Heat and carbon air-sea exchange in the Southern Ocean

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With input from many others including Alison Gray, Ken Johnson, Matt Mazloff, Ariane Verdy

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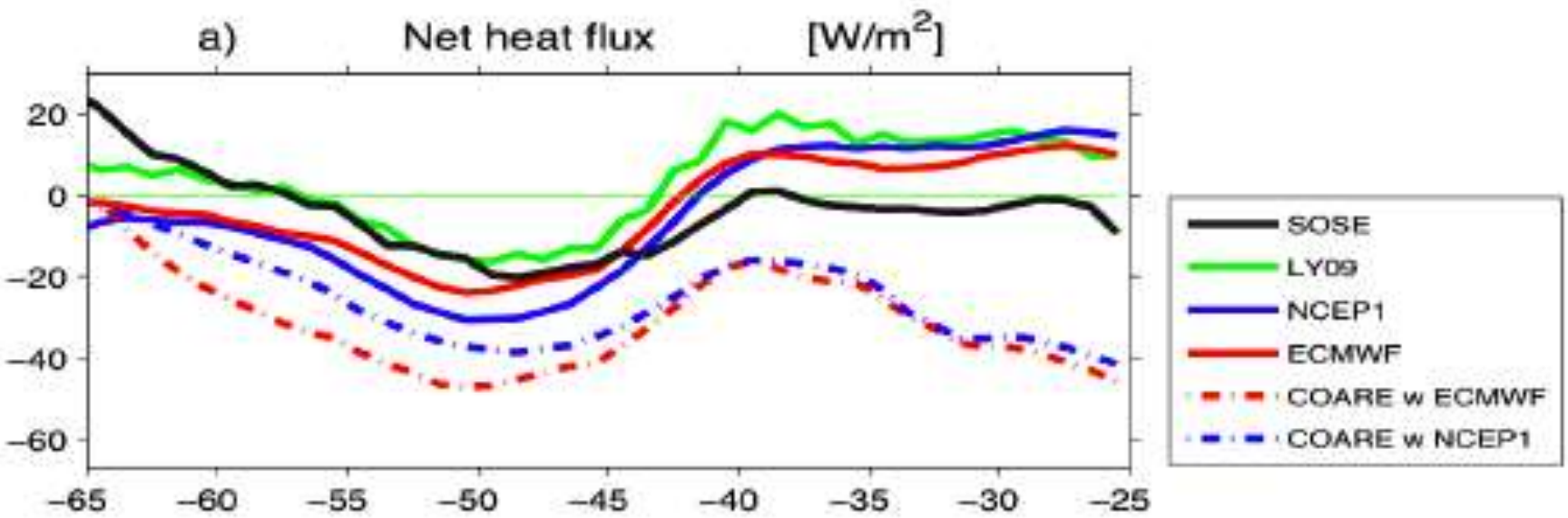
Photo: Riming on Eppley pyranometer, August 21, 2009
Southern Ocean GasEx, Chris Fairall

Outline

- Air-sea heat fluxes: Challenges in determine fluxes, and what we learn from Argo profiling floats
- Air-sea CO_2 flux: Extending the Argo lessons to Biogeochemical Argo in SOCCOM

Challenges: Time-Mean Fluxes Disagree

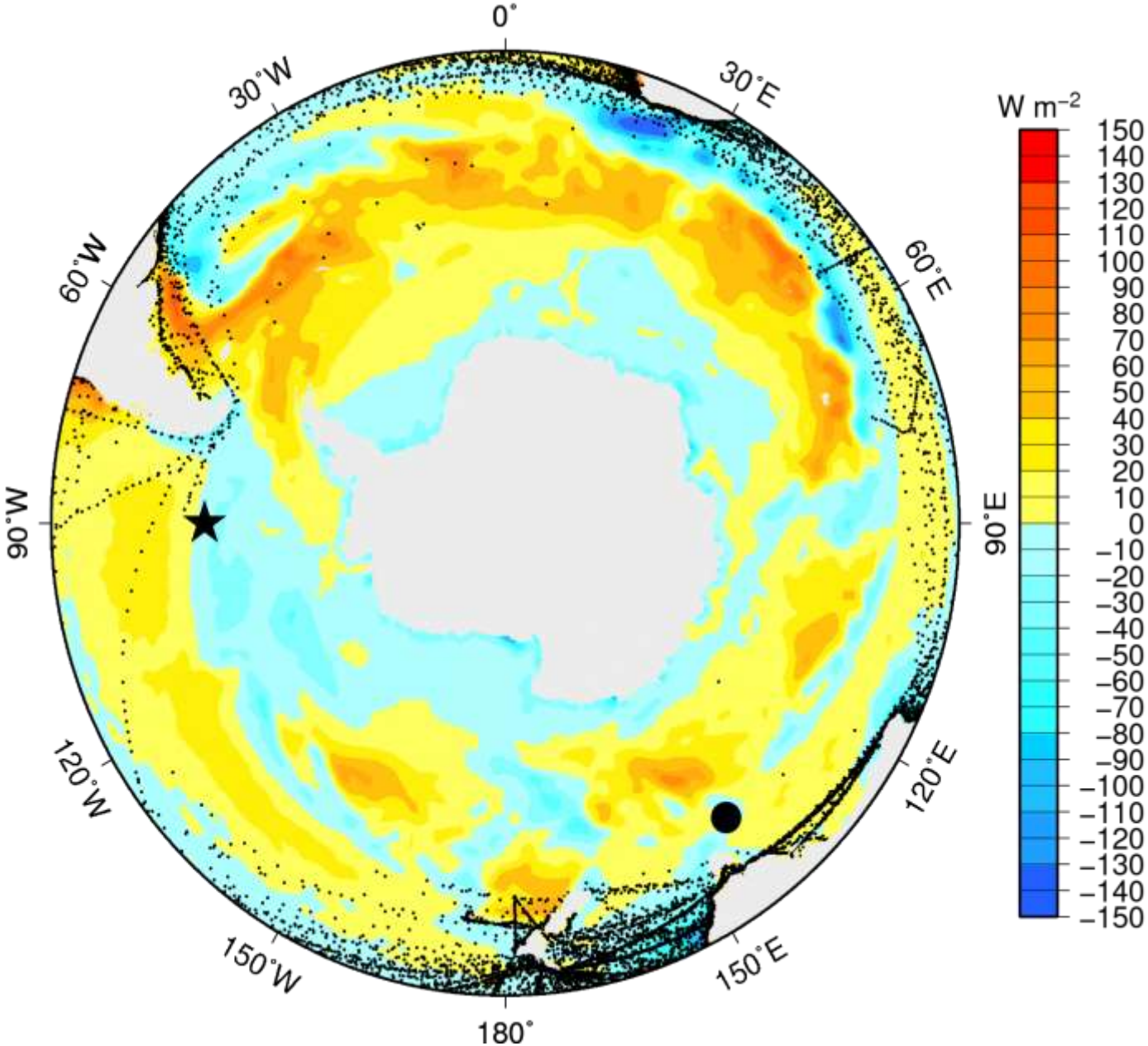


Q_{net} comparison: Zonal average, 2005-07

- *SOSE (Southern Ocean State Estimate);*
- *LY09 (Large and Yeager, 2009)*

(Cerovecki et al., 2010)

Air-Sea Flux Observations: woefully sparse



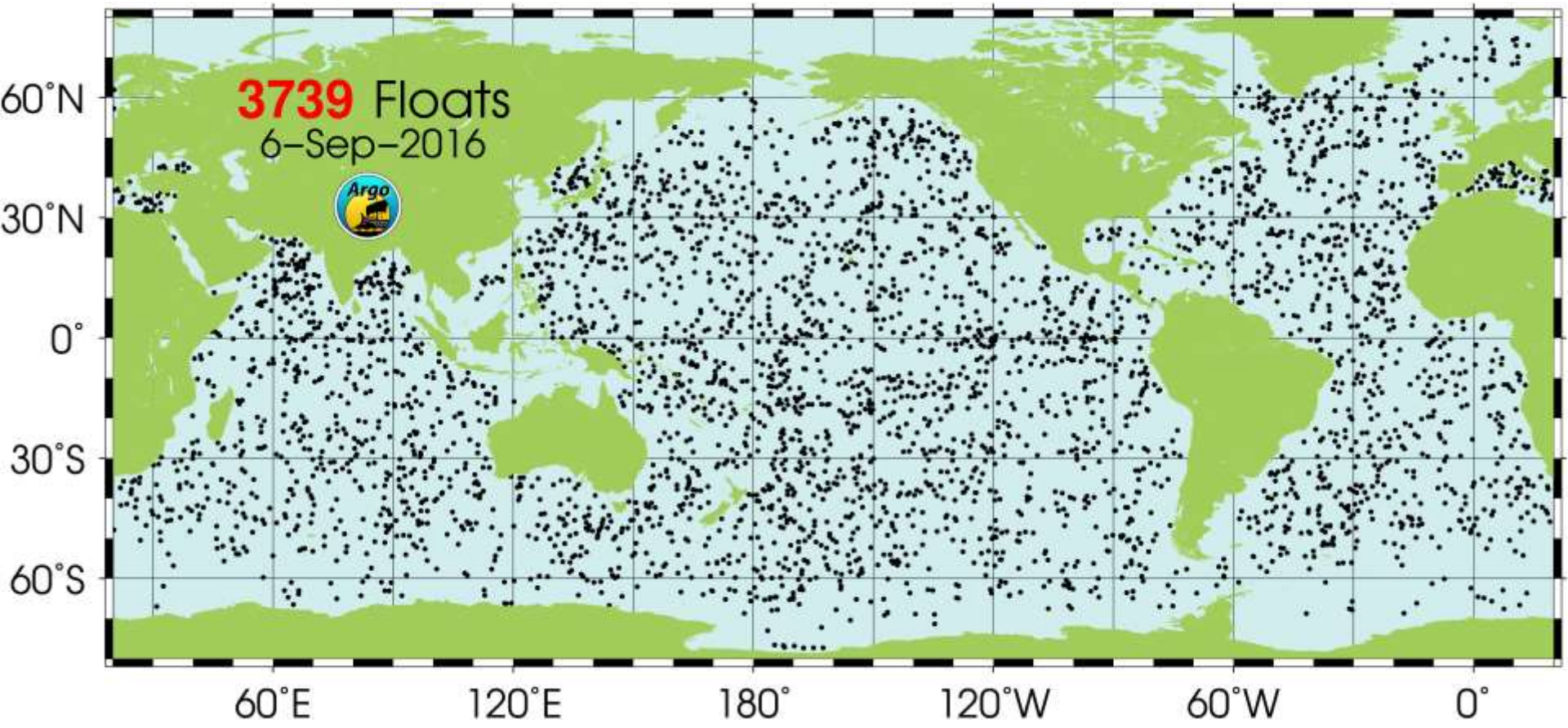
- Q_{net} from ERA-Interim (2008-2010; blue=loss to atmosphere).
- Small dots: 5 years of July flux observations (2000-2004)
- Large circle: SOFS mooring
- Large star: OOI mooring

Challenges to in situ observing

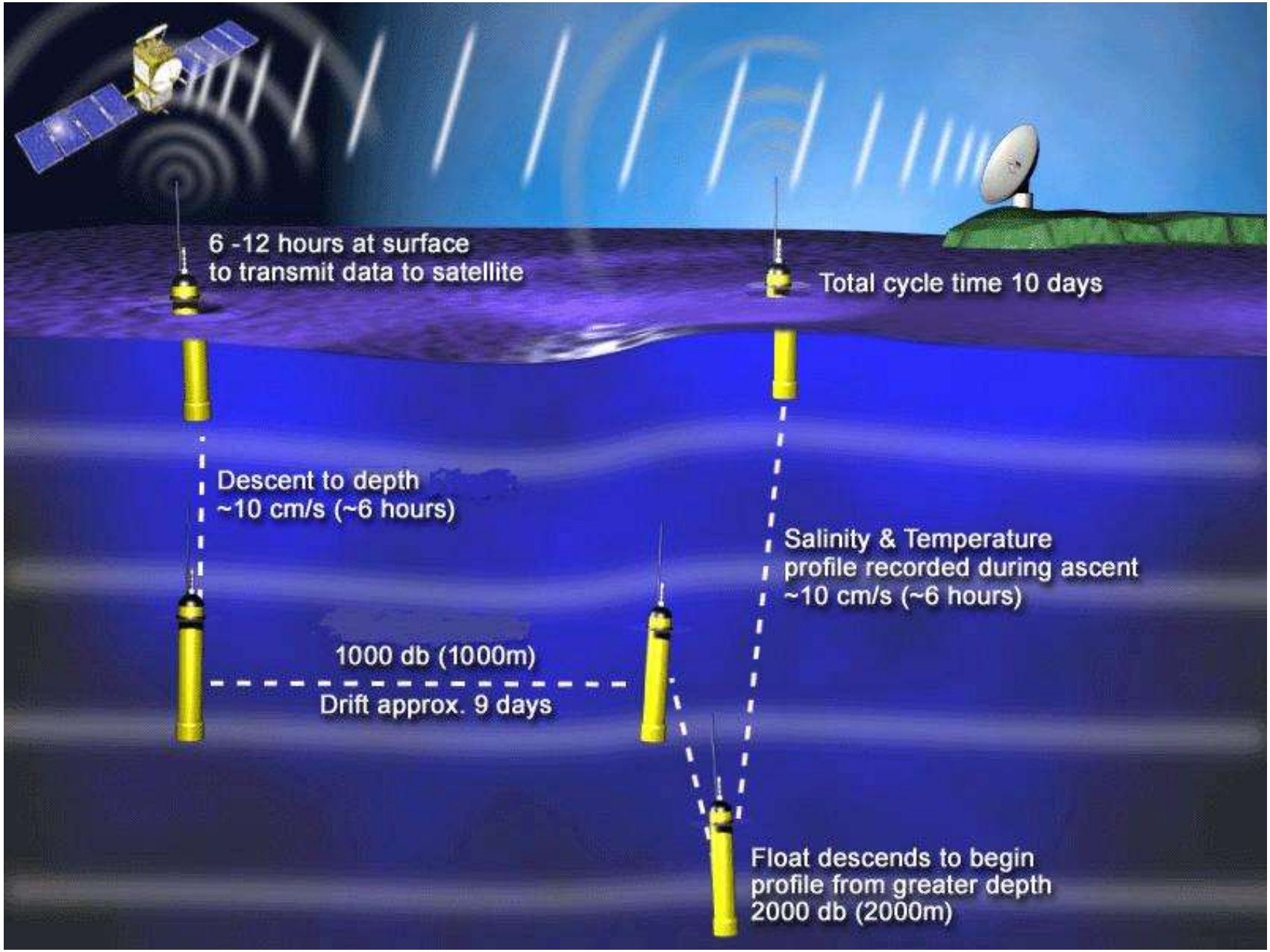
- **Ships:** poor characterization of flow distortion and ship sensor performance
- **Flux moorings:** OOI and IMOS, battery/solar cell issues
- **Aircraft:** grounding due to icing or poor weather, limited flight time
- **Drones/UAVs:** comparatively new, cannot operate continuously
- **Wavegliders:** New technology, low elevation places measurements between waves, plus battery power constraints

Photo: Wave glider met sensors after ~2-week Deployment In Southern Ocean (May 2016, Andy Thompson)

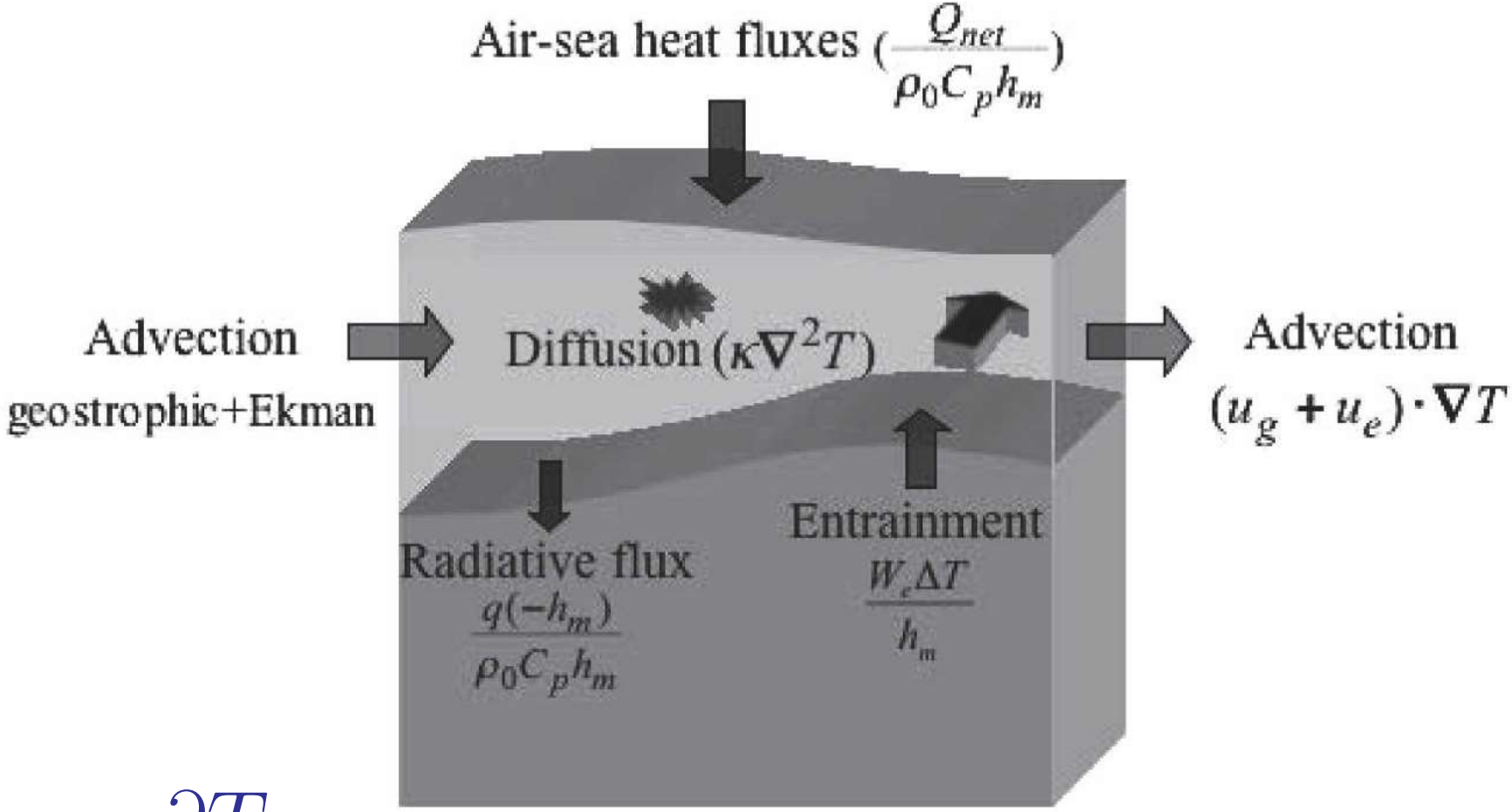
Argo floats as of 6 September 2016



Argo float 10-day cycle



Schematic Framework: Upper Ocean Heat Balance

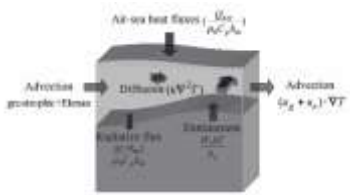


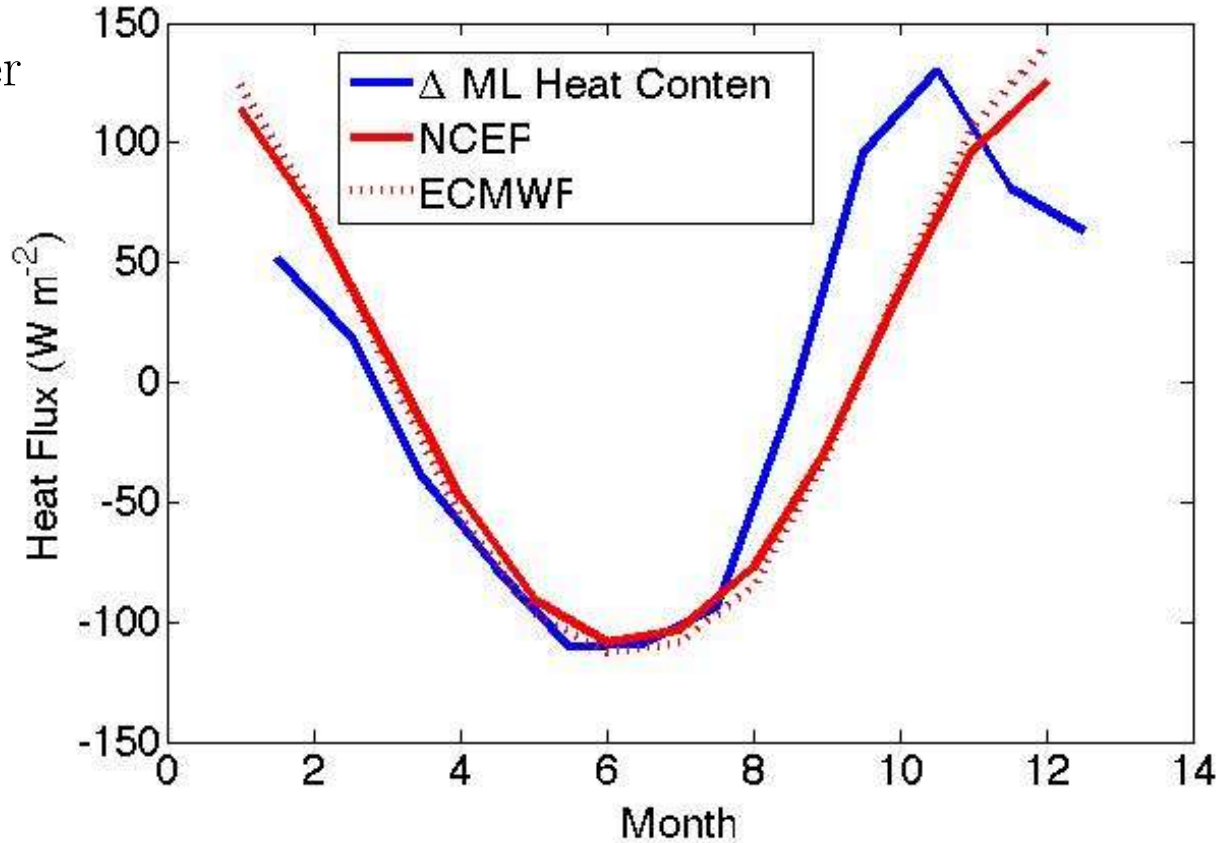
$$\rho c_p h \frac{\partial T}{\partial t} = Q_{net} + \text{Other}$$

Dong et al 2007

Seasonal cycle: Mixed-Layer Heat Budget (40-60S)

$$\rho c_p h \frac{\partial T}{\partial t} = Q_{net} + \text{Other}$$



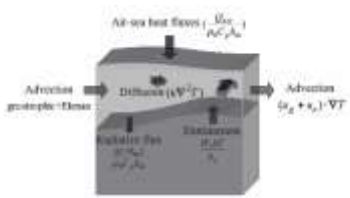


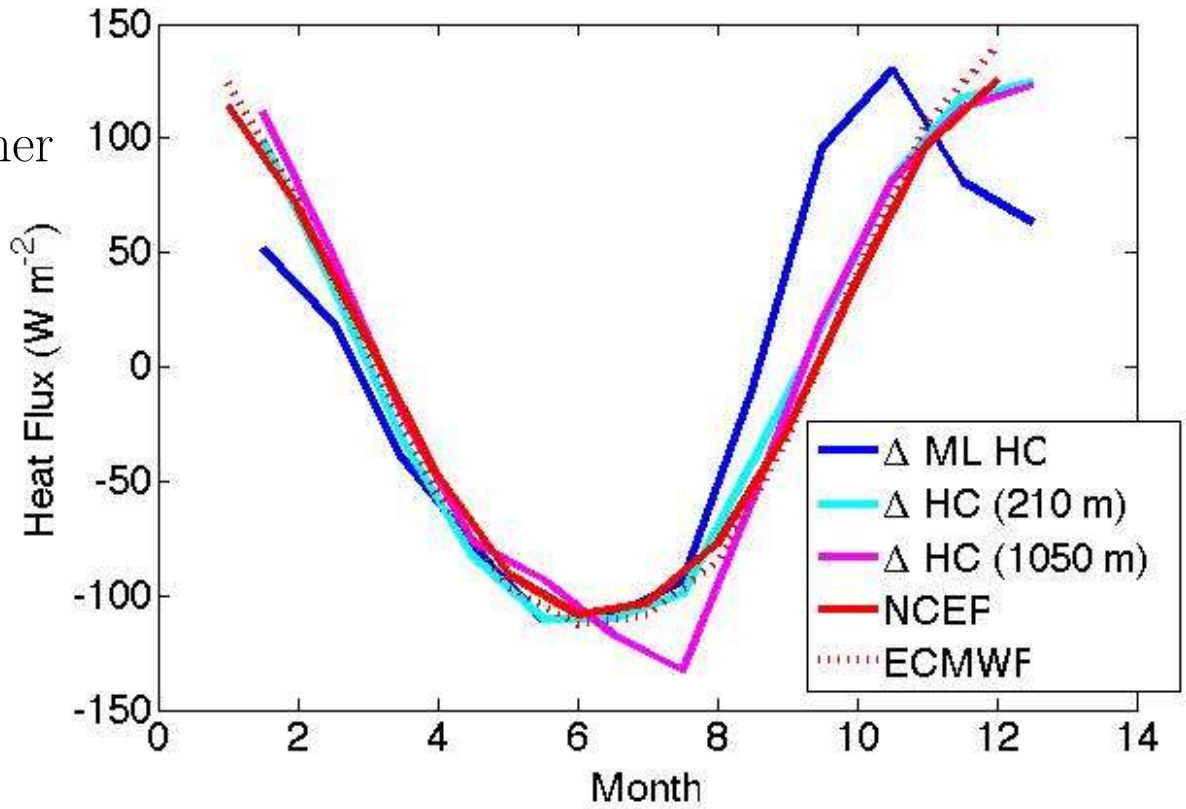
- Mixed-layer temperatures from Roemmich and Gilson Argo-based climatology, weighted by Holte mixed-layer climatology.
- Fluxes from ERA Interim and NCEP-2 (demeaned).
- Surface heat fluxes shifted relative to tendency of ML heat content.

Seasonal cycle: Upper Ocean Heat Budget (40-60S)

$$\rho c_p h \frac{\partial T}{\partial t} = Q_{net} + \text{Other}$$

$$\int_z^0 \rho c_p \frac{\partial T(z)}{\partial t} dz = Q_{net} + \text{Other}$$





- Top 200 m or top 1000 m: Upper ocean temperatures from Roemmich and Gilson Argo-based climatology, weighted by Holte mixed-layer climatology.
- Fluxes from ERA Interim and NCEP-2 (demeaned).
- Upper ocean heat content changes coincide with heat fluxes

Seasonal cycle: Upper Ocean Heat Budget (40-60S)

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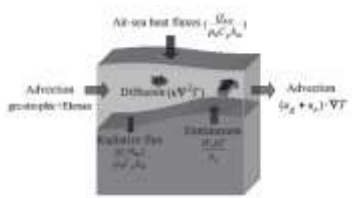

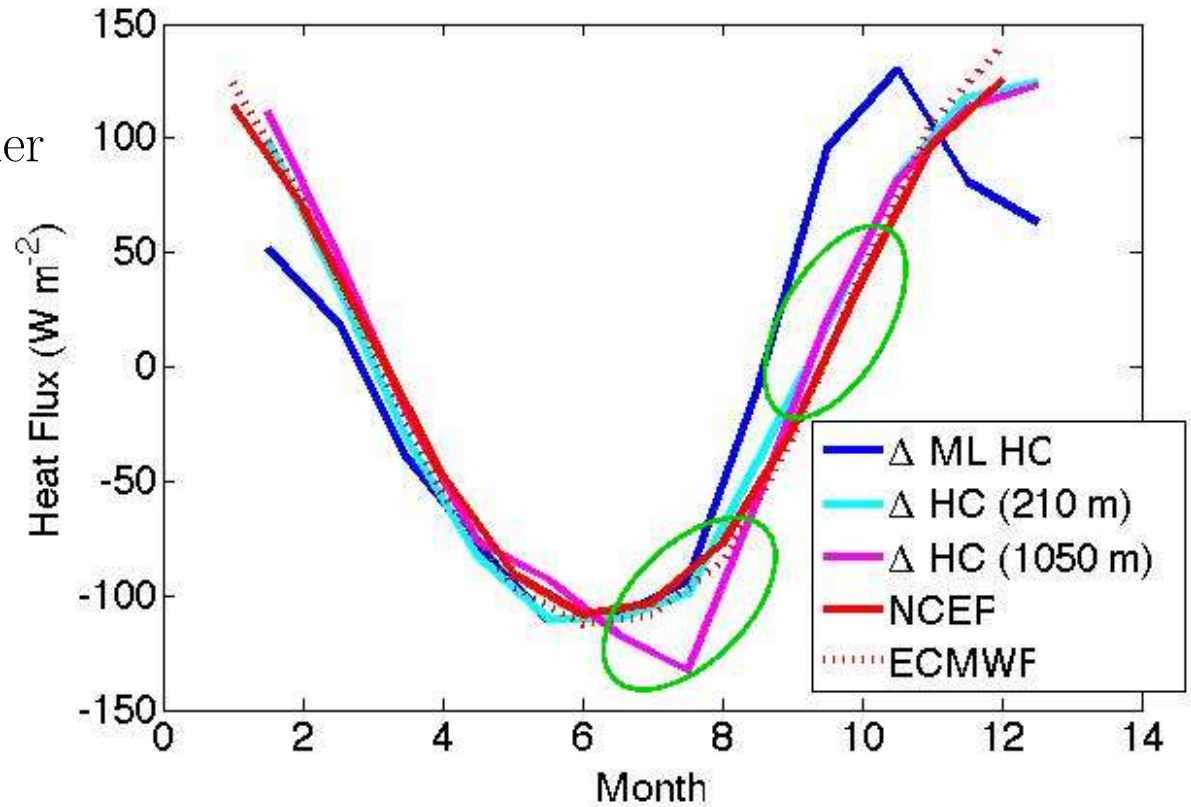

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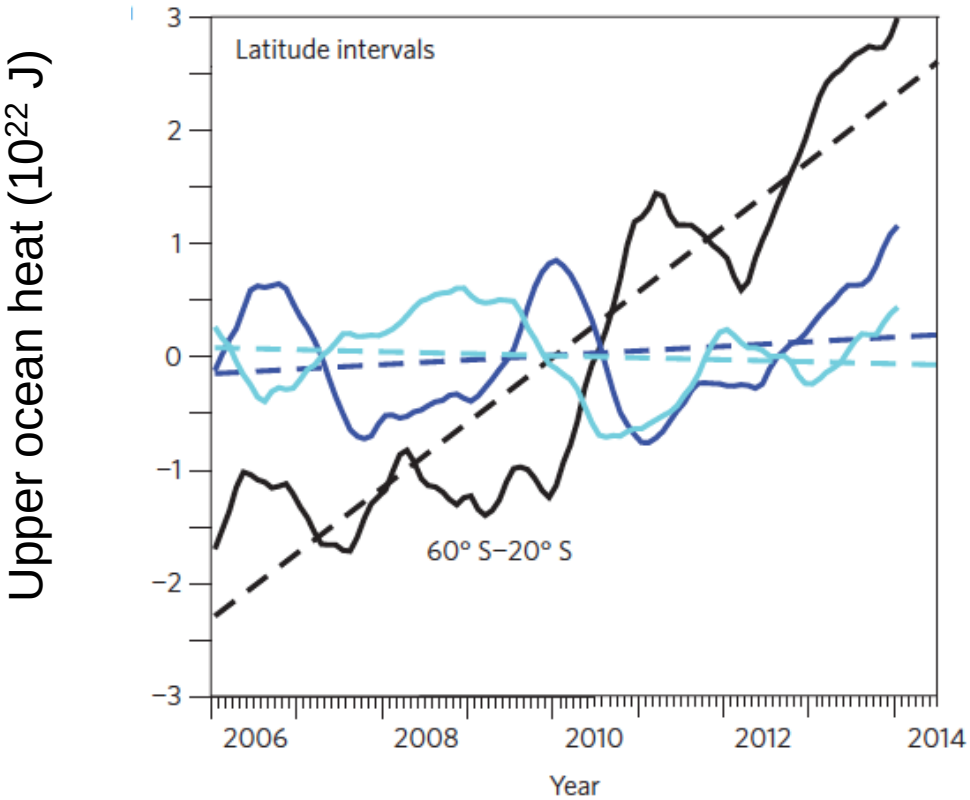
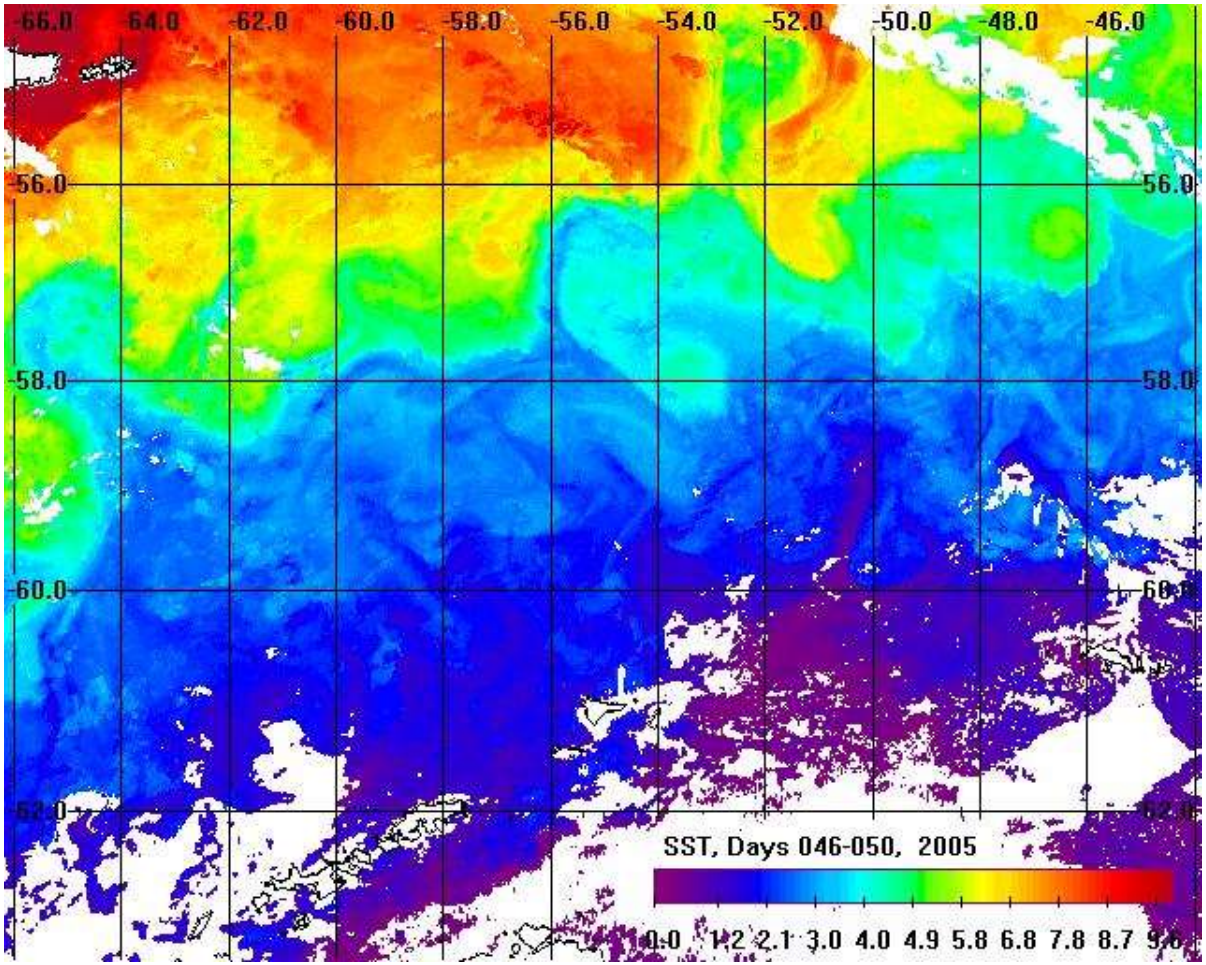
Increases in ocean heat content from Argo

- Top 2000 m
- Global heat content increase consistent with 0.4-0.6 W m^{-2} surface flux imbalance
- For Argo era (2006-2013), most warming in Southern Ocean



(Roemmich et al, *Nature Climate Change*, 2015)

How do fluxes work?

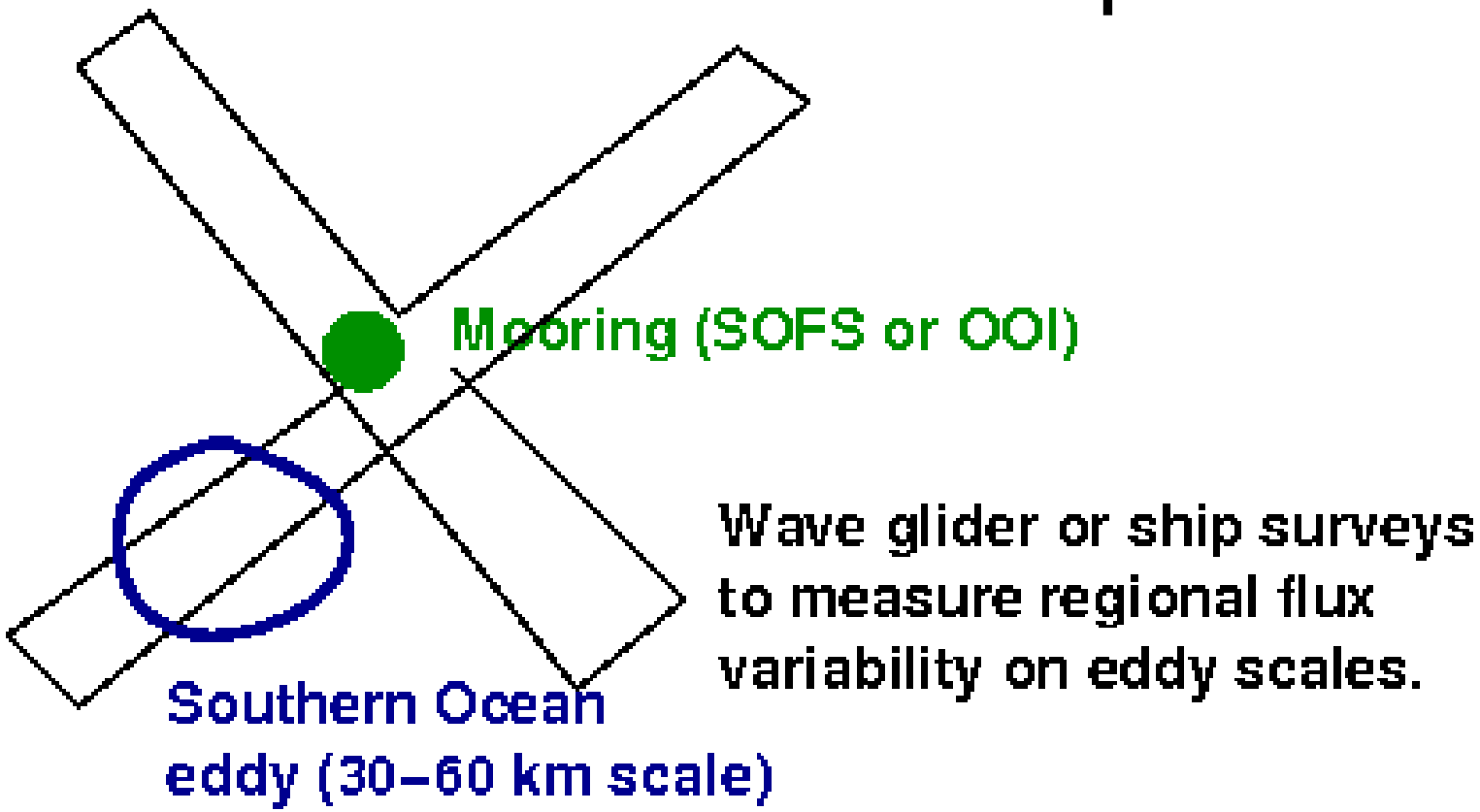


- What time-scales matter for air-sea flux?
- How do sea surface temperature gradients (at fronts and eddies) modulate fluxes?

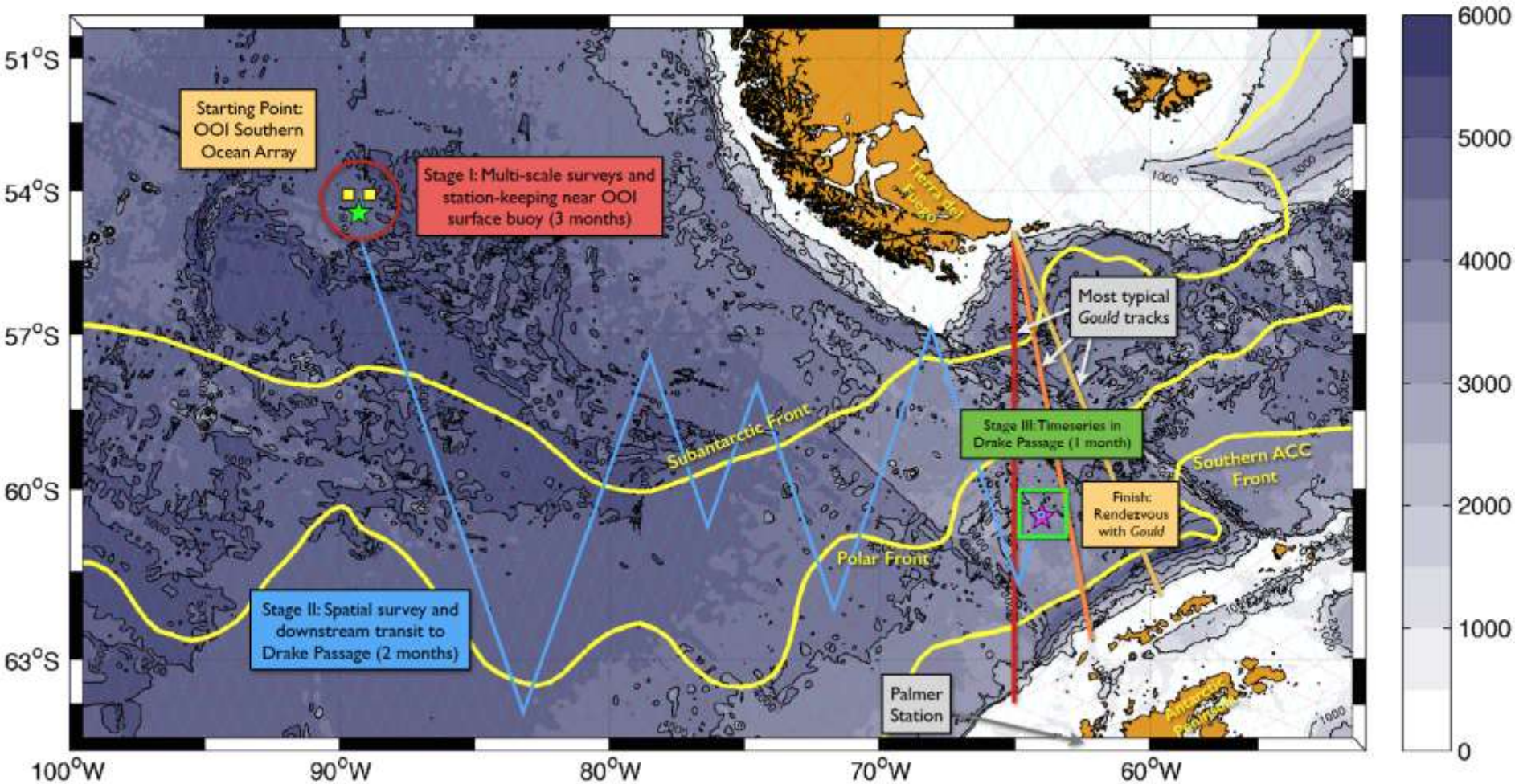
5-day sea surface temperature from Drake Passage

(Kahru, http://spg.ucsd.edu/Show2SetsOfImages/Show2SetsofImages.aspx)

Pilot Study concept from Southern Ocean Observing System (SOOS) Frascati Workshop



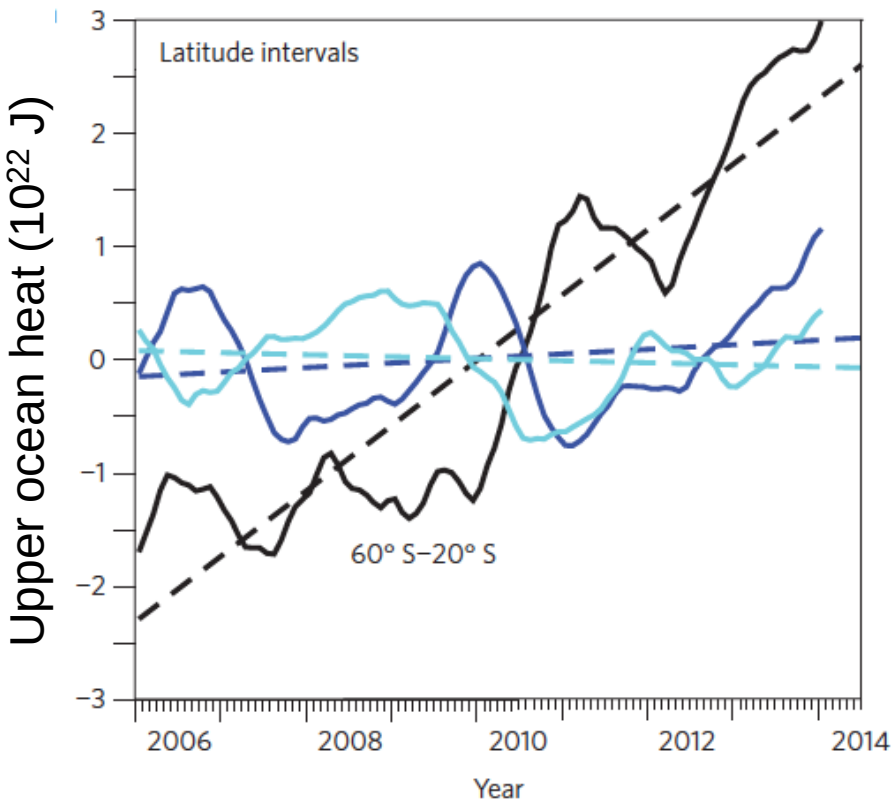
Girton and Thomson: Waveglider



- NSF: James Girton and Jim Thomson (UW/APL)
- Deployment in November/December 2016 OOI turnaround cruise; recovery March-April 2017

Air-sea heat exchange summary

- In situ heat flux measurements are sparse
- Annual cycle in mixed layer (i.e. as measured from SST) is inconsistent with fluxes
- Can infer fluxes on seasonal to interannual scales by evaluating heat storage in Argo data: consistent with net heat flux into ocean of O(0.5 W m^{-2})
- Additional observations needed to infer impact of eddies and fronts on fluxes



(Roemmich et al, *Nature Climate Change*, 2015)

Beyond heat: Inferring carbon fluxes from floats?

Southern Ocean Carbon and Climate Observations and Modeling (SOCCOM): Argo floats augmented for biogeochemistry:

- Dissolved oxygen
- Nitrate
- pH
- (fluorescence or backscatter)

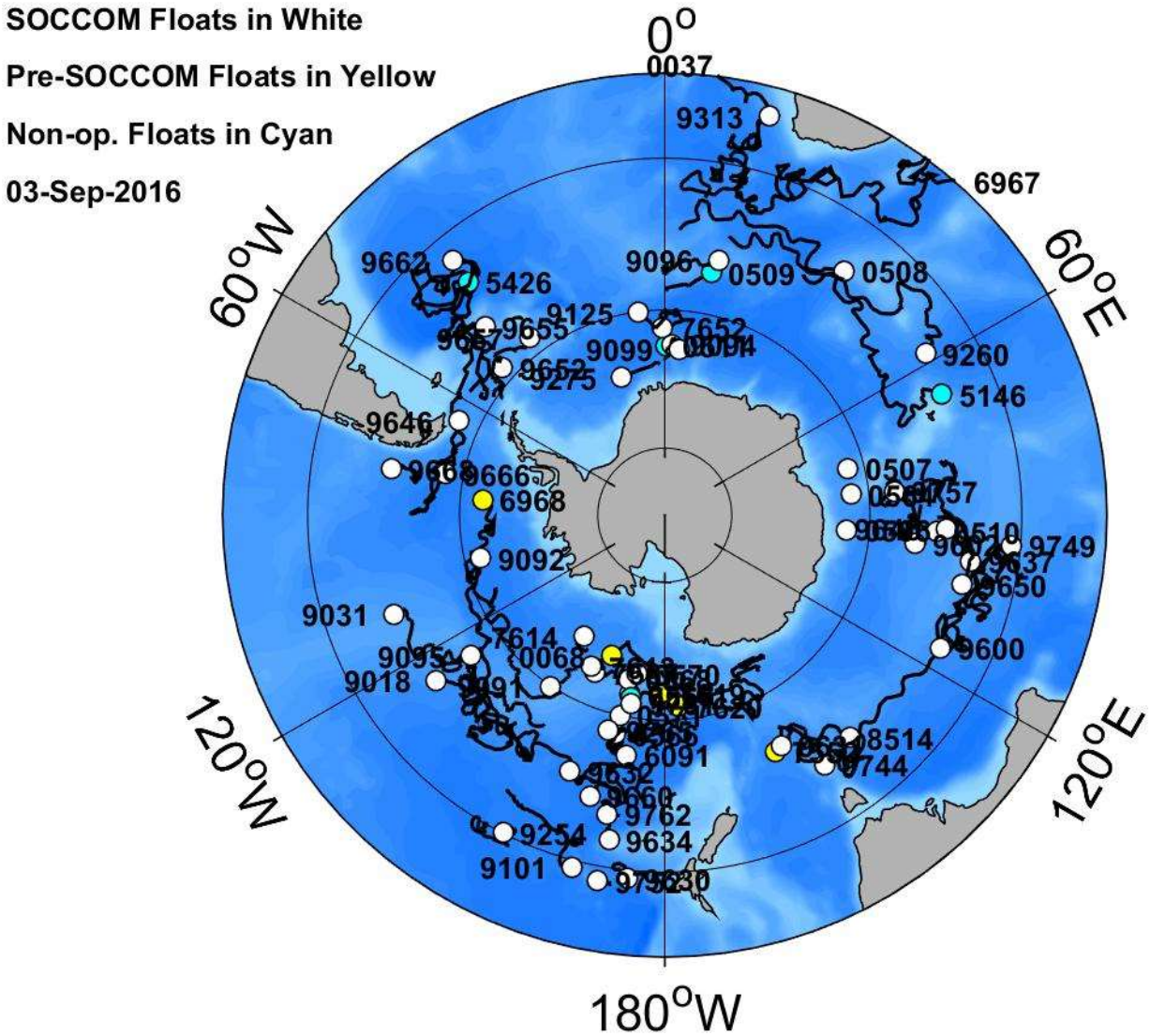
Plus

- Temperature
- Salinity

CO_2 budget requires 2 of 4 parameters:

- pH ✓
- Total dissolved inorganic carbon ☒
- Total alkalinity ☐ *infer from linear regression (Locally interpolated alkalinity regression: LIAR, Carter et al 2016)*
- pCO_2 or fugacity (fCO_2)☒

Southern Ocean Carbon and Climate Observations and Modeling (SOCCOM)

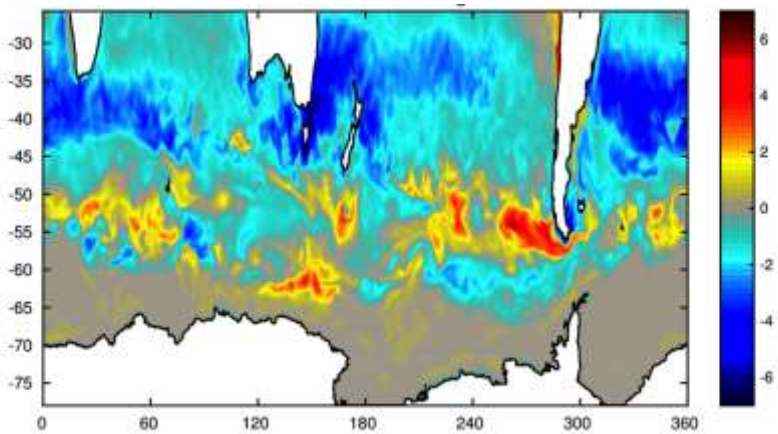


- Plan: 200 floats to be deployed through full Southern Ocean including under ice
- 5-year project kicked off in 2014
- Approximately 60 floats so far

http://soccom.princeton.edu/

SOCCOM approach #1: assimilate data into Southern Ocean State Estimate + Biology Light Iron Nutrient and Gas model

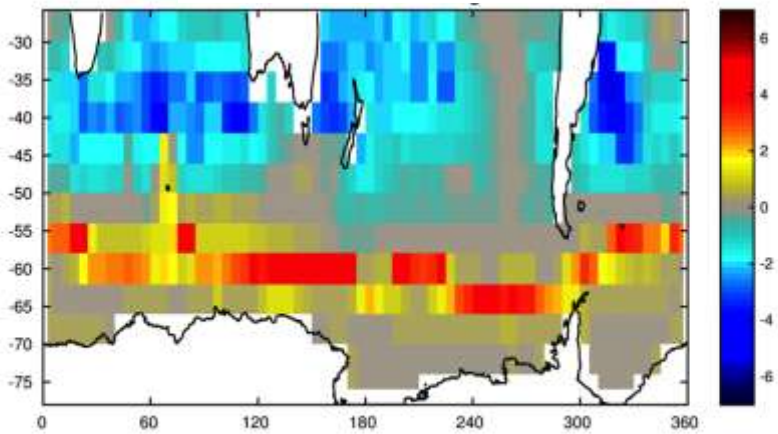
SOSE, August average (2008-2012)



mol C m^{-2} yr^{-1}

- August CO_2 flux mostly into ocean in SOSE+BLING

Takahashi August mean



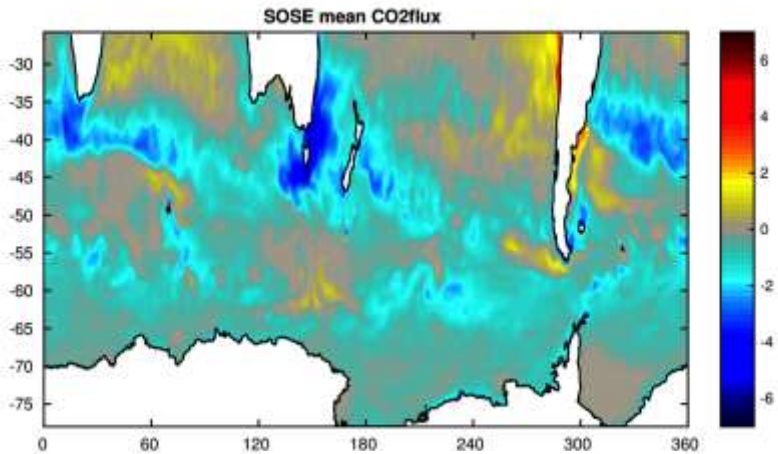
mol C m^{-2} yr^{-1}

- Takahashi inferred ocean to atmosphere flux in ACC; atmosphere-to-ocean flux to north

http://sose.ucsd.edu

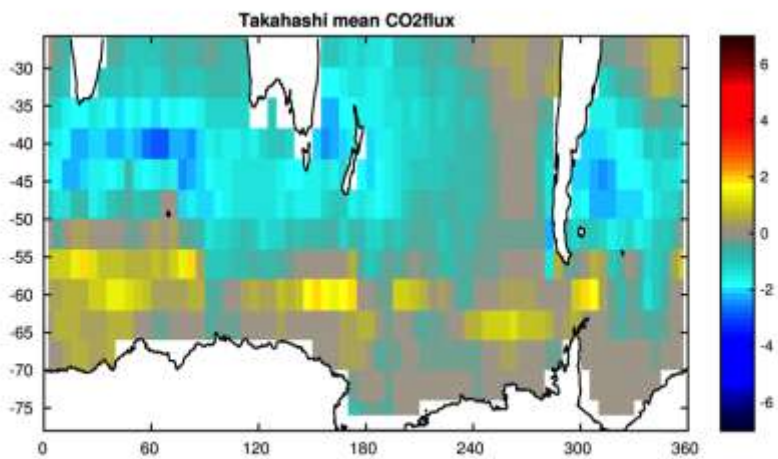
SOCCOM approach #1: assimilate data into Southern Ocean State Estimate + Biology Light Iron Nutrient and Gas model

SOSE, annual average (2008-2012)



Takahashi annual mean

mol C m^{-2} yr^{-1}

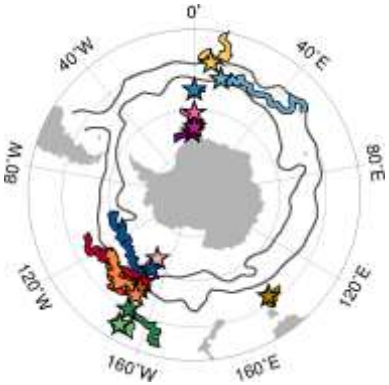


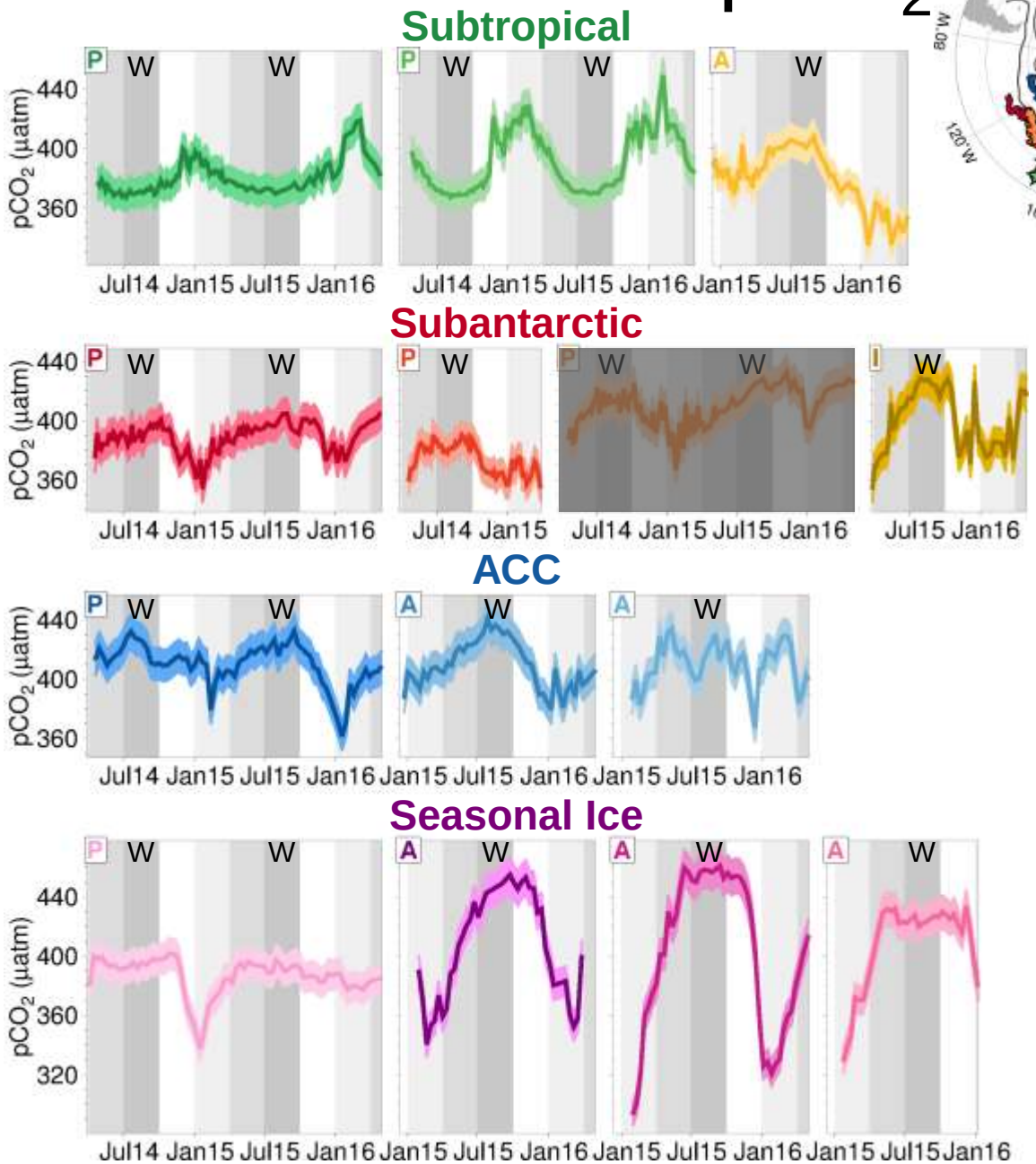
mol C m^{-2} yr^{-1}

- Annual average CO2 flux into ocean in SOSE+BLING
- Significant eddy-scale structure in 5-year mean
- Flux into ocean opposite results inferred by Gray et al from floats

- Takahashi inferred ocean to atmosphere flux in ACC; atmosphere-to-ocean flux to north

SOCCOM #2: FLOAT-BASED pCO_2





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

Alkalinity estimated using multiple linear regression

Carter et al. 2016

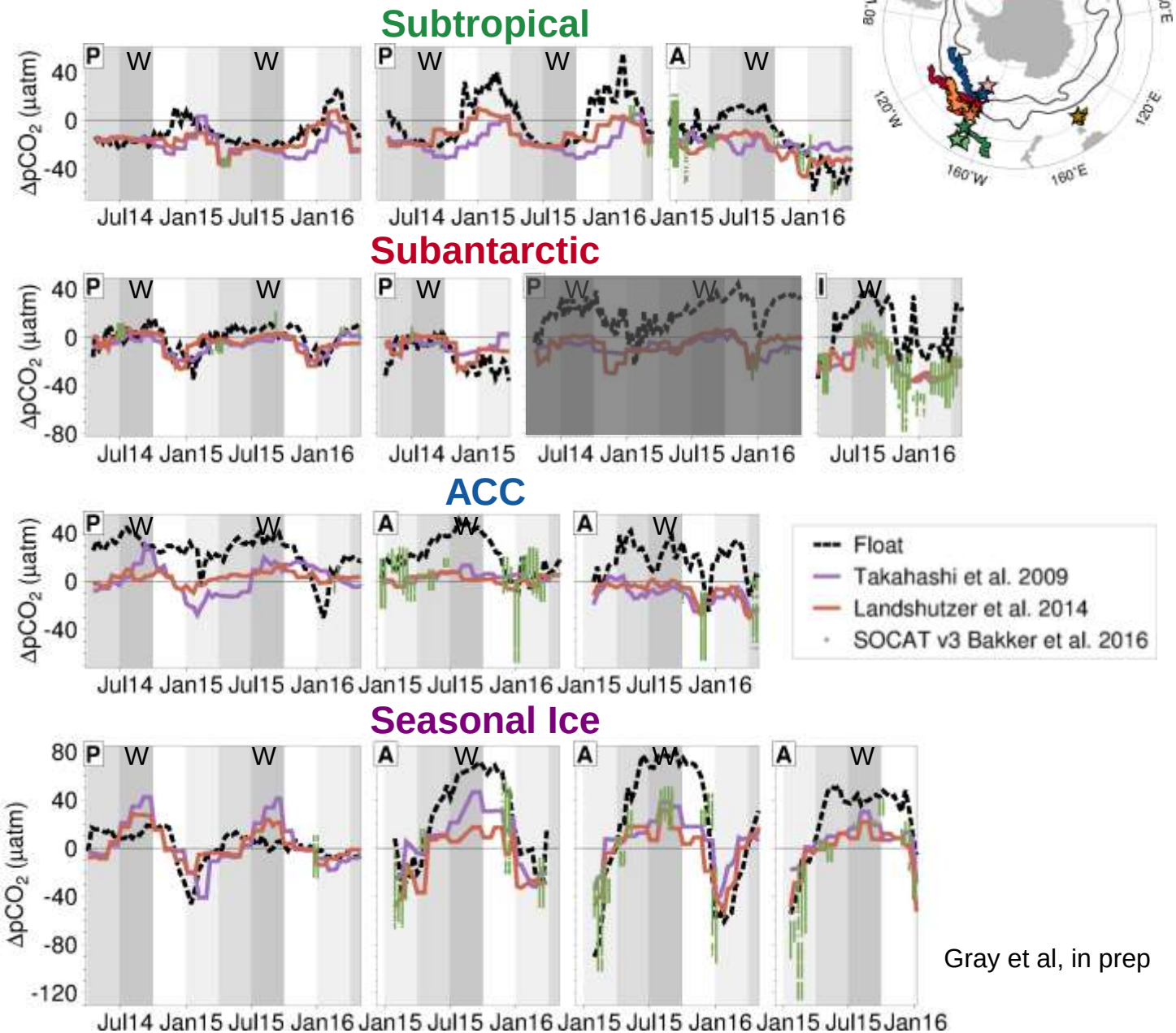
Gray et al, in prep

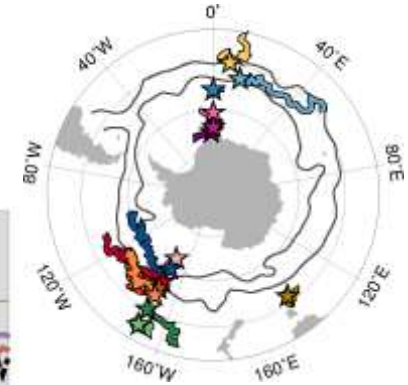
$\Delta pCO_2 = pCO_2^{ocn} - pCO_2^{atm}$

pCO_2^{atm} from Cape Grim observations

Float-based estimates compare well to in situ data when available

Larger disagreements at higher latitudes and in winter





Gray et al, in prep

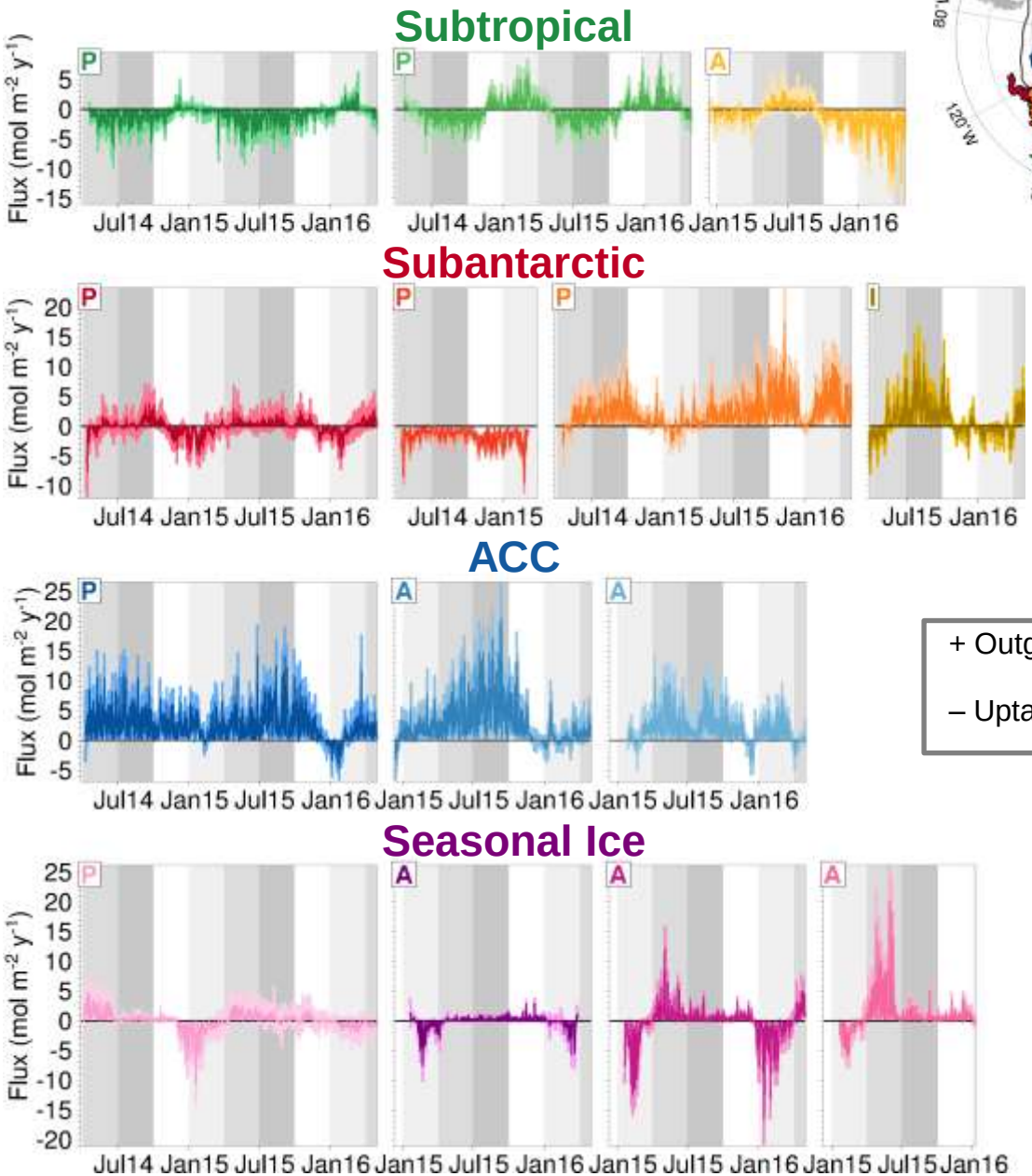
FLOAT-BASED AIR-SEA CO_2 FLUX

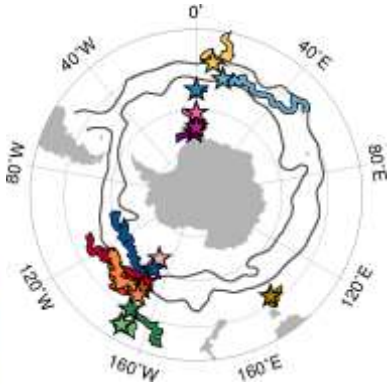
Gas transfer velocity, wind speed squared

Wanninkhof 2014

6-hourly ERA-Interim winds

solubility constant





+ Outgassing

– Uptake

ANNUAL NET OCEANIC CO_2 UPTAKE

Region south of 35°S

+ Outgassing – Uptake

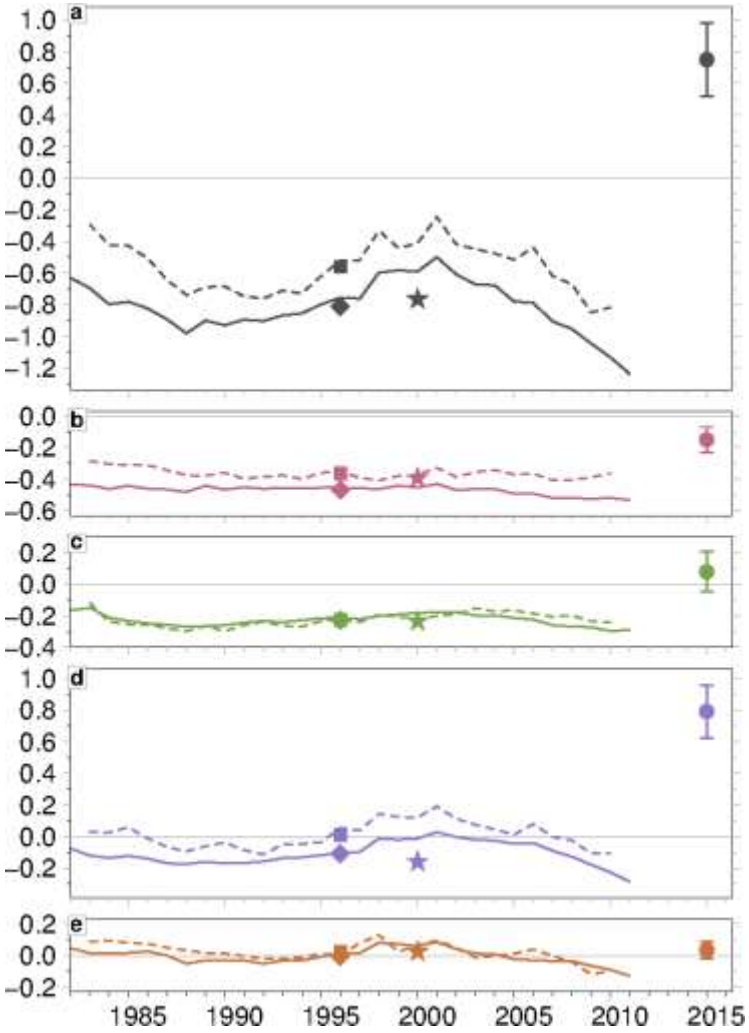
Total

Subtropical

Subantarctic

ACC

Seasonal Ice



This estimate

Takahashi et al. 2009

Landschutzer et al. 2014

Landschutzer et al. 2014 subsampled

Inference from float-based analysis: Southern Ocean CO_2 flux to atmosphere is greater than previous estimates

Hypothesis 1: Methodology

Hypothesis 2: Climatological baseline should have a stronger Southern Ocean source of CO_2.

Hypothesis 3: 2014-present is anomalous.

Inference from float-based analysis: Southern Ocean CO_2 flux to atmosphere is greater than previous estimates

Hypothesis 1: Methodology

Small number of floats, but results otherwise robust

Hypothesis 2: Climatological baseline should have a stronger Southern Ocean source of CO_2.

Would require source to balance climatological outgassing in floats

Hypothesis 3: 2014-present is anomalous.

ENSO-related shifts in wind and CO_2 concentrations?

Summary and Open Questions

	Large scale	Eddy scale
Q_{net}	Ocean heat content from **Argo** consistent with seasonal cycle of air-sea heat flux; long-term imbalance implies 0.5 Wm^{-2} input	Mechanisms governing fluxes need focused approach; targeted by **SOOS Working Group** on Air-Sea fluxes; *moorings, satellite data, wave gliders?*
CO_2 flux	**SOCCOM** designed for this. Biology plays a role, so change in CO_2 content doesn't imply CO_2 flux. Estimates from SOSE and from floats not in agreement. *More floats? Global?*	Infer fluxes from **SOCCOM** floats? Also an objective for **SOOS Working Group,** but measurement methods and requirements will need discussion.

What would be transformative?

- Global biogeochemical Argo *(proposal to MacArthur Foundation "100 & Change" competition: $100 million for 1000 floats, assuming partner contributions)*
- New (low-cost) sensors for BGC Argo? *(pCO2, total alkalinity, or total DIC?)*
- In situ process studies resolving eddy-scale fluxes of heat and gases *(flux covariance measurements to cover parameter space)*
- More global pCO_2 observations + BGC Argo *(constraints for state estimate)*

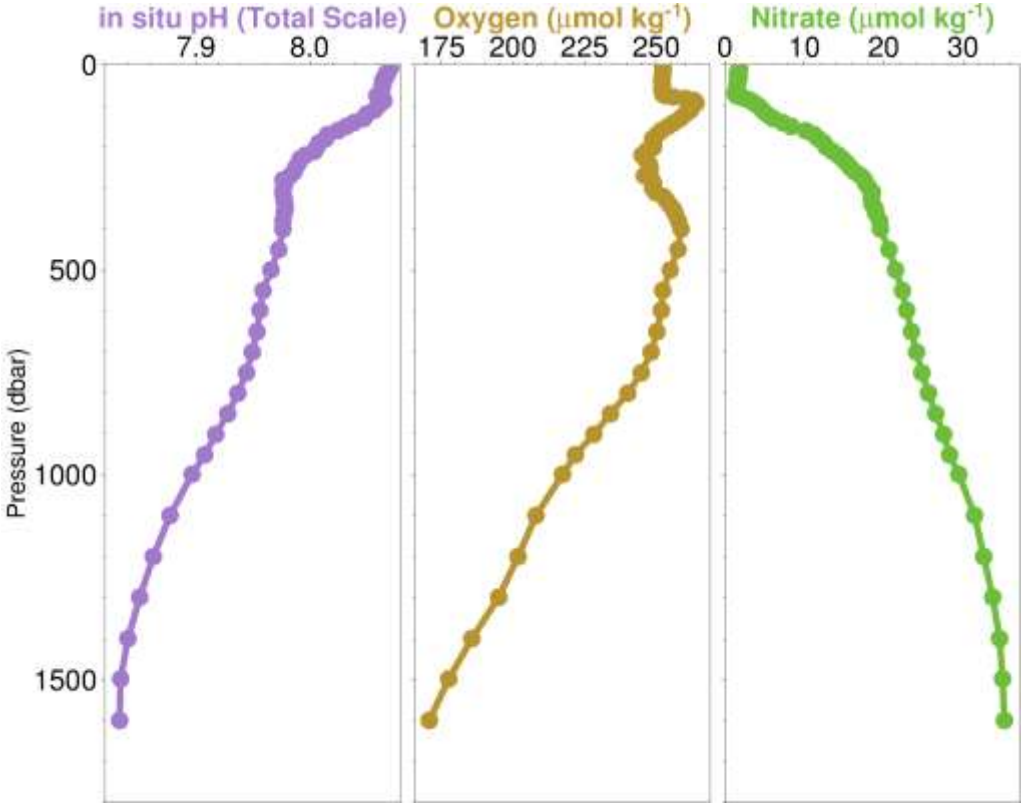
BIOGEOCHEMICAL PROFILING FLOATS

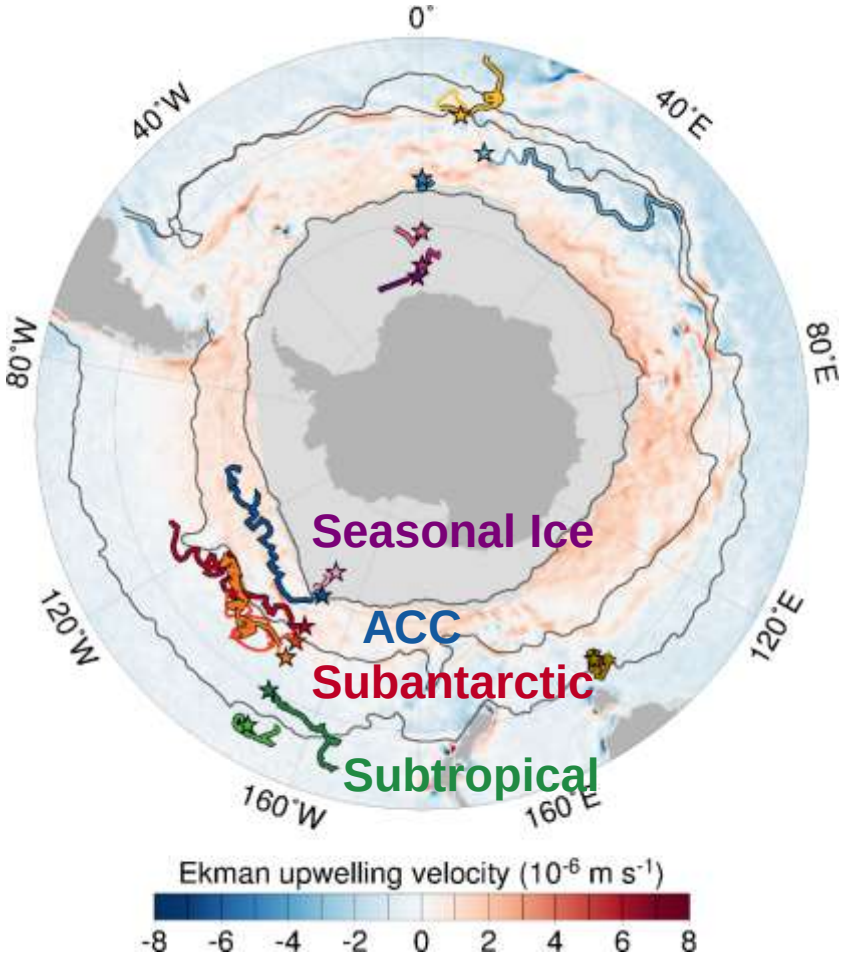
14 floats deployed by SOCCOM project with > 1 year of data

pH Martz et al. 2010, Johnson et al. 2016

O_2 Tengberg et al. 2006, Johnson et al. 2015

NO_3 Johnson et al. 2010, 2013



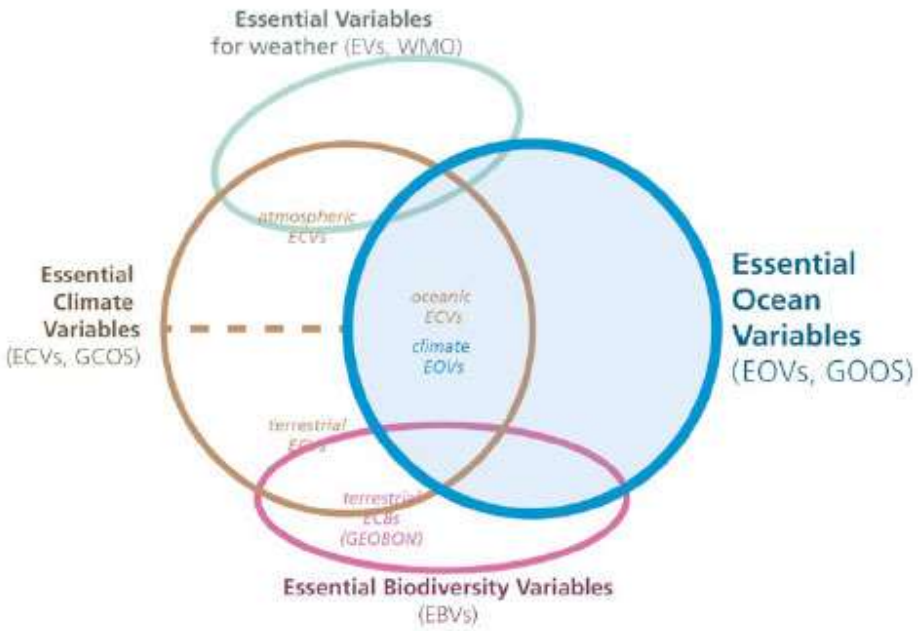


Based on QuikScat wind stress

Risien and Chelton, 2008

Challenges to in situ observing: Constraints of ECVs and EOVs

- **Essential Climate Variables (ECVs):** Global Climate Observing System (GCOS) defines---must be feasible and required for IPCC/UNFCC.
- **Essential Ocean Variables (EOVs):** Global Ocean Observing System (GOOS):
- *vector wind stress* (new, also ECV)
- *sensible/latent fluxes* (proposed)
- *shortwave/longwave* (under discussion)



http://ioc-goos-oopc.org/obs/