Observing the carbon cycle in the Southern Ocean from biogeochemical floats with pH sensors

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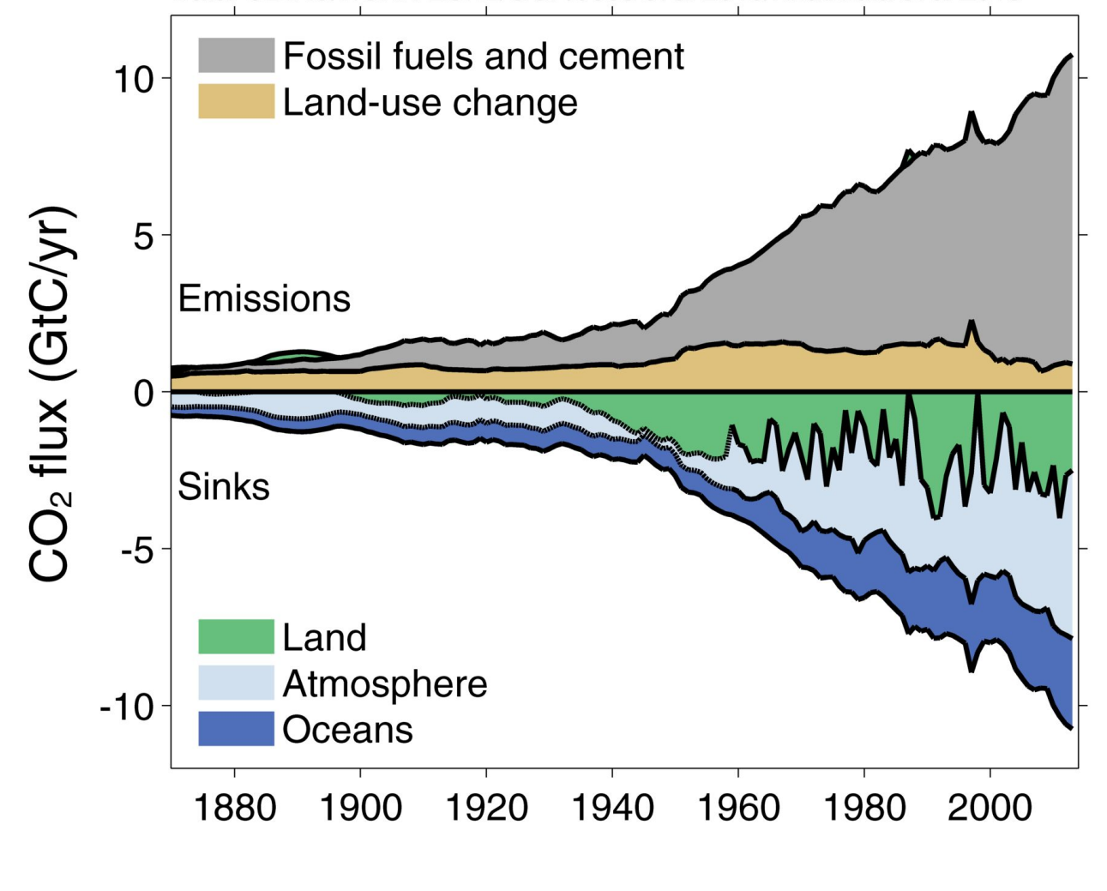
SOCCOM
Southern Ocean Carbon and Climate Observations and Modeling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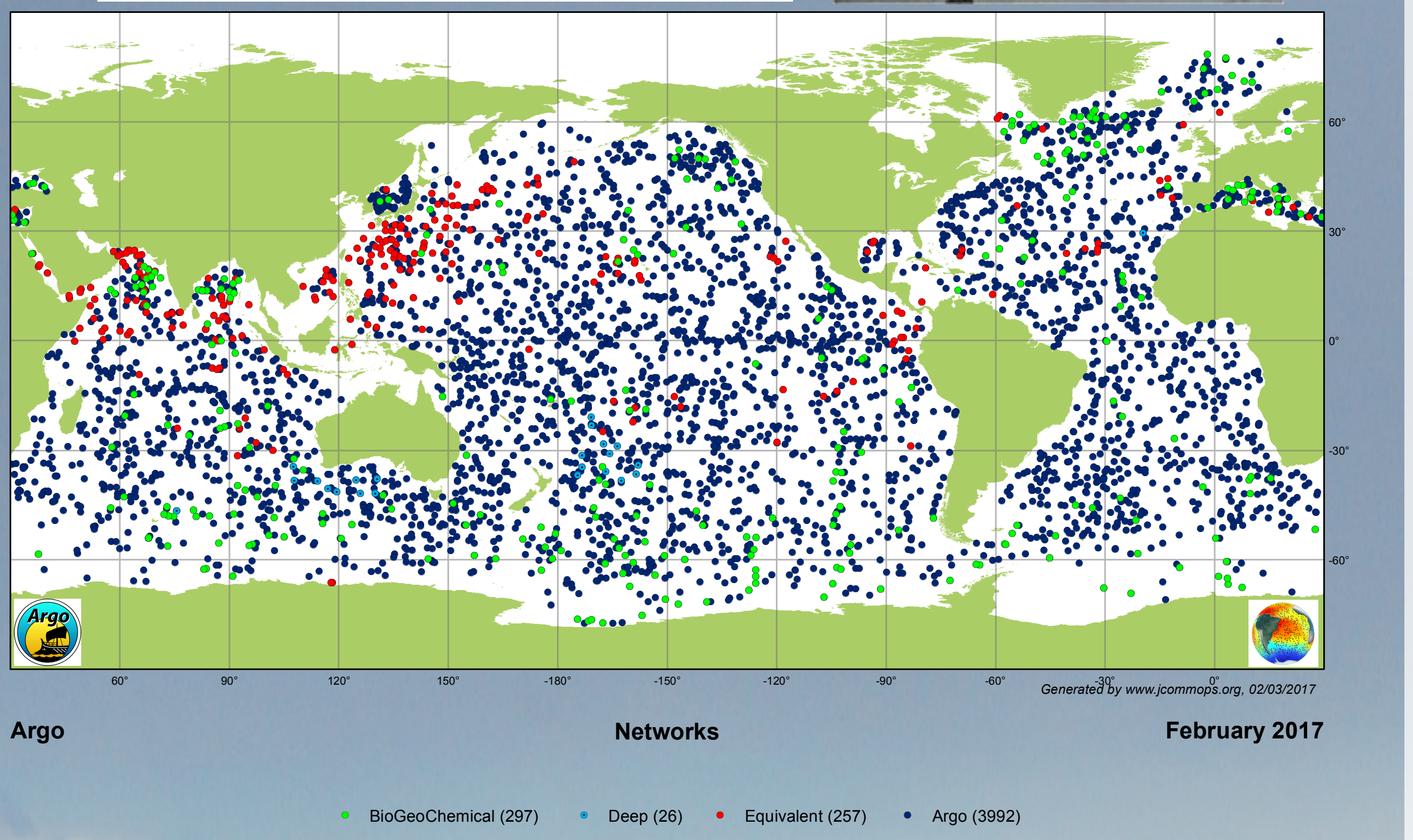
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Overview of SOCCOM

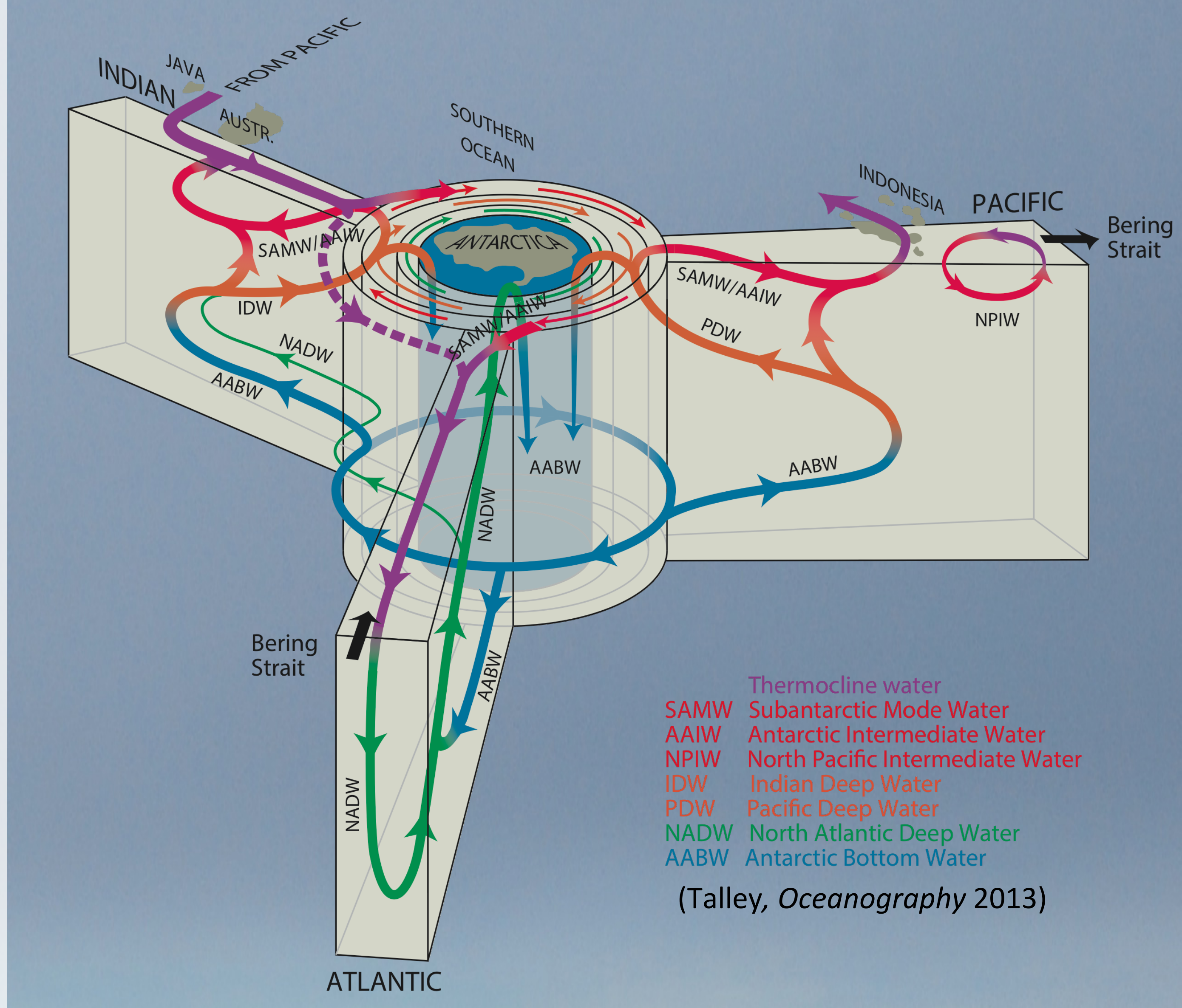
The Southern Ocean plays a major role in the global carbon cycle by accounting for around half of the overall ocean carbon sink yet it is relatively undersampled and not well-represented in climate models. The Southern Ocean Carbon and Climate Observations and Modeling (SOCCOM) project aims to fill this observational gap by deploying 200 autonomous biogeochemical profiling floats in the Southern Ocean over 5 years. Now in year 3, there are over 75 floats in the water and reporting data back every 10 days (green dots in the Southern Ocean in the map to the left). These data are publicly available and are quality controlled in near-real time.

What is a SOCCOM float?

A SOCCOM float, pictured at left, is an autonomous profiling float that measures temperature (T) and salinity (S) and carries the following additional biogeochemical sensors:

- Deep Sea DuraFET (Johnson et al. 2016)
- ISUS UV Nitrate (Johnson et al. 2013)
- WETLabs FLBB backscattering and chlorophyll (Boss et al., 2008))
- Aanderaa or Seabird oxygen optode (Tengberg et al., 2006)

A SOCCOM float is generally set to "park" at 1000 m depth, drifting with the currents until, every 10 days, it descends to 2000 m, turns on its sensors, and then ascends to the surface taking measurements along the way. When the float reaches the surface it transmits the profile data back to a data center via satellite before descending back to its park depth. These floats are ice-enabled, meaning that they can safely sample under seasonal sea ice and report their data when the ice opens in spring.



	Thermocline water
SAMW	Subantarctic Mode Water
AAIW	Antarctic Intermediate Water
NPIW	North Pacific Intermediate Water
IDW	Indian Deep Water
PDW	Pacific Deep Water
NADW	North Atlantic Deep Water
AABW	Antarctic Bottom Water

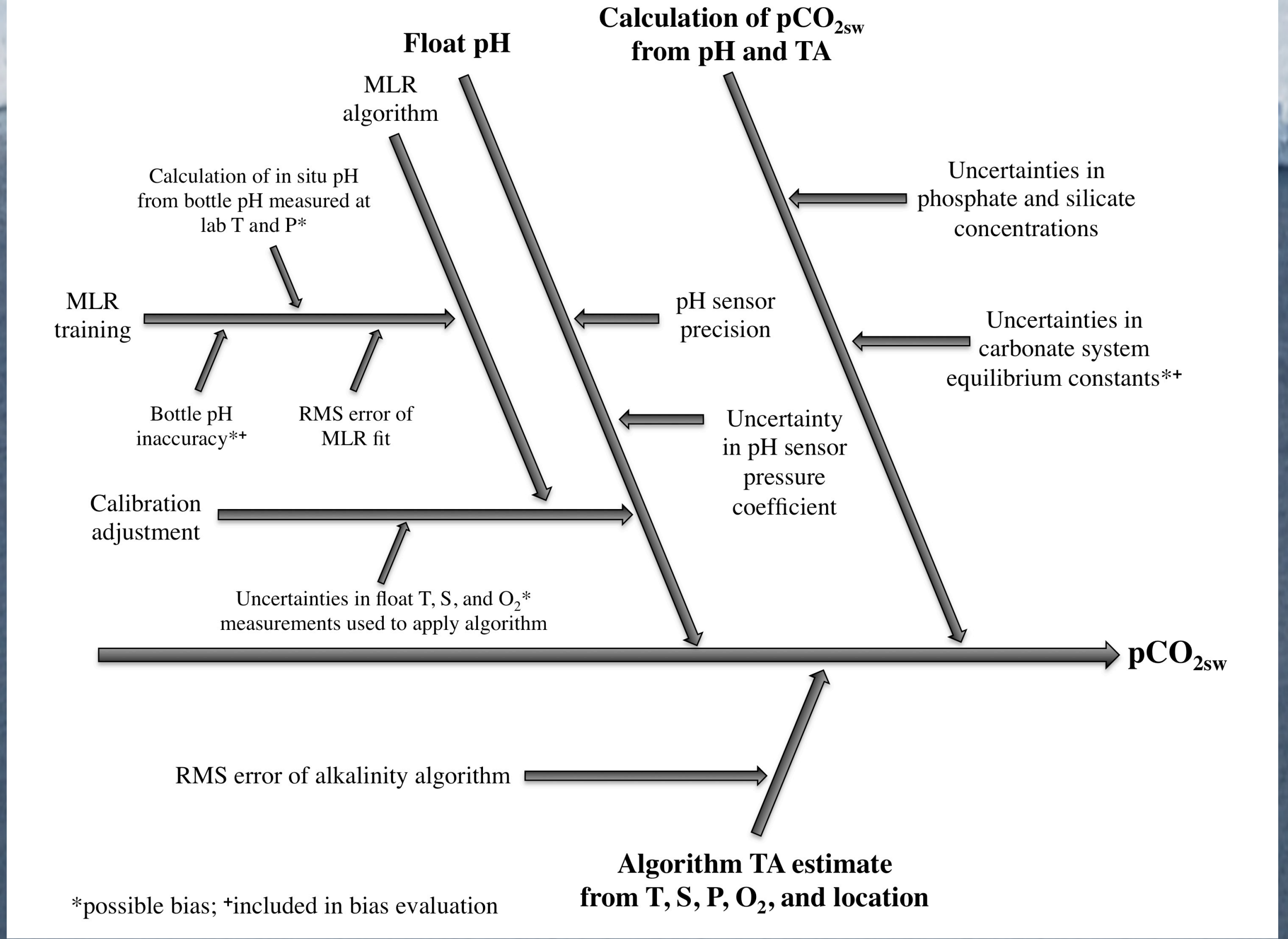
(Talley, *Oceanography* 2013)

How well can we calculate $pCO_{2seawater}$ from float pH?

To calculate the flux of carbon dioxide between the atmosphere and the ocean we need to calculate the ΔpCO_2:

$$\Delta pCO_2 = pCO_{2seawater} - pCO_{2atmosphere}$$

A positive ΔpCO_2 implies that the ocean will release carbon to the atmosphere. A float-based estimate of $pCO_{2seawater}$ can be calculated using the float pH measurements and an estimate for total alkalinity (Carter et al., 2016). The uncertainty in float pCO_2 is 2.7% as compared to a 1% uncertainty in a traditional ship-based underway measurement. This uncertainty was estimated using a careful analysis of uncertainties from three main sources: the float pH measurement, the alkalinity estimate, and the calculation of pCO_2 from pH and TA, as summarized in the fishbone diagram below.



Float pH

Calculation of pCO_{2sw} from pH and TA

MLR algorithm

Calculation of in situ pH from bottle pH measured at lab T and P*

Uncertainties in phosphate and silicate concentrations

MLR training

pH sensor precision

Uncertainties in carbonate system equilibrium constants*⁺

Bottle pH inaccuracy*⁺

RMS error of MLR fit

Uncertainty in pH sensor pressure coefficient

Calibration adjustment

Uncertainties in float T, S, and O_2* measurements used to apply algorithm

pCO_{2sw}

RMS error of alkalinity algorithm

Algorithm TA estimate from T, S, P, O_2, and location

*possible bias; ⁺included in bias evaluation

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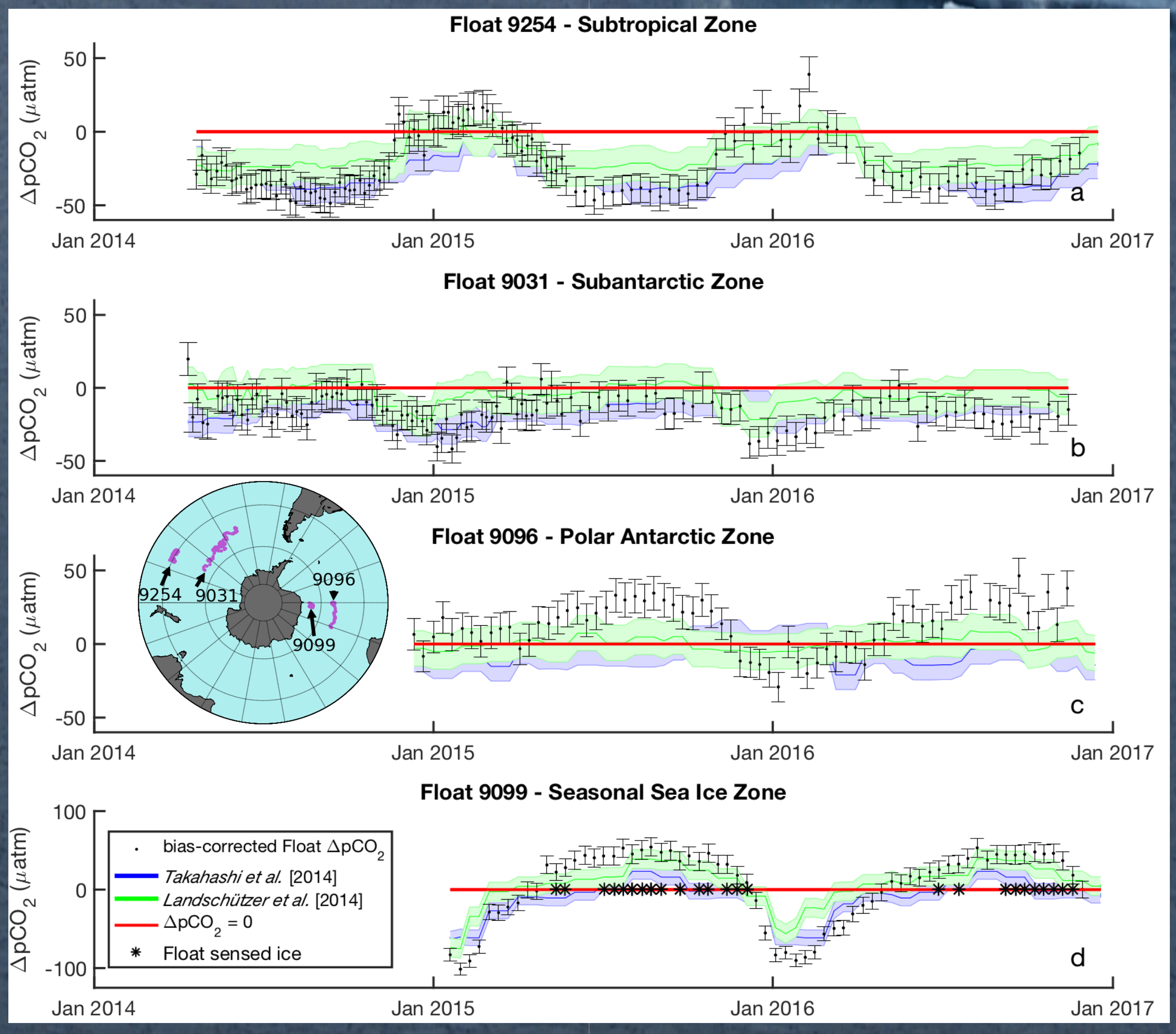
Results

While float-based calculated $pCO_{2seawater}$ is inherently more uncertain than most ship- or mooring-based $pCO_{2seawater}$ measurements, a well-calibrated array of biogeochemical floats can complement the existing global dataset by providing a seasonal context to regions where wintertime measurements are sparse. The figure below shows ΔpCO_2 from four floats each representing one of four major Southern Ocean frontal zones. In the Polar Antarctic Zone (panel c) and in the Seasonal Sea Ice Zone (panel c) the floats (black dots) see significantly higher ΔpCO_2 (leading to more carbon flux out of the ocean) than either the Takahashi et al. (2014) or the Landschützer et al. (2014) climatology (blue and green lines, respectively).

The climatologies tend to agree with the floats within their respective uncertainties during the austral summer when there are significantly more underway $pCO_{2seawater}$ data to create the climatology. Large disagreements arise when there are no suitable data to constrain the climatology, such as austral winter (see lack of measurements in panel b in the figure to the right) and in ice-covered waters. This disagreement is not surprising, considering (1) the limited availability of austral winter and under ice observations to compute the climatologies and (2) the $pCO_{2seawater}$ climatologies are based on climatological sea ice cover, which may differ from float observations.


Float 9254 - Subtropical Zone

Float 9031 - Subantarctic Zone

Float 9096 - Polar Antarctic Zone

Float 9099 - Seasonal Sea Ice Zone

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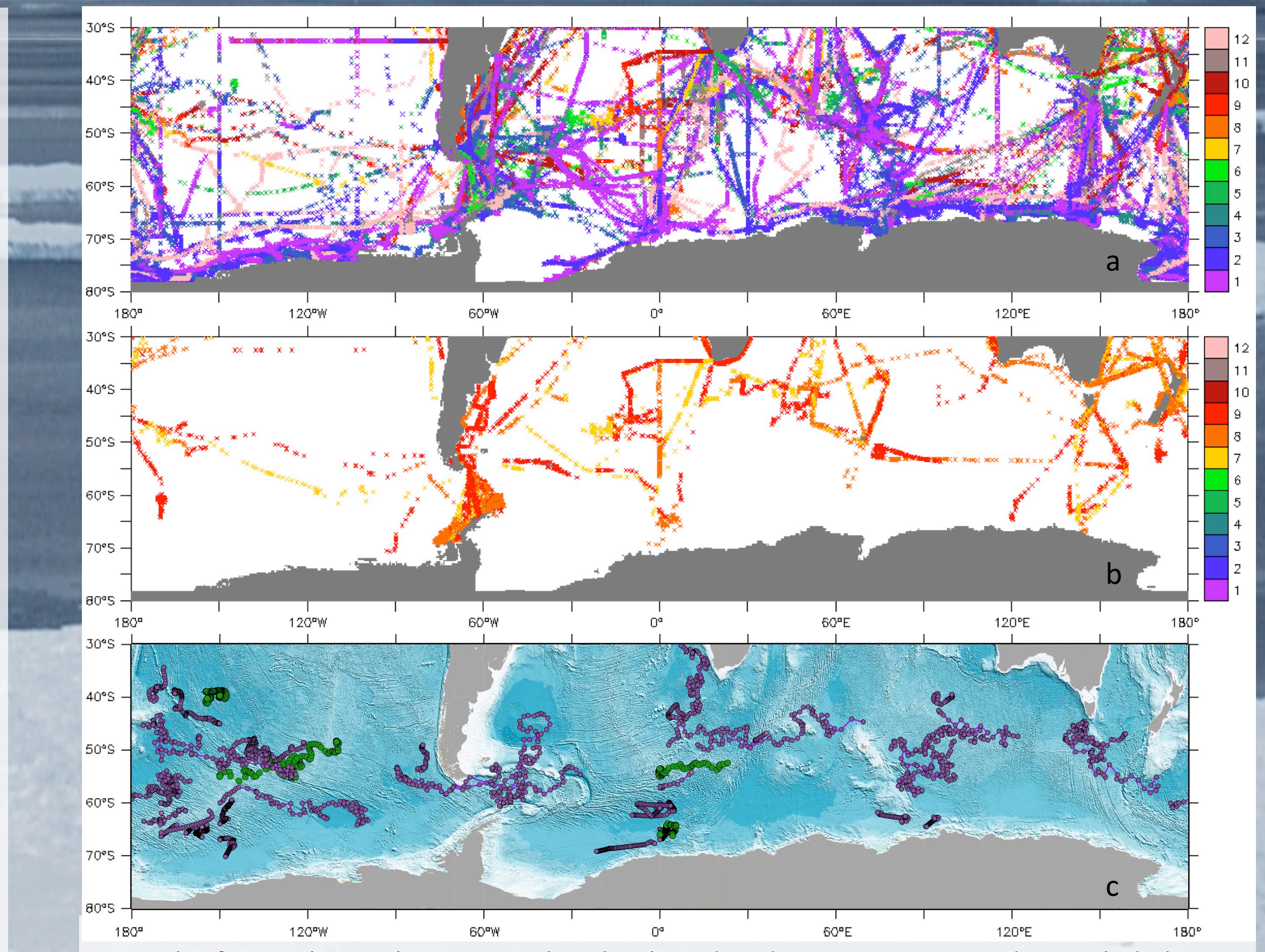

In the figure above, the top panel is ship-based underway $pCO_{2seawater}$ data included in the SOCAT (Surface Ocean CO_2 Atlas, Bakker et al., 2016) database from all years colored by month. The middle panel shows all SOCAT data from austral winter (July, August, September) and the bottom panel shows the locations of the SOCCOM floats as of January 2017.

Conclusions

Ongoing shipboard and moored observation programs show that the $pCO_{2seawater}$ is increasing globally as a result of anthropogenic emissions. Nonetheless, our current understanding of the seasonal cycle and interannual variability, and thus the mechanisms controlling $pCO_{2seawater}$ and air-sea CO_2 flux, is lacking over many parts of the world ocean. Despite the estimated 2.7% relative standard uncertainty in current biogeochemical float- based $pCO_{2seawater}$ (pH, TA) estimates, it is clear from the differences between existing climatologies and new float pH-based $pCO_{2seawater}$ (pH, TA) estimates that incorporating information from these novel carbon observational platforms can improve climatologies, climate models, and future projections. While true space/time cross-overs between biogeochemical floats and shipboard pCO_2 systems are rare, and spatial and temporal heterogeneity make direct comparisons difficult, we have shown that a well-calibrated biogeochemical float provides meaningful data that strengthen the current body of $pCO_{2seawater}$ observations.

Acknowledgments

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