A large Southern Ocean CO_2 source detected by biogeochemical profiling floats

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

→ I. Introduction

II. Methods & results

A. pCO_2

B. ΔpCO_2

C. CO_2 flux

III. Hypotheses

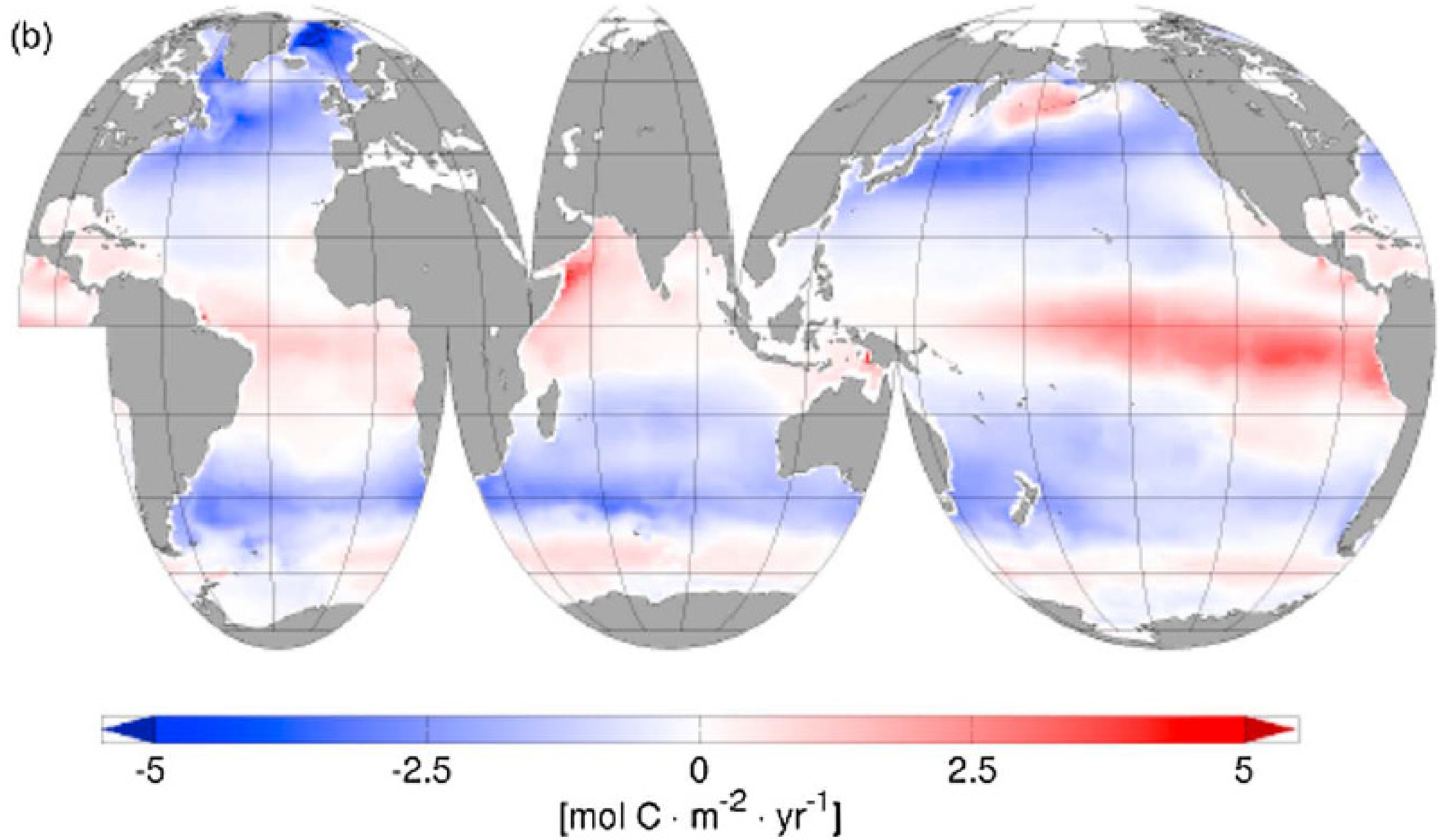
A. Methodology is flawed?

B. Previous studies underestimate winter degassing?

C. Recent years are anomalous?

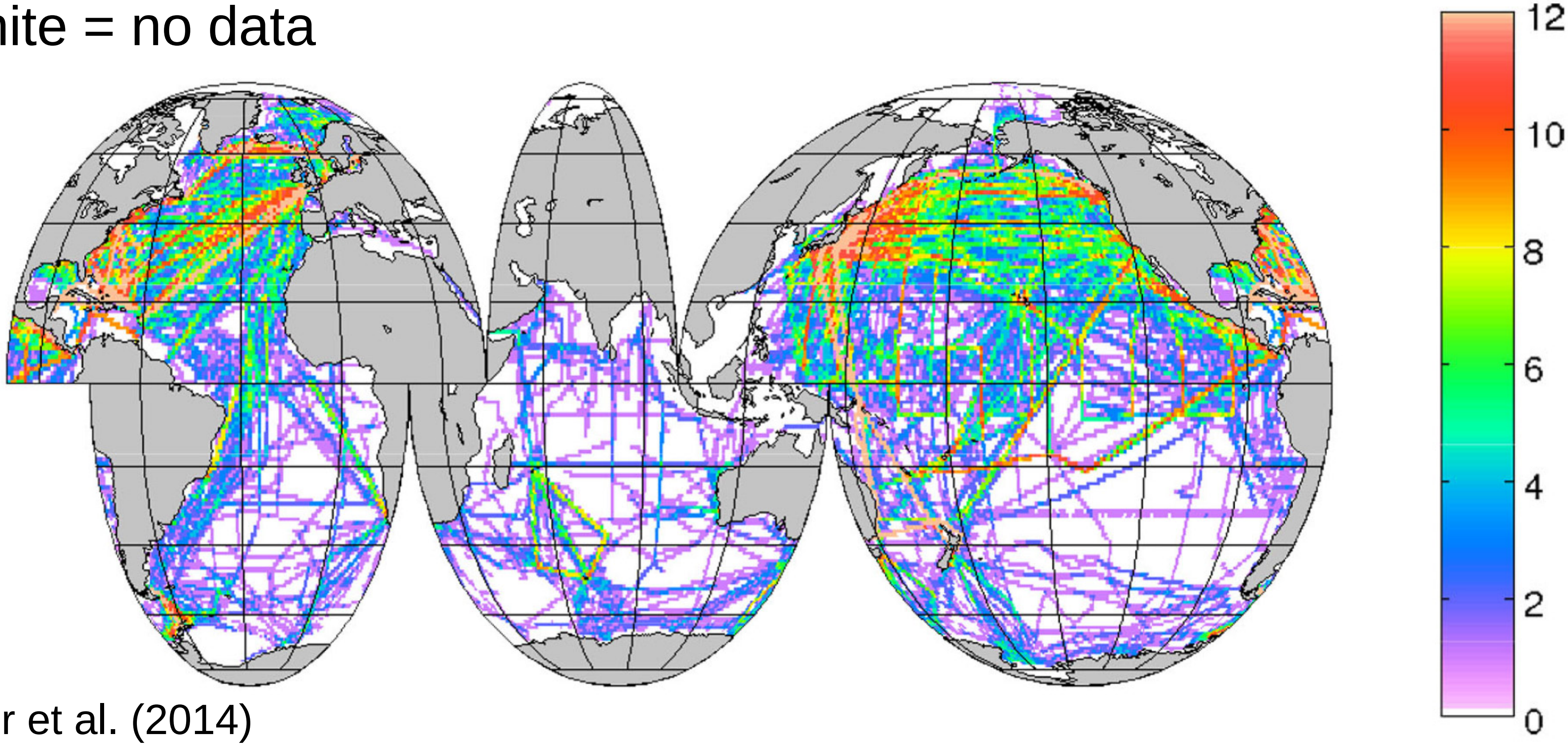
Conclusion: CO_2 flux to atmosphere >> than previous estimates

Landschützer et al. (2014) climatological air-sea flux estimate for 1998-2011



Undersampling of pCO_2

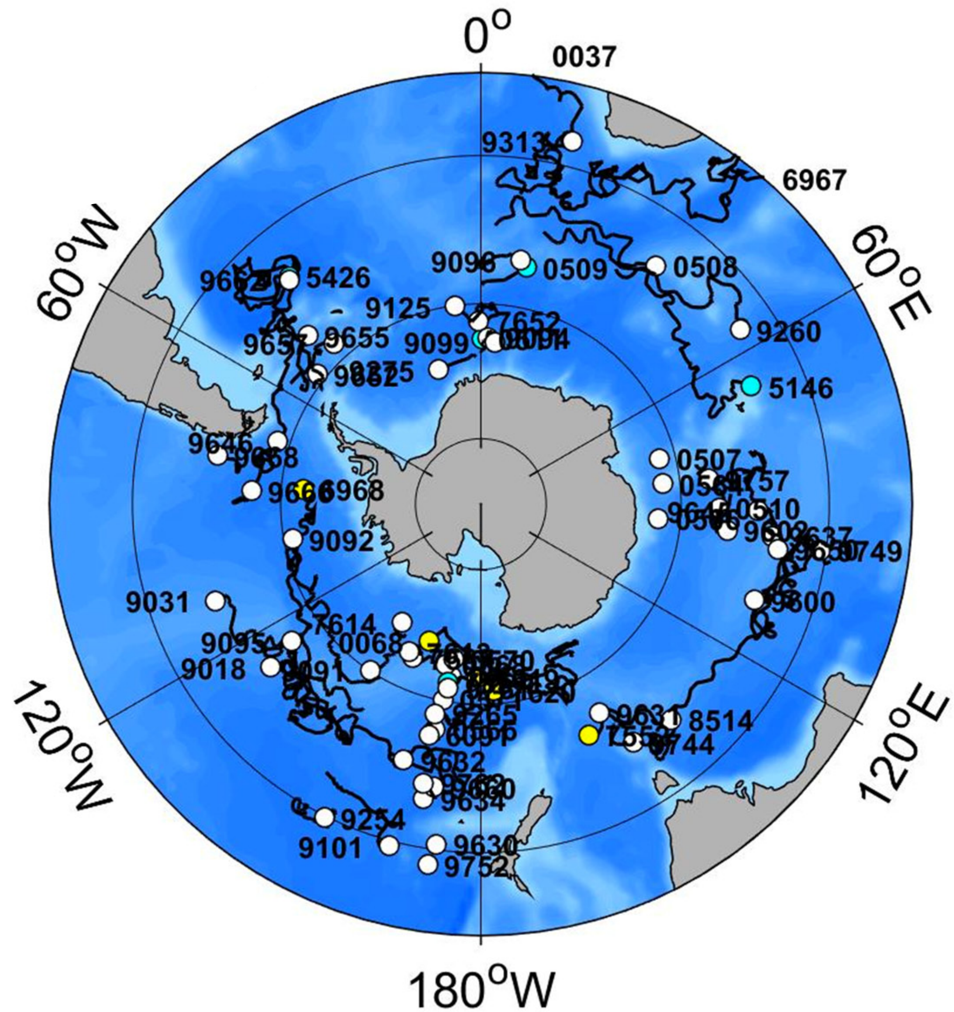
Months of year with surface pCO_2 measurements based on all measurements between 1970 to 2011 binned in 1° squares.
White = no data



Bakker et al. (2014)

SOCCOM Floats (so far...)

Hannah Zanowski



SOCCOM floats

Pre-SOCCOM floats

Non-operational floats

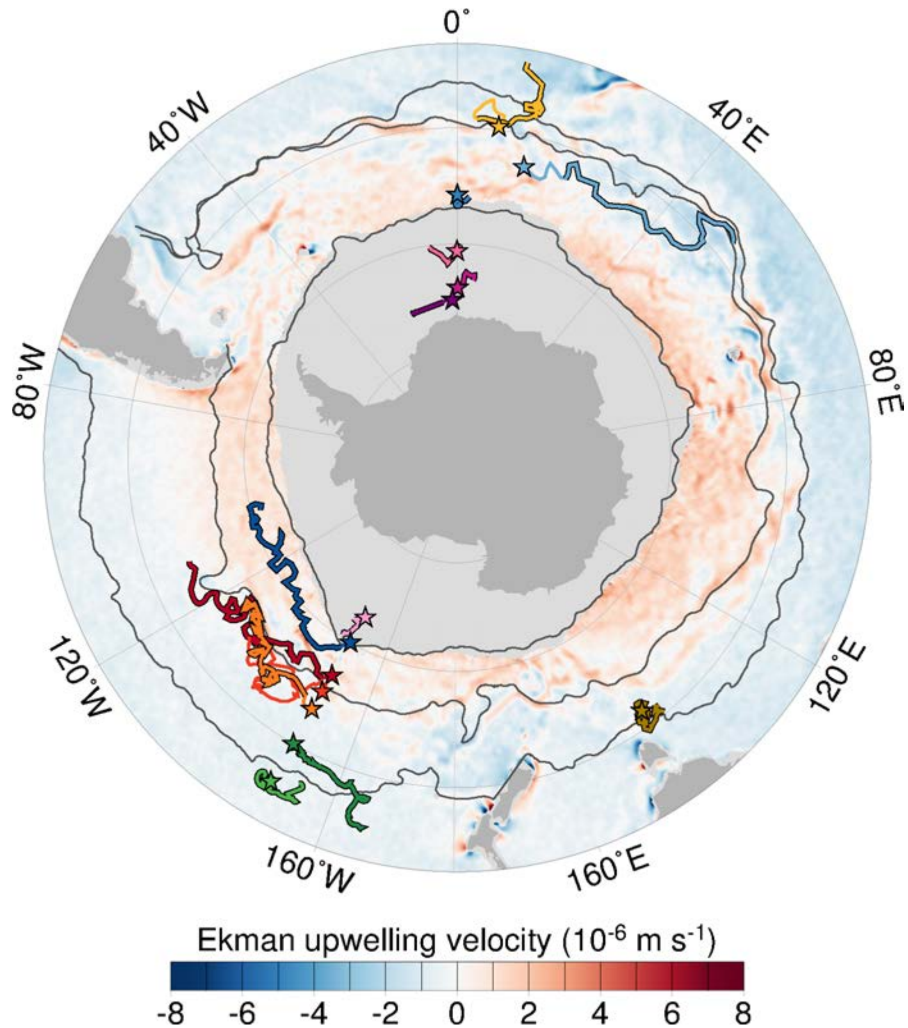
As of July 22, 2016

SOCCOM floats we will discuss (14)

Four zones are defined by the fronts:

- Subtropical Zone (STZ)
- Subantarctic Zone (SAZ)
- Antarctic Circumpolar Current Zone (ACCZ)
- Seasonal Ice Zone (SIZ)

Ekman velocity is from QuikSCAT 1999-2009 winds (Risien and Chelton 2011).



SOCCOM floats we will discuss (14)

Four zones are defined by the fronts:

- Subtropical Zone (STZ)
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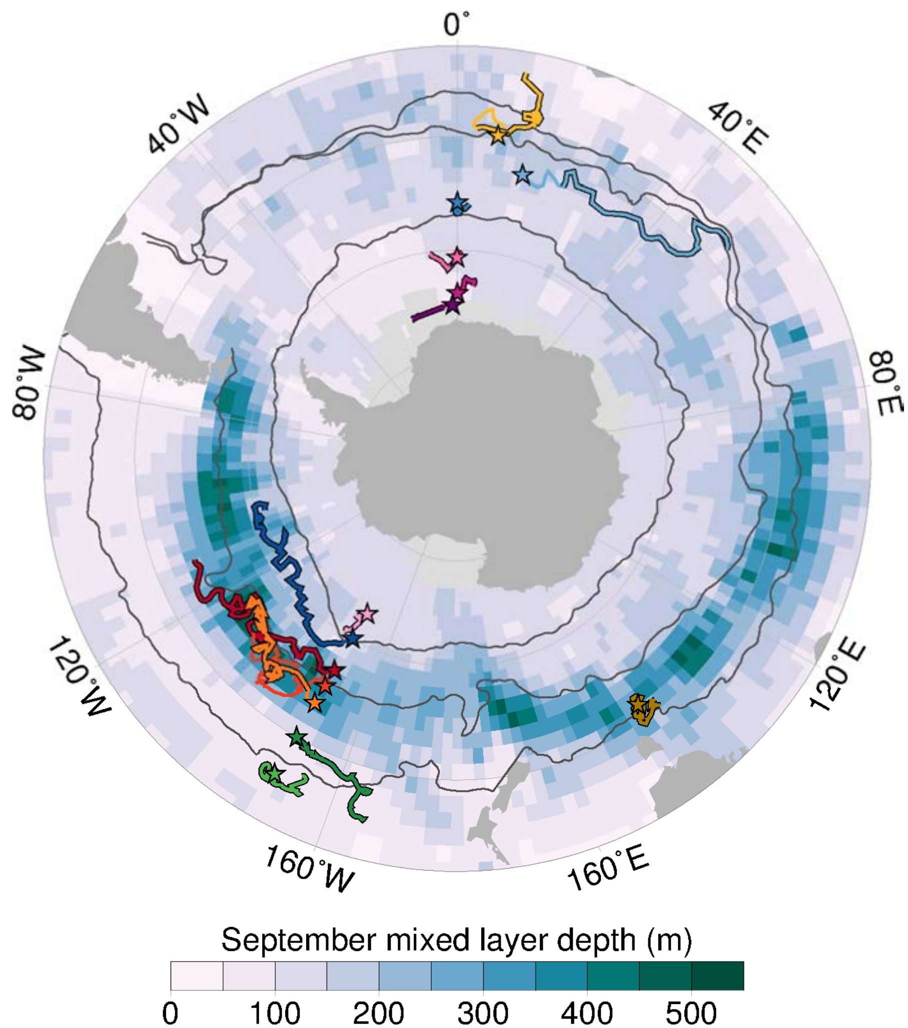
- Antarctic Circumpolar Current Zone (ACCZ)
- Seasonal Ice Zone (SIZ)

MLDs from the de Boyer-Montégut et al. (2004) climatology.



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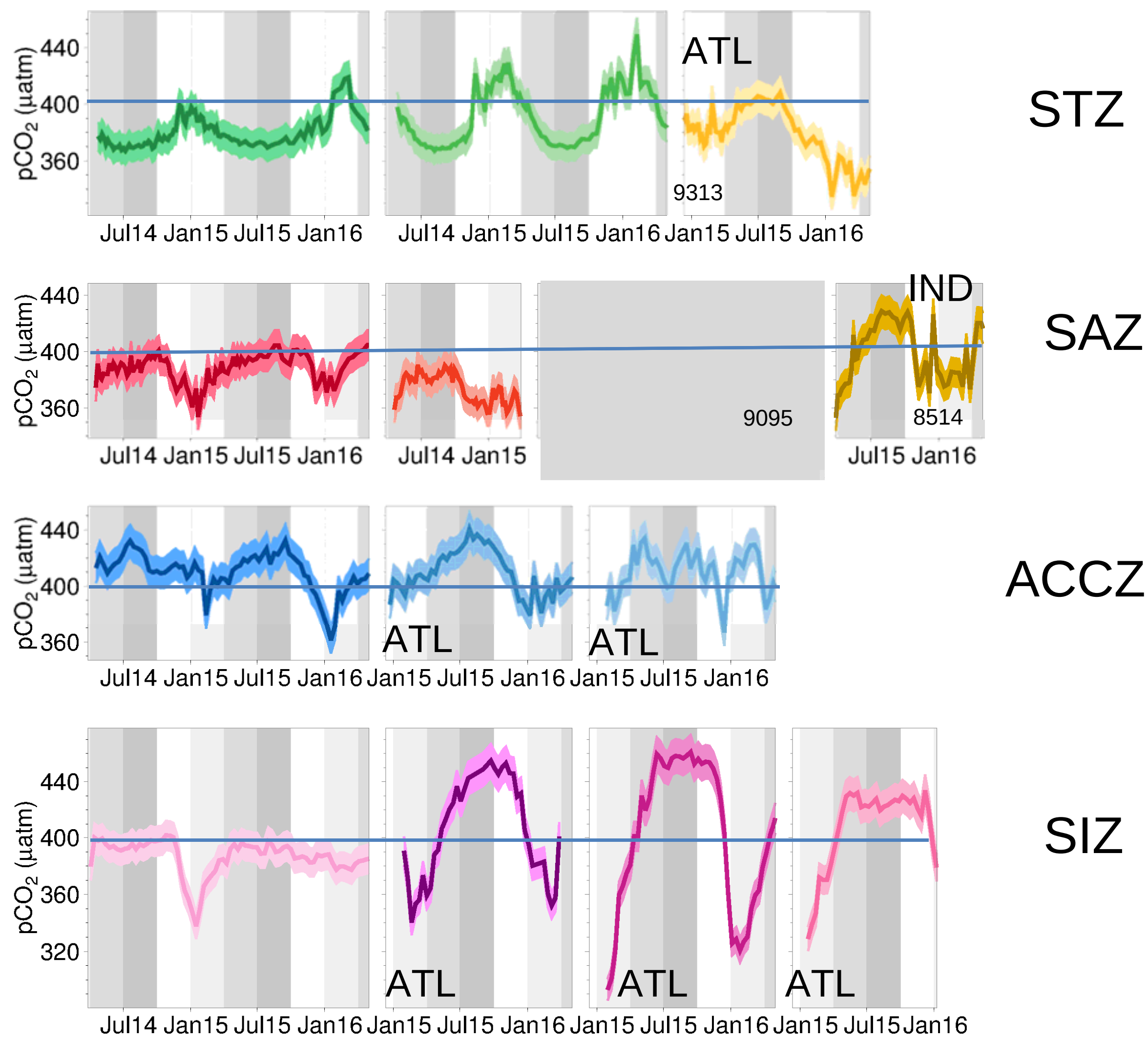
   B. ΔpCO_2
   C. CO_2 flux

III. Hypotheses
   A. Methodology is wrong
   B. Previous estimates are wrong
   C. Recent years are anomalous

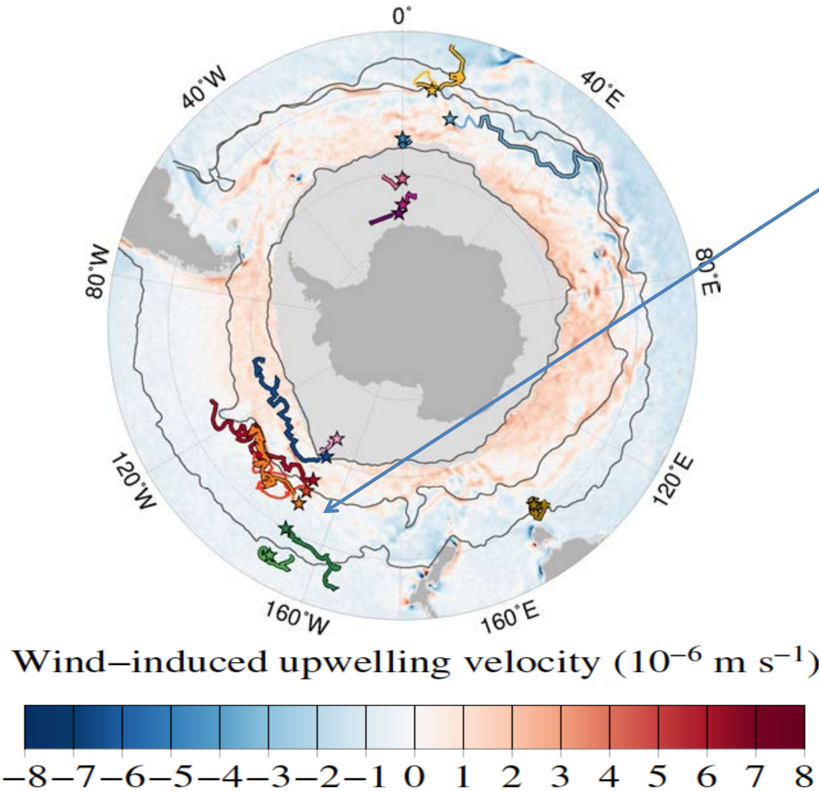
Conclusion: CO_2 flux to atmosphere
>> than previous estimates

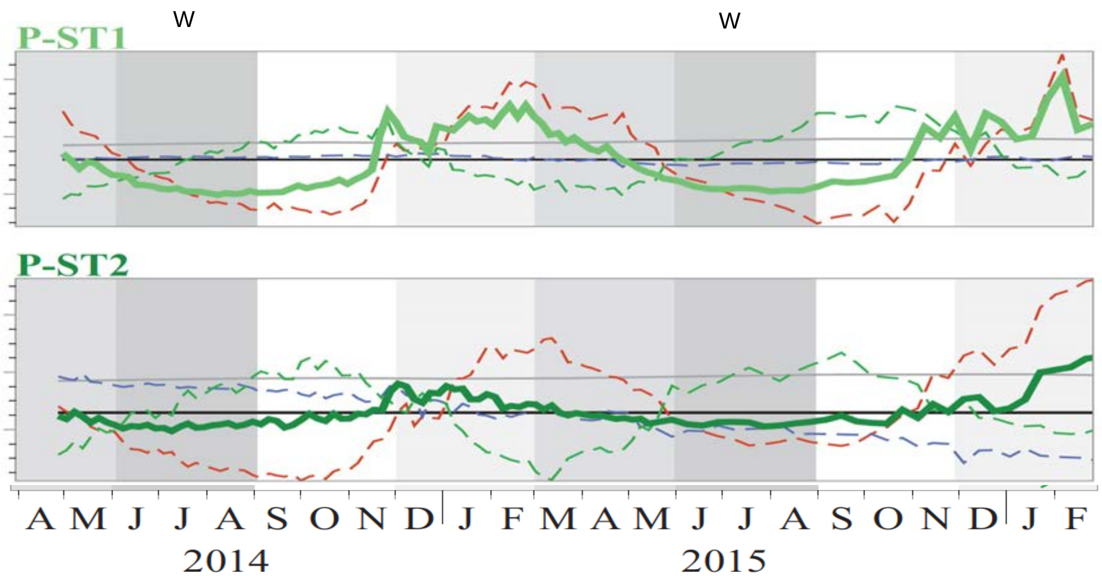
pCO_2 from float pH & MLR alkalinity

- All floats are in the Pacific unless labeled otherwise
- Dark gray bar is winter
- Unusual floats:
  - **Float 9313** (yellow) from Atlantic STZ crosses front
  - **Float 9095** (grayed out) from Pacific SAZ: *p*H sensor had uncharacteristically large drift. Left out of subsequent analyses.
  - **Float 8514** (gold) from Indian Ocean is in an active eddy region

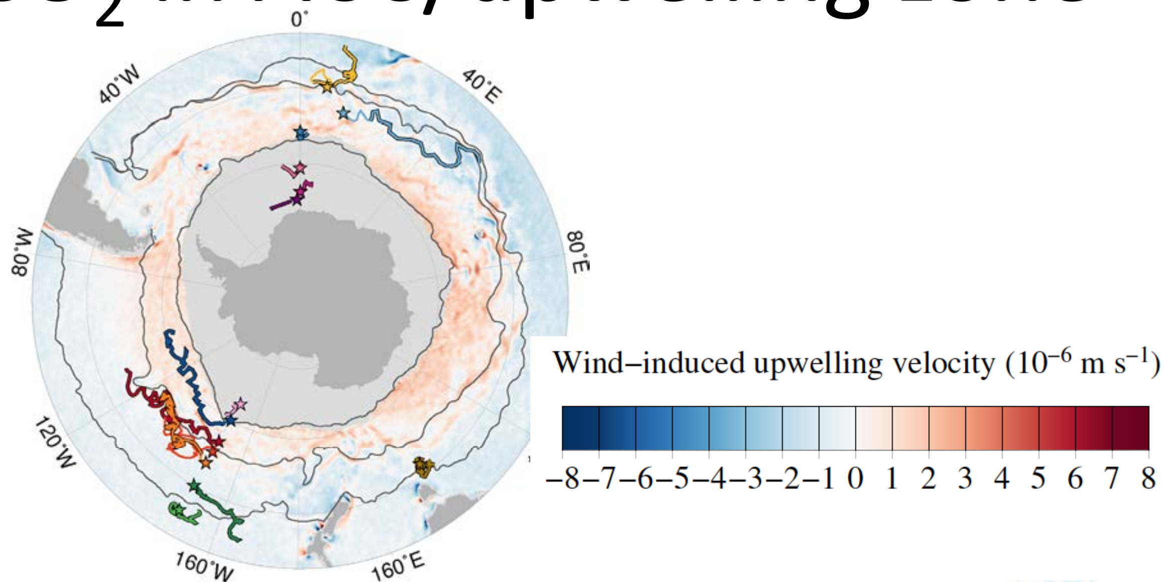


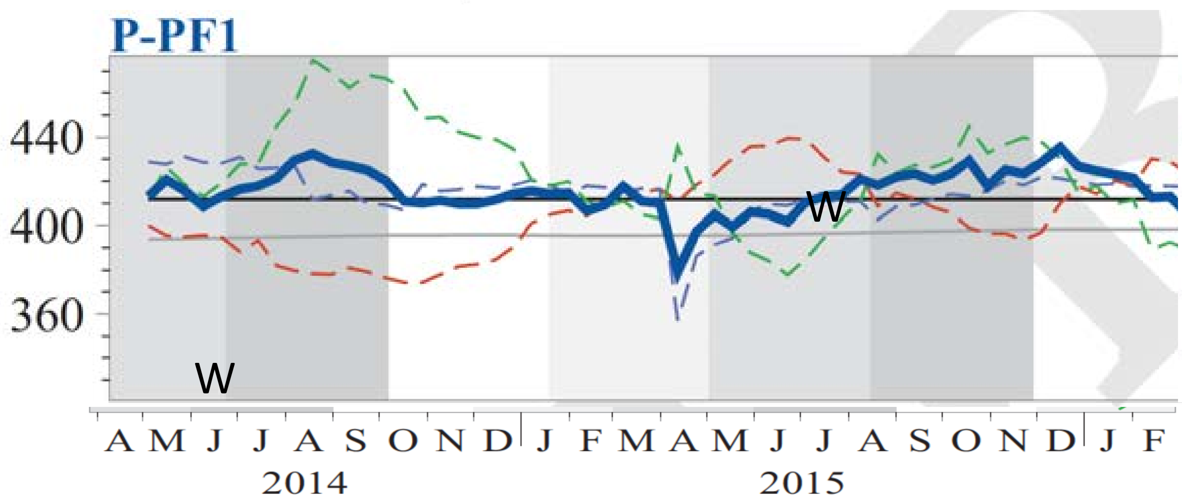
pCO_2 in subtropical gyre (Pacific only)

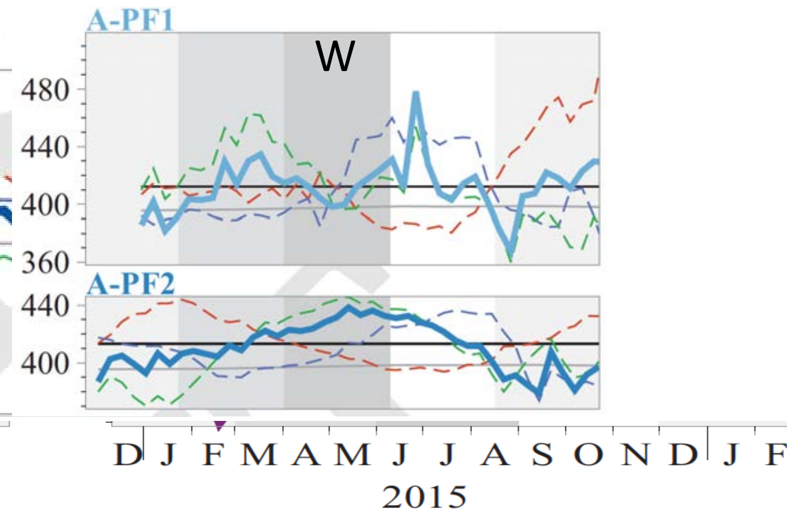




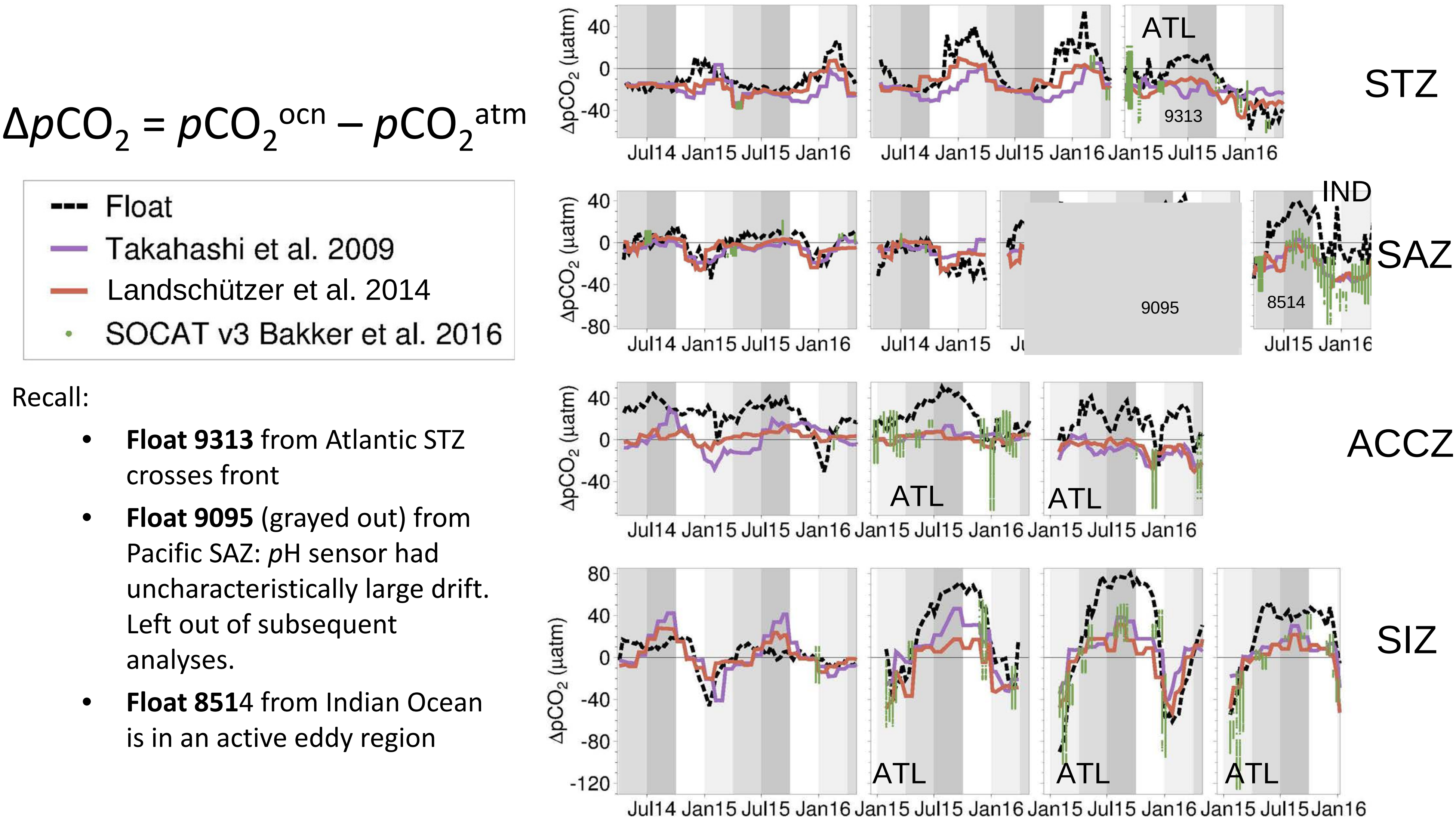
pCO_2 in ACC/upwelling zone







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

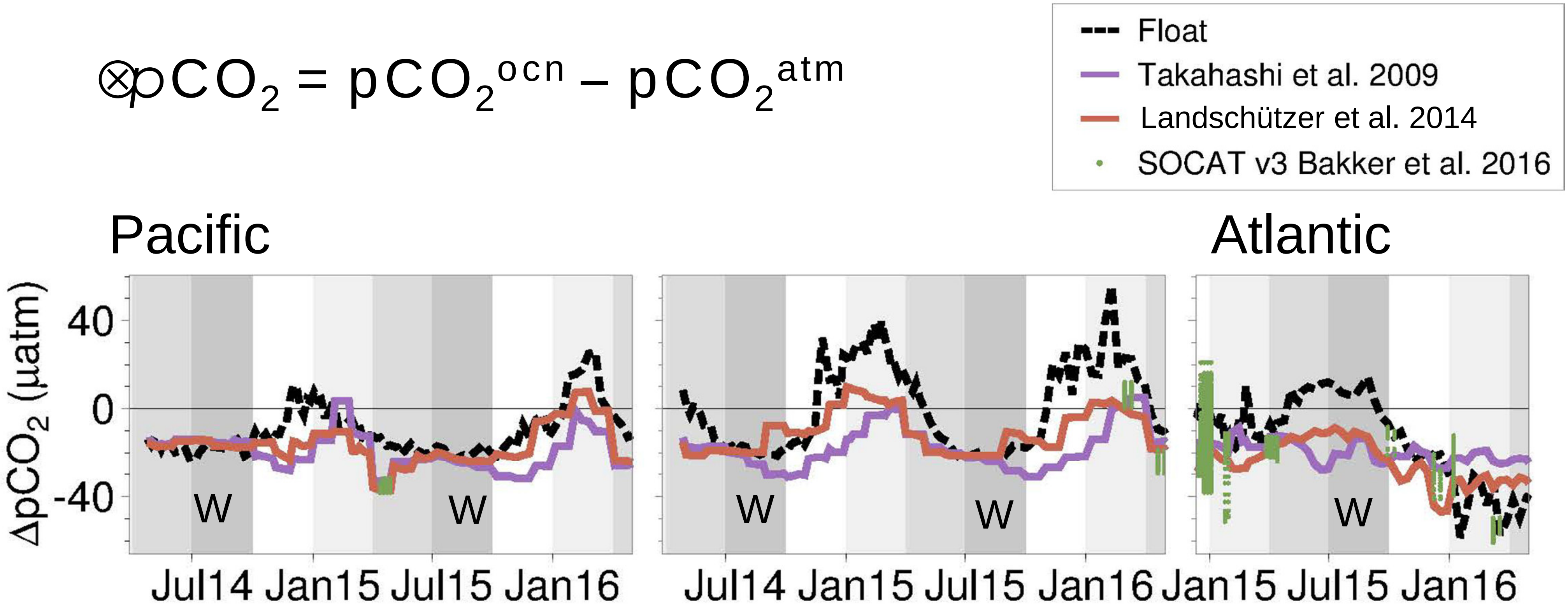


Recall:

- **Float 9313** from Atlantic STZ crosses front
- **Float 9095** (grayed out) from Pacific SAZ: *p*H sensor had uncharacteristically large drift. Left out of subsequent analyses.
- **Float 8514** from Indian Ocean is in an active eddy region

ΔpCO_2 in STZ

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

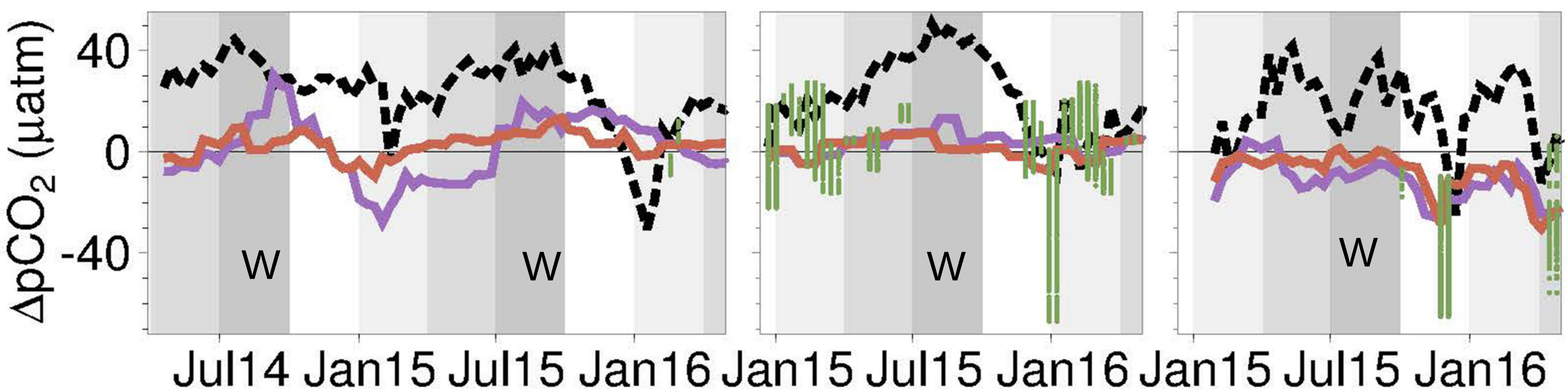


ΔpCO_2 in ACC zone

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

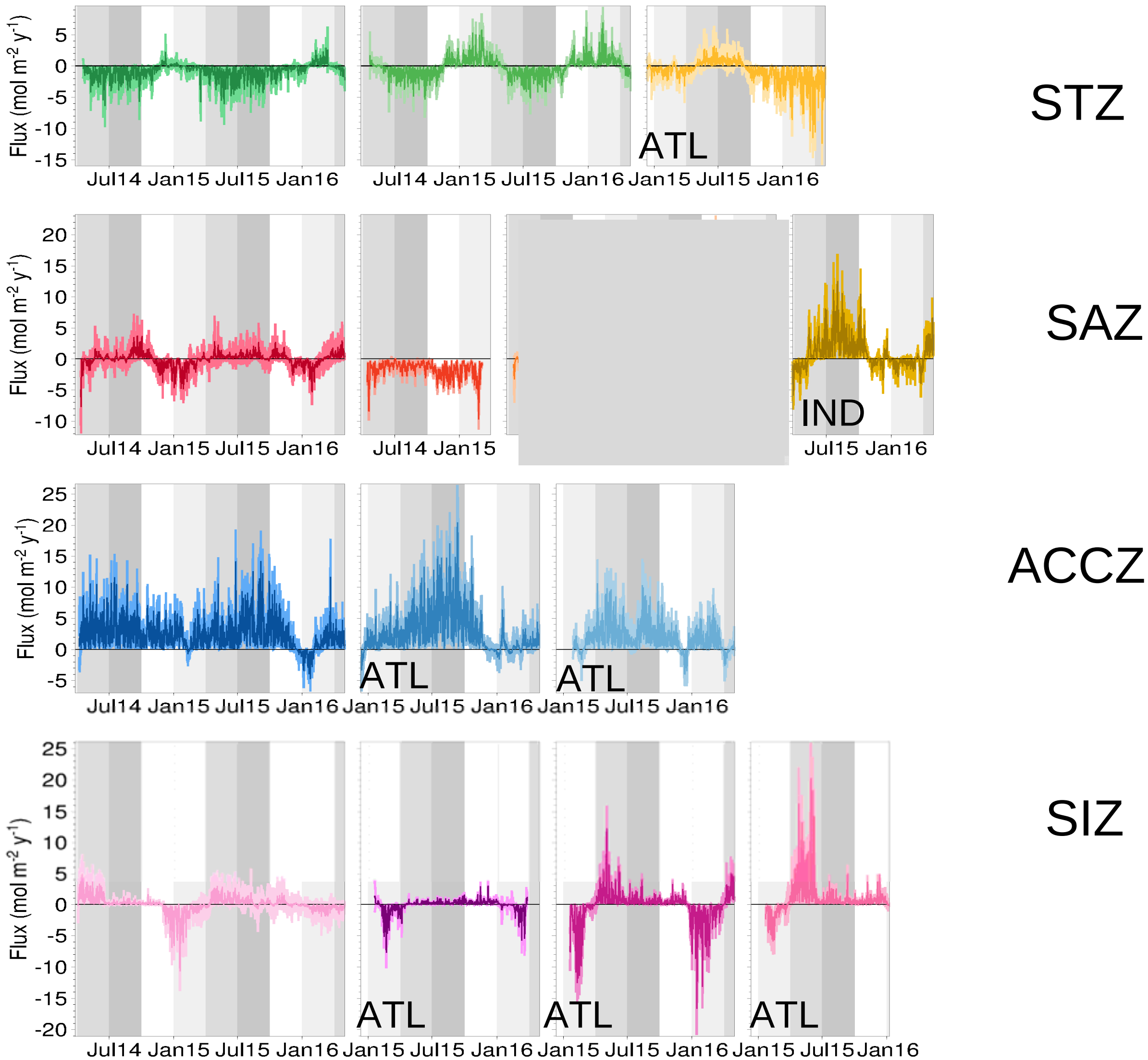
Pacific

Atlantic



Sea-air CO_2 flux

- Flux equation: $F = k_g * K_0 * \Delta pCO_2$
- k_g = wind speed squared dependent gas transfer velocity from Wanninkhof (2014)
- Winds are 6-hourly ERA-interim
- K_0 = solubility constant
- $\Delta pCO_2 = pCO_2^{ocn} - pCO_2^{atm}$ with pCO_2^{atm} from Cape Grim monthly data



Annual net CO_2 flux to atmosphere

- Units: mol m^{-2} y^{-1}
- Covers region south of 35°S
- Positive indicates net outgassing, negative is uptake.
- Bold numbers are statistically different from zero
- .
- For scale, the average anthropogenic CO_2 uptake is 0.46 ± 0.14 mol m^{-2} y^{-1}
- **Note:** problematic float 9095 (in parentheses) is not included in mean

Zone	Float	Flux May14-May15	Flux May15-May16	Mean mol m^{-2} y^{-1}
STZ	P-ST1	-0.09 ± 0.5	-0.2 ± 0.5	**-0.6 ± 0.3**
	P-ST2	**-0.8 ± 0.5**	**-0.8 ± 0.5**	
	A-SA1	-	**-1.0 ± 0.7**	
SAZ	P-SA1	(**1.3 ± 0.7**)	(**2.9 ± 0.8**)	0.3 ± 0.5
	P-SA3	-0.2 ± 0.8	0.1 ± 0.7	
	I-SA1	-	**1.1 ± 0.7**	
ACCZ	P-ACC1	**2.6 ± 0.8**	**2.2 ± 0.8**	**2.4 ± 0.5**
	A-ACC1	-	**1.9 ± 0.8**	
	A-ACC2	-	**3.1 ± 1.0**	
SIZ	P-SI1	-0.2 ± 0.5	0.1 ± 0.7	0.2 ± 0.3
	A-SI1	-	**0.9 ± 0.4**	
	A-SI2	-	-0.006 ± 0.2	
	A-SI3	-	0.03 ± 0.16	

Annual net oceanic CO_2 uptake

- Units Pg C y^{-1}
- Covers region south of 35°S
- Positive indicates net outgassing, negative is uptake.
- Dashes indicate fluxes less than 0.03

Zone	SOCCOM floats	Takahashi et. al. (2009)	Landschützer et al. (2014)
STZ	-0.2 ± 0.1	-0.4	-0.5
SAZ	0.1 ± 0.1	-0.2	-0.2
ACCZ	0.8 ± 0.2	-0.2	-0.1
SIZ	--	--	--
TOTAL	0.7 ± 0.2	-0.8	-0.8

Annual net oceanic CO_2 uptake

- Units Pg C y^{-1}
- Covers region south of 35°S
- Positive indicates net outgassing, negative is uptake.
- Dashes indicate fluxes less than 0.03

- Final column is calculated from Landschützer et al. (2015) by subsampling where the float profiles are, then integrating, averaging, and multiplying by the same areas.

Zone	SOCCOM floats	Landschützer et al. (2014)	Subsampled as SOCCOM
STZ	-0.2 ± 0.1	-0.5	-0.3
SAZ	0.1 ± 0.1	-0.2	-0.2
ACCZ	0.8 ± 0.2	-0.1	--
SIZ	--	--	--
TOTA	0.7 ± 0.2	-0.8	-0.5

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.

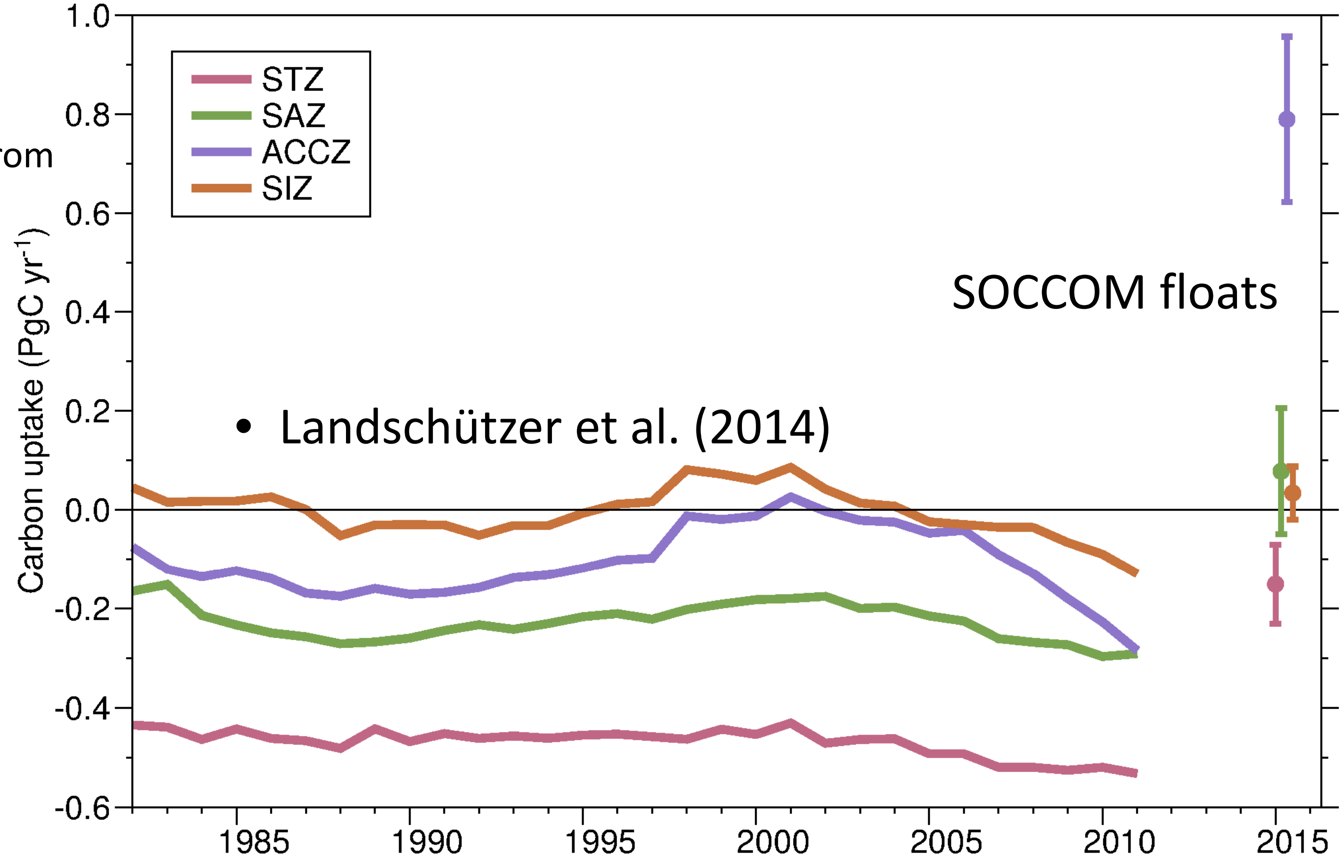
- Hypothesis 2: Climatological baseline should have a stronger Southern Ocean source
  - Our results support this.
  - However, there must be a larger sink elsewhere to compensate the Southern Ocean source and maintain large ocean carbon sink

- Hypothesis 3: 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 1.5 Pg C y^{-1} anomaly we find

Time history of CO_2 fluxes ($PgC\ y^{-1}$)

- The 1982 to 2011 time history is from Landschützer et al. (2014)
- Positive is degassing
- The individual points are from SOCCOM floats

- STZ = subtropical zone
- SAZ = subantarctic zone
- ACC = ACC upwelling zone
- SIZ = seasonal ice covered zone



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  - Method for converting pH to pCO_2 looks good.
- Hypothesis 2: Climatological baseline should have a stronger Southern Ocean source
  - Our results support this (if there were data in winter, the baseline would shift up)
  - However, there must be a larger sink elsewhere to compensate the Southern Ocean source and maintain large ocean carbon sink
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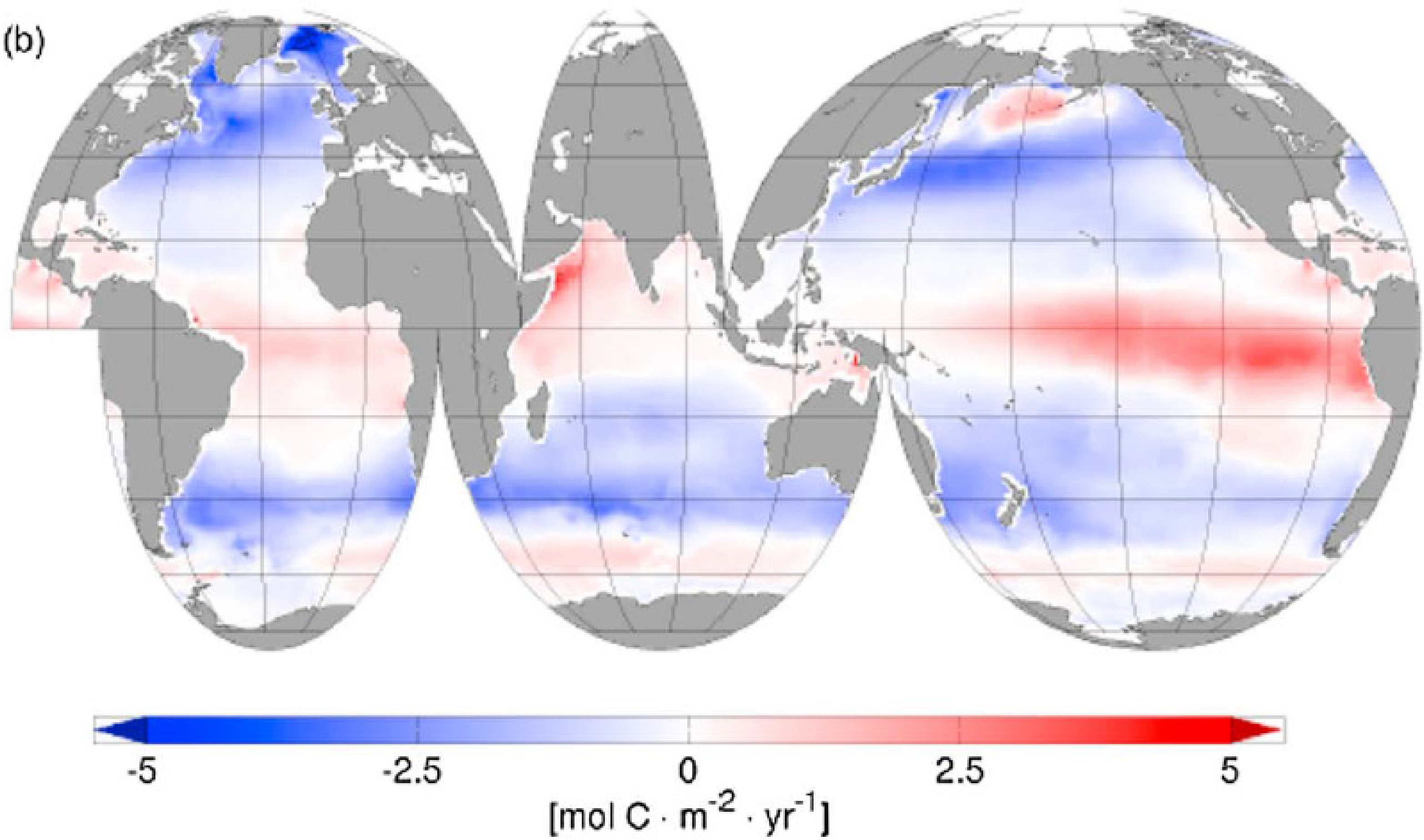
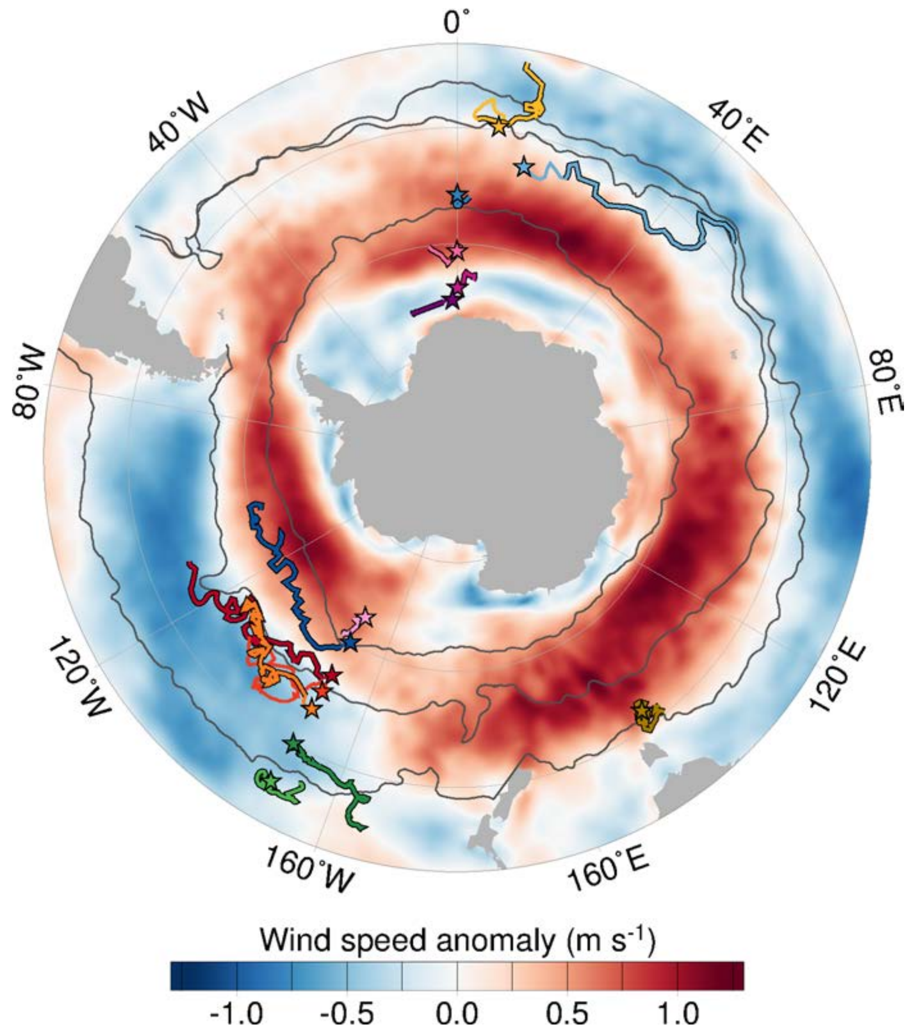
Landschützer et al. (2014) climatological air-sea flux estimate for 1998-2011



Wind speed anomaly (April 2014 to 2016)

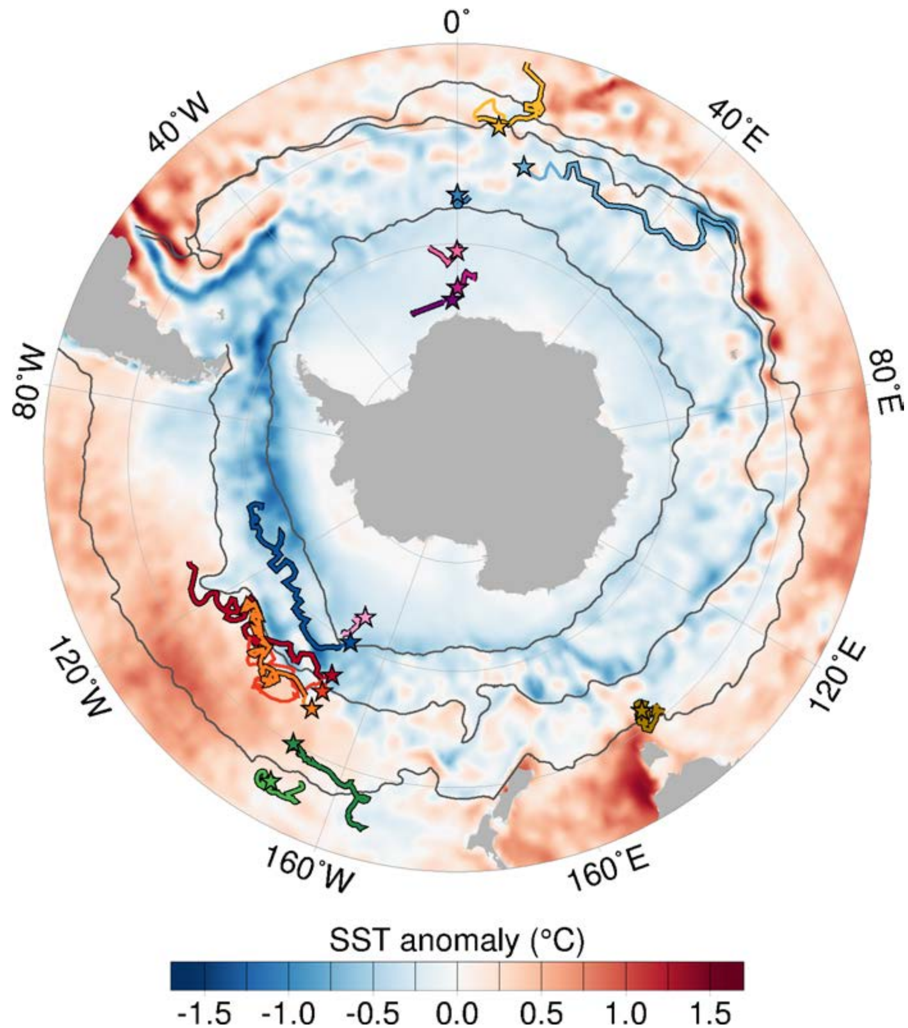
- The ACC region has increased winds which would imply more upwelling & thus outgassing.
- ERA-interim wind fields, calculated as the mean over Apr 2014 - Apr 2016 minus the mean over Apr 1979 - Apr 2016



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



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Future work

- SOCCOM
  - Keep adding floats!
  - SOSE
- Test consistency with other constraints
  - Atmospheric observations & atmospheric inversion models
  - Interior ocean DIC observations & ocean inverse, SOSE, etc.
  - How would addition of float data affect the Landschützer neural network map?

What is driving changes? – ML budget

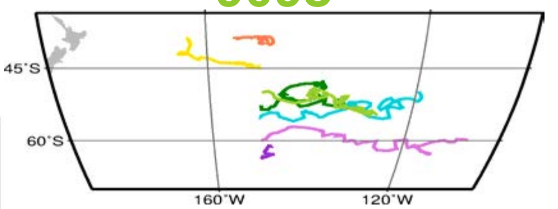
Change in C_T^{ml} =	Estimated from float obs
Entrainment +	Observed *dMLD/dt*, $C_T(z)$
Vertical mixing +	Observed dC_T/dz, assume K_z *(1x10⁻⁴ m s⁻²)*
Air-sea flux +	ECMWF wind speed, observed ΔpCO_2, Wanninkhof 2014 coefficient
Dilution +	ECMWF Evaporation, Precipitation
Advection +	AVISO $\mathbf{u}_{geo}$, ECMWF wind $\mathbf{u}_{ek}$, AVHRR SST, linear regression with GLODAPv2
Biology	Residual optimized with nitrate budget

Mixed layer budget

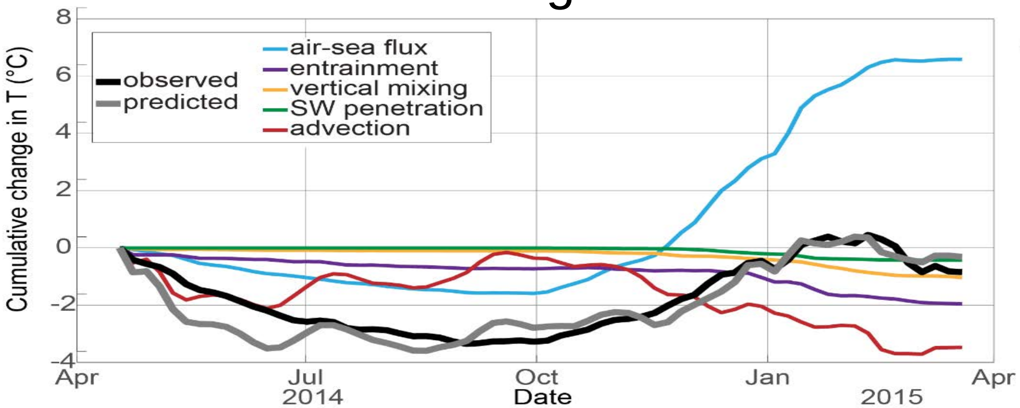
C:N = 6.0

NCP = 2.3 molC m^{-2} m^{-y}

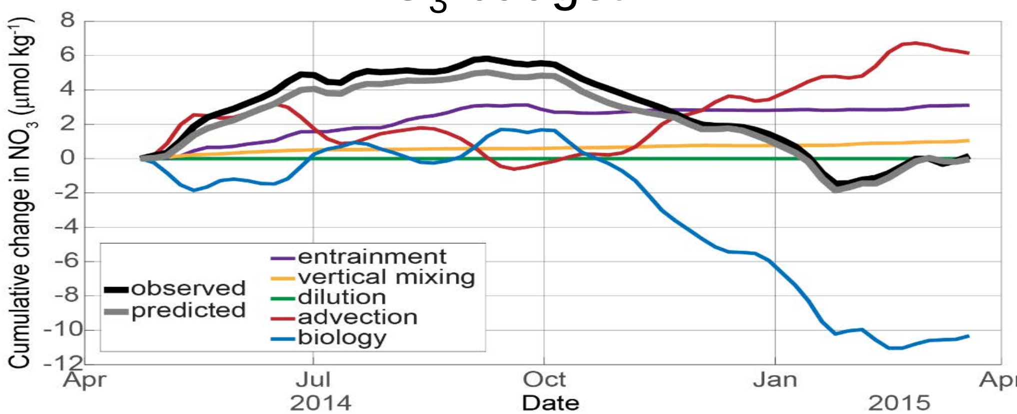
9095



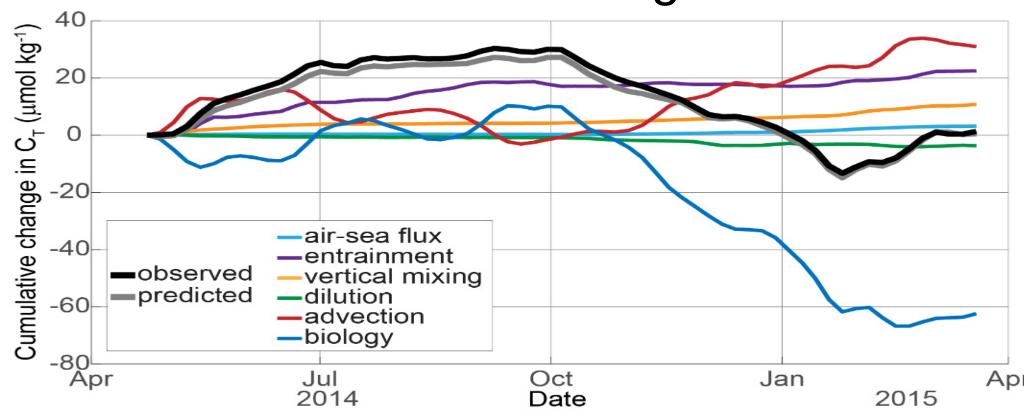
T budget



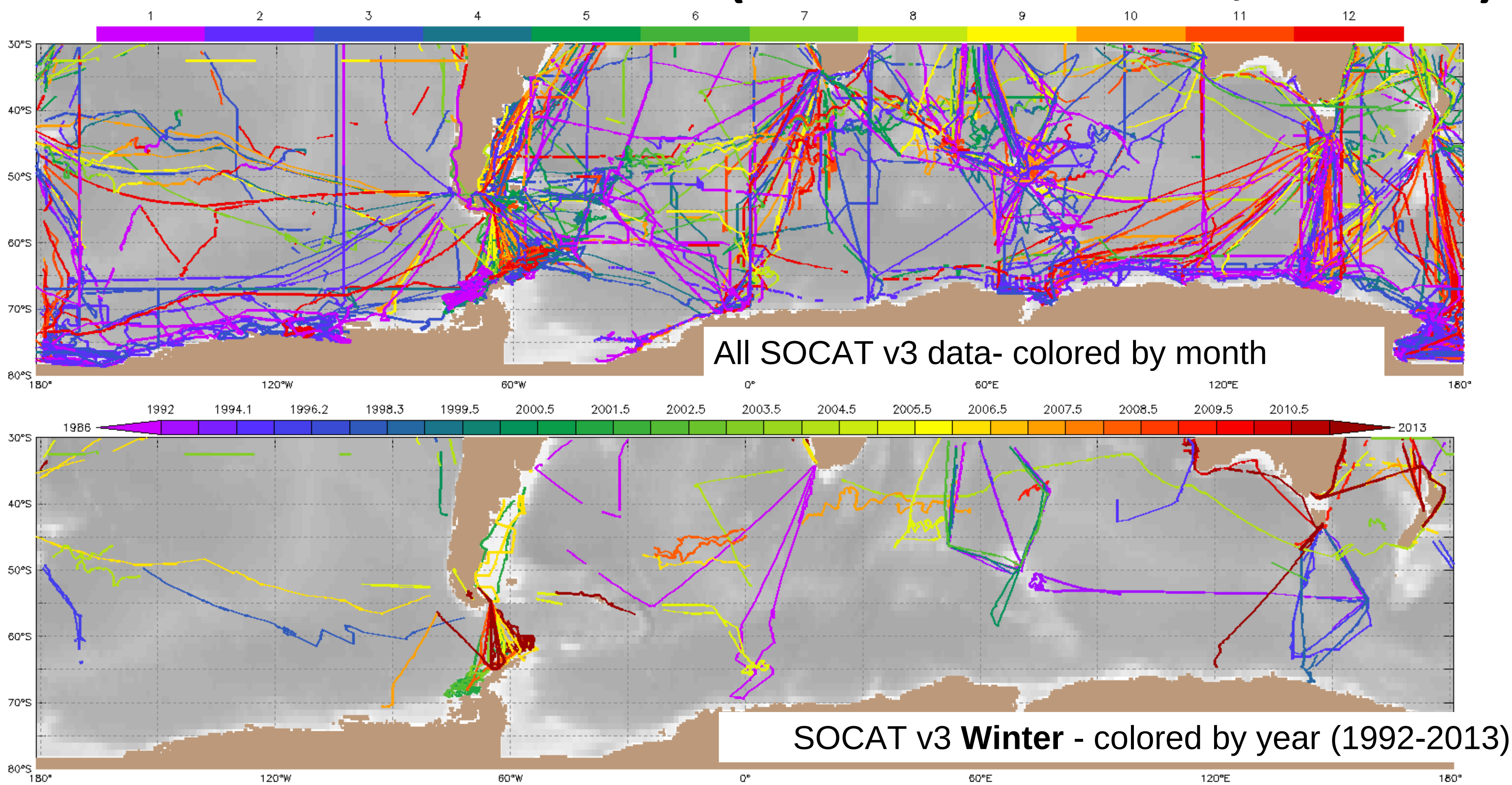
NO_3 budget



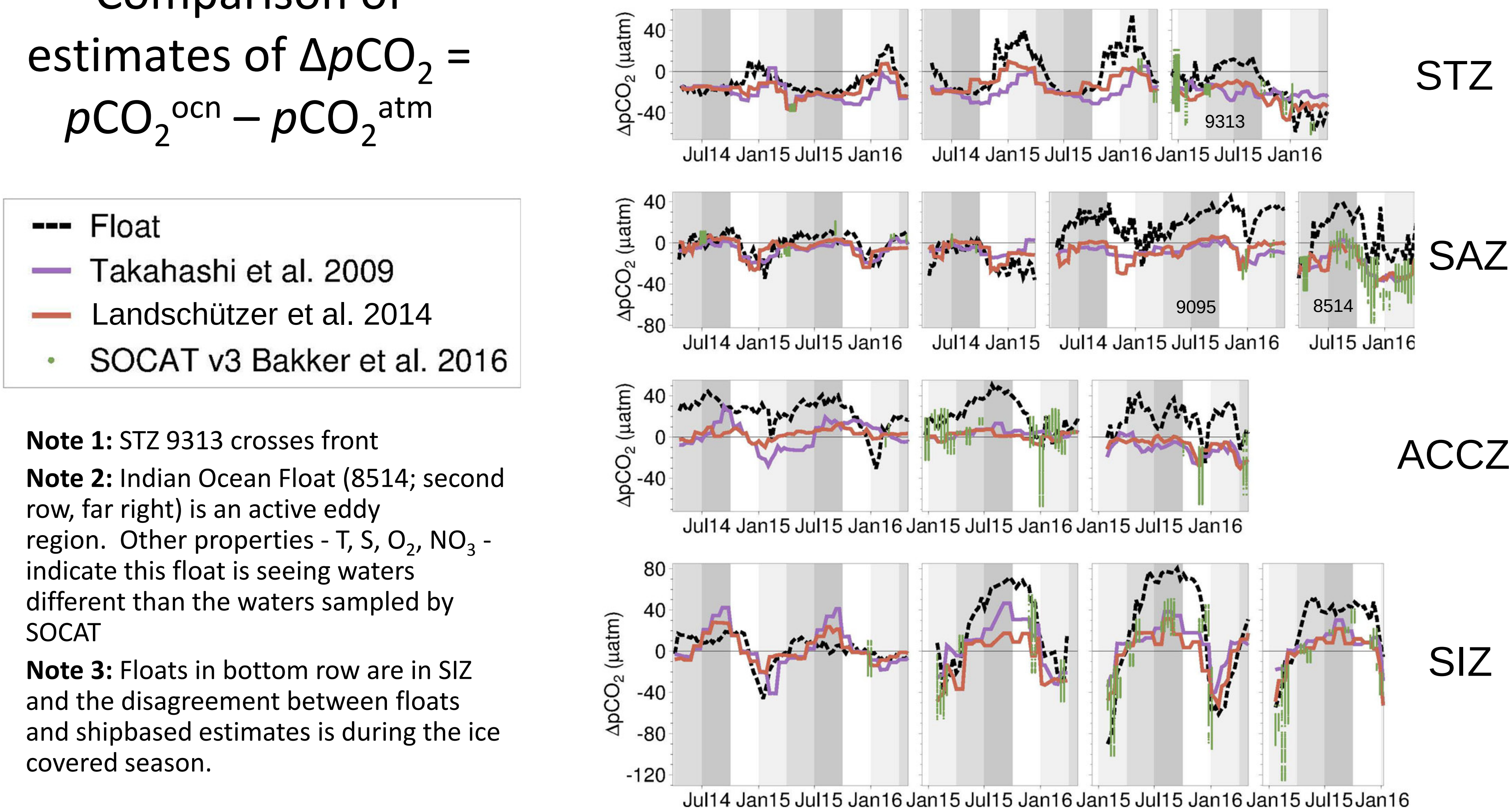
Carbon budget



SOCAT v. 3 data (Bakker et al., 2016)



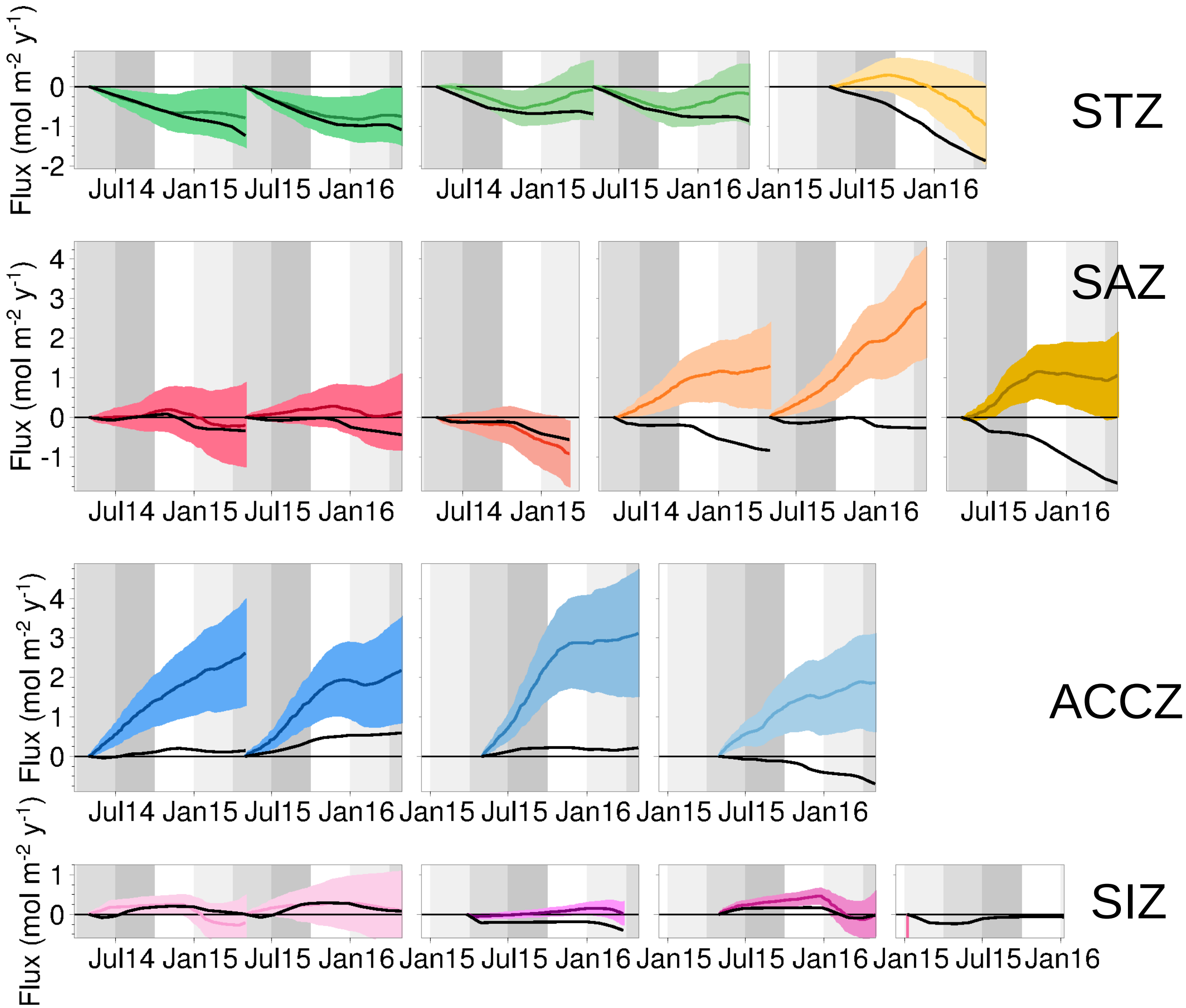
Comparison of estimates of $\Delta pCO_2 = pCO_2^{ocn} - pCO_2^{atm}$



- **Note 1:** STZ 9313 crosses front
- **Note 2:** Indian Ocean Float (8514; second row, far right) is an active eddy region. Other properties - T, S, O_2, NO_3 - indicate this float is seeing waters different than the waters sampled by SOCAT
- **Note 3:** Floats in bottom row are in SIZ and the disagreement between floats and shipbased estimates is during the ice covered season.

Cumulative annual air-sea CO_2 flux comparison

- STZ
  - Agreement between estimates is good except float 9313 (yellow) which crosses front
  - Accumulates carbon when water is cold (winter & spring)
- ACCZ
  - Agreement between estimates is bad.
  - Floats show ocean losing carbon, mostly when water is cold
- SAZ and SIZ



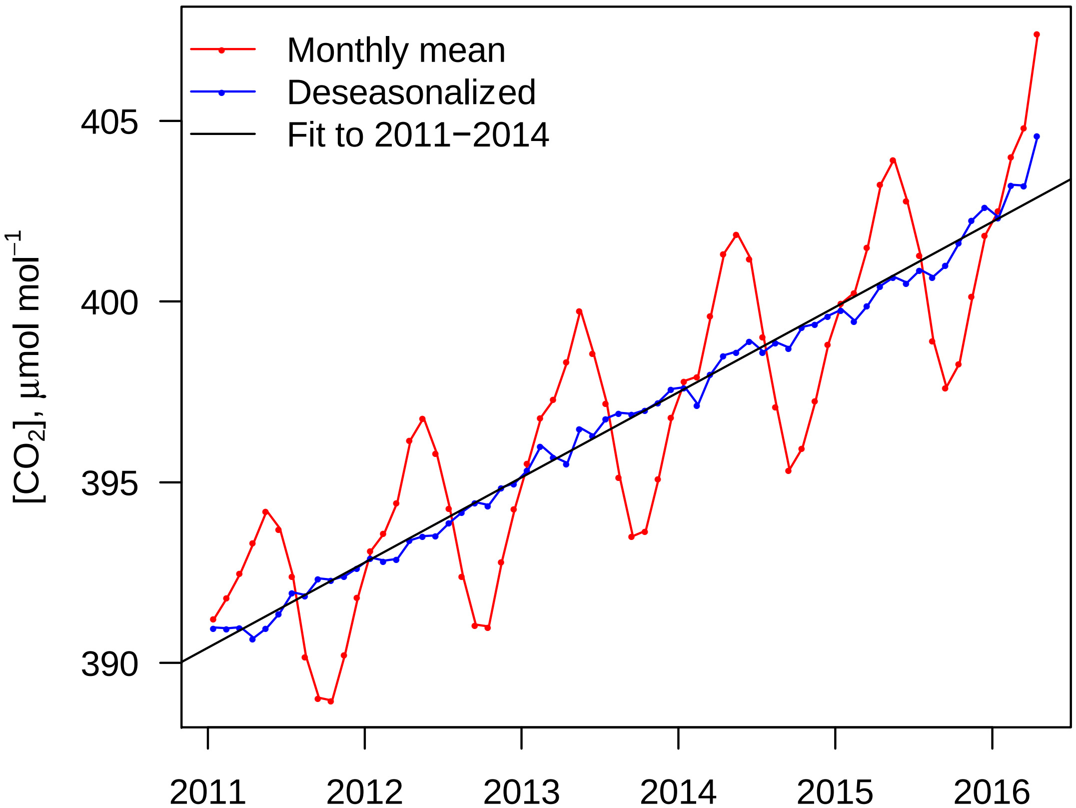
Climate is anomalous

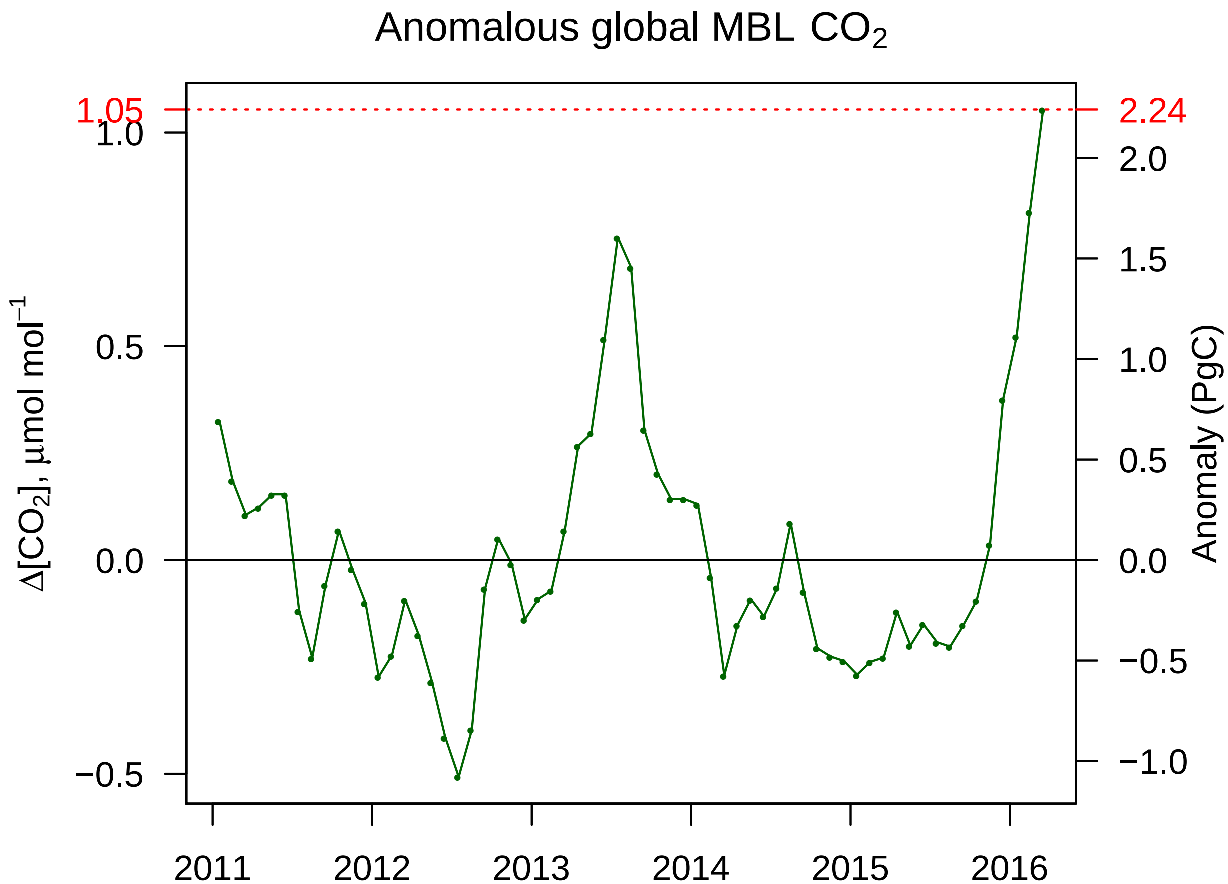
Gray et al., in preparation

But where is all the extra carbon going?

Jacobson (pers. comm.)

Monthly mean CO_2 at Mauna Loa

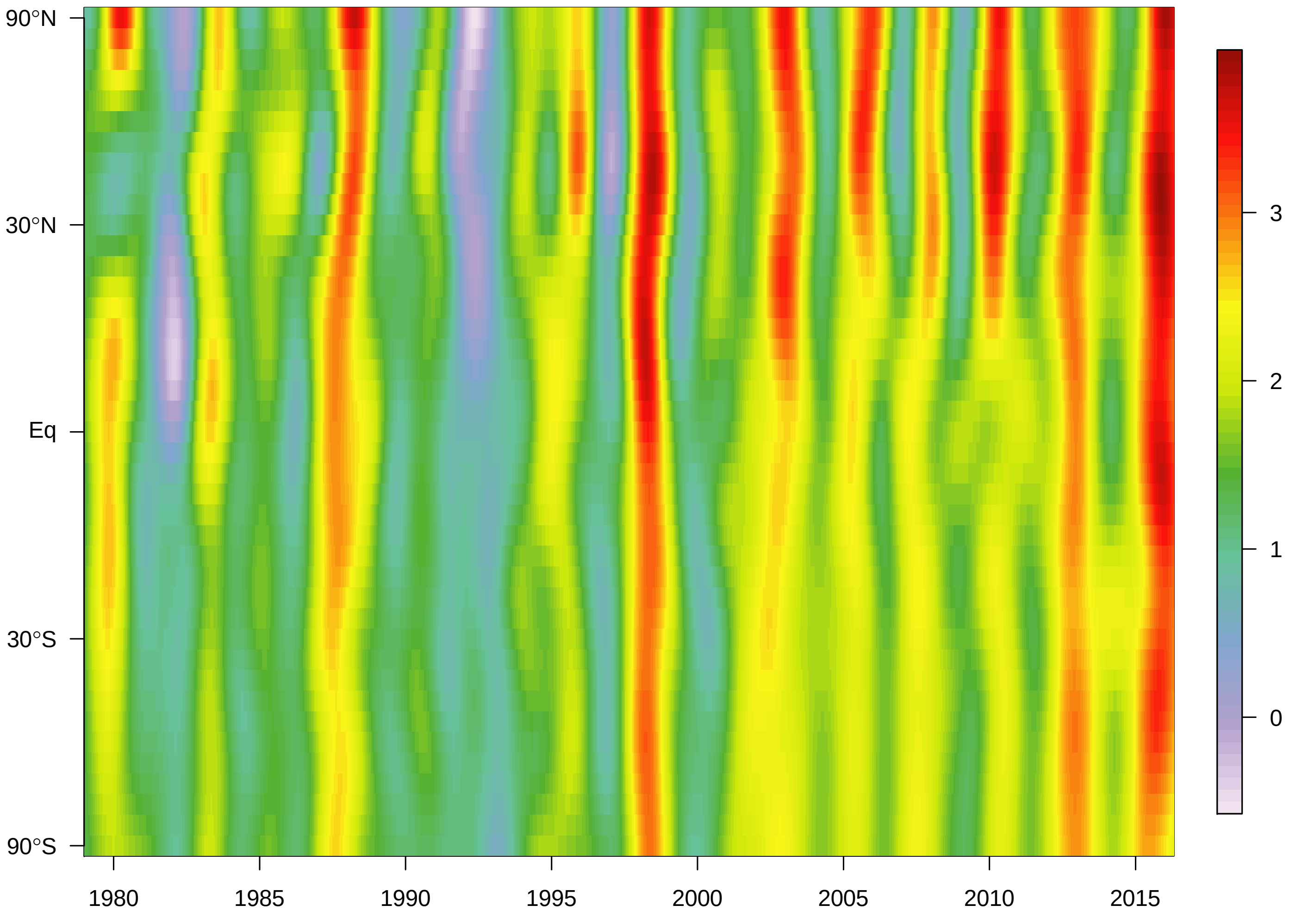


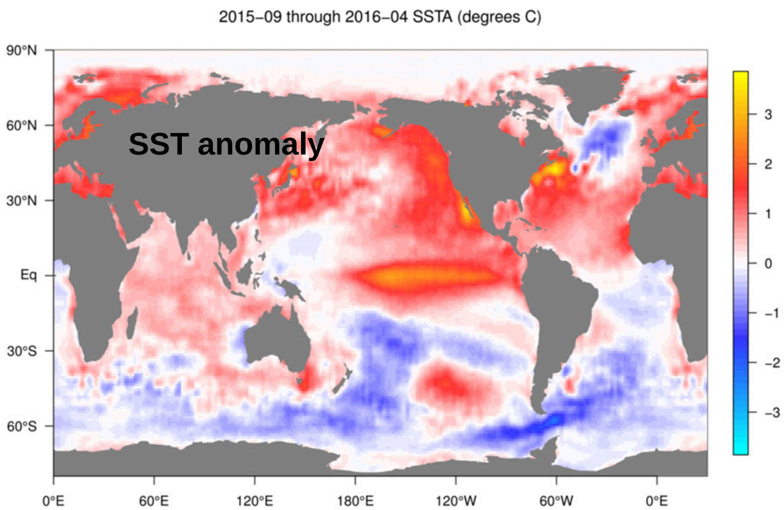


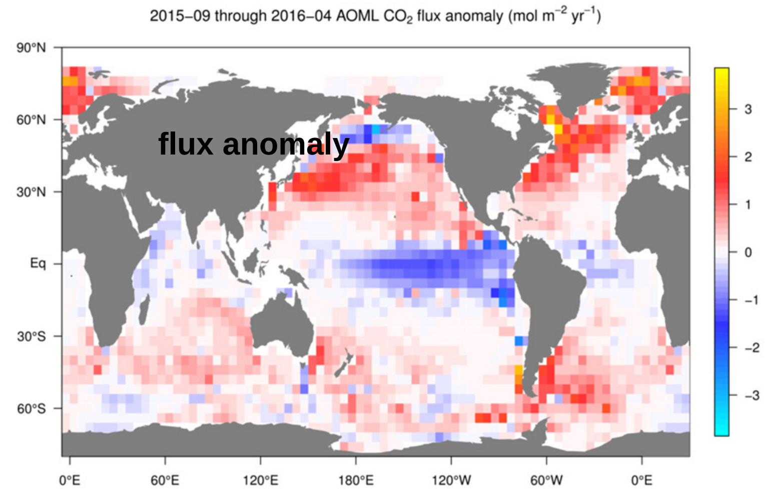
Anomalous global MBL CO_2
1.05
1.0
0.5
0.0
−0.5
2.24
2.0
1.5
1.0
0.5
0.0
−0.5
−1.0
2011
2012
2013
2014
2015
2016
$\Delta[CO_2]$, µmol mol^{-1}
Anomaly (PgC)

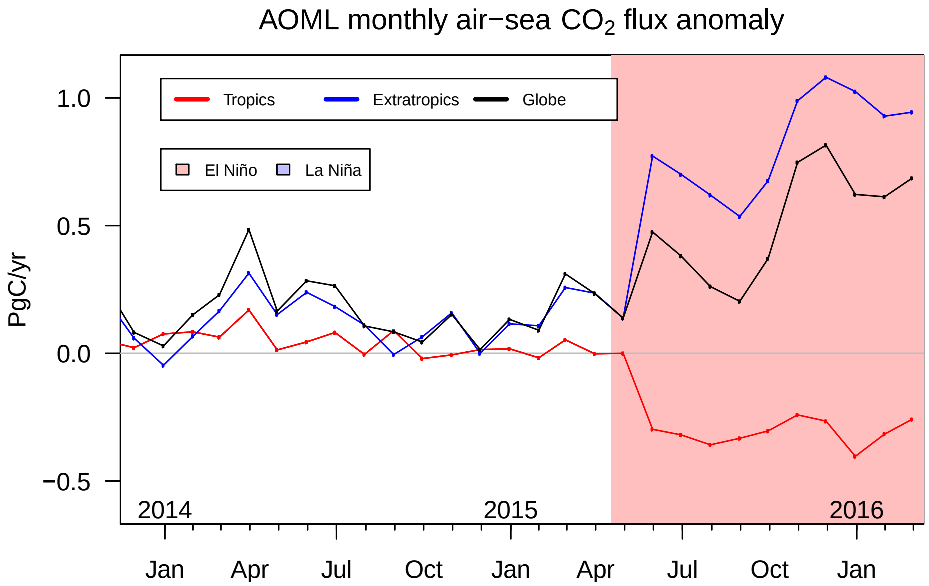
Note timing

CO_2 zonal−mean growth rate (µmol yr^{-1})




2015–09 through 2016–04 SSTA (degrees C)
SST anomaly
90°N
60°N
30°N
Eq
30°S
60°S
0°E
60°E
120°E
180°E
120°W
60°W
0°E
3
2
1
0
−1
−2
−3


2015–09 through 2016–04 AOML CO2 flux anomaly (mol m−2 yr−1)
flux anomaly
90°N
60°N
30°N
Eq
30°S
60°S
0°E
60°E
120°E
180°E
120°W
60°W
0°E
3
2
1
0
−1
−2
−3


AOML monthly air−sea CO2 flux anomaly
Tropics
Extratropics
Globe
El Niño
La Niña
PgC/yr
1.0
0.5
0.0
−0.5
2014
2015
2016
Jan
Apr
Jul
Oct
Jan
Apr
Jul
Oct
Jan

El Niño-driven anomalous CO_2 (PgC)

	1997-98	2015-16
Atmosphere	1.9 to 2.2[1]	2.2 to 3.6[1]
Oceans	-0.5[2] to -0.7[3]	(-0.3 to) 0.4[2]

1. This work
2. NOAA AOML monthly pCO_2
3. Chavez *et al.* (Science, 1999)

Time history of CO_2 fluxes (PgC y^{-1})

- The 1982 to 2011 time history is from Landschützer et al. (2014)
- The individual points are from SOCCOM floats

- STZ = subtropical zone
- SAZ = subantarctic zone
- ACC = ACC upwelling zone
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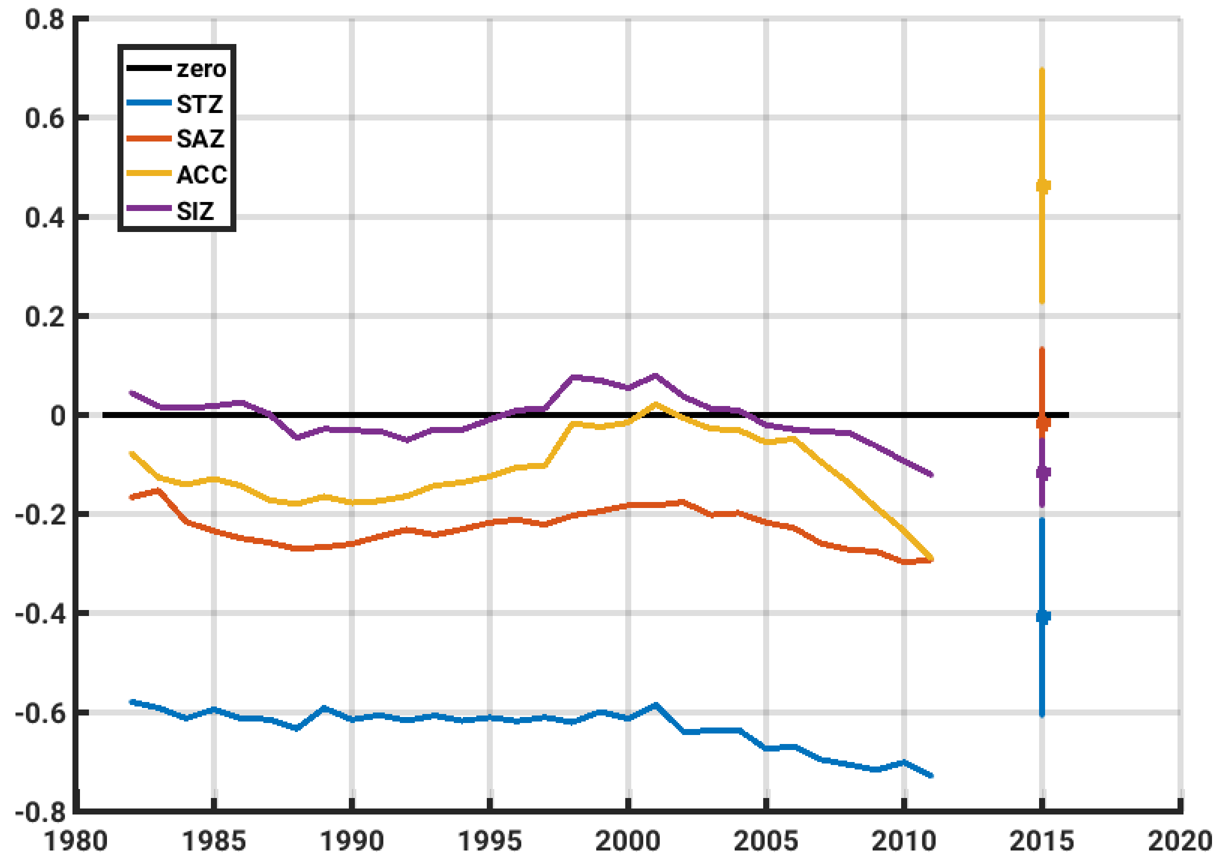
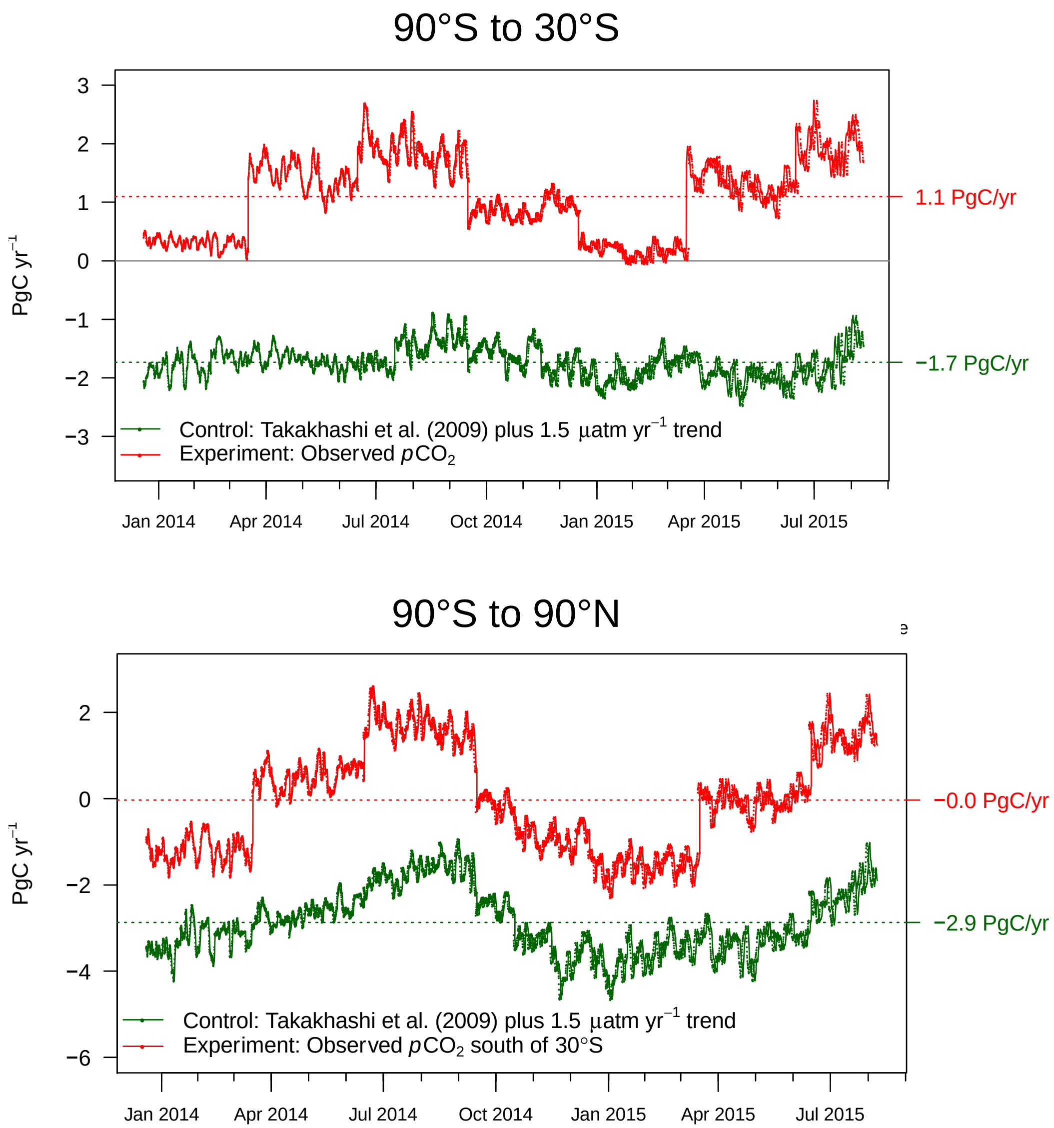


Ocean fluxes calculated by TM5

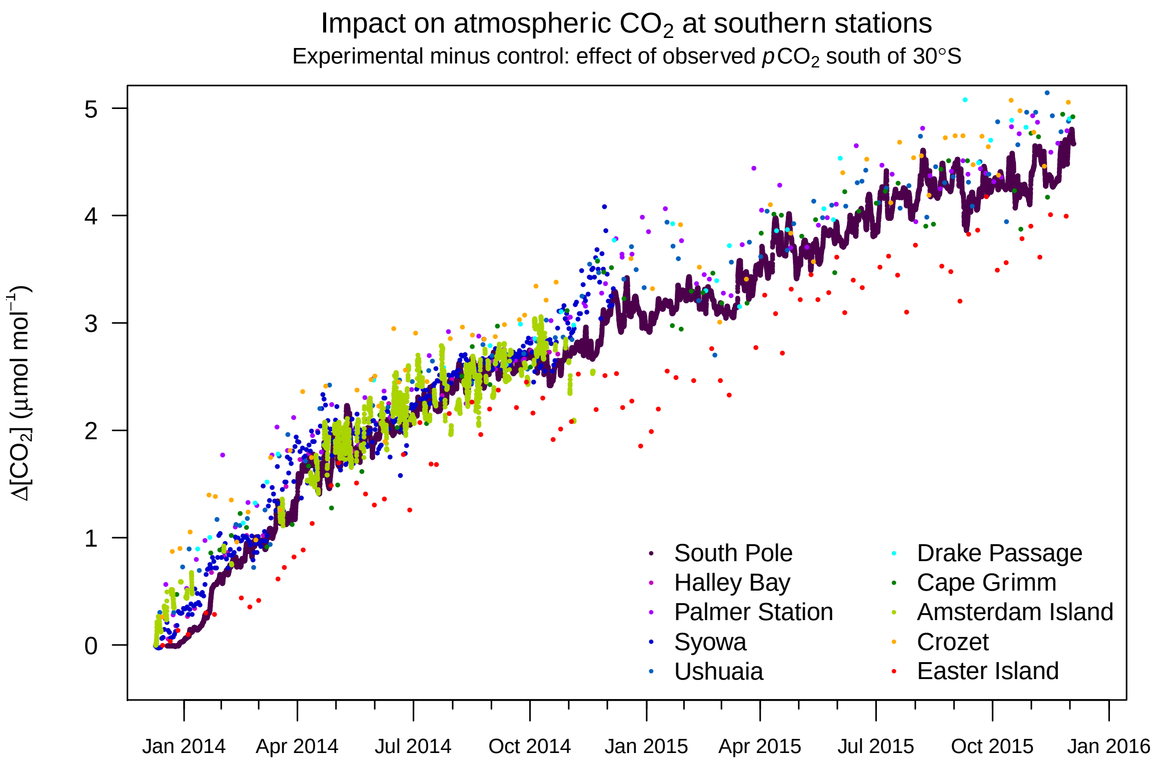
- From Jacobson (pers. comm.)
- These fluxes are "like" priors using TM5 to compute them.
- TM5-4DVar (Transport Model 5 – Four-Dimensional Variational model), is an atmospheric transport model used for CO_2 flux estimation (cf. Basu et al., 2013)
- Gas exchange parameters:
    - solubility and Schmidt No. from WOA09,
    - ERA-interim winds,
    - NOAA marine boundary layer atmospheric pCO_2 with extrapolated trend.
- Numbers on the right-hand axis are the time-mean fluxes



Impact on atmospheric pCO_2 south of 30°S

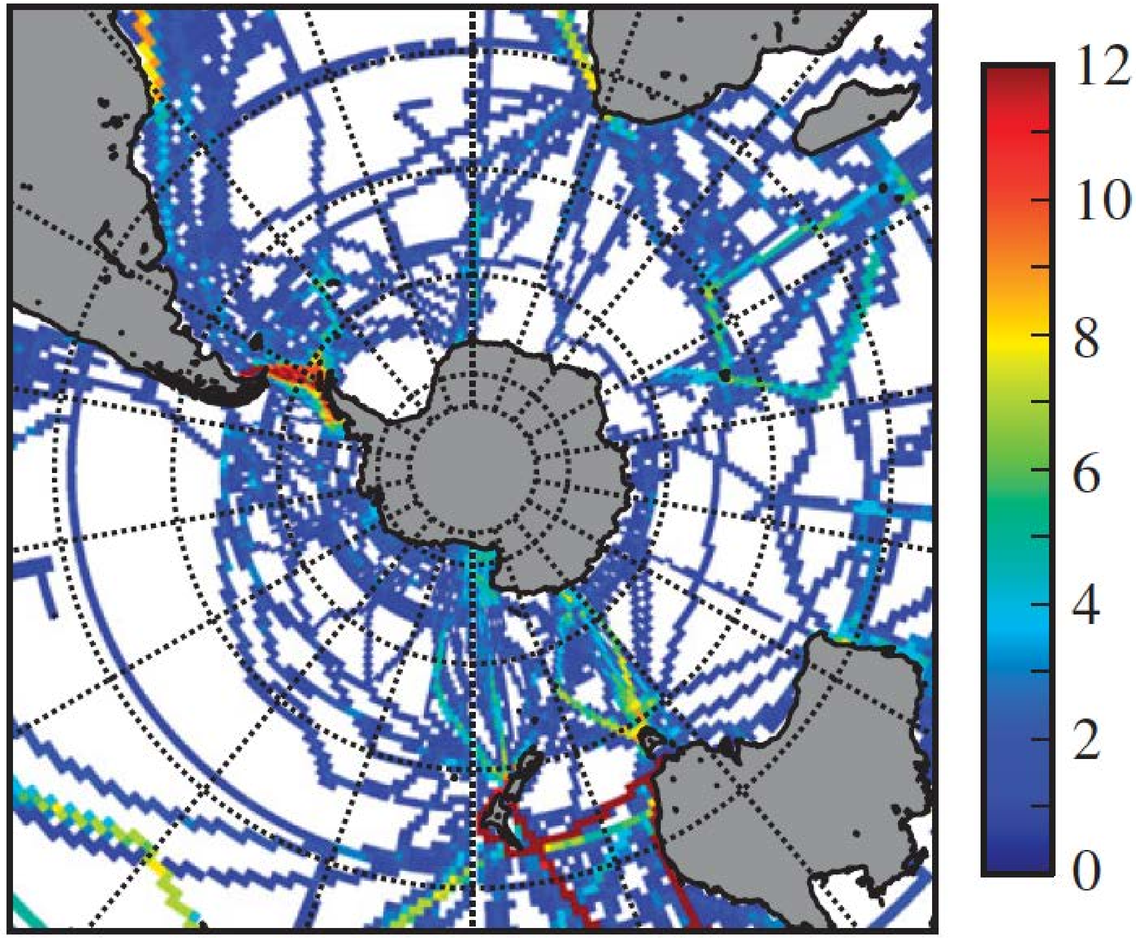
- impact on atmospheric observations of the "experimental" air-sea fluxes in the Southern Ocean.
- The impact is cumulative over time but reaches about 3 ppm after one year.
- No evidence from CarbonTracker that we're missing this large a CO_2 flux difference.

- Jacobson (pers. comm.)



Underway sampling of pCO_2 from ships

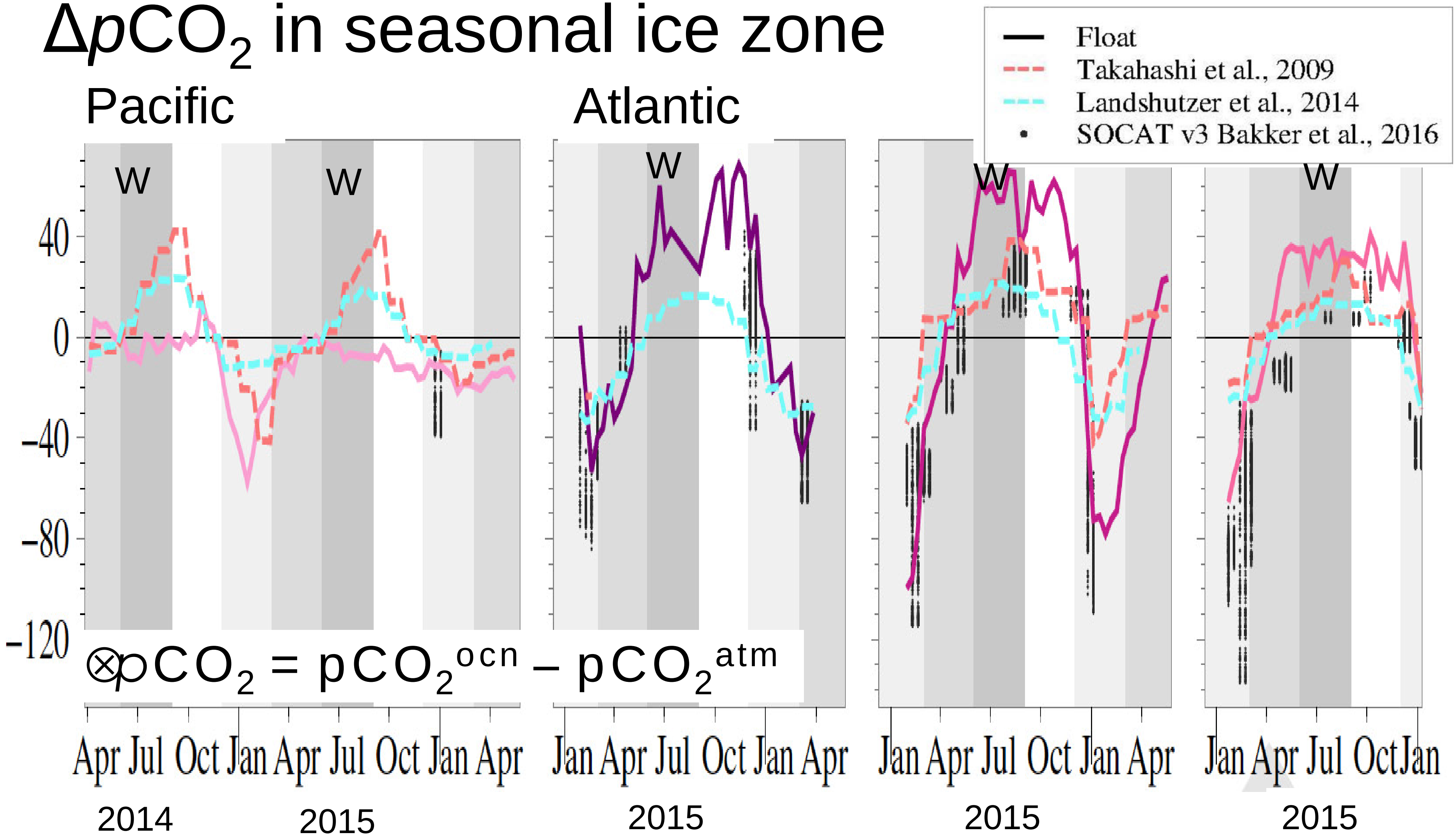
- The color scale shows the months of the year with surface pCO_2 measurements
- Based on all measurements between 1970 to 2011 binned in 1° squares.
- White = no data



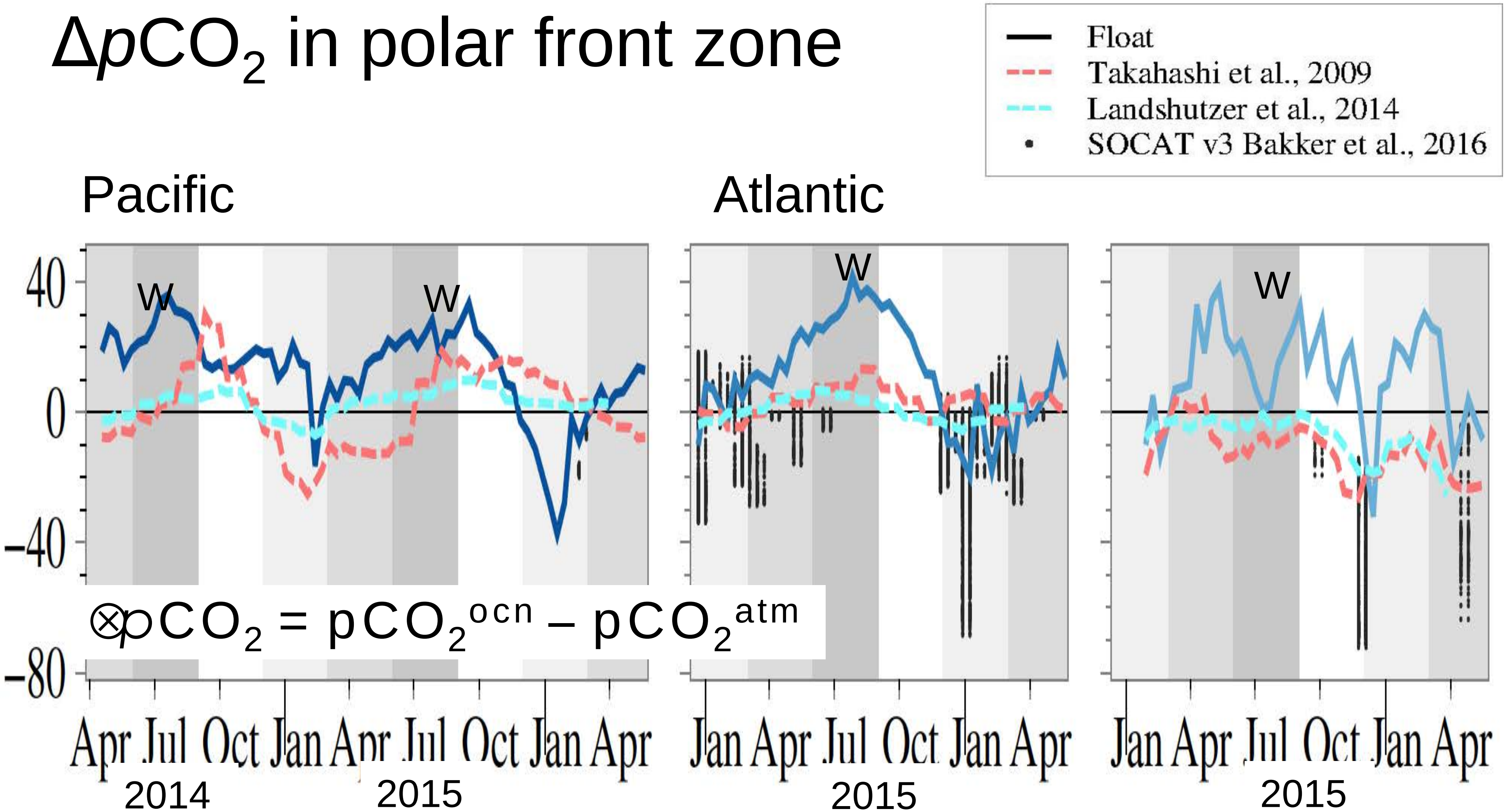
Verification of CO_2 estimation

Williams et al. (in preparation)

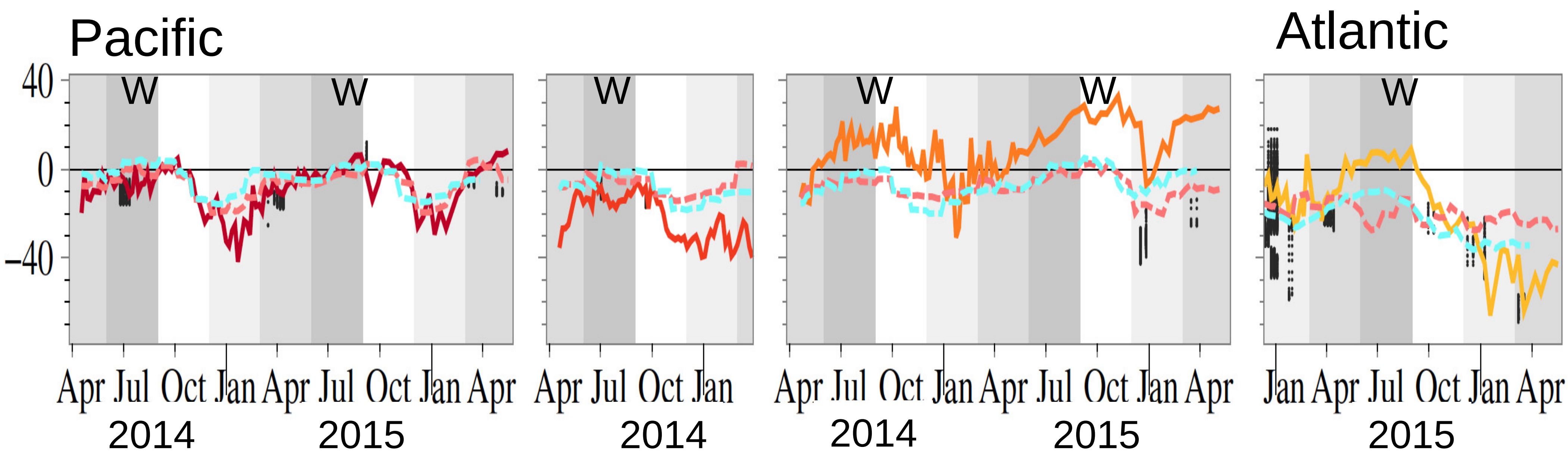
ΔpCO_2 in seasonal ice zone



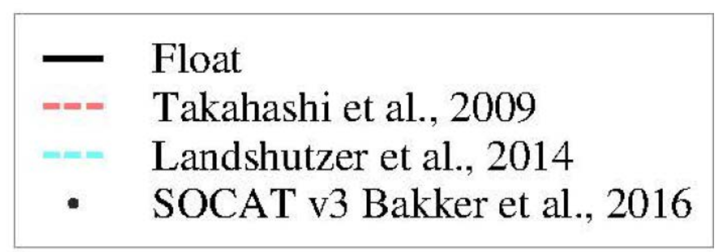
ΔpCO_2 in polar front zone



ΔpCO_2 in subantarctic zone

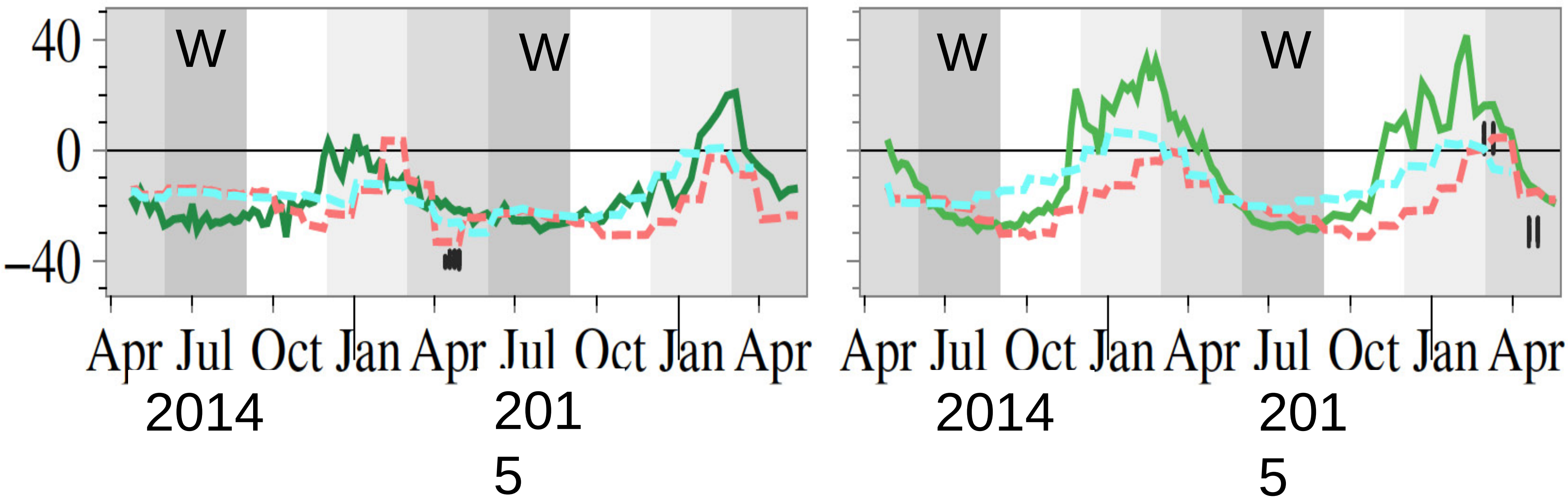


$$\otimes pCO_2 = pCO_2^{ocn} - pCO_2^{atm}$$

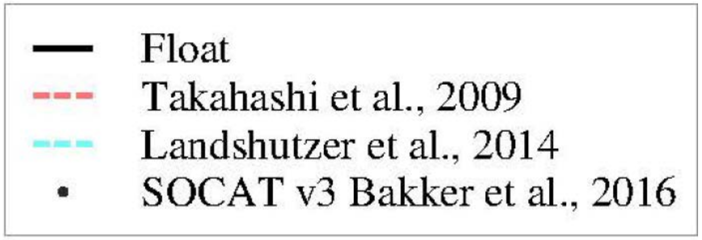


ΔpCO_2 in subtropical zone

Pacific



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



CO_2 flux estimate

We are interested in the flux of CO_2 out of ocean

$$F = k_g * K_0 * \Delta pCO_2$$

- k_g = wind speed squared dependent gas transfer velocity from Wanninkhof (2014)
- K_0 = solubility constant
- $\Delta pCO_2 = pCO_2^{ocn} - pCO_2^{atm}$

Calculation of ΔpCO_2

- pCO_2^{atm} from Cape Grim monthly data

Annual net oceanic CO_2 uptake

- Positive indicates net outgassing, negative is uptake.
- Bold numbers are statistically different from zero.
- Italic numbers in Landschützer column are the total uptake obtained by subsampling where the float profiles are, then integrating, averaging, and multiplying by the same areas.
- The total for the Takahashi estimate is wrong. It should be -0.8, not -1.03.

Zone	Total PgC y^{-1}	Takahashi PgC y^{-1}	Landschutzer PgC y^{-1}
STZ	**-0.2 ± 0.08**	-0.4	-0.5 *-0.3*
SAZ	0.08 ± 0.1	-0.2	-0.2 *-0.2*
ACCZ	**0.8 ± 0.2**	-0.2	-0.07 *0.02*
SIZ	0.03 ± 0.05	0.02	-0.02 *-0.02*
	0.7 ± 0.2	-1.03	-0.8 *-0.5*

CO_2 fluxes (mol m^{-2} y^{-1})

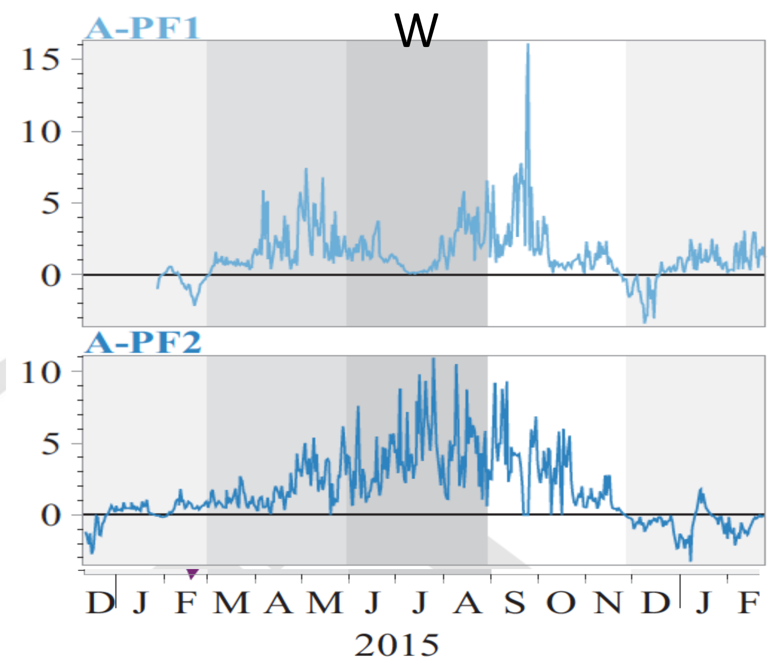
Pacific		Atlantic	
Subtropics (Significant uptake)			
P-ST1	**-0.9 ± 0.7**		
P-ST2	**-1.6 ± 0.7**		
Subantarctic Zone			
P-SA1	-0.1 ± 1.1	A-SA1	-0.8 ± 0.9
P-SAA3	-1.0 ± 1.1		
Polar Front Zone (Significant degassing)			
P-PF1	**1.6 ± 1.1**	A-PF1	**1.5 ±1.2**
		A-PF2	**2.2 ± 1.3**
Seasonal Ice Zone			
P-SI1	-0.6 ± 0.6	A-SI1	0.2 ± 0.7
		A-SI2	-0.7 ± 0.3
		A-SI3	-0.3 ± 0.2

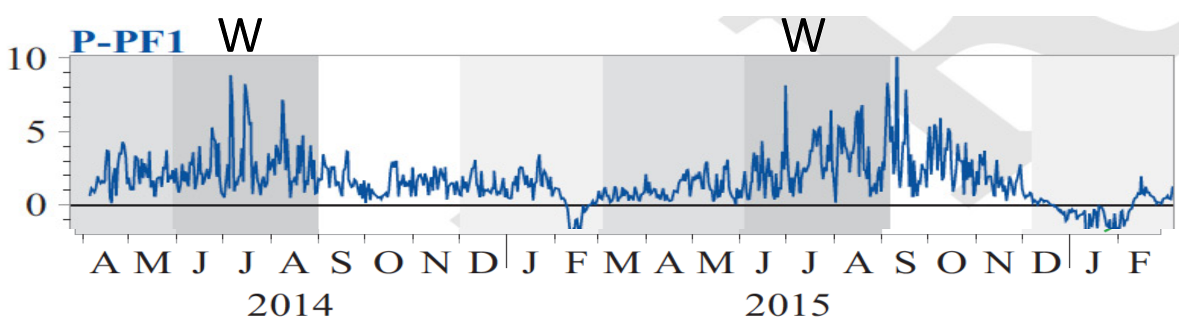
For scale, the average anthropogenic CO_2 uptake is 0.46 ± 0.14 mol m^{-2} y^{-1}

CO_2 fluxes in Polar Front zone (mol m^{-2} y^{-1})

Pacific		Atlantic	
P-PF1	**1.6 ± 1.1**	A-PF1	**1.5 ±1.2**
		A-PF2	**2.2 ± 1.3**

Anthropogenic CO_2 uptake is 0.46 ± 0.14 mol m^2 y^{-1}

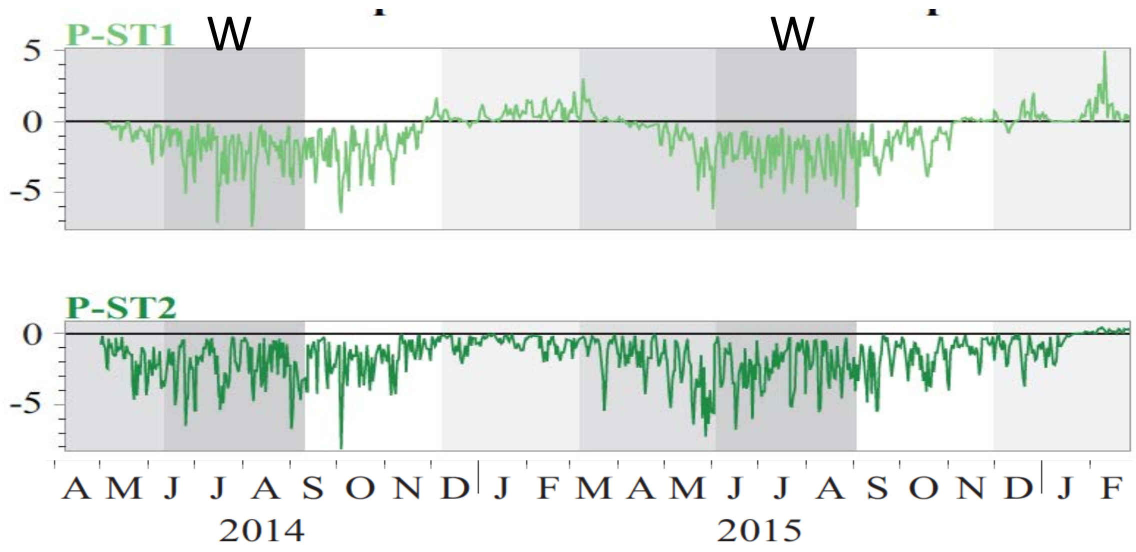




CO_2 fluxes in subtropics (mol m^{-2} y^{-1})

Pacific subtropics	
P-ST1	**-0.9 ± 0.7**
P-ST2	**-1.6 ± 0.7**

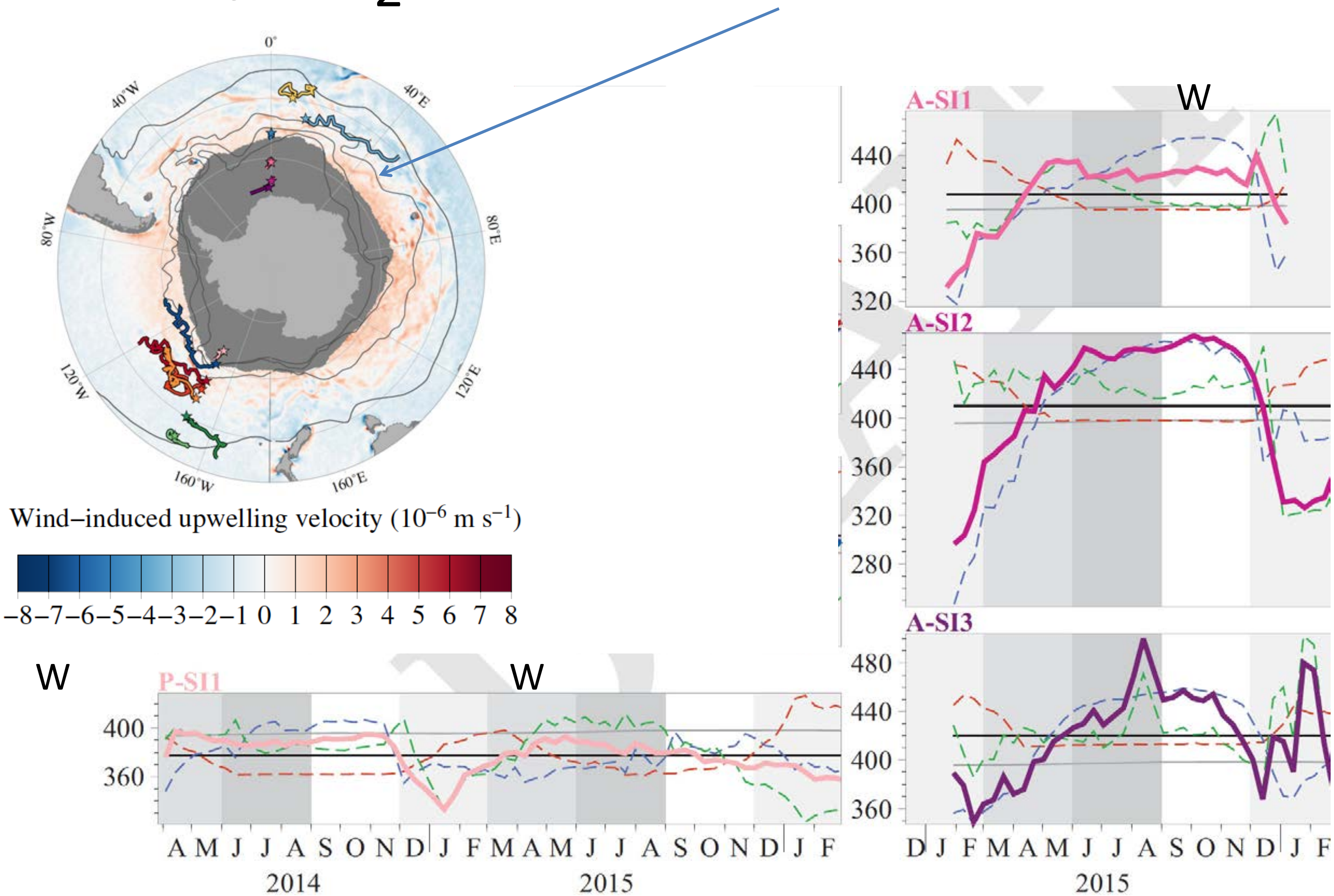
Anthropogenic CO_2 uptake is 0.46 ± 0.14 mol m^2 y^{-1}



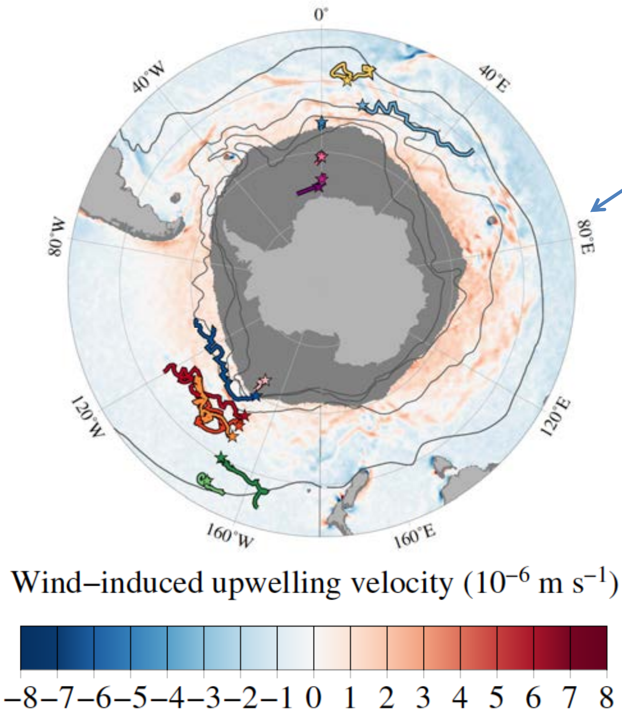
Causes of CO_2 seasonality

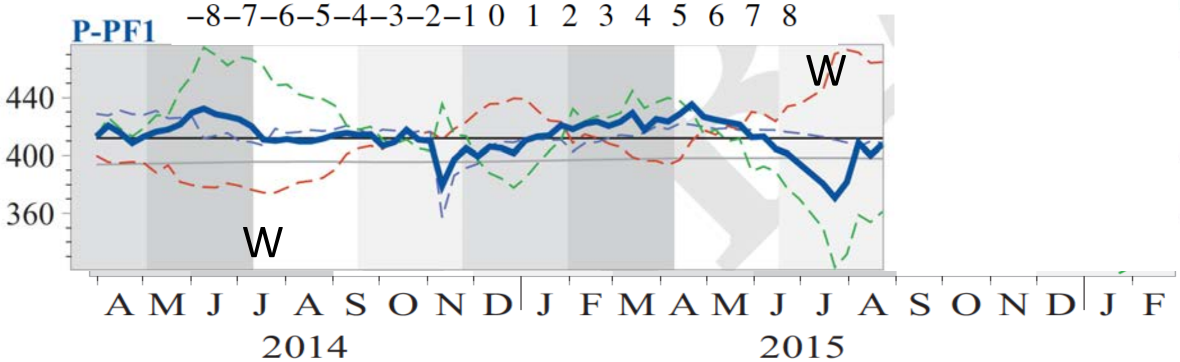
Gray et al. (in preparation)

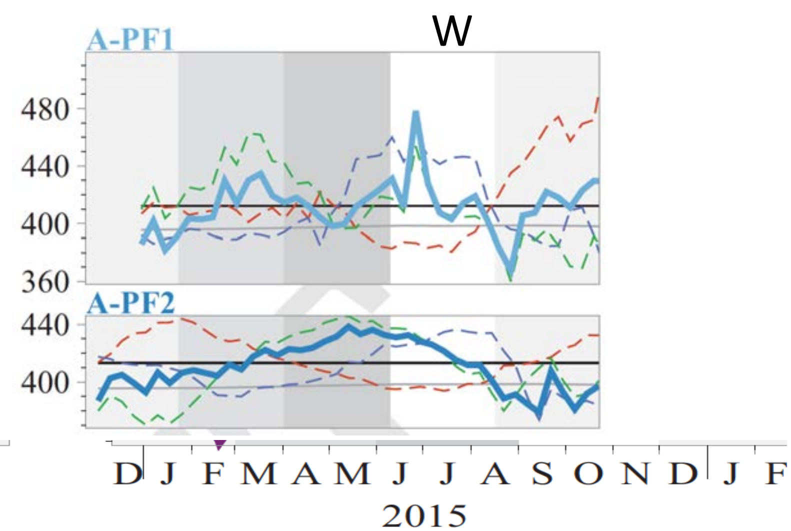
pCO_2 in seasonal ice zone



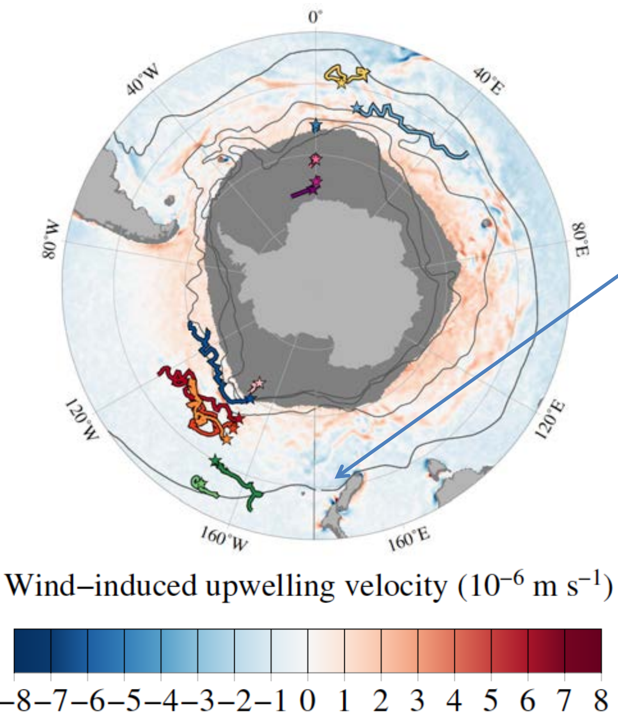
pCO_2 in Polar Front zone

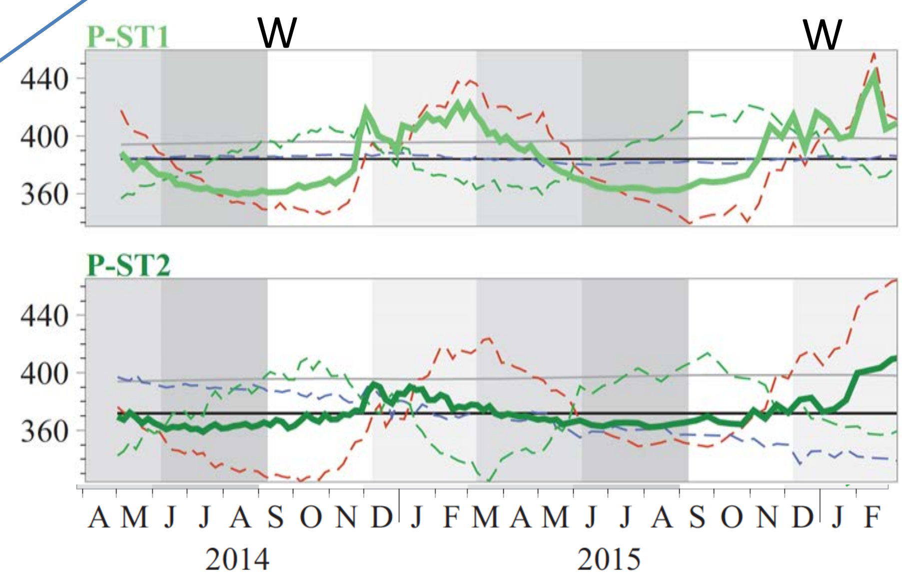




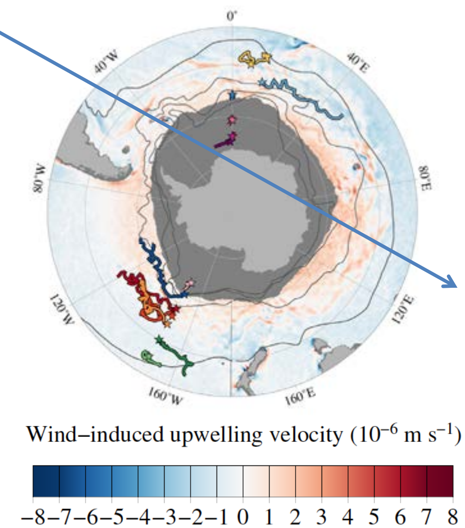


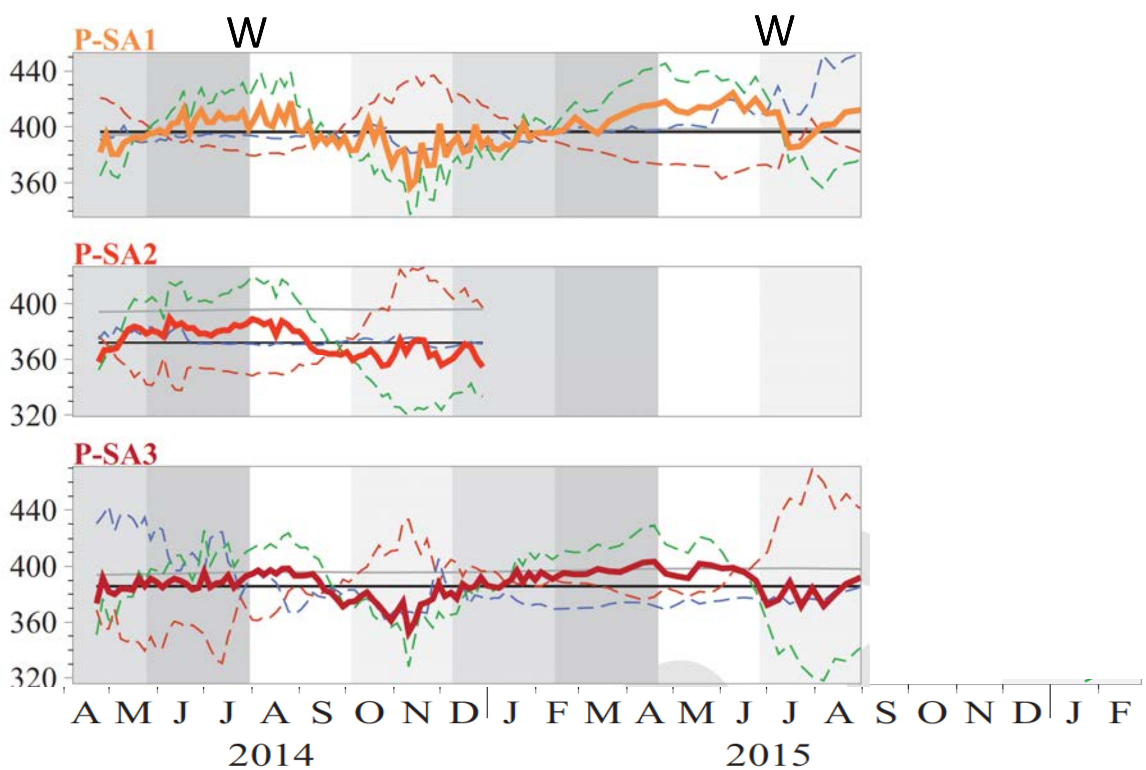
pCO_2 in subtropical gyre (Pacific only)

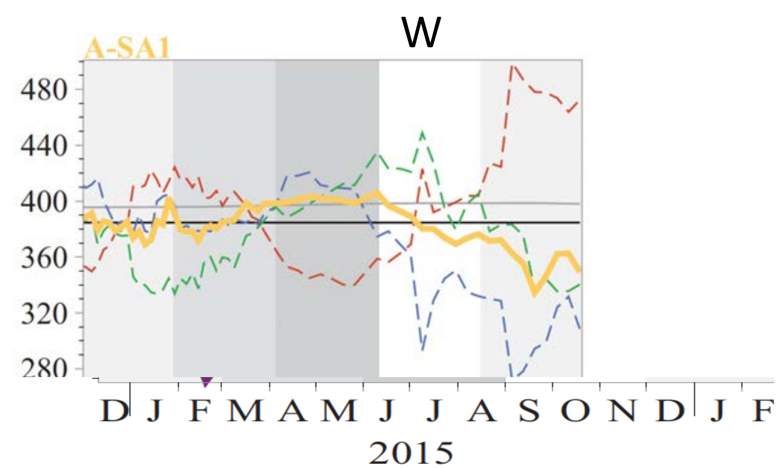




pCO_2 in SubAntarctic Front zone







Th role of the Southern Ocean in the global climate system.

1

It accounts for **67-98%** of the excess heat that is transferred from the atmosphere into the ocean each year.

2

It accounts for **up to half** of the annual oceanic uptake of anthropogenic carbon dioxide from the atmosphere.

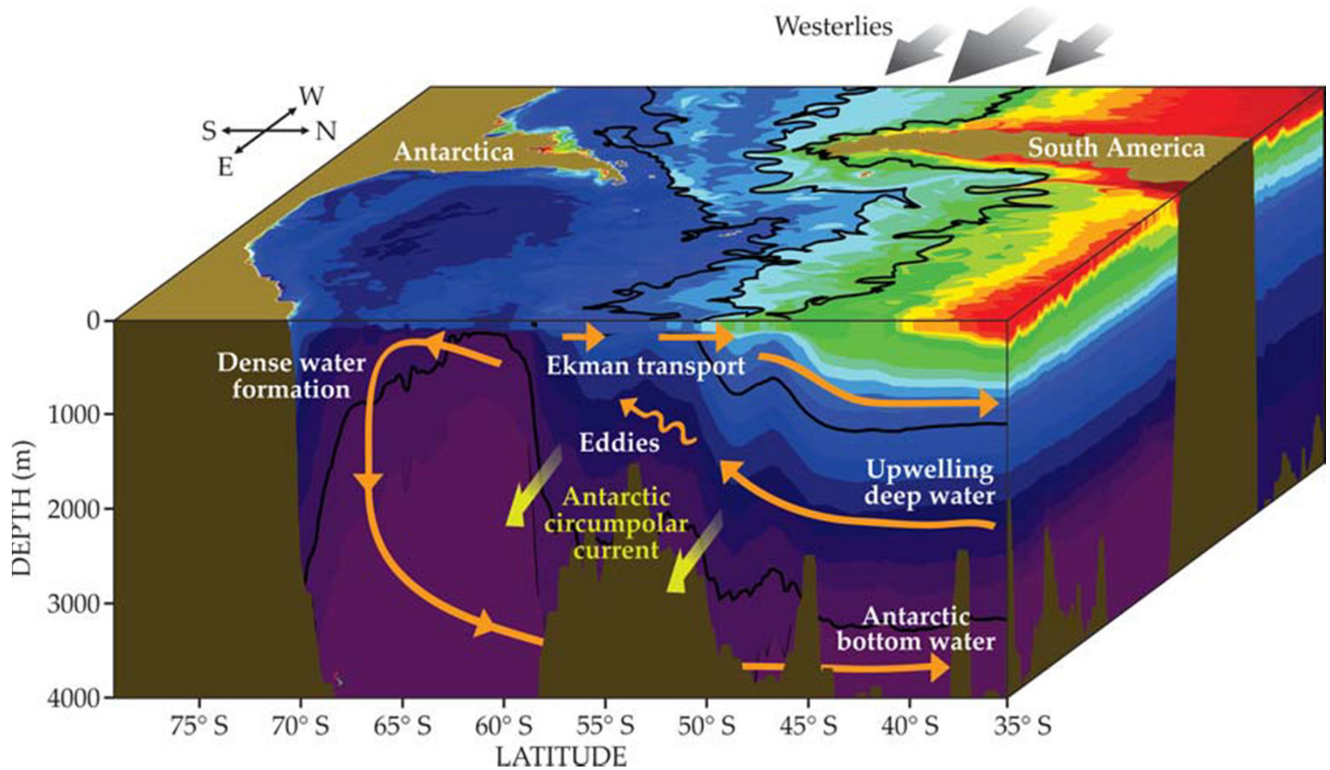
3

Vertical exchange in the Southern Ocean is responsible for supplying nutrients that fertilize **three-quarters** of the biological production in the global ocean north of 30°S.

Roemmich et al. 2015 Gruber et al. 2009, Landschützer et al. 2015 Sarmiento et al. 2004

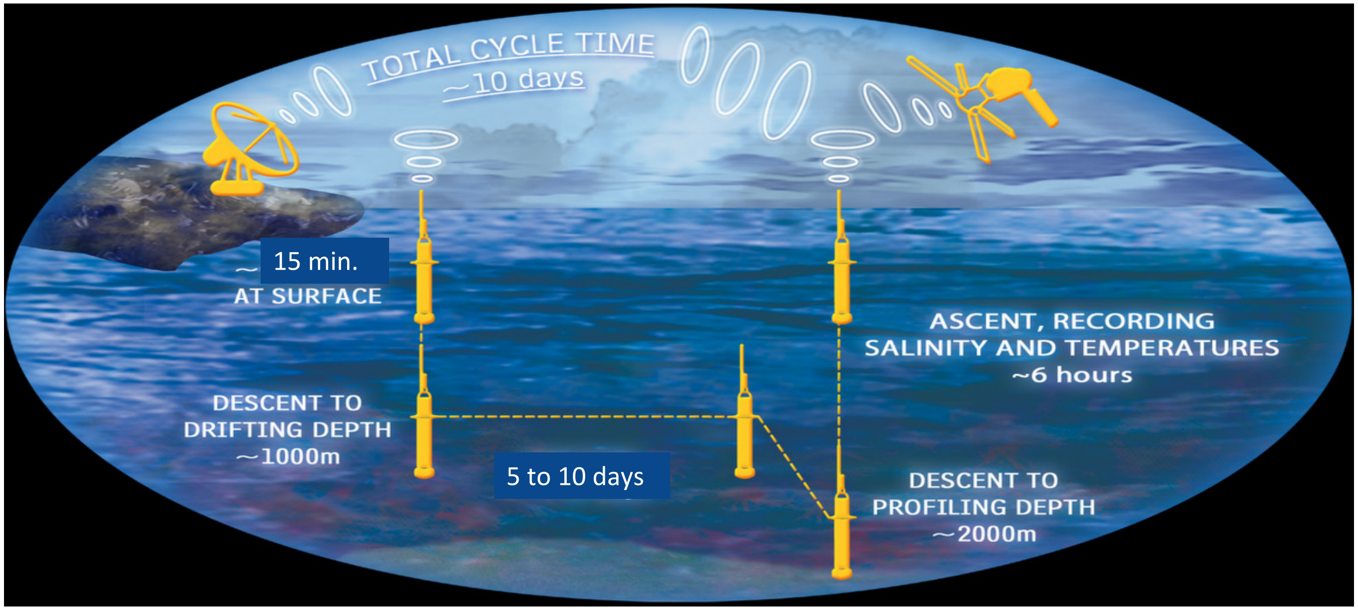
Why is the Southern Ocean so important?

- “Window to the deep ocean”
- Southern Ocean is the only place where there is direct upwelling from very deep waters to the sea surface over a very large region

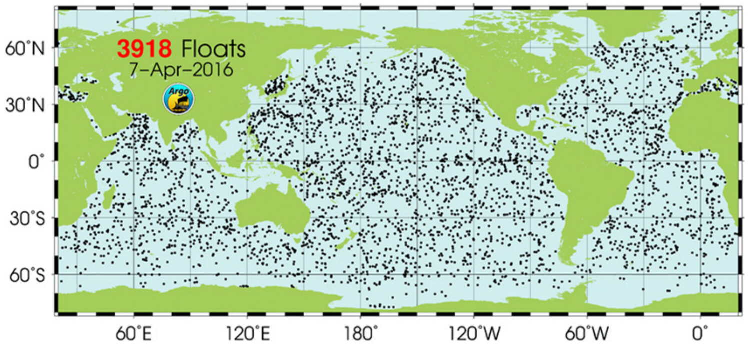


Morrison et al. (2015) based on Talley & Olbers (2014, after Speer et al. 2000, and NRC 2011)

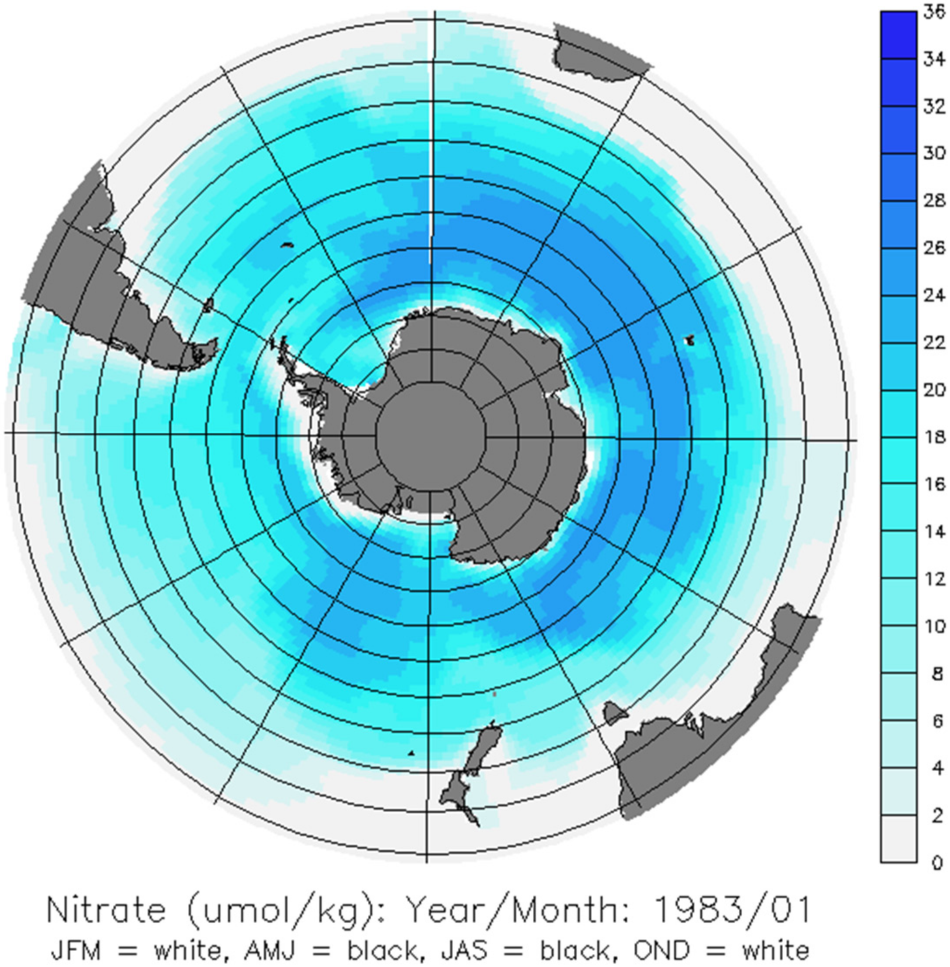
Argo Floats



- 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.



Undersampling of Nitrate

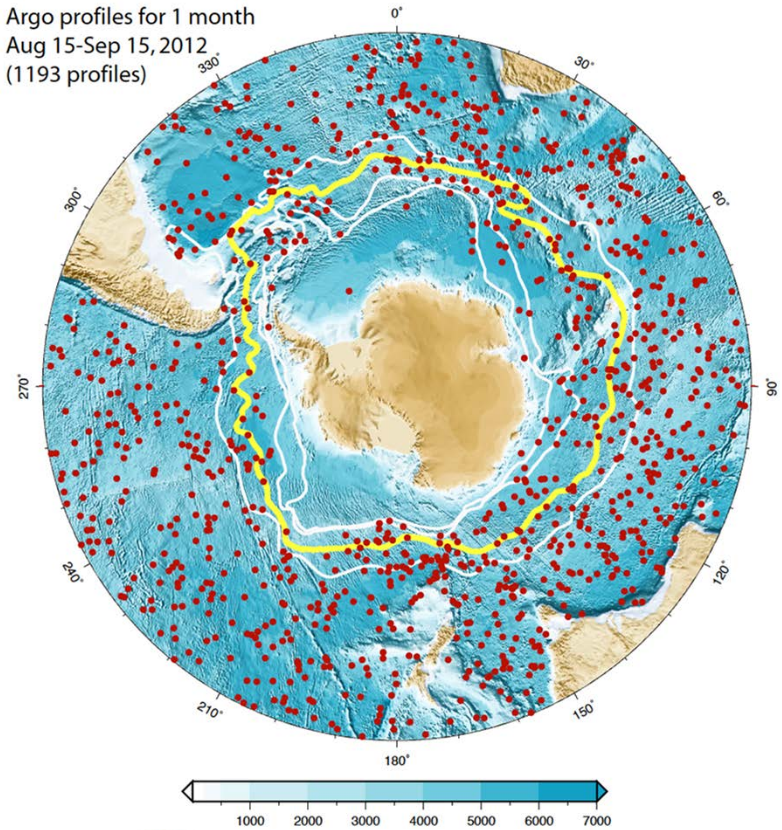


Animation of actual Southern Ocean nitrate observations

- Background is World Ocean Atlas monthly climatology.
- End of animation shows additional measurements that would have been made if Argo floats had nitrate sensors

Courtesy of R. Slater, Princeton U.

The Opportunity



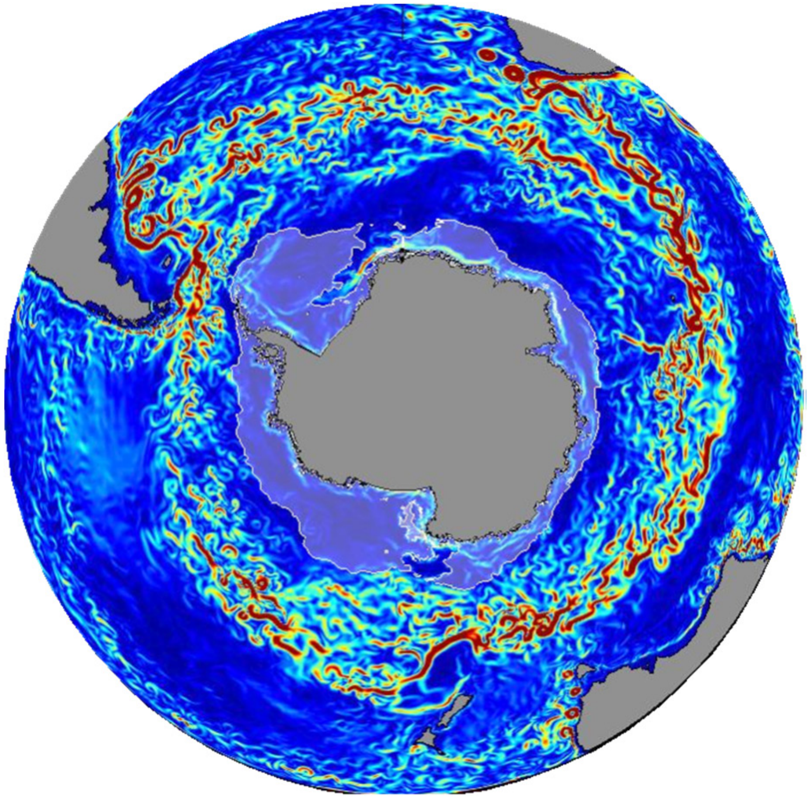
(1) A paradigm shift – Transformative observing system

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

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

SOCCOM

The Opportunity

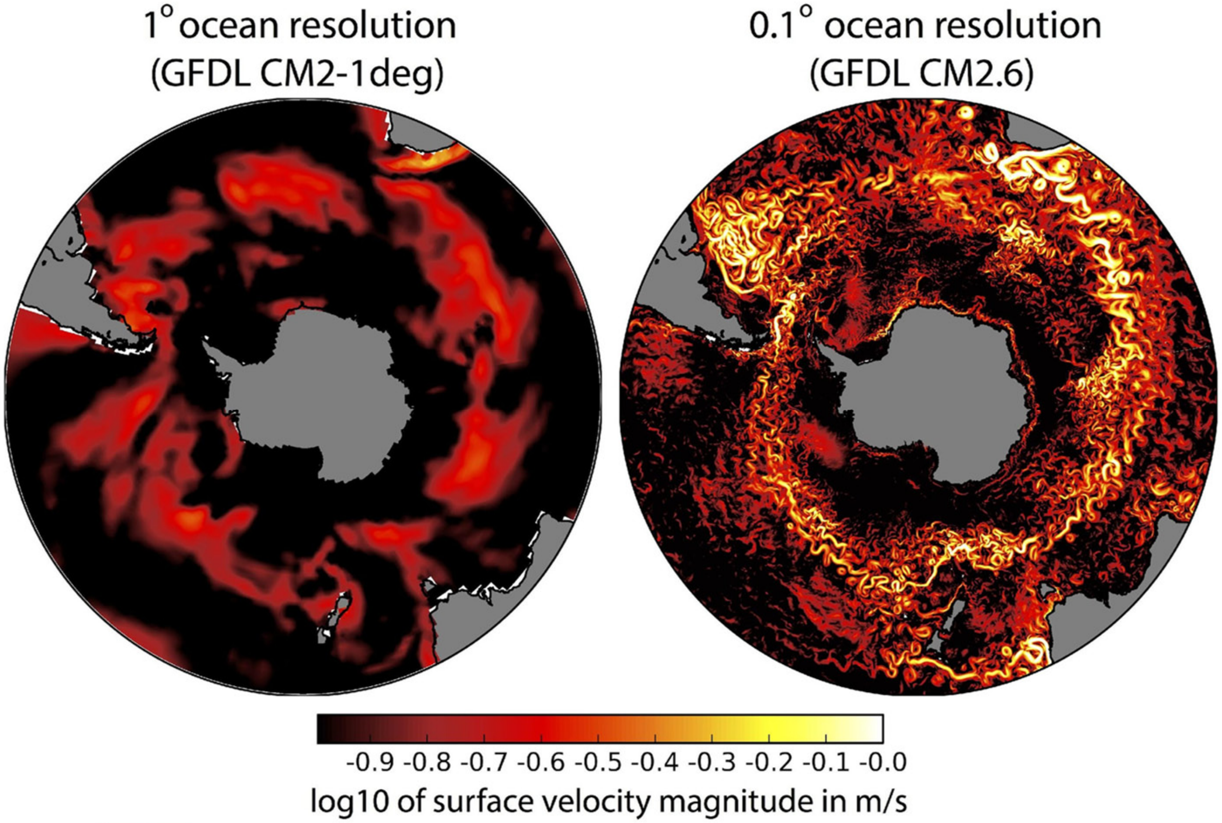


(2) Transformative observational analysis methods

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

SOCCOM

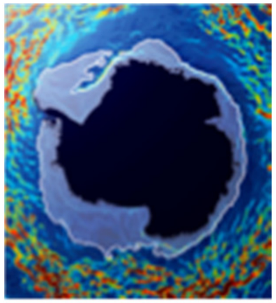
The Opportunity



(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.

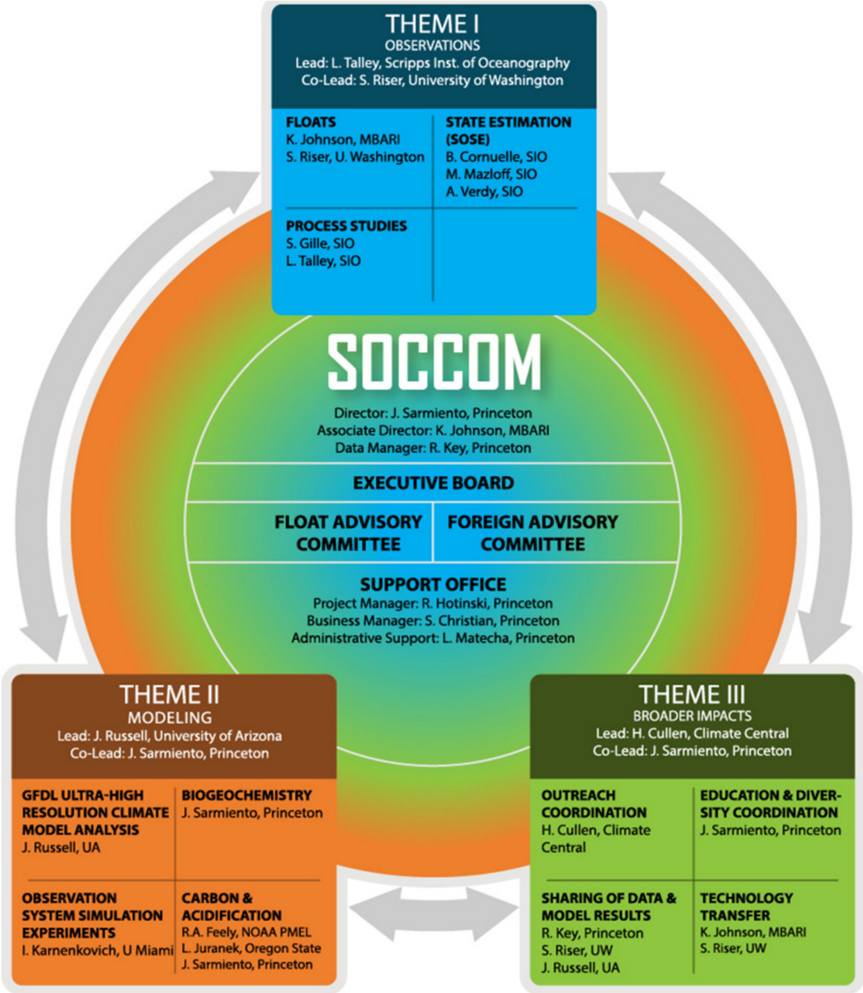
Educating a new generation of ocean scientists trained in both ocean observation and simulation, and develop a sophisticated outreach effort to disseminate results to the broadest possible community.

Directorate

Director
Jorge Sarmiento, Princeton

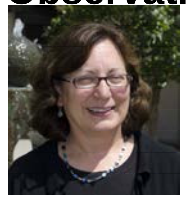
Associate Director
Ken Johnson, MBARI

Project Manager
Roberta Hotinski, Princeton



Executive Board

Theme I Observations



Lynne Talley, UCSD

Steve Riser, U. Washington

Theme II Modeling

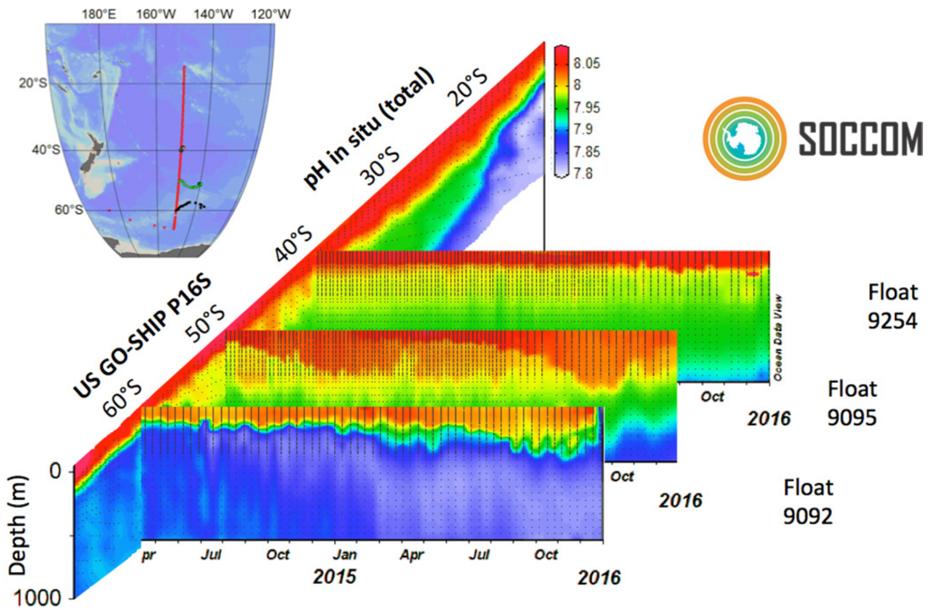
Joellen Russell
U. Arizona

Broader Impacts

Heidi Cullen, Climate Central

SOCCOM

SOCCOM float observations



Extension of decadal-scale GO-SHIP carbon observations into the seasonal and interannual domain

Some details:

(1) Calibration – goal is to produce climate quality data

(2) All data immediately available on the web

(3) Ice avoidance software

(4) Southern Ocean State Estimate (SOSE):

- Least squares fit to data by the adjoint method (M. Mazloff as part of ECCO consortium funded by the NSF)
- Earlier development of BGC model was *supported by NASA CMS*
- Nominal resolution is 1/6°