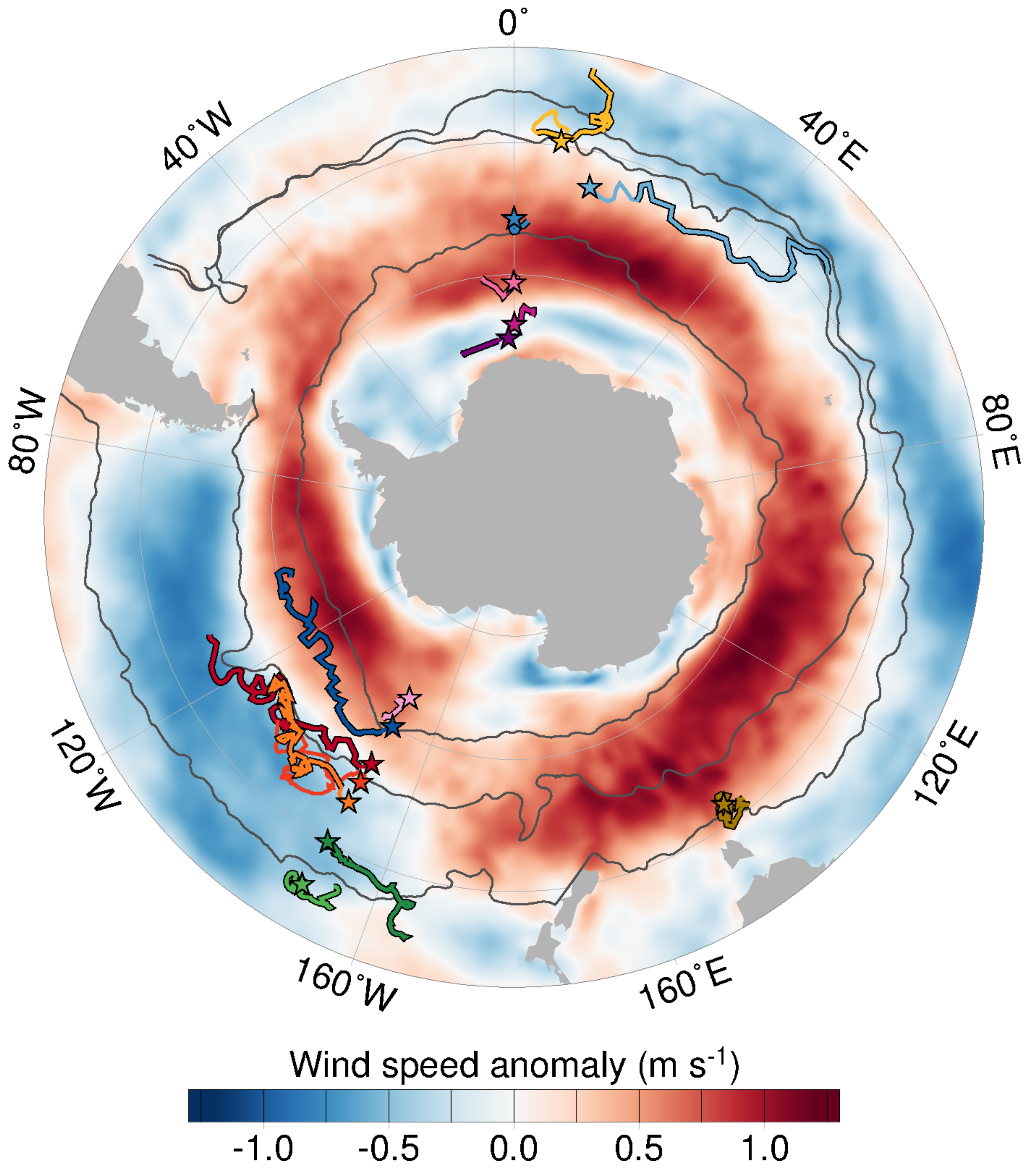
Bakker et al. (2014)

Or is it interannual variability?

Wind speed anomaly (April 2014 to 2016)

- The ACC region has increased winds which would imply more upwelling & thus outgassing.

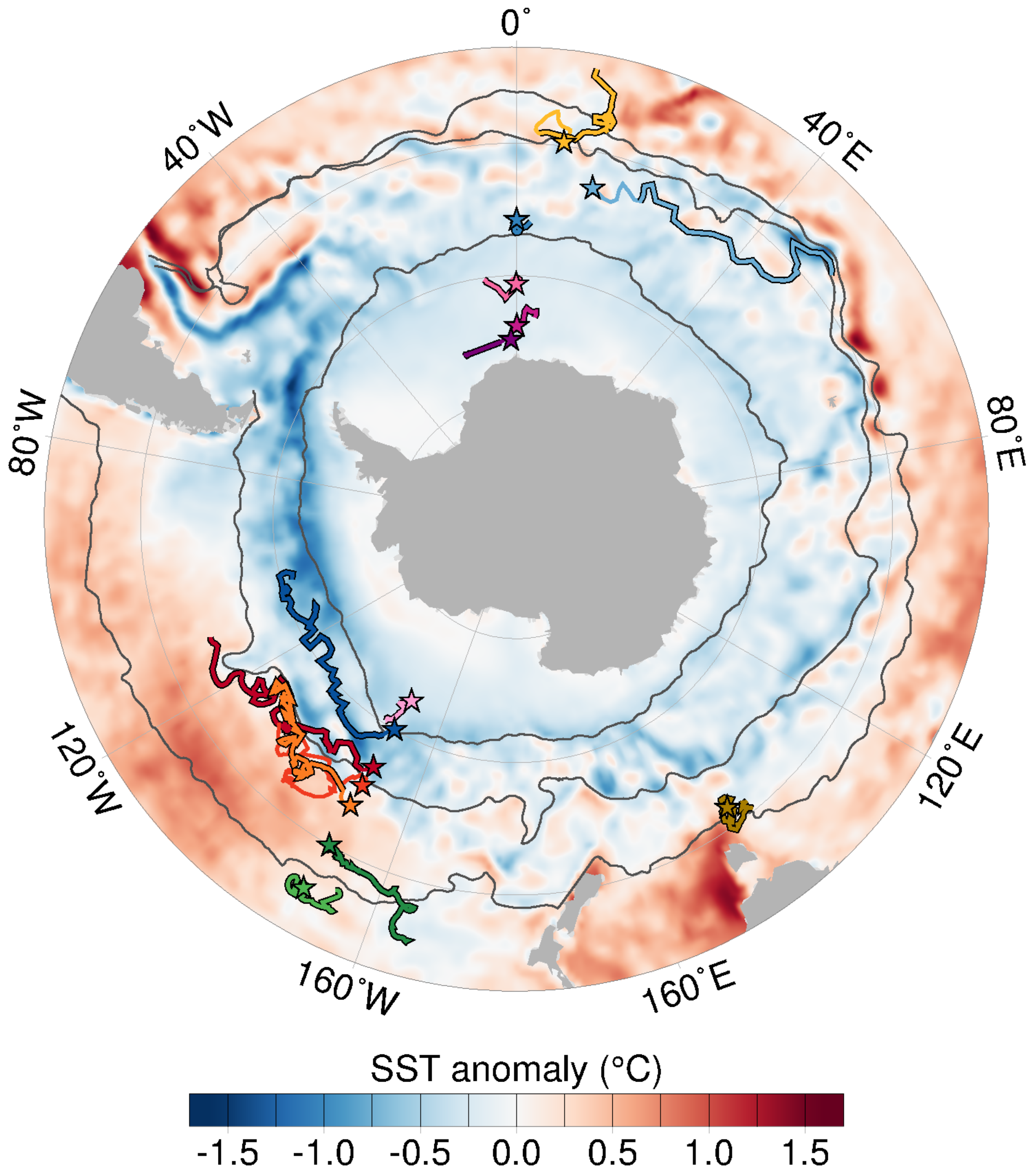
- ERA-interim wind fields, calculated as the mean over Apr 2014 - Apr 2016 minus the mean over Apr 1979 - Apr 2016

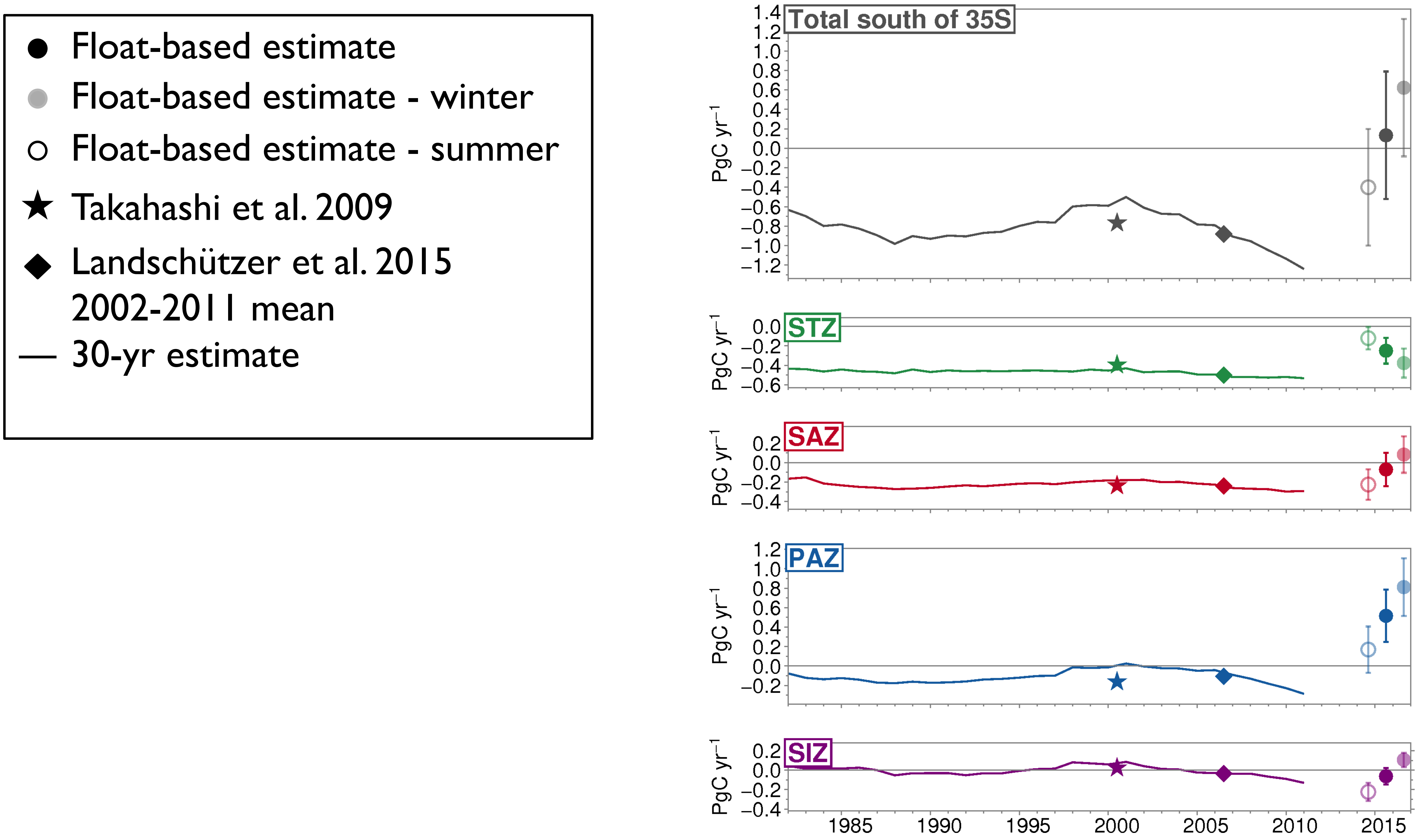


SST Anomaly
(April 2014 to 2016)

- The subtropics are warmer, consistent with increased outgassing.
- The ACC region has colder temperatures, consistent with higher upwelling.

- ERA-interim SST fields, calculated as the mean over Apr 2014 - Apr 2016 minus the mean over Apr 1979 - Apr 2016




Float-based estimate
Float-based estimate - winter
Float-based estimate - summer
Takahashi et al. 2009
Landschützer et al. 2015
2002-2011 mean
30-yr estimate
Total south of 35S
STZ
SAZ
PAZ
SIZ
PgC yr^{-1}
1985
1990
1995
2000
2005
2010
2015

How do models do?

Dufour et al. (in prep.)

cf. also Gloor et al. (2003)

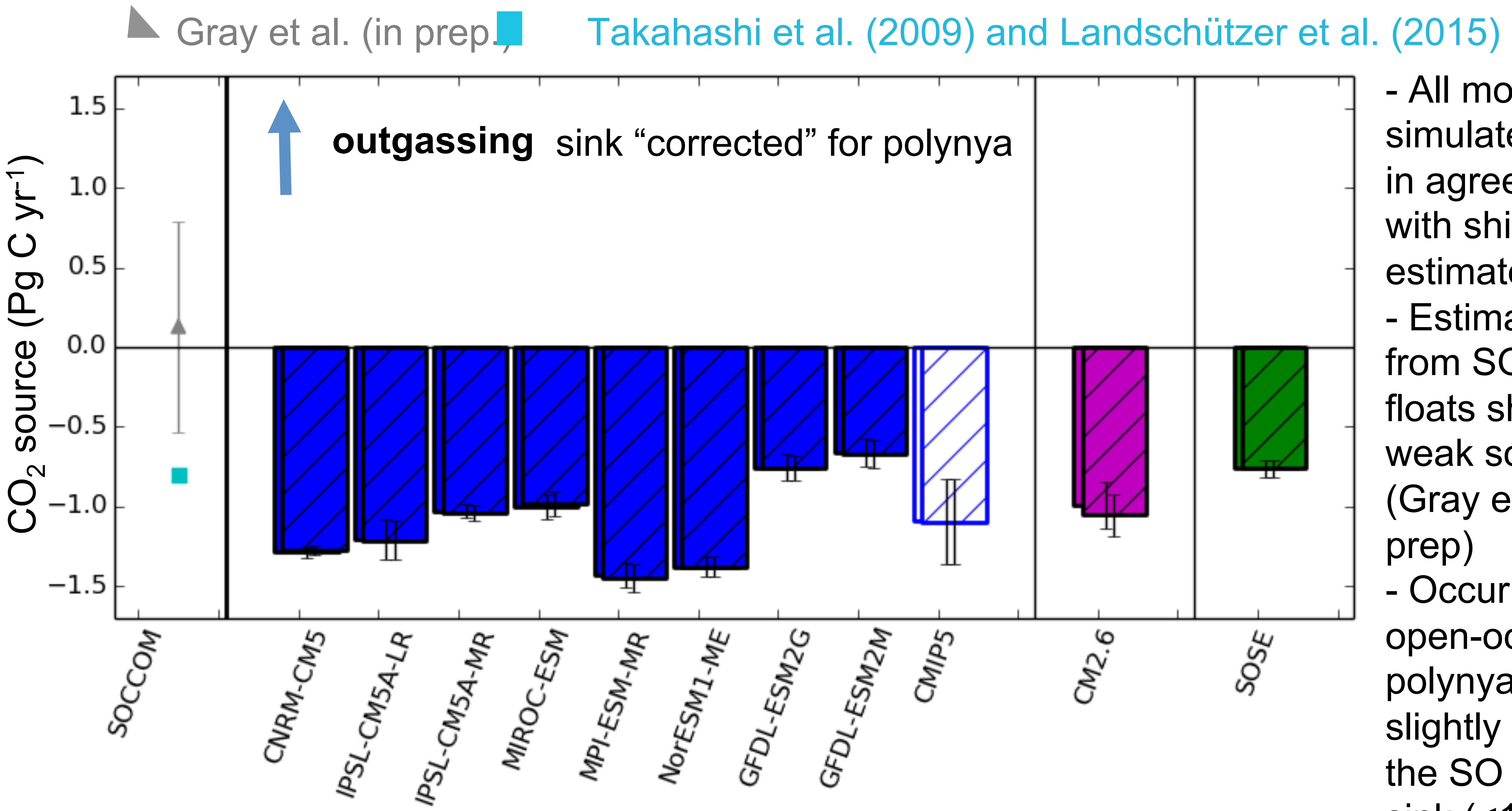
Models & simulations used in analysis

center	name	vertical coordinate	ocean resolution	scenario (time period)
CERFACS	CNRM-CM5	z	0.4° to 2°	historical (1996-2005)
NOAA-GFDL	GFDL-ESM2G	isopycnal		
NOAA-GFDL	GFDL-ESM2M	z		
IPSL	IPSL-CM5A-LR	z		
IPSL	IPSL-CM5A-MR	z		
MIROC	MIROC-ESM	isopycnal		
MPI-M	MPI-ESM-MR	z		
NCC	NorESM1-ME	z		
NOAA-GFDL	CM2.6	z	0.1°	idealized 1%/yr (years 21-30)
Scripps	SOSE*	z	1/6°	historical (2008-2012)

CMIP5 models

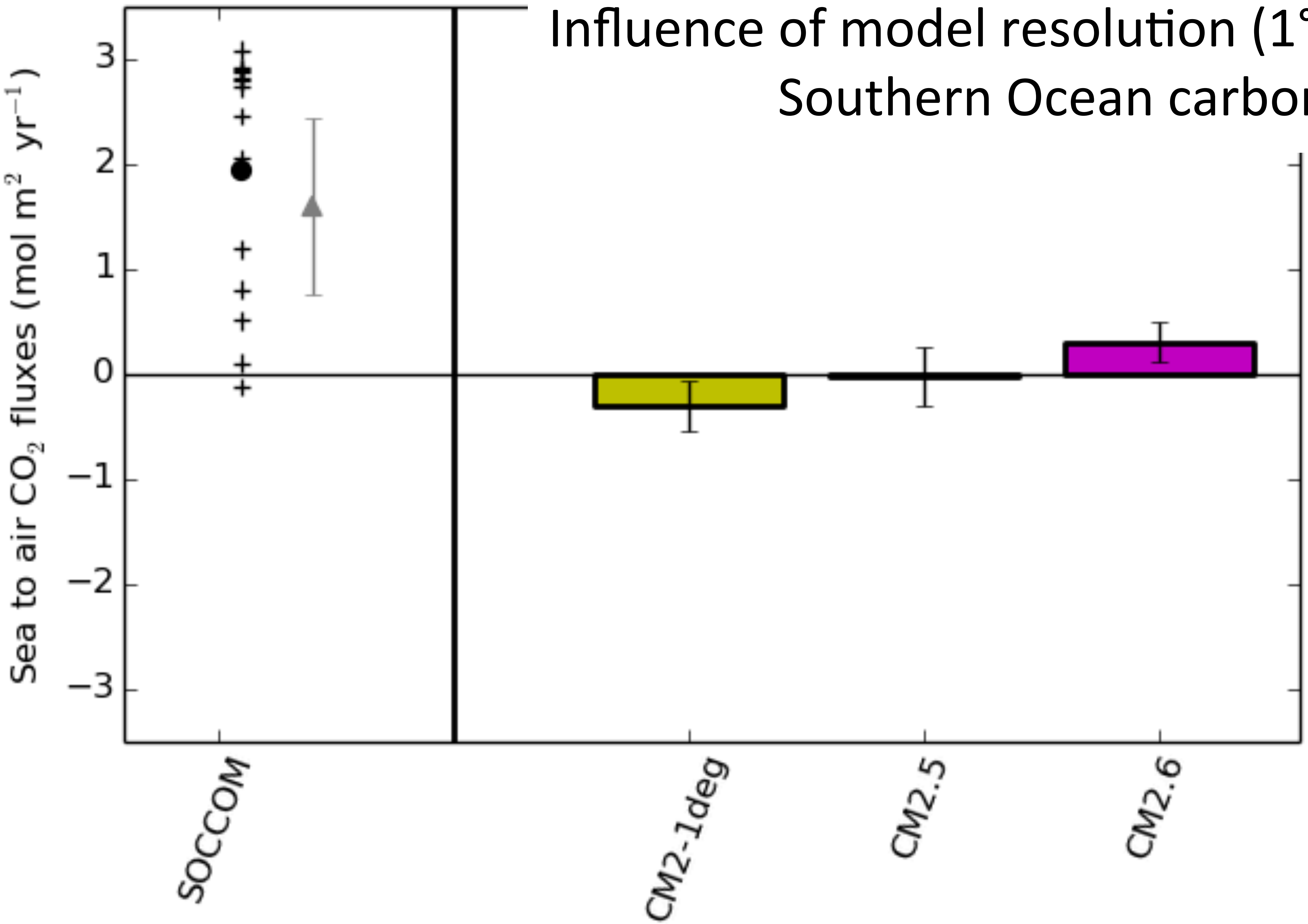
All models are climate models except SOSE which is an ocean-sea ice data assimilating model forced by atmospheric reanalyses (NCEP)

Annual CO_2 Southern Ocean sink



- All models simulate a sink in agreement with shipbased estimates
- Estimates from SOCCOM floats show a weak source (Gray et al., in prep)
- Occurrence of open-ocean polynyas slightly impact the SO carbon sink (<10%)

Influence of model resolution (1°, 0.25°, 0.1°) on Southern Ocean carbon flux)



Strong sensitivity of Southern Ocean carbon uptake and nutrient cycling to wind stirring

K. B. Rodgers[1], O. Aumont[2], S. E. Mikaloff Fletcher[3], Y. Plancherel[4], L. Bopp[5], C. de Boyer Montégut[6], D. Iudicone[7], R. F. Keeling[8], G. Madec[9,10], and R. Wanninkhof[11]

This is tested with a sensitivity study using an ad hoc parameterization of wind stirring in an ocean carbon cycle model, where the objective is to identify the way in which perturbations to the vertical density structure of the planetary boundary in the ocean impacts the carbon cycle and ocean biogeochemistry.

Wind stirring leads to reduced uptake of CO_2 by the Southern Ocean over the period 2000–2006, with a relative reduction with wind stirring on the order of 0.9 $\mathrm{Pg\,C\,yr^{-1}}$ over the region south of 45° S. This impacts not only the mean carbon uptake, but also the phasing of the seasonal cycle of carbon and other ocean biogeochemical tracers. Enhanced wind stirring delays the seasonal onset of stratification, and this has large impacts on both entrainment and the biological pump.

Biogeosciences, 11, 4077–4098, 2014

Conclusion: Southern Ocean CO_2 flux to atmosphere is greater than previous estimates

- Hypothesis 1: flawed methodology
  - Small number of floats is worrisome, but
  - Good agreement when shipboard data is available is reassuring
  - Method for converting pH to pCO_2 looks good.

- Hypothesis 2: Climatological baseline should have a stronger Southern Ocean source
  - but is this due to pre-industrial component or anthropogenic component, or both?
  - Maintaining a large global ocean anthropogenic carbon sink requires a larger carbon uptake elsewhere to compensate the smaller carbon uptake in the Southern Ocean

- Hypothesis 3: Interannual variability: 2014-present is anomalous
  - This appears to be the case, but past history suggest this can only explain ~0.5 Pg C y^{-1} of 0.9 Pg C y^{-1} anomaly we find

Thank you

Alison Gray & Ken Johnson

Nancy Williams,
Seth Bushinsky, Carolina Dufour & Peter Landschützer

Stephen Riser, Joellen Russell, Lynne Talley,
& Rik Wanninkhof

The End

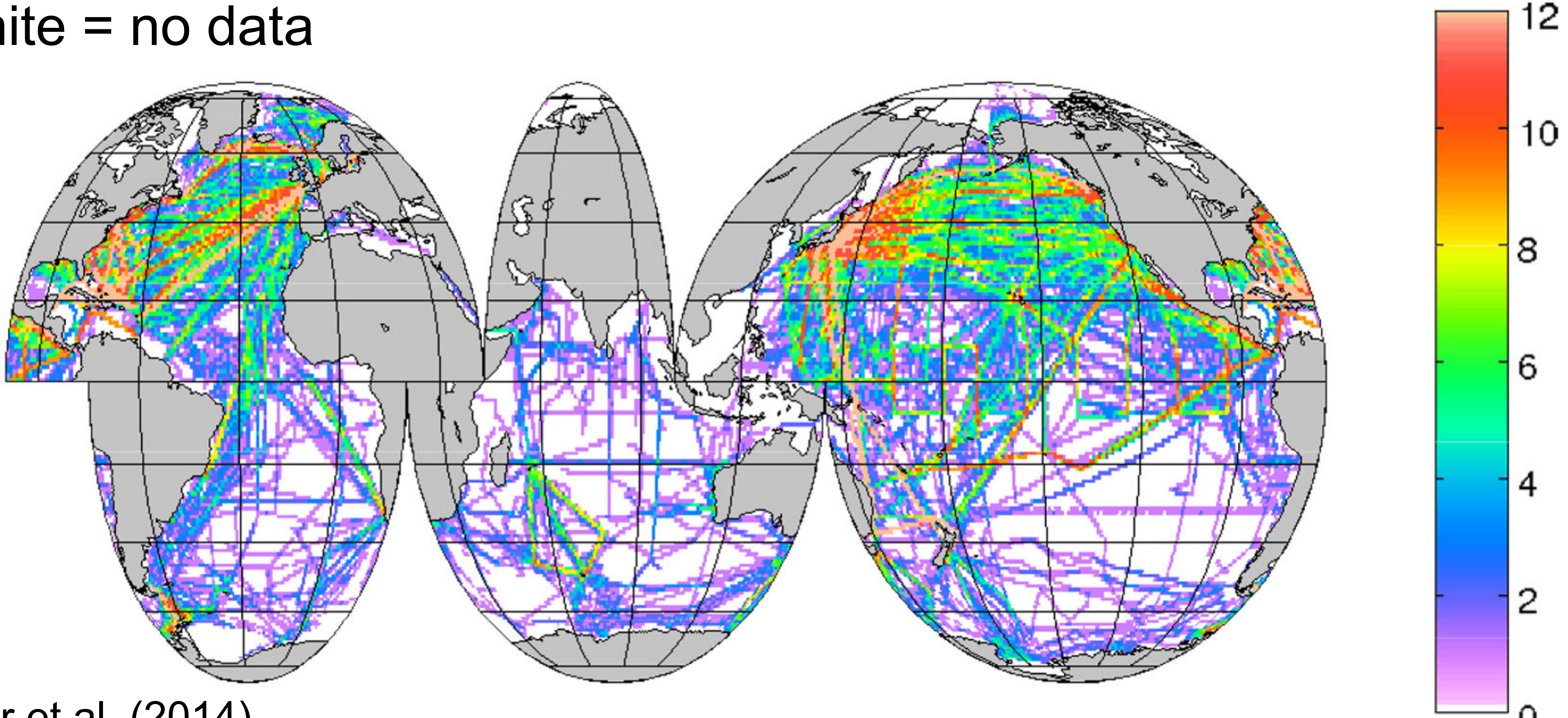
Extra slides

Implications for global carbon cycle in the ocean & on land

Landschützer et al. (in preparation)

Undersampling of pCO_2

Months of year with surface pCO_2 measurements based on all measurements between 1970 to 2011 binned in 1° squares.
White = no data



Bakker et al. (2014)

Tests of adequacy of data coverage

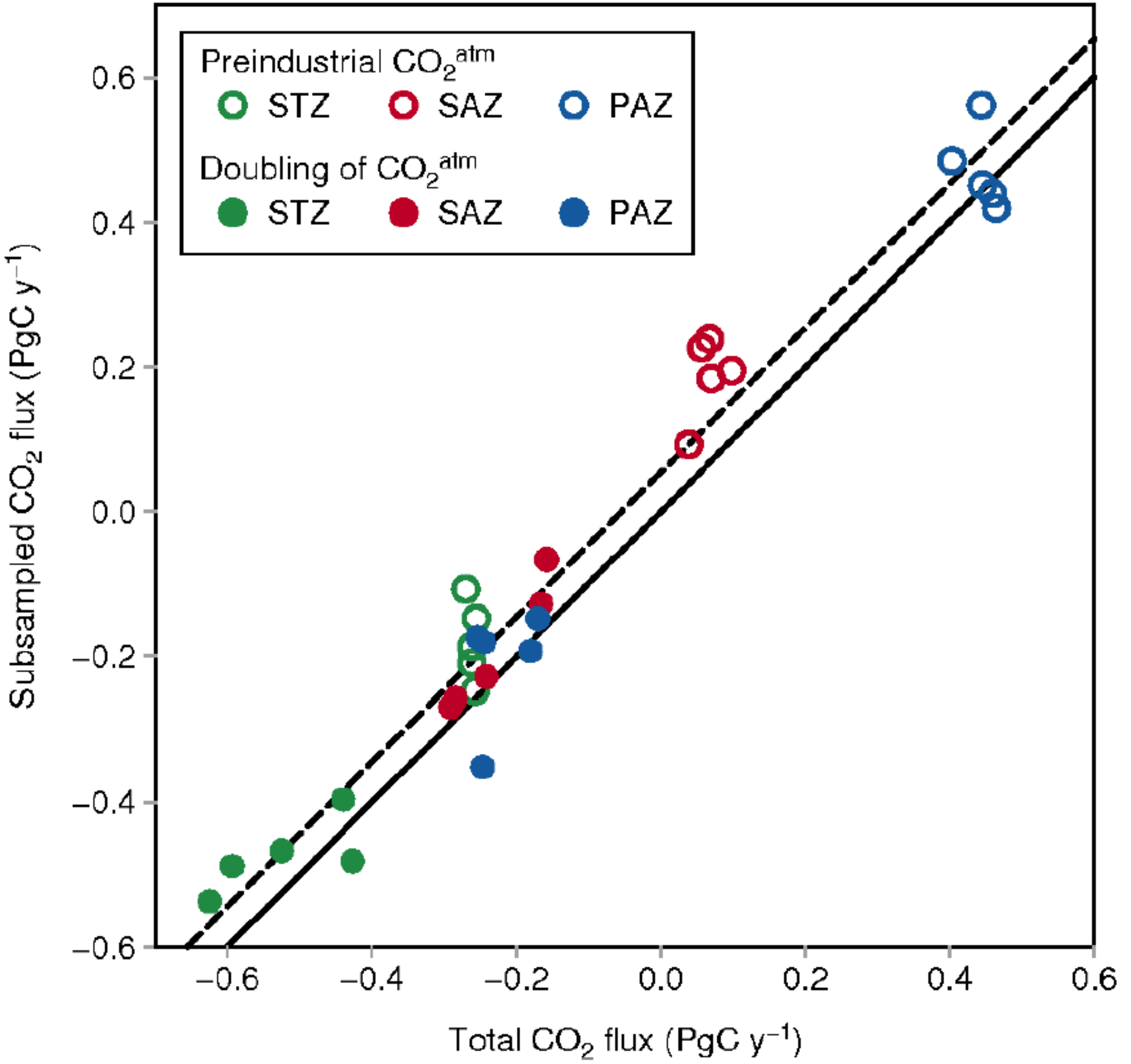
Wilson et al. (accepted, GBC)

Gray et al. (in preparation)

Test using high resolution (GFDL CM2.6) ocean model

- Units Pg C y^{-1}
- Covers region south of 35°S
- Positive indicates net outgassing, negative is uptake.

- Impact of sampling using CM2.6 1/10th degree ocean model simulation results



Support from nitrate measurements

L. Arteaga (pers. comm.)

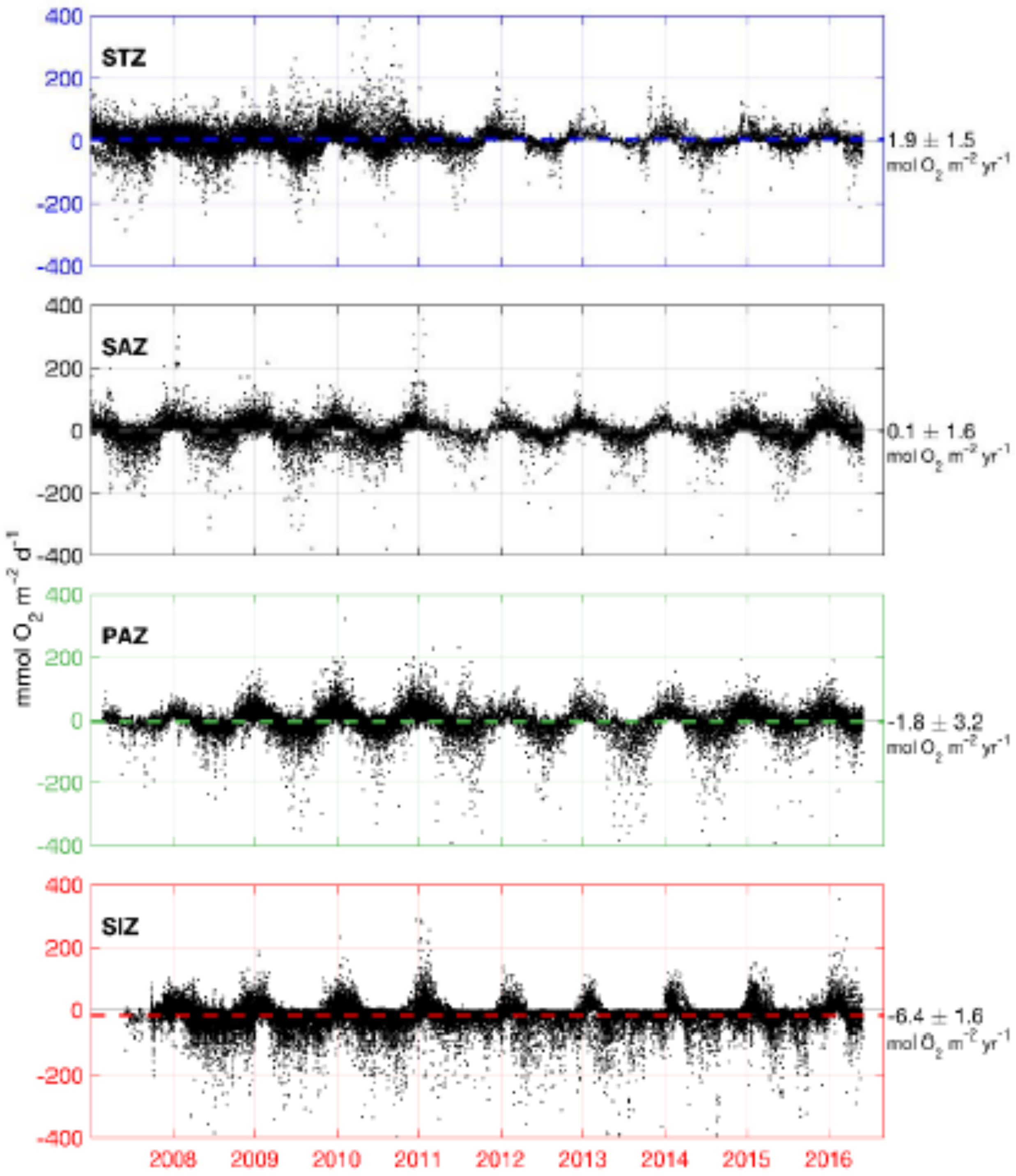
Support from oxygen measurements

S. Bushinsky (pers. comm.)

Southern Ocean oxygen fluxes

+ Outgassing
– Uptake

Bushinsky et al., in prep



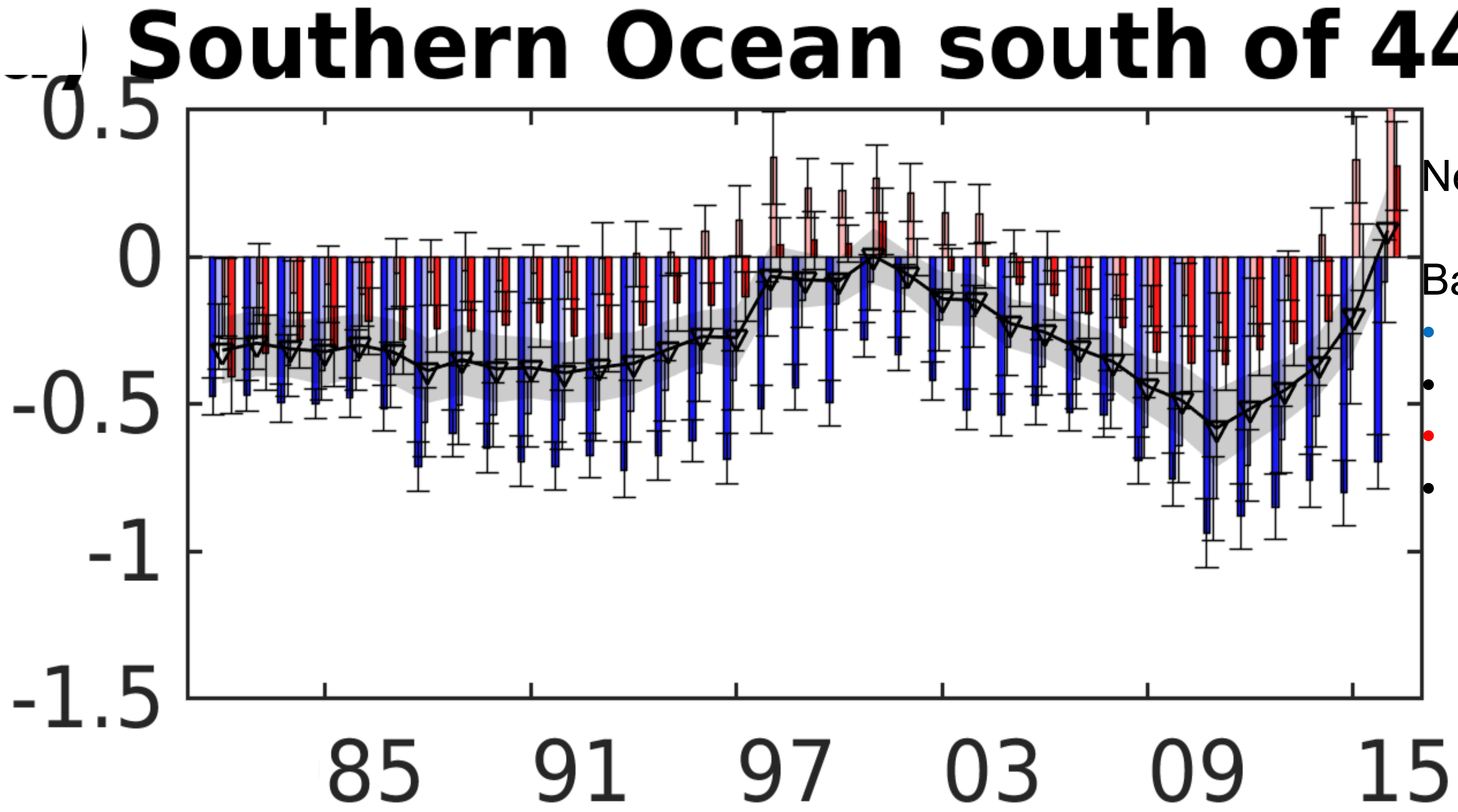
Zone	Flux (mol m^{-2} y^{-1})	
	O_2	CO_2
STZ	1.9 ± 1.5	-0.9 ± 0.5
SAZ	0.1 ± 1.6	-0.3 ± 0.7
PAZ	-1.8 ± 3.2	1.6 ± 0.8
SIZ	-6.4 ± 1.6	-0.3 ± 0.4

Consistent with upwelling of Circumpolar Deep Water

High in NO_3 and DIC
Low in O_2

Or is it interannual variability?

CO_2 Flux (Pg C yr^{-1})

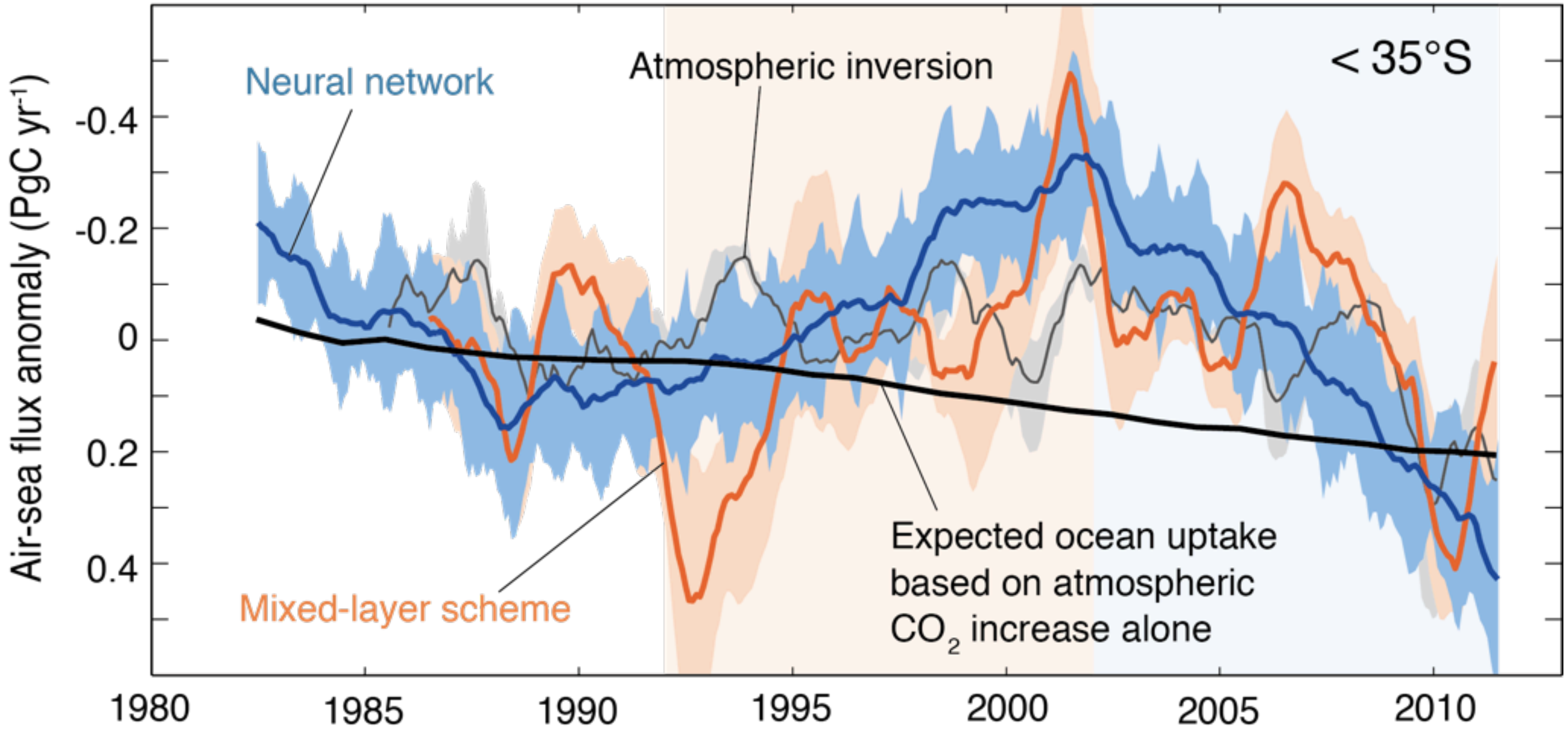


Negative into ocean

Bar colors:

- dark blue SH summer
- light blue SH fall
- light red SH winter
- dark red SH spring

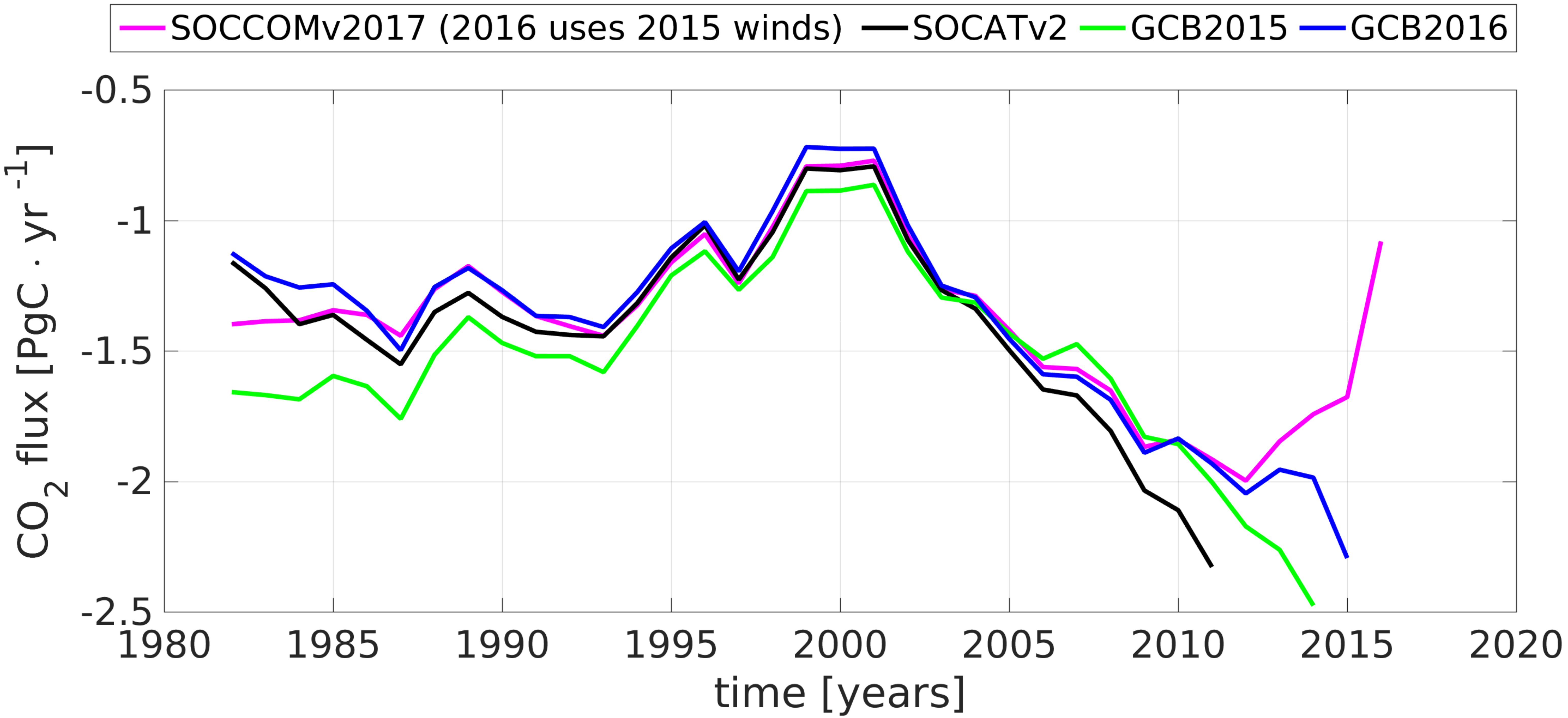
Recent CO_2 flux trend into the Southern Ocean



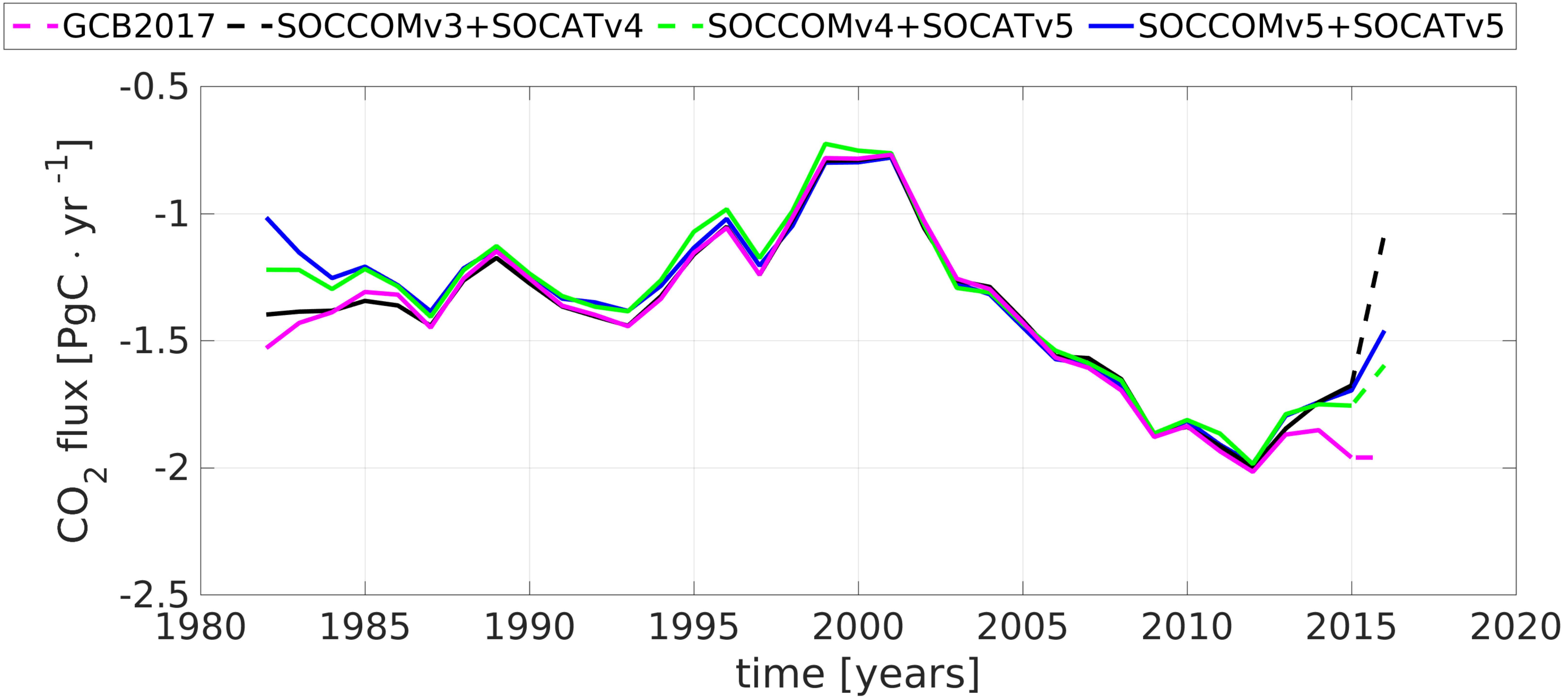
Le Quéré et al. (2007, Science): Saturation of Southern Ocean CO_2 sink?

Landschützer et al. (2015, Science): Reinvigoration of Southern Ocean carbon sink

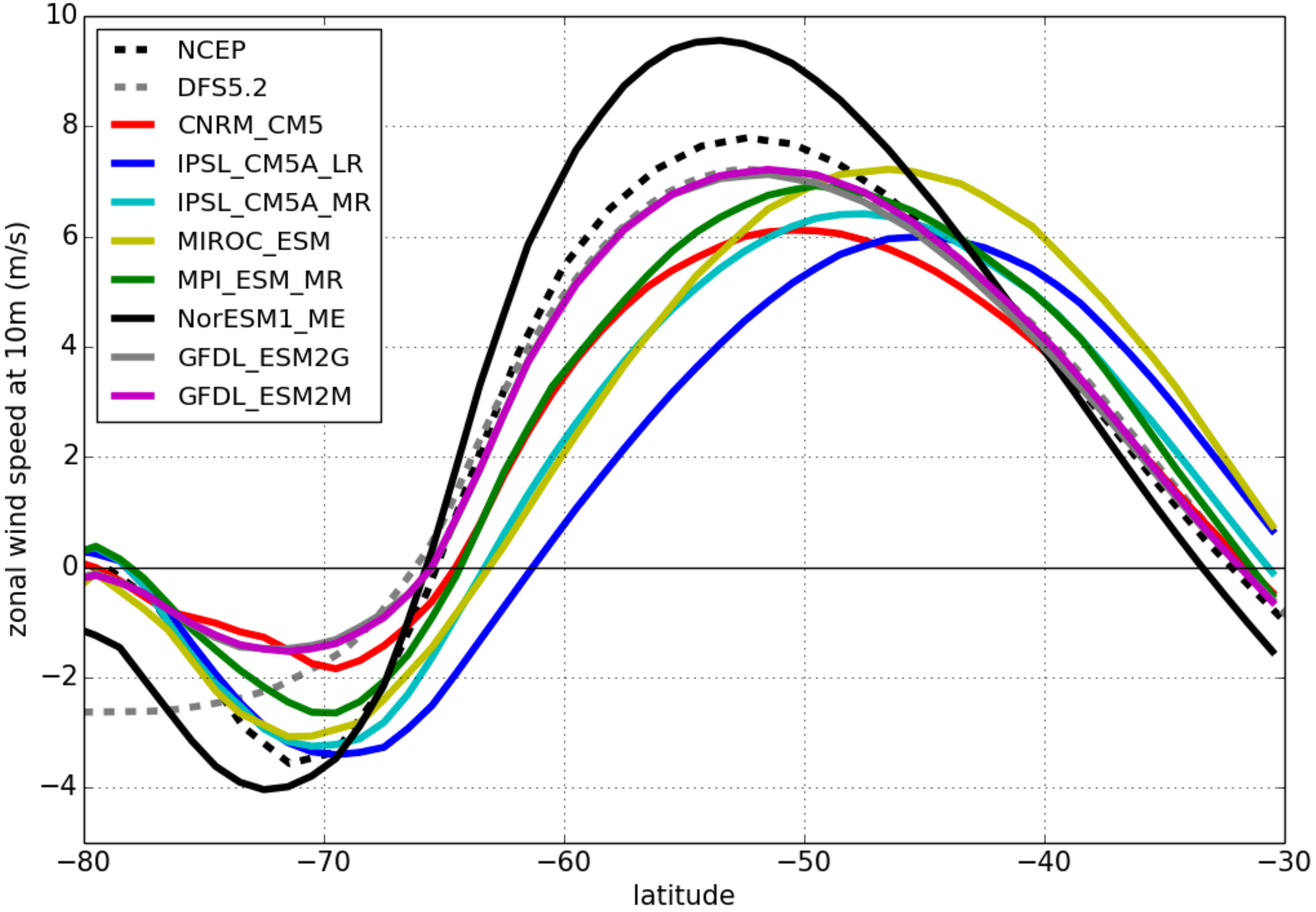
Global ocean carbon sink



Global ocean carbon sink



Zonal average wind speed at 10 m

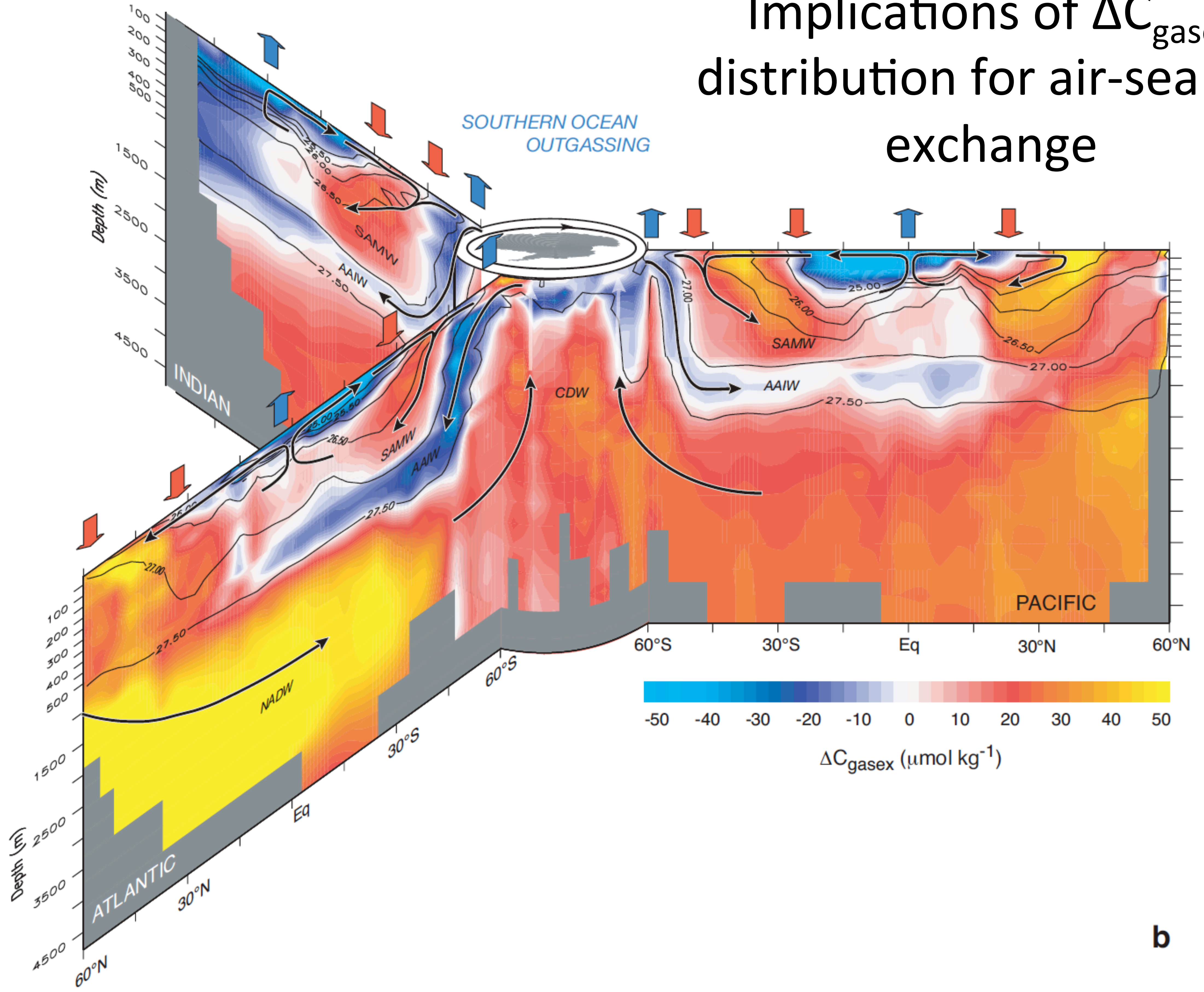


The outsized role of the Southern Ocean in the regulation of carbon

Jorge L. Sarmiento
Princeton University

The Southern Ocean accounts for half the oceanic uptake of anthropogenic carbon. Initial results from a fleet of new BGC Argo floats equipped with biogeochemical sensors are forcing us to rethink the current paradigm.

Implications of ΔC_{gasex} distribution for air-sea gas exchange



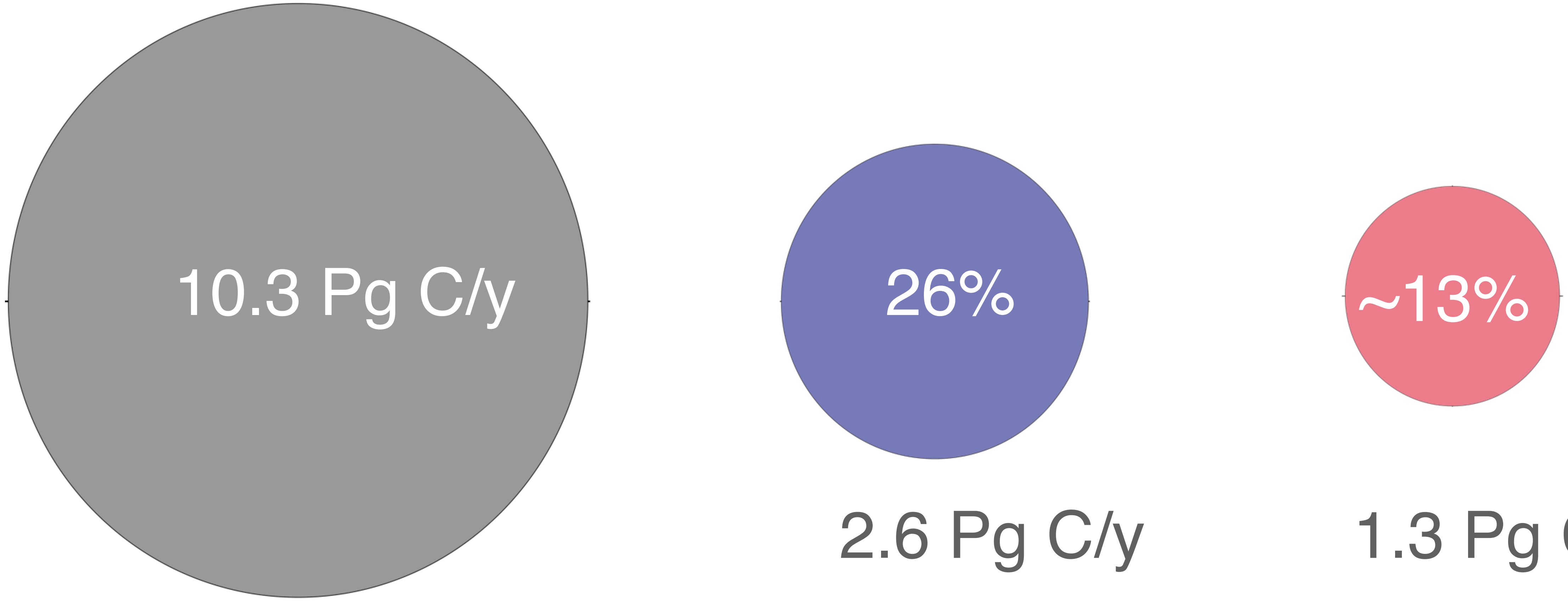
The Southern Ocean accounts for half of ocean CO_2 uptake, 10-15% of total emissions

Anthropogenic carbon budget (2006-2015)

Total emissions (fossil fuel + land-use)

Global ocean uptake

Southern Ocean uptake



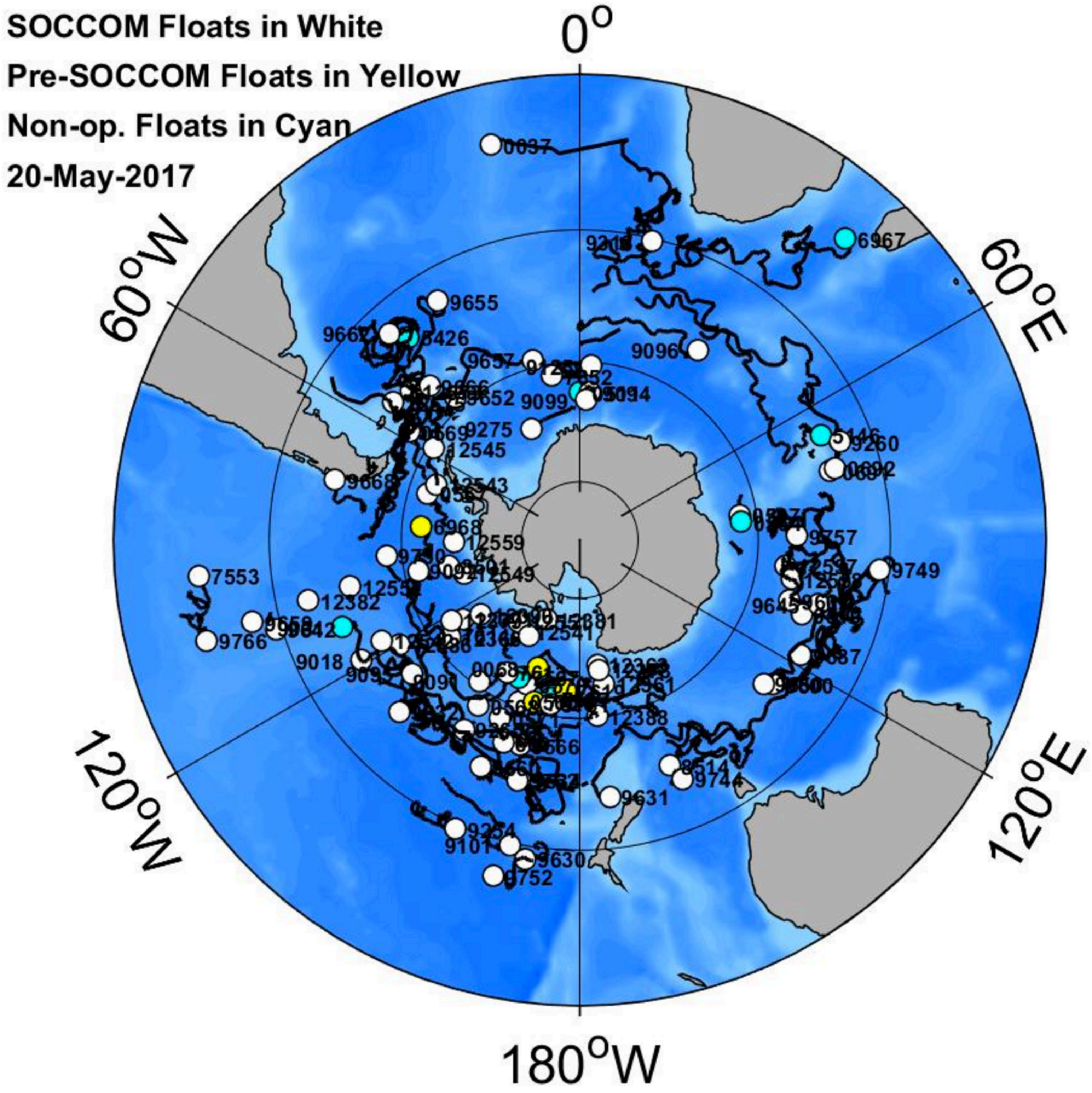
2.6 Pg C/y

1.3 Pg C/y

Based on Global Carbon Budget 2016

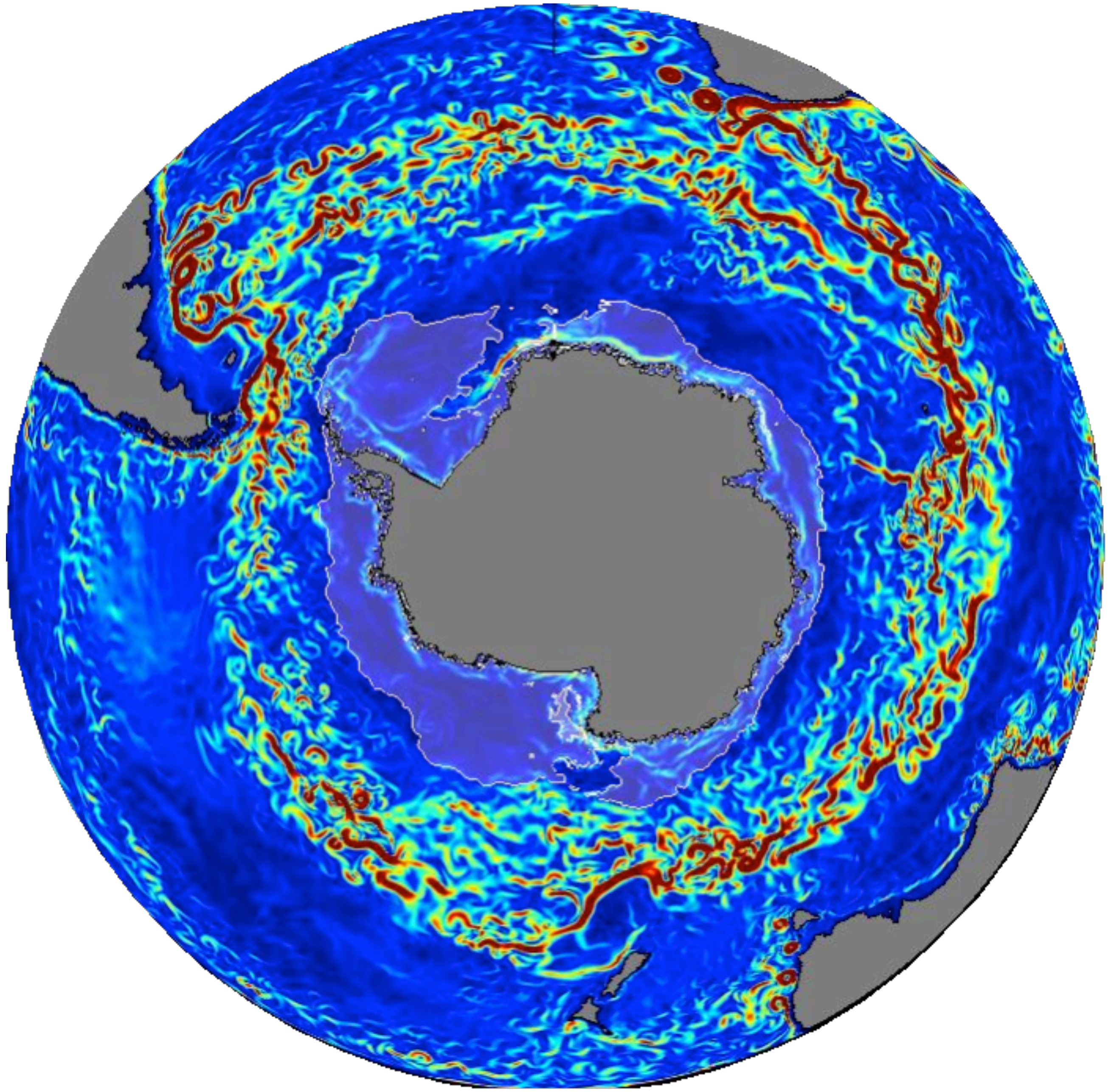
Le Quéré et al. (2015, Earth System Science Data)

Highlights - Float Deployments



- 80 floats operational
- 32 deployed this year on 5 cruises (+1 more cruise with 7 floats)
- Data freely available

The Opportunity

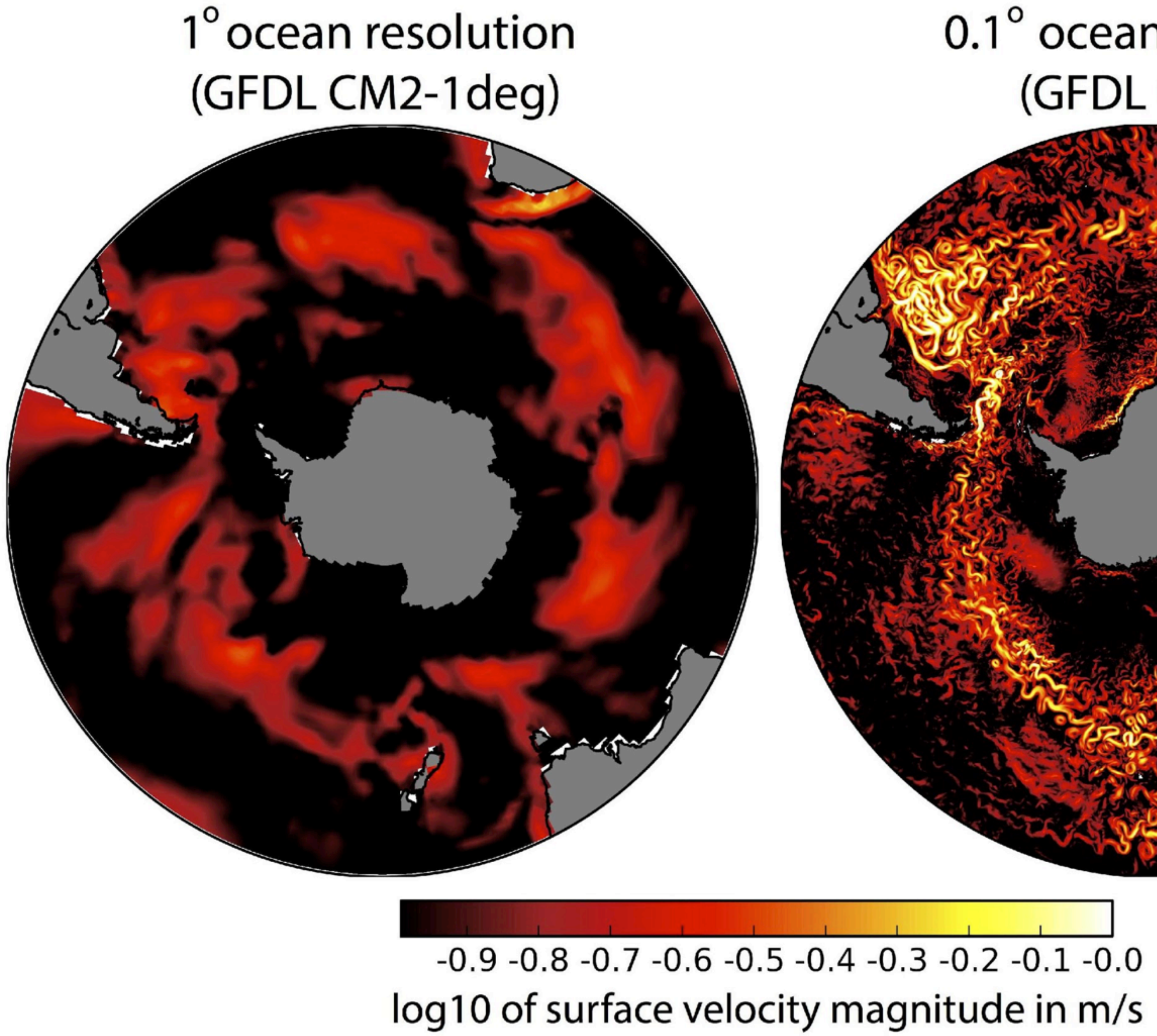


(2) Development of improved oibservational analysis methods

- Southern Ocean State Estimation (SOSE) using data fitting to produce full 4D estimates of ocean properties

SOCCOM

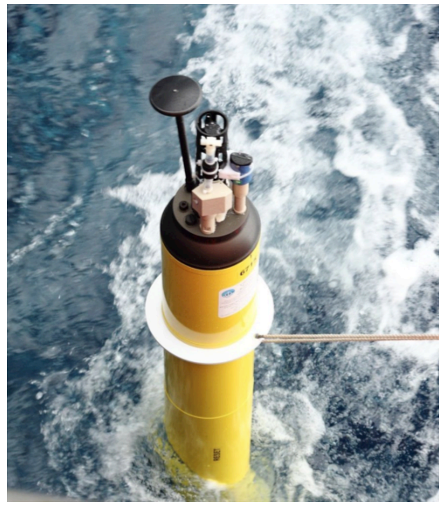
The Opportunity



(3) Eddy rich-high resolution climate models

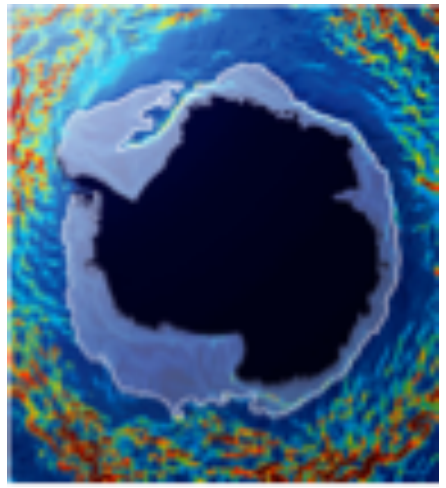
SOCCOM

What is SOCCOM?



- SOCCOM’s mission is to drive a transformative shift in our understanding of the role of the Southern Ocean in climate change and biogeochemistry by:

Extending sparse Southern Ocean biogeochemical observations by deploying a robotic observing system composed of ~200 autonomous BGC Argo floats that will provide nearly continuous coverage in time and horizontal space over the entire Southern Ocean, as well as vertical coverage deep into the water column.



Using these observations to analyze and improve a new generation of high resolution (1/10°) earth system models to both increase our understanding of the Southern Ocean’s current workings and make better projections of the future trajectory of the Earth’s climate and biogeochemistry.

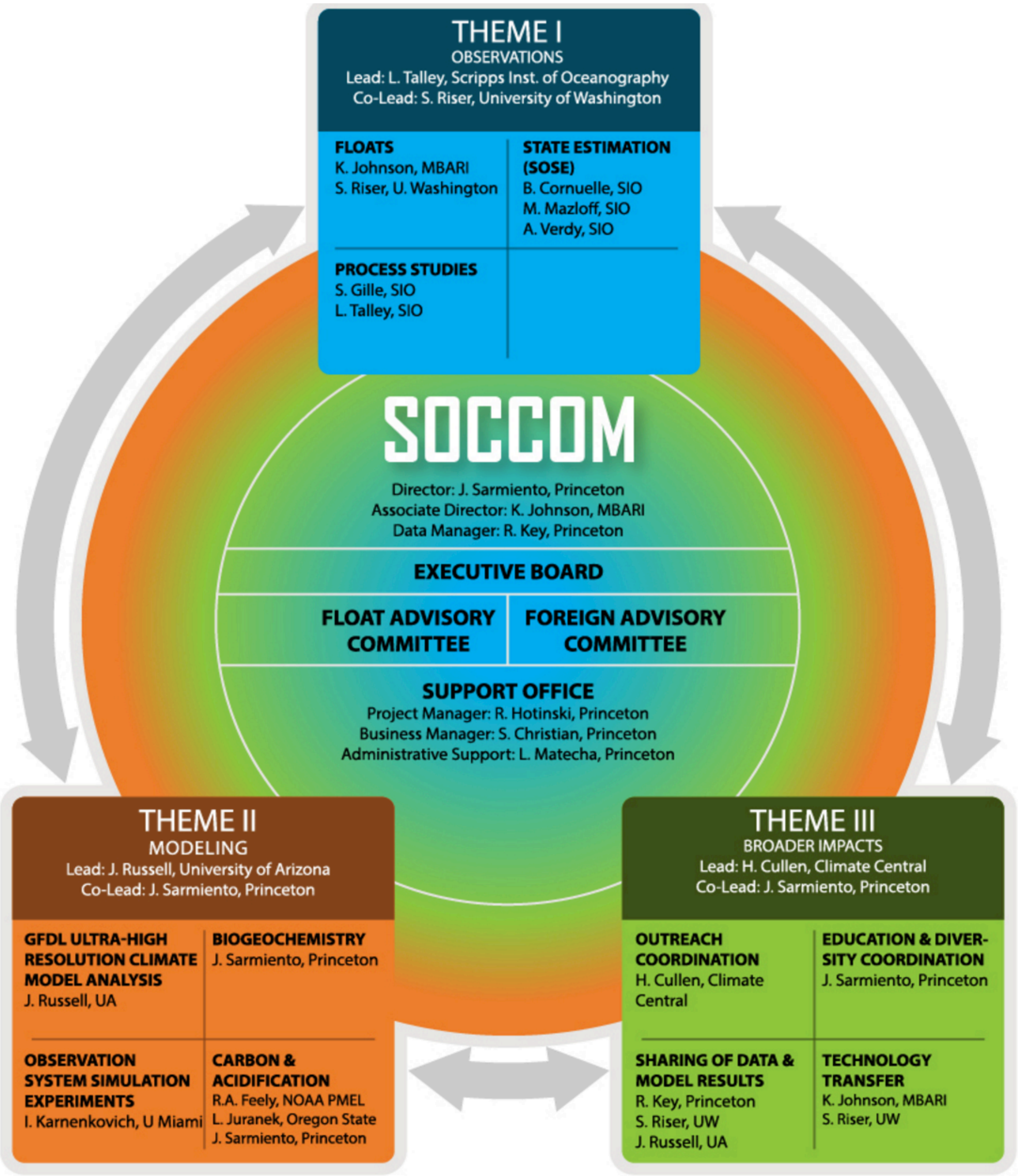
Educating a new generation of ocean scientists trained in both ocean observation and simulation, and develop a sophisticated outreach effort to disseminate results to the broadest possible community

Directorate

Director
Jorge Sarmiento,
Princeton

Associate
Director
Ken Johnson, MBARI

Project
Manager
Roberta Hotinski,
Princeton



Executive Board

Theme I Observations

Lynne Talley, UCSD

Steve Riser, U. Washington

Theme II Modeling

Joellen Russell
U. Arizona

Broader Impacts

Heidi Cullen,
Climate Central

FLOAT-BASED CO_2 FLUXES

$$F = k\, K_0\, (pCO_2^{ocn} - pCO_2^{atm})$$

pCO_2^{ocn} estimated from SOCCOM floats

pCO_2^{atm} from Cape Grim observations

k Gas transfer velocity, $\propto$ wind speed squared (Wanninkhof 2014) using 6-hourly ERA-Interim winds

K_0 solubility constant from float *T*, *S*

DuraFET pH sensor

Algorithm TA (eg., Carter et al. 2016)

CO2SYS(**pH_{Total}**, **TA**, T, S, P) → **pCO_2**

Error analysis gives a 2.7% uncertainty in pCO_2 (11 μatm at a pCO_2 of 400 μatm)

Williams et al., 2017(*GBC*)

Estimating surface ocean pCO_2 from float-based pH

DuraFET pH sensor

Algorithm TA (eg., Carter et al. 2016)

CO2SYS(pH_{Total}, TA, T, S, P) → pCO_2

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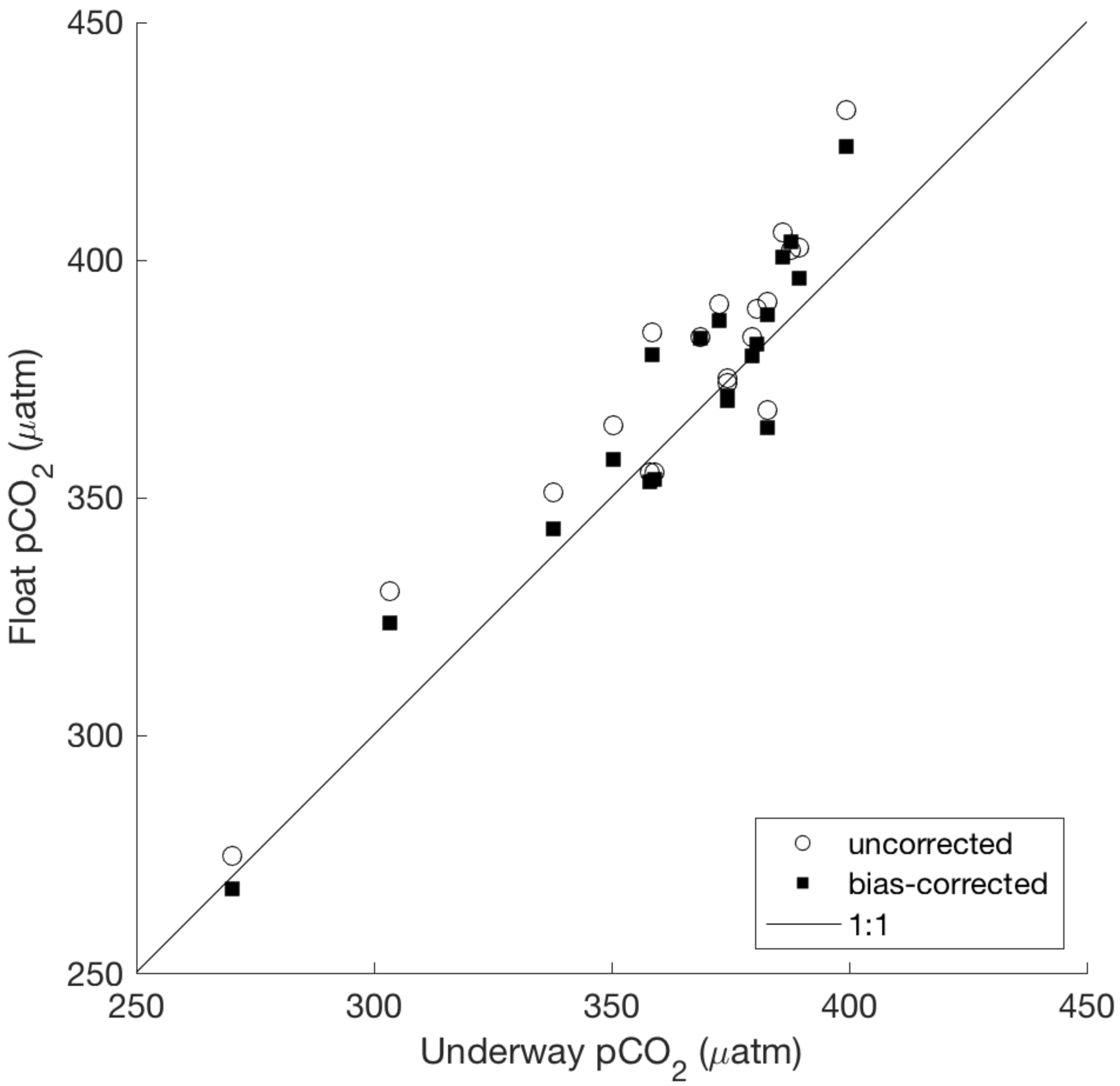


FLOAT-BASED pCO_2

$$pCO_2 = f(pH, T, S, A_T)$$

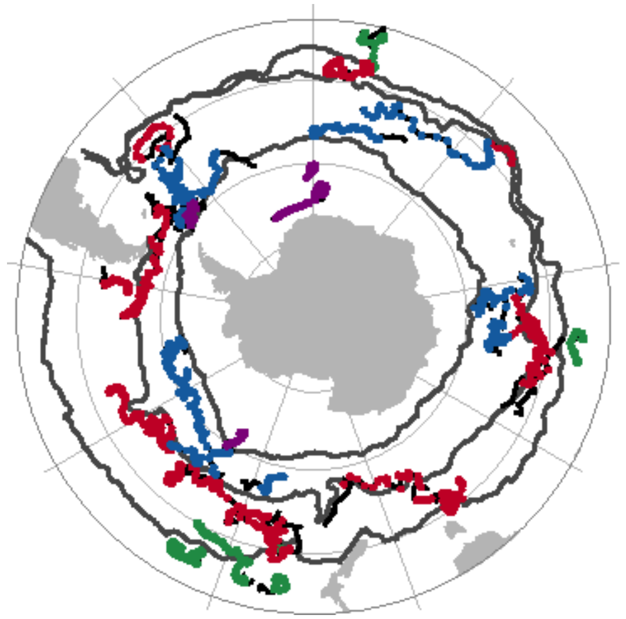
pH, *T*, and *S* measured by floats

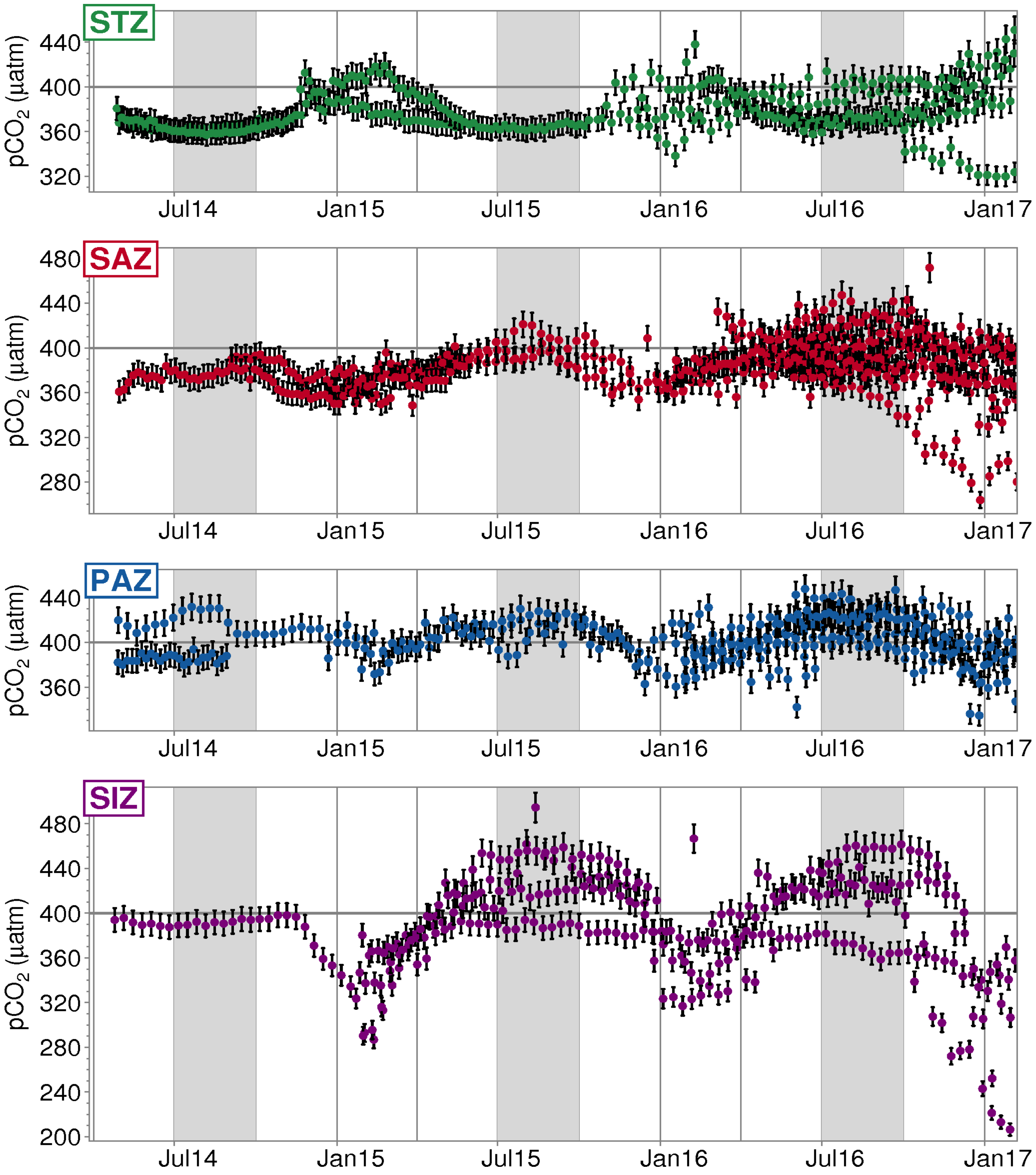
Alkalinity estimated using multiple linear regression

Carter et al. 2016

Uncertainty after bias-correction estimated at 2.7% (median 10.5 μatm)

Williams et al. 2017





Estimating surface ocean pCO_2 from float-based pH

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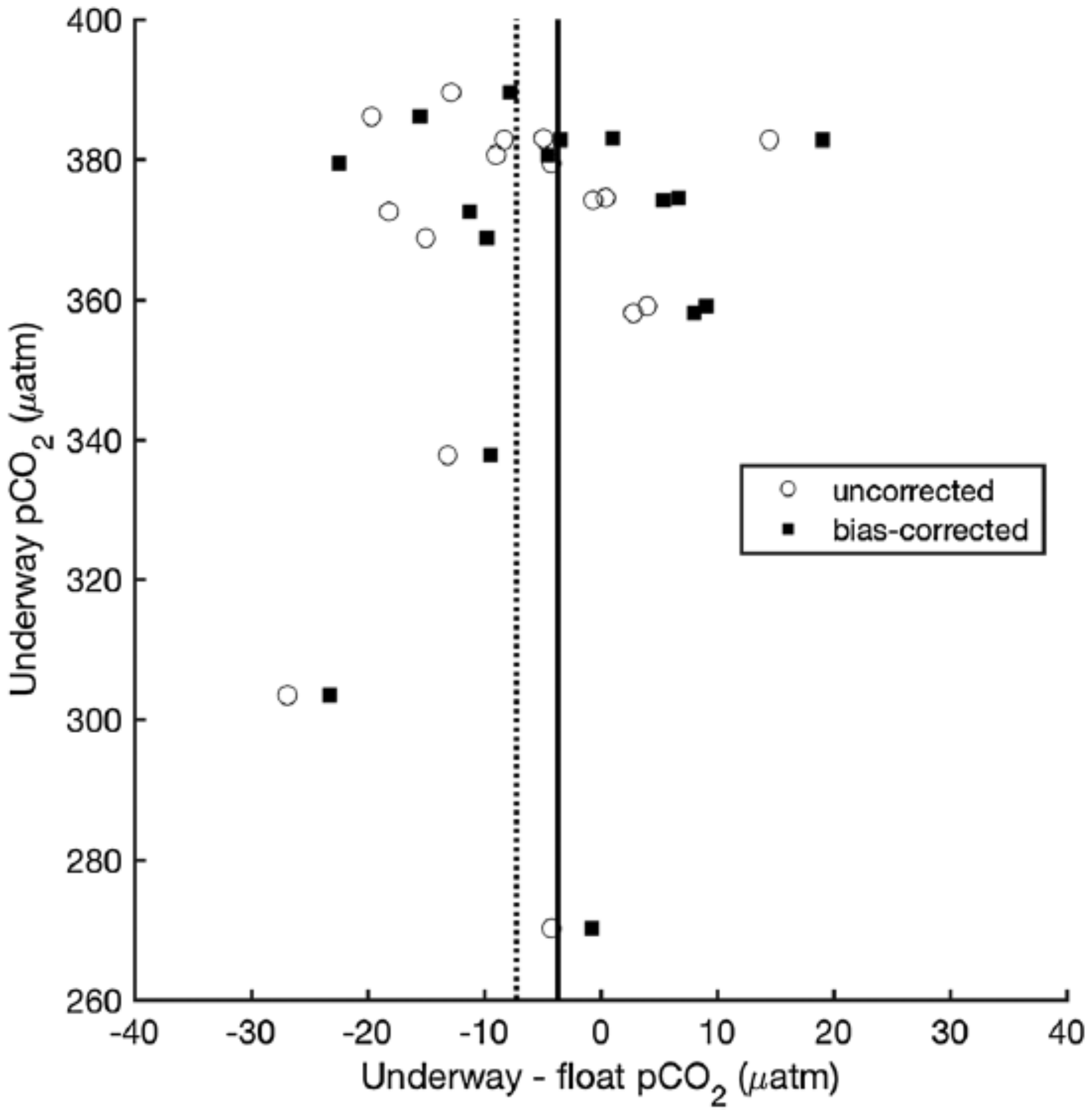
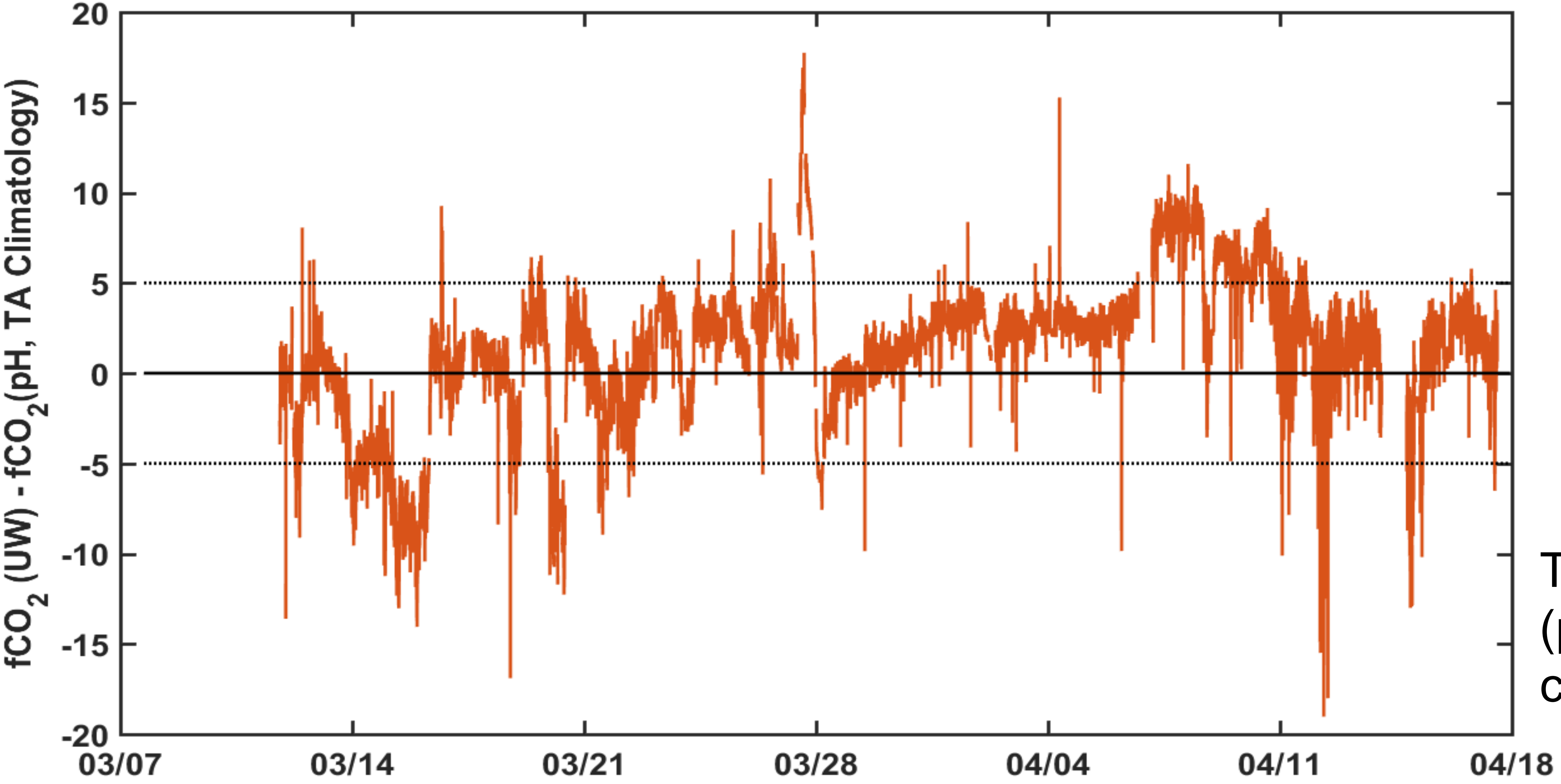


Underway fCO_2 anomaly: measured minus calculated



Takeshita (pers. comm.)

FLOAT-BASED CO_2 FLUXES

$$F = k\,K_0\,(pCO_2^{ocn} - pCO_2^{atm})$$

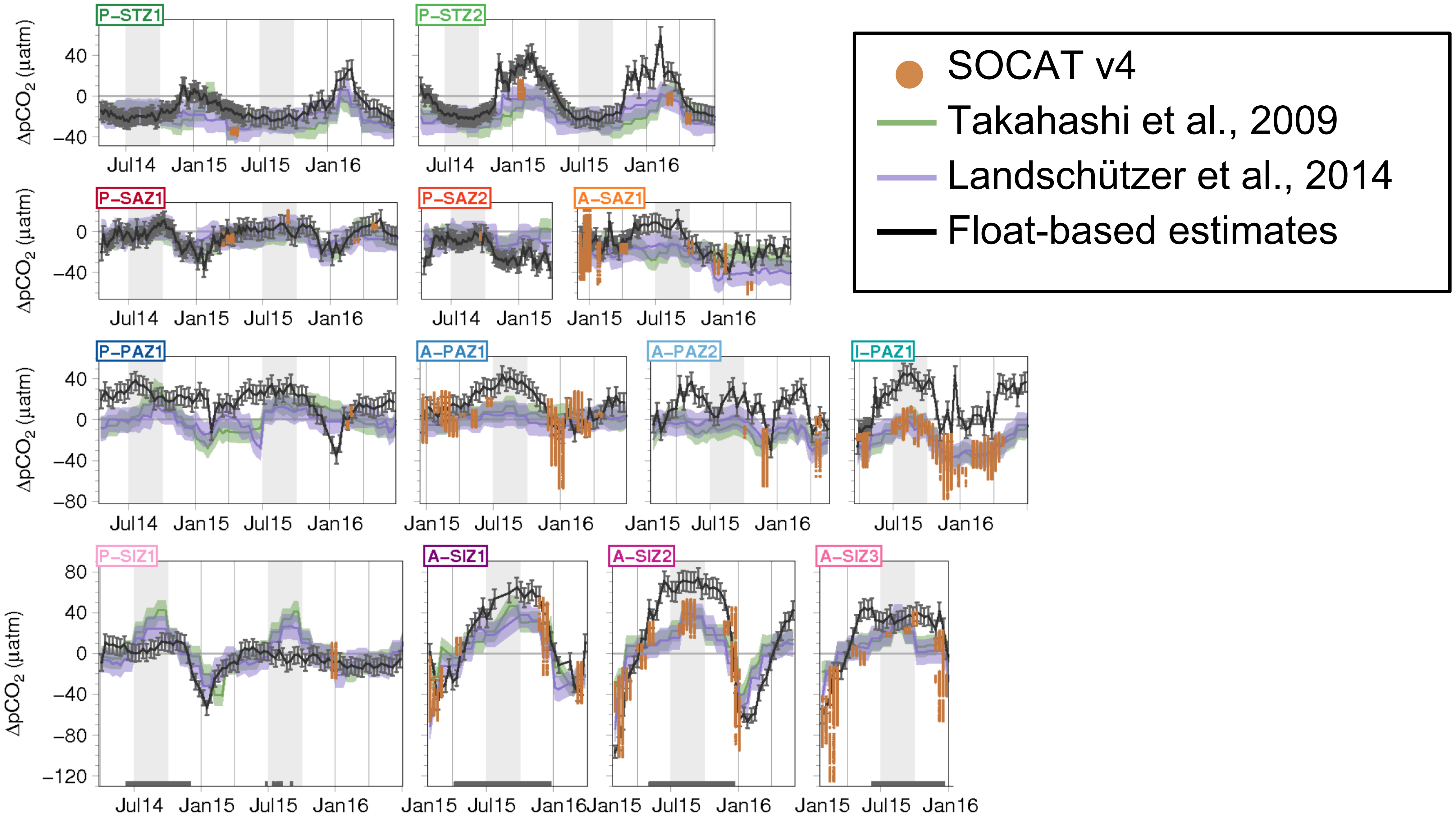
pCO_2^{ocn} estimated from SOCCOM floats

pCO_2^{atm} from Cape Grim observations

k Gas transfer velocity, ∝ wind speed squared (Wanninkhof 2014) using 6-hourly ERA-Interim winds

K_0 solubility constant from float T, S

$\Delta pCO_2 = (pCO_2^{ocn} - pCO_2^{atm})$ from 13 SOCCOM floats deployed in first two years compared to in situ data and climatologies



Float-based CO_2 fluxes

$$F = k\, K_0\, (pCO_2^{ocn} - pCO_2^{atm})$$

pCO_2^{ocn} estimated from SOCCOM floats

pCO_2^{atm} from Cape Grim observations

k Gas transfer velocity, $\propto$ wind speed squared (Wanninkhof 2014) using 6-hourly ERA-Interim winds

K_0 solubility constant from float T, S

$$\Delta pCO_2 = pCO_2^{ocn} - pCO_2^{atm}$$

ANNUAL NET AIR-SEA CO_2 FLUX

+ Outgassing

– Uptake

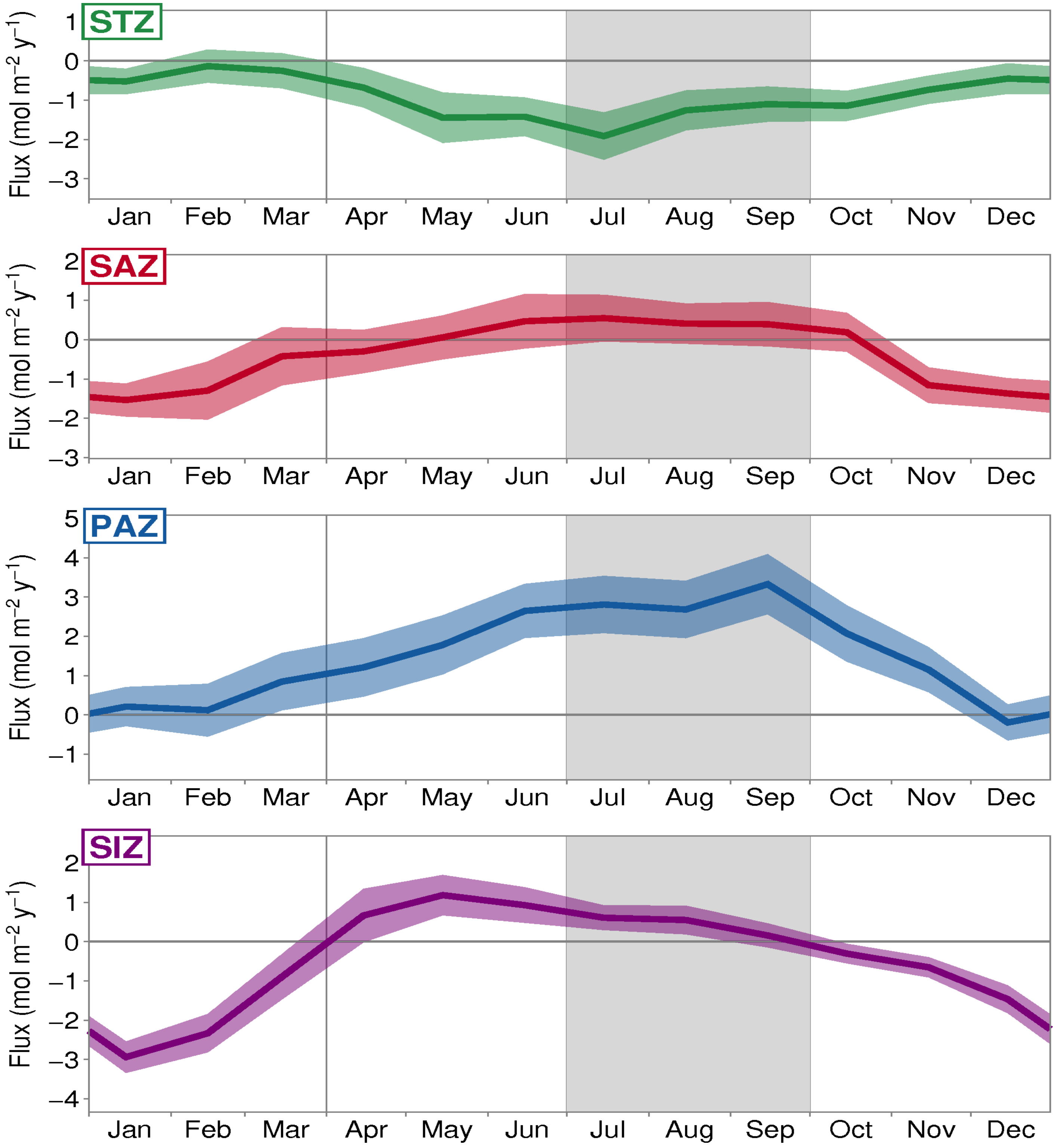
Mean ($mol\ m^{-2}\ y^{-1}$)

STZ: -0.9 ± 0.5

SAZ: -0.3 ± 0.5

PAZ: 1.6 ± 0.7

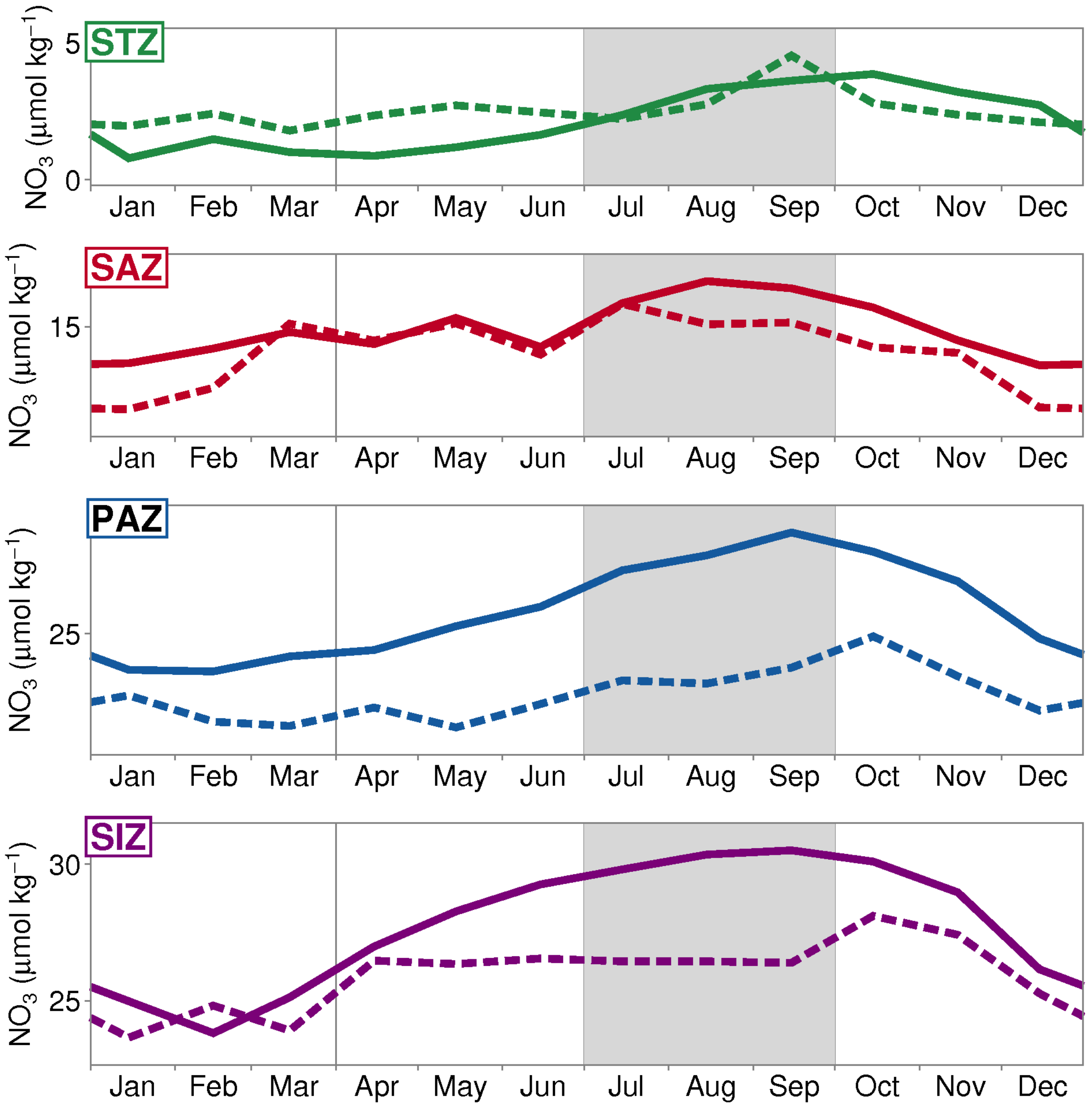
SIZ: -0.4 ± 0.4



Average global anthropogenic CO_2 uptake = -0.46 ± 0.14 $mol\ m^{-2}\ y^{-1}$

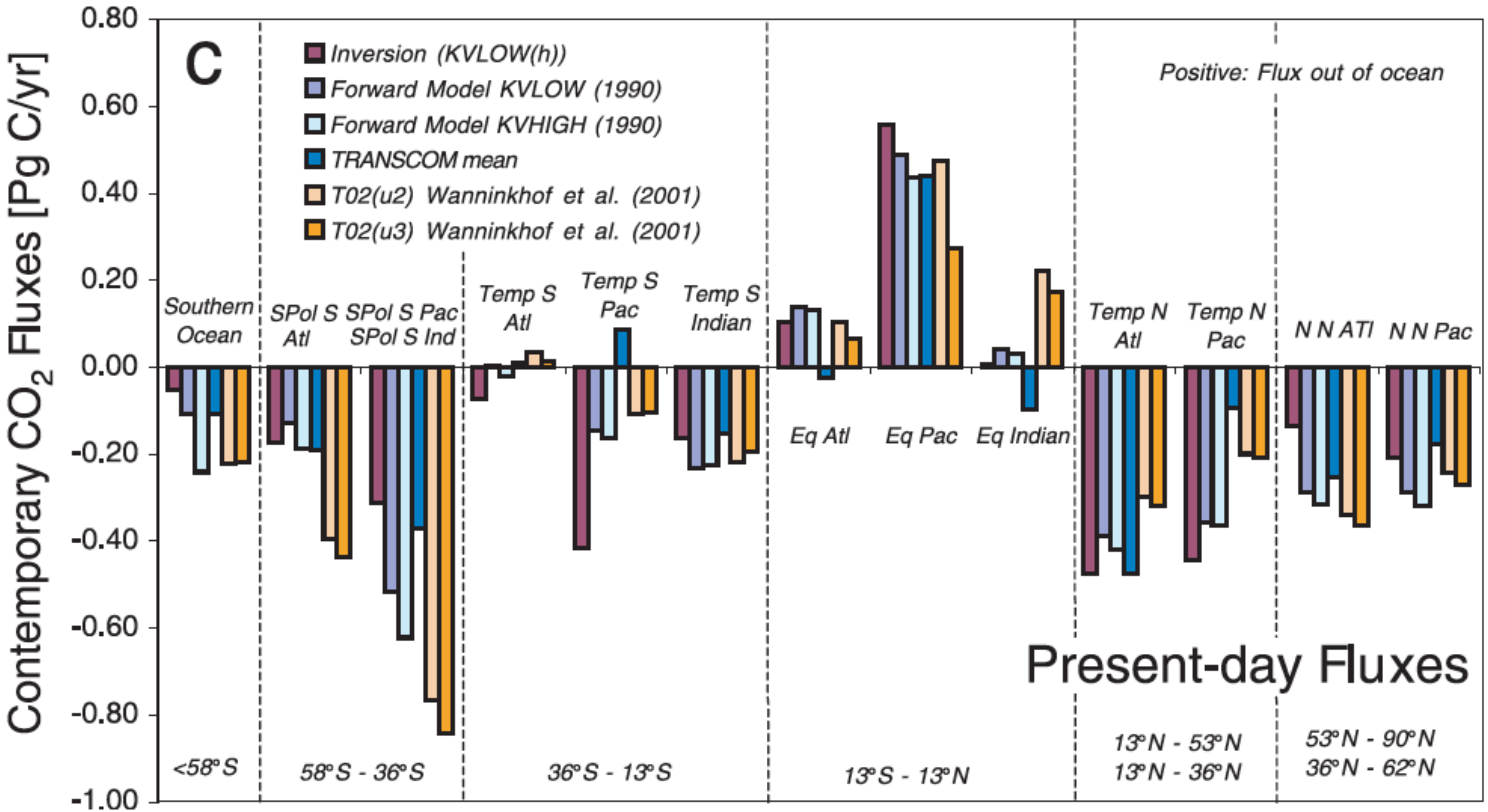
SEASONAL CYCLE OF NITRATE IN UPPER 20 M

Floats measure higher nitrate in PAZ compared to World Ocean Atlas



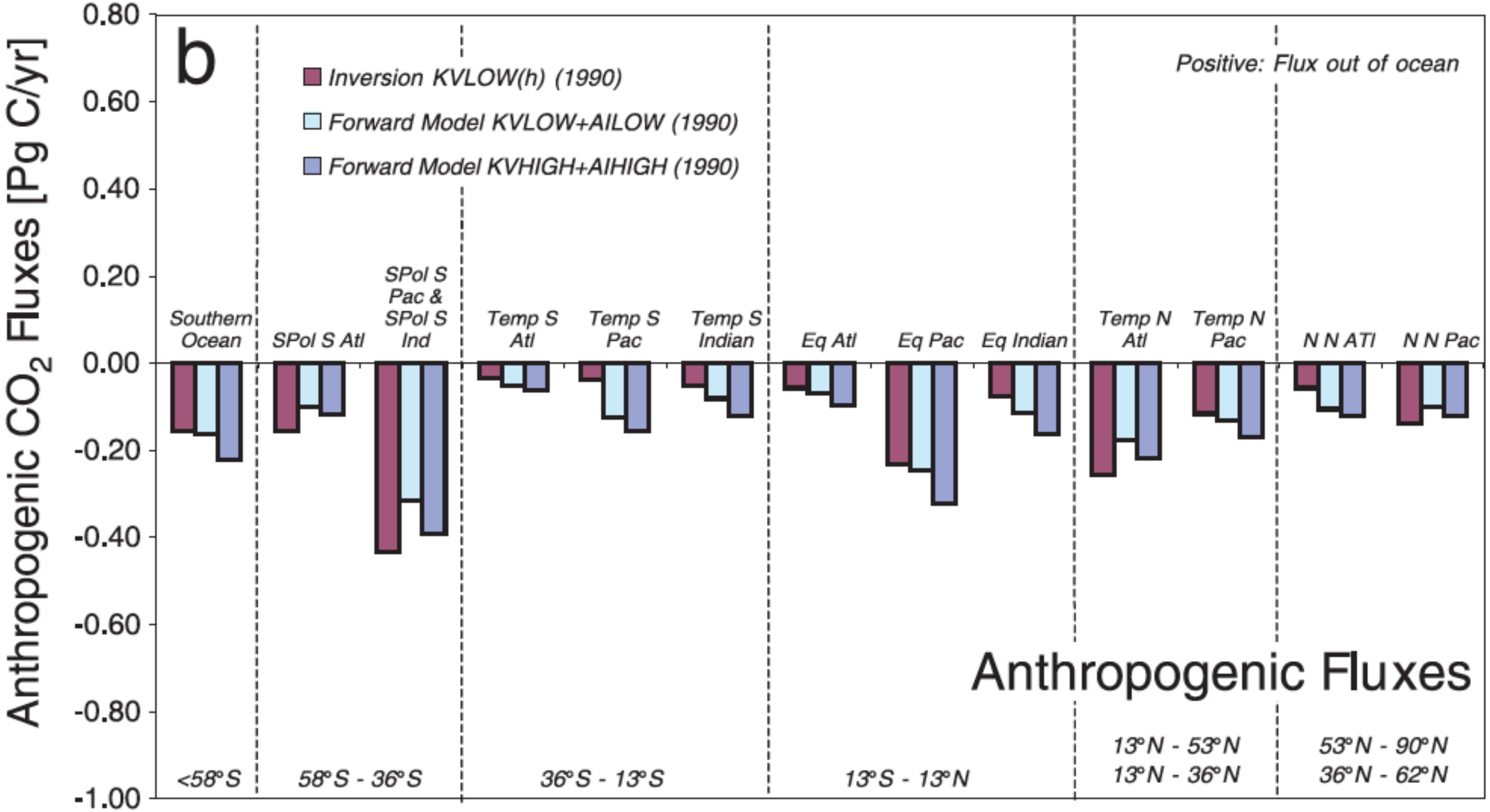
——	This estimate
- - - -	WOA 13

CO_2 fluxes across the air-sea interface



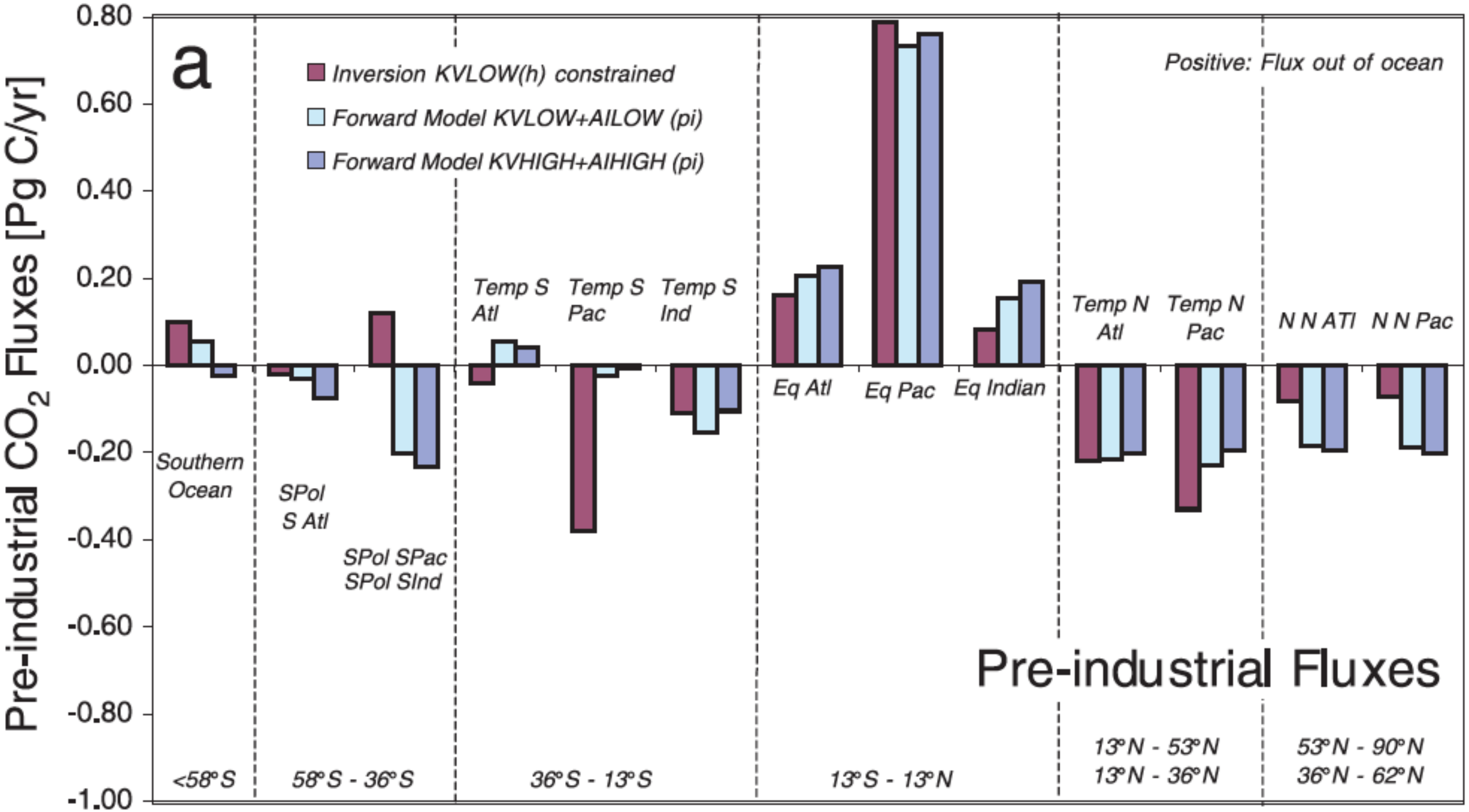
Gloor et al. (2003)

CO_2 fluxes across the air-sea interface



Gloor et al. (2003)

CO_2 fluxes across the air-sea interface



Gloor et al. (2003)