Heat and carbon air-sea exchange in the Southern Ocean

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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

\[ Q_{\text{net}} \] 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

- $Q_{\text{net}}$ 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

3739 Floats
6-Sep-2016
Argo float 10-day cycle

6 - 12 hours at surface to transmit data to satellite

Descent to depth
~10 cm/s (~6 hours)

1000 db (1000m)
Drift approx. 9 days

Total cycle time 10 days

Salinity & Temperature profile recorded during ascent
~10 cm/s (~6 hours)

Float descends to begin profile from greater depth
2000 db (2000m)
Schematic Framework: Upper Ocean Heat Balance

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

Dong et al. 2007
Seasonal cycle: Mixed-Layer Heat Budget (40-60S)

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

- 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)

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

\[ \int_0^z \rho c_p \frac{\partial T(z)}{\partial t} \, dz = Q_{net} + \text{Other} \]

- 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)

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

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- Top 200 m or top 1000 m: Upper ocean temperatures from Roemmich and Gilson Argo-based climatology, weighted by Holte mixed-layer climatology.
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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

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

Mooring (SOFS or OOI)

Wave glider or ship surveys to measure regional flux variability on eddy scales.

Southern Ocean eddy (30–60 km scale)
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 $O(0.5 \text{ W m}^{-2})$
- Additional observations needed to infer impact of eddies and fronts on fluxes

Beyond heat: Inferring carbon fluxes from floats?

**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): Argo floats augmented for biogeochemistry:

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

Plus

- Temperature
- Salinity
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

- August CO$_2$ flux mostly into ocean in SOSE+BLING

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

SOSE, August average (2008-2012)

Takahashi August mean

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)

- 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

mol C m⁻² yr⁻¹

mol C m⁻² yr⁻¹
SOCCOM #2: FLOAT-BASED pCO$_2$

Subtropical

Subantarctic

ACC

Seasonal Ice

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

Alkalinity estimated using multiple linear regression

Carter et al. 2016

Gray et al., in prep
\[ \Delta pCO_2 = pCO_2^{\text{ocn}} - pCO_2^{\text{atm}} \]

\( pCO_2^{\text{atm}} \) 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

Subtropical

Subantarctic

ACC

Seasonal Ice

+ Outgassing
– Uptake
ANNUAL NET OCEANIC CO$_2$ UPTAKE
Region south of 35°S

This estimate
Takahashi et al. 2009
Landschutzer et al. 2014

Subtropical
Subantarctic
ACC
Seasonal Ice

Total

+ Outgassing  – Uptake

subsampled
INFERENCES FROM FLOAT-BASED ANALYSIS:
SOUTHERN OCEAN CO₂ FLUX TO ATMOSPHERE IS GREATER THAN PREVIOUS ESTIMATES

Hypothesis 1: Methodology

Hypothesis 2: Climatological baseline should have a stronger Southern Ocean source of CO₂.

Hypothesis 3: 2014-present is anomalous.
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

<table>
<thead>
<tr>
<th>( Q_{\text{net}} )</th>
<th>Large scale</th>
<th>Eddy scale</th>
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<tbody>
<tr>
<td>Ocean heat content from <strong>Argo</strong> consistent with seasonal cycle of air-sea heat flux; long-term imbalance implies 0.5 Wm(^{-2}) input</td>
<td>Mechanisms governing fluxes need focused approach; targeted by <strong>SOOS Working Group</strong> on Air-Sea fluxes; <em>moorings, satellite data, wave gliders?</em></td>
<td>( \text{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. <em>More floats? Global?</em></td>
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<tr>
<td>CO(_2) flux</td>
<td>Infer fluxes from <strong>SOCCOM</strong> floats?</td>
<td>Also an objective for <strong>SOOS Working Group</strong>, but measurement methods and requirements will need discussion.</td>
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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 pCO₂ 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
- **O₂** Tengberg et al. 2006, Johnson et al. 2015
- **NO₃** 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/