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Utilizing the Drake Passage Time-series to understand variability and change in subpolar Southern Ocean pCO_2

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Abstract

The Southern Ocean is highly under-sampled for the purpose of assessing total carbon uptake and its variability. Since this region dominates the mean global ocean sink for anthropogenic carbon, understanding temporal change is critical. Underway measurements of pCO_2 collected as part of the Drake Passage Time-series (DPT) program that began in 2002 inform our understanding of seasonally changing air-sea gradients in pCO_2, and by inference the carbon flux in this region. Here, we utilize all available pCO_2 observations collected in the subpolar Southern Ocean to evaluate how the seasonal cycle, interannual variability, and long-term trends in surface ocean pCO_2 in the Drake Passage region compare to that of the broader subpolar Southern Ocean. Our results indicate that the Drake Passage is representative of the broader region in both seasonality and long term pCO_2 trends shown through the agreement of timing and amplitude of seasonal cycles as well as trend magnitudes. The high temporal density of sampling by the DPT is critical to constraining estimates of the seasonal cycle of surface pCO_2 in this region, as winter data remain sparse in areas outside of the Drake Passage. From 2002-2015, data show that carbon uptake has strengthened with surface ocean pCO_2 trends less than the global atmospheric trend in the Drake Passage and the broader subpolar Southern Ocean. Analysis of spatial correlation shows Drake Passage pCO_2 to be representative of pCO_2 and its variability up to several hundred kilometers upstream of the region. We also compare DPT data from 2016 and early 2017 to contemporaneous pCO_2 estimates from

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autonomous biogeochemical floats deployed as part of the Southern Ocean Carbon and Climate Observations and Modeling project (SOCCOM) so as to highlight the opportunity for evaluating data collected on autonomous observational platforms. Though SOCCOM floats sparsely sample the Drake Passage region for 2016-2017, their pCO_2 estimates typically fall within the range of underway observations. Going forward, continuation of the Drake Passage Time-series will reduce uncertainties in Southern Ocean carbon uptake seasonality, variability, and trends, and provide an invaluable independent dataset for post-deployment quality control of sensors on autonomous floats. Together, these datasets will vastly increase our ability to monitor change in the ocean carbon sink.

1. Introduction

The Southern Ocean plays a disproportionately large role in the global carbon cycle. Over the past few decades, the ocean has absorbed approximately 26% of the carbon dioxide (CO_2) emissions from fossil fuel burning and land use change [Le Quéré et al., 2016, 2017], and since the preindustrial era, the ocean has been the primary sink for anthropogenic emissions [McKinley et al. 2017; Ciais et al., 2013]. The Southern Ocean (south of 30°S) accounts for almost half of the total oceanic sink of anthropogenic CO_2 [Frölicher et al. 2015; Gruber et al. 2009; Takahashi et al. 2009]. Though the importance of this region is widely understood, the scarcity of surface ocean carbon-related observations in the Southern Ocean hampers our ability to understand how this anthropogenic CO_2 uptake occurs against the background of natural variability.

Observations and models suggest large variability in the strength of Southern Ocean CO_2 uptake on decadal timescales. Several studies have reported a slow-down or reduction in the efficiency of Southern Ocean CO_2 uptake from the 1980's to the early 2000's [Le Quéré et al. 2007; Lovenduski et al. 2008; Metzl 2009; Takahashi et al. 2012; Fay and McKinley, 2013; Lovenduski et al. 2015; Landschützer et al. 2014a, 2015a], followed by a substantial strengthening of the Southern Ocean CO_2 sink since 2002 [Fay and McKinley, 2013; Fay et al. 2014; Landschützer et al. 2015a; Munro et al. 2015a; Xue et al. 2015]. Continued observational sampling efforts and coordination are required for quantifying and understanding decadal changes in this important CO_2 sink region.

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Initiated in 2002 and continuing to present, the Drake Passage Time-series (DPT) is unique among Southern Ocean research programs in both its spatial and temporal coverage. High-frequency underway observations of the surface ocean partial pressure of CO_2 (pCO_2) are collected on the Antarctic Research and Supply Vessel *Laurence M. Gould* on up to 20 crossings per year from the southern tip of South America to the Antarctic Peninsula, spanning the Antarctic Circumpolar Current (ACC) and its associated Antarctic Polar Front [Munro et al. 2015a, 2015b]. The DPT is also notable for sampling surface ocean pCO_2 during the austral winter in all years from 2002 to present, providing valuable information about the full seasonal cycle of pCO_2 in the poorly sampled Southern Ocean. Other ships have contributed observations in the Drake Passage region including the *Polarstern* and the *Nathaniel B. Palmer*, however none have the consistent temporal coverage as provided by the DPT.

The surface ocean pCO_2 observations from the DPT have provided the foundation for larger data sets, which have been extensively used to examine variability and trends in CO_2 uptake in the broader Southern Ocean [Fay and McKinley, 2013; Fay et al. 2014; Majkut et al. 2014; Landschützer et al. 2014b, 2015b; Rödenbeck et al. 2015]. In many of these studies, interpolated estimates of Southern Ocean pCO_2 are used in conjunction with measurements of atmospheric pCO_2 to estimate variability and trends in the air-sea pCO_2 gradient and when combined with wind speed, air-sea CO_2 fluxes.

The physical oceanography of the Drake Passage region is unique in the Southern Ocean. Here, the strong flow of the zonally unbounded ACC is funneled through a narrow constriction (~800 km), making it an ideal location for sampling across the entire ACC system over a relatively short distance [Sprintall et al. 2012]. At the same time, the unique nature of the circulation could potentially reduce the degree to which the Drake Passage region is representative of the broader region. The DPT program takes advantage of frequent *Gould* crossings to conduct physical and biogeochemical sampling of the ACC system. Thus, before conclusions can be drawn about large-scale Southern Ocean carbon uptake and its variability using data from the DPT, it is important to document how pCO_2 in this particular region compares with pCO_2 measured elsewhere in the subpolar Southern Ocean. In this study, we utilize all available pCO_2

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observations collected in the subpolar Southern Ocean to evaluate how the seasonal cycle, interannual variability, and long-term trends in surface ocean pCO_2 in the Drake Passage region compare to that of the broader subpolar Southern Ocean. Further, we highlight the opportunity for quality control of autonomous observational platforms passing through the Drake Passage utilizing the underway pCO_2 measurements from the DPT.

2. Data

This study uses several observational datasets and data products of surface ocean pCO_2 in the Southern Ocean: measurements from the Surface Ocean CO_2 Atlas (SOCAT), which includes underway measurements from the DPT, interpolated estimates of the SOCAT data using a self-organizing map feed-forward neural network (SOM-FFN) approach, and calculated pCO_2 estimates from biogeochemical Argo floats. While the SOCAT database reports the fugacity of carbon dioxide (fCO_2), for our analysis we consider datasets reporting pCO_2 and fCO_2 to be interchangeable which is an acceptable assumption for surface ocean observations as CO_2 behaves closely to an ideal gas. Globally, the difference between these parameters is less than 2μatm, which is roughly the reported uncertainty of shipboard observations of pCO_2 and well within the uncertainty of the observation-based pCO_2 estimates. Below, we describe each of these data sources in turn.

2.1 The Drake Passage Time-series (DPT)

A unique dataset of ongoing year-round observations beginning in 2002 is available from the Drake Passage Time-series (DPT), providing an unprecedented opportunity to characterize the mean and time varying state of the Drake Passage and the surrounding waters using direct observations. This dataset includes high frequency underway observations of surface ocean pCO_2, in addition to other physical and biogeochemical variables including discrete measurements of total CO_2 (TCO_2) which, together with pCO_2 and nutrients, allow a complete understanding of the carbonate system in the DPT. Analytical methods used to measure pCO_2, as well as the methods used to calculate nutrient and carbonate parameters are described in detail by Munro et al. [2015a, 2015b].

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2.2 Surface Ocean CO_2 Atlas (SOCAT)

SOCAT is a global surface ocean carbon dataset of fCO_2 values (pCO_2 corrected for the non-ideal behavior of CO_2) starting in 1957 [Sabine et al. 2013; Pfeil et al. 2013]. In this study we utilize version 4 of this product (SOCATv4), which includes roughly 18.5 million observations globally [Bakker et al., 2016], including 737,000 observations contributed from the DPT. Despite the large number of observations available in the Southern Ocean, data is spatially and temporally concentrated, with strong seasonal biases. Most data is collected during reoccupations of supply routes to Antarctic bases or on repeat hydrographic lines, which leaves large bands of the Southern Ocean completely unsampled [Bakker et al. 2016].

2.3 Self-organizing Map Feed-forward Network Product (SOM-FFN)

Landschützer et al. [2014b] use a two-step neural network approach to extrapolate the monthly gridded SOCAT product in space and time. This results in reconstructed basin-wide monthly maps of the sea surface pCO_2 at a resolution of 1° × 1° [Landschützer et al. 2017]. Air–sea CO_2 flux maps are then computed using a standard gas exchange parameterization and high-resolution wind speeds. The neural network estimate is described and substantially validated in past publications [Landschützer et al. 2014, 2015a, 2016] and it was shown that the estimates fit observed pCO_2 data in the Southern Ocean with a root mean square error (RMSE) of about 20 µatm and with almost no bias [Landschützer et al. 2015a, supplementary material].

The SOM-FFN product used in this analysis is created from SOCATv4. Additionally, we generated an alternative SOM-FFN product (SOM-FFN-noDP) using the same methodological setup but excluding the pCO_2 data collected in the Drake Passage region for years 2002-2015, which represents the years of the DPT program.

2.4 SOCCOM Floats

The Southern Ocean Carbon and Climate Observations and Modeling (SOCCOM) project (http://soccom.princeton.edu) aims to deploy approximately 200 biogeochemical profiling floats over a five-year period (2015 to 2020) in an effort to fill observational gaps in the Southern Ocean. In total, over

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90 floats carrying some combination of additional biogeochemical sensors (i.e., pH, nitrate, oxygen, fluorescence, and backscattering) have been collecting data since April 2014 [Johnson & Claustre, 2016]. With the float's capability to measure pH and utilization of existing algorithms for predicting total alkalinity, pCO_2 can be calculated from the collected observations [Williams et al. 2017] and compared to underway observations.

The uncertainty range for these calculated pCO_2 values is estimated to be ±11 µatm and results from various components of the calculation procedure [Williams et al. 2017]. pCO_2 estimates from autonomous floats such as the SOCCOM floats have not been included in the SOCAT database because they do not report original surface water CO_2 data. For consistency, we maintain this separation in our analysis and limit our study of SOCCOM floats to direct comparisons to DPT values in Section 5.

3. Methods

The SOCATv4 database sub-sampled from 2002-2015 is considered here to match the years of overlap with DPT observations, which began in 2002. The SOCAT dataset is then subsampled to include only observations with reported salinity values in the 33.5 - 34.5 psu range and a distance-to-land value greater or equal to 50 km. This step restricts our analysis to open-ocean observations, since coastal observations report lower salinity values, which correspond to low pCO_2 values, due to the influence of fresh water and ice melt. SOCCOM float files were downloaded on 26 September 2017 and reported pCO_2 values are an average of all data collected in the top 20m of water to remain consistent with previous SOCCOM float analysis (Williams et al. 2017).

The Southern Ocean region of interest is the Southern Ocean Subpolar Seasonally Stratified (SPSS) biome as defined in Fay and McKinley [2014] (Figure 1) as it encompasses the Drake Passage. We further define the Drake Passage region as the portion of the Southern Ocean SPSS biome bounded by 55°W and 70°W lines of longitude (Figure 1). This is similar to the region analyzed in Munro et al [2015a] however it extends the region of interest to the northern and southern extents of the SPSS biome.

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Alternate definitions of the larger Southern Ocean region of interest were considered during our analysis, including a subdivision of the SPSS into a Northern SPSS and Southern SPSS, with the boundary defined by the location of the mean position in the Antarctic Polar Front [Freeman and Lovenduski 2016; Freeman et al. 2016; Munro et al. 2015b], as well as the Polar Antarctic Zone [Williams et al. 2017] (Supplementary Figures 1-3). The overall conclusions remain largely unchanged when using these alternate regional definitions.

In order to compare the seasonal cycle and long-term trends in the Drake Passage with the broader SPSS biome, we analyze surface ocean pCO_2 from 3 subsets of the SOCAT database: SOCAT-all which includes all available SOCATv4 data from 2002-2015 in the SPSS biome, SOCAT-DP which includes SOCATv4 data within the longitudinally-defined Drake Passage region (Figure 1, with 62% of data this collected onboard the *R/V Gould*), and SOCAT-noDP which excludes any data within the longitudinally-defined Drake Passage region of the SPSS biome. All datasets are first averaged to monthly, 1^ox1^o resolution. Monthly means are then calculated for the SPSS biome by first removing the background mean climatological value of pCO_2 at each 1^ox1^o location [Landschützer et al. 2014a] to aid in accounting for the potential of spatial aliasing in the sparsely sampled Southern Ocean [Fay and McKinley, 2013].

Biome-scale monthly means are compared and used to calculate seasonal cycles and trends. Seasonal cycles are calculated by first removing a 1.95 μatm yr^{-1} trend to account for increasing atmospheric CO_2 during the 2002-2015 period [Dlugokencky et al. 2015]. Seasonal uncertainties (Figure 2) are estimated as 1 standard error from the mean of all available biome mean values for a given month. This is a conservative estimate of the uncertainty in any given month because of inconsistent annual coverage and spatial undersampling biases. Reported trends are calculated by fitting a single harmonic and linear trend to the biome-scale monthly means as done in Fay and McKinley [2013]. Trends are not statistically different if the calculated mean seasonal cycle is removed instead of the choice to fit a harmonic to the data. Seasonal trends are calculated with a simple linear fit to the seasonal monthly means.

4. Results and Discussion

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205 **4.1 Seasonal cycle**

The mean seasonal cycle of pCO_2 in the Southern Ocean SPSS biome for the 3 SOCAT datasets and the full SOM-FFN estimate indicate broad agreement (Figure 2). Here, surface ocean pCO_2 levels reach a maximum in austral winter (June to August), when deep mixing delivers carbon-rich water to the surface, and a minimum in austral summer (December to February), when biological production draws down the
210 inorganic carbon from the surface [Takahashi 2009]. Temperature also plays a role in modulating the pCO_2 seasonal cycle in the Southern Ocean. Winter cooling drives pCO_2 lower at the same time as deep winter mixing elevates surface carbon levels. During the summer, warming temperatures raise pCO_2 while biological utilization of carbon drives surface pCO_2 levels lower [Munro et al. 2015b]. The average amplitude of the detrended seasonal cycle of pCO_2 (max-min) is 23 µatm (Figure 2), smaller than the high
215 latitude oceans in the Northern Hemisphere [Takahashi et al. 2002, 2009; Landschützer et al. 2015b]. The small amplitude of the pCO_2 seasonal cycle in this region is due to the similar magnitude and opposite phasing of temperature and carbon supply/utilization effects. In all months, surface ocean pCO_2 levels in the Southern Ocean SPSS are below atmospheric which ranges from an annual mean of 372 µatm in 2002 to 399 µatm in 2015, indicating that this region has been a persistent CO_2 sink over the period of analysis
220 [Dlugokencky & Tans, 2017].

Figure 2 also shows the uncertainty of the seasonal mean, with shading representing 1 standard error from the monthly mean for each dataset. Uncertainty estimates vary for each month of the seasonal cycle with a minimum uncertainty of 1.1 µatm (June, SOCAT-DP) to a maximum of 5 µatm (July, SOCAT-DP).
225 Seasonal cycles are consistent when analyzing the PAZ region (Supp Figure 2), however the SOCAT-DP seasonal cycle exhibits two maxima possibly due to the omission of the southern area of the Drake Passage. The June peak in SOCAT-noDP also remains when considering the PAZ region.

Figure 3 indicates how inconsistent Southern Ocean pCO_2 data density is in space and time. Even given the
230 sampling efforts of the DPT, repeated occupations of SR03 south of Australia [Shadwick et al. 2015], along the Prime Meridian [Hoppema et al. 2009; Van Heuven et al. 2011], and in the southwestern Indian sector [Metzl et al. 1999; Lo Monaco et al. 2005, 2010; Metzl, 2009], consistent monthly observations are not

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always possible. Specifically, during austral winter, data availability outside of the Drake Passage region is extremely limited due to the few ships operating in winter and the difficult conditions that the wintertime Southern Ocean presents to data collection efforts (Figure 3b).

The average seasonal cycles of the 3 SOCAT datasets are quite similar, with few statistically-significant differences given the uncertainty bounds. SOCAT data from the Drake Passage region (SOCAT-DP) exhibits relatively large estimated uncertainty (average for all months = 2.31 µatm), despite the high temporal coverage and smaller region considered. This indicates that large interannual variability is inherent to the Drake Passage region, especially in the well-observed austral summer months. Despite data being much more regularly collected in this region than in the rest of the Southern Ocean (Figure 3), there are still months of quite limited observations, specifically July and August (Figure 2). SOCAT-all has monthly uncertainties averaging 1.8 µatm with the largest uncertainties in January and July. Data availability for SOCAT-all is consistent for much of the year, with most months having observations in at least 12 of the 14 years considered in this analysis (Figure 2). The exceptions are July and August that have data from only 7 and 9 years, respectively.

The SOCAT-noDP seasonal cycle is similar to that of the other datasets but deviates in the austral fall/winter, specifically May and June. In winter, SOCAT-noDP suggests higher pCO_2 than SOCAT-DP or SOCAT-all, though the limited data in June and July must be considered when drawing conclusions from this difference (Figure 2, 3b). With June and July data available for fewer than 4 of the 14 years covered in the analysis it is possible that the peak shown here could be biased by the few years included, specifically for the month of June. In contrast, SOCAT-DP and SOCAT-all have data for nearly all of the years considered in these months. The data that is available during May and June in SOCAT-noDP is from regions downstream of the Drake Passage (Figure 3b) where we expect data to be less similar to that collected in the Drake Passage.

Similar comparisons are seen in the PAZ region (Supp Figure 2). The double maxima seasonal cycle exhibited by the SOCAT-DP dataset is likely caused by the smaller region which eliminates data south of

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the front (Supp Figure 1) which would cause PAZ region averages to be greater than those shown for the DP region of the SPSS.

Overall, given available data, the seasonal cycles are statistically indistinguishable for data collected inside and outside of the Drake Passage region, for all months with at least 4 years of observations (Figure 2). This indicates that the Drake Passage seasonal cycle is representative of the broader SPSS biome seasonality, based on the available observations to date, but increased observations outside of the Drake Passage during May and June would provide a more robust comparison. Additionally, the seasonal cycles from all 3 SOCAT datasets closely resemble the smoothed seasonality of the interpolated SOM-FFN product in the SPSS biome (Figure 2). However, sparse sampling outside of the Drake Passage during winter months leads to this estimated seasonal cycle likely being driven by Drake Passage data. Enhanced wintertime data collection, especially in regions outside of the Drake Passage, is required to better constrain the full seasonal cycle of surface ocean pCO_2 in the Southern Ocean SPSS.

4.2 Interannual variability

The high resolution of the time-series data in the Drake Passage allows for close examination of temporal variability in pCO_2 with relatively low uncertainty [Munro et al. 2015a]. We investigate the interannual variability in Drake Passage pCO_2 in Figure 4a, where deseasonalized and detrended anomalies [Fay and McKinley, 2013] from the SOCAT-DP dataset are shown in gray, with the black line representing these anomalies smoothed with a 12-month running mean. Over the 2002-2015 period, the variance in pCO_2 anomalies is 60 μatm^2. Monthly anomalies are as large as ±25μatm, and 12-month smoothed anomalies as large as ±8μatm in this dataset.

A model-based study by Lovenduski et al. [2015] find interannual variability in pCO_2 to be low in the Drake Passage compared to other Southern Ocean regions. However, we find that detrended and deseasonalized anomalies from SOCAT-noDP and SOCAT-DP have comparable variances (56 μatm^2 and 60 μatm^2). This result, however, is likely strongly affected by the previously-discussed seasonal data gaps outside of the DP region. Conducting a similar analysis of the reported SOCAT sea surface temperature

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(SST) values does find the variance for SOCAT-DP to be significantly lower than SOCAT-noDP (0.92°C^2 and 2.73°C^2 respectively). As the same sampling issues exist for SST as for pCO_2 in SOCAT, an alternate method to address this issue is needed to resolve these conflicting results.

The SOM-FFN data product does offer complete seasonal and regional coverage, and thus the comparison of variance in Drake Passage to all the Southern Ocean can be made in this context. Results for SOM-FFN are different from both the SOCAT findings above and the results of Lovenduski et al. [2015]. For the SPSS biome area of SOM-FFN pCO_2, the variance of detrended and deseasonalized anomalies is significantly higher within the Drake Passage region than outside of the region (10.4 µatm^2 and 4.4 µatm^2, respectively). It should be noted that variances are significantly lower for the SOM-FFN because of its interpolation. We are left without a clear picture as to whether Drake Passage is more or less variable in pCO_2 than the rest of the Southern Ocean SPSS. This conundrum is clearly due to the lack of data availability, particularly outside the Drake Passage during winter months (Figure 3b).

Given the lack of data, the degree to which Drake Passage represents the interannual variability of the Southern Ocean SPSS can only be considered in the context of the SOM-FFN data product. To produce independent estimates of correlations between Drake Passage and other points, we use a version of the SOM-FFN product created without the inclusion of any observations in our defined Drake Passage region (SOM-FFN-noDP, Figure 4b), and assess correlations to SOCAT data within the Drake Passage. Anomalies have been detrended and deseasonalized, and grayed areas indicate that the correlation is not significant at the 95% confidence level (Figure 4b). The strongest positive correlations are within Drake Passage, upstream of the Drake Passage into the central Pacific SPSS, and in the Indian Ocean sector of the SPSS biome (Figure 4b). Weaker positive correlations are found in the western Pacific SPSS, as well as a few areas in the Atlantic sector of the SPSS. No regions of widespread strong negative correlations are observed in the SPSS biome. Surface ocean pCO_2 in the central and eastern Pacific regions, upstream of the Drake Passage, are highly correlated on interannual timescales with the pCO_2 measured in the Drake Passage. This is consistent with the analysis of Munro et al. [2015b] who estimate the footprint of the Drake Passage extending upstream into the eastern Pacific sector of the ACC.

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4.3 Trends, 2002-2015

Trends for all data (annual), as well as summer and winter, are estimated from the three SOCAT datasets, the SOM-FFN data product, and the SOM-FFN product subsampled as SOCAT-DP, in all cases following the approach of Fay & McKinley [2013]. Similar to the climatological pCO_2 seasonal cycle, annual trends for the 3 SOCAT datasets are indistinguishable given the 68% confidence intervals (Figure 5).

All annual trends are less than the 2002-2015 atmospheric pCO_2 trend of 1.95 µatm yr^{-1} [Dlugokencky et al. 2015], indicating that the Southern Ocean has been a growing sink for atmospheric carbon over 2002-2015 (Figure 5, far left). Comparing the different estimates, SOCAT-DP (gray bar) has an annual trend just slightly below that of the full SOM-FFN, however with a much greater uncertainty. The annual trend from the SOCAT-all dataset (blue) is nearly identical to the SOCAT-DP trend in both mean and uncertainty. These are not statistically different from the SOCAT-noDP or the SOM-FFN. SOCAT-noDP yields the largest annual trend, but falls well below the atmospheric trend and remains indistinguishable from all the other datasets considered given the 1σ uncertainty bounds.

Sampling the SOM-FFN data product as the SOCAT-DP dataset is one way to estimate the impact of the available data coverage in the Drake Passage region as compared to the hypothetical situation of perfect data coverage in the SPSS biome. Sampling lowers the trend, making it significantly smaller than the full SOM-FFN trend. This reduction leads to an annual trend very similar to that of SOCAT-DP and SOCAT-all. This conclusion emphasizes the need for increased observations around the Southern Ocean as it implies we are not accurately capturing the theoretical trend in this region with the available data.

These comparisons are largely maintained for summer and winter trends (Figure 5, center and right). Uncertainty increases when considering seasonal trends due to reduced data quantity. All trends are statistically indistinguishable for summer months. For winter, SOCAT-noDP is not shown because unlike SOCAT-all and SOCAT-DP, not all years have available data during this season (Figure 2). Overall, winter trends are slightly higher than summer trends, but given the uncertainties, winter and summer trends are

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only clearly distinguishable for the full SOM-FFN product, where the winter trend is nearly 0.45 µatm yr^{-1} higher than the summer trend. For summer and winter trends, the full and subsampled SOM-FFN products have trends that are indistinguishable within each season. Winter trends have larger differences and larger uncertainties, consistent with reduced data availability.

A further investigation of trends from the full SOM-FFN product and that of the SOM-FFN-noDP product for the entire Southern Ocean south of 35°S for years 2002-2015 indicates a steadily increasing carbon uptake by the ocean (Figure 6). If the Drake Passage data is omitted during the creation of the product (SOM-FFN-noDP), flux trends are unchanged (Figure 6a). However, the mean difference between these two products is a consistently lower estimate of the mean Southern Ocean pCO_2 (Figure 6b). Both estimates illustrate that for 2002-2015, the Southern Ocean was an important sink of carbon dioxide. The comparison also shows that the mean pCO_2 of the SOM-FFN product for the Southern Ocean is impacted by the inclusion of the Drake Passage data as shown by the offset between the lines in Figure 6.

5. DPT as a pCO_2 evaluation point for biogeochemical profiling floats

Starting in late 2014, autonomous biogeochemical profiling floats have been deployed as part of the SOCCOM project, and as of summer 2017, several floats had traveled through or were approaching the Drake Passage region (Figure 7b). These floats offer a new opportunity to complement our oceanographic understanding that has been developed primarily with traditional shipboard observations. Floats provide more frequent observations, regardless of weather or sea conditions. With satellite relays, float data can be made available in near-real time. However, as will be discussed in more detail, there are limitations of float observations (i.e. instrument drift, high uncertainty levels) that could potentially be addressed by taking advantage of the complementary strengths of the Drake Passage Time-series dataset. As the floats provide autonomous observations covering existing spatial and temporal gaps throughout the Southern Ocean and ship-based systems provide high density observations at considerably higher accuracy (±11 µatm for floats compared to ± 2 µatm for ships), there is great potential for these two observational platforms to work in concert to provide a whole Southern Ocean carbon observing system.

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Here, underway DPT pCO_2 data for 2016 and 2017 are used for comparison to SOCCOM floats. This is instead of the SOCATv4 because these data are not available after 2015. For March 2002-June 2017, underway Drake Passage Time-series pCO_2 data in the SPSS biome has a large range, often spanning over 100 µatm each month (Figure 7a). pCO_2 from all floats east of 90°W and west of 55°W (Figure 7b) are also plotted on the time-series (Figure 7a,c) with their calculated pCO_2 value averaged from all depths <20m. Float-based pCO_2 estimates mostly fall within the range of the direct underway pCO_2 observations, however anomalies do exist. Float estimates in June and July 2017 (Figure 7c) report higher pCO_2 values than nearby DPT observations, however a lack of cruise data during this specific time limits direct comparisons. Overall, the range of the shipboard observations is far larger than the range of estimated pCO_2 from the floats in most cases. This is likely due to the fact that shipboard observations regularly span across the width of the Drake Passage where decorrelation length scales are relatively short [Eveleth et al. 2017], while the floats sample along the ACC path. Despite the difference shown in this region, the agreement of these few floats with the underway data is very encouraging (Figure 7a,c). As the floats offer autonomous, frequent observations and the ship offers data of the highest-quality, it is ideal for these two platforms to work in partnership.

A direct comparison between DPT data and SOCCOM floats indicates more precisely this potential (Figure 8). As of September 2017, six floats surfaced near DPT observations within a window of 75 km, 3 consecutive days, and have a reported SST within 0.3°C of each other (Figure 8a). This window is consistent with the crossover criteria used by the SOCAT community to quality control shipboard data [Pfeil et al. 2013; Olsen et al. 2013]. Figure 8a shows locations of the floats and the nearby DPT observations that fit this crossover window. As DPT offers high frequency observations, all available measurements over the 3-day window are shown (Figure 8b). Also indicated are DPT observations that crossover within a 50km and 2-day window and 25km and 1-day window, both also with the 0.3°C SST criteria as well, for completeness (Figure 8b, black 'x' and boxes). A comparison of the calculated pCO_2 from the floats and observed DPT pCO_2 reveals a broad correspondence (passing through the 1:1 line) in all 6 crossover instances within the ±11 µatm relative standard uncertainty of the SOCCOM float measurements (Figure 8b shading). While all crossover floats do intersect the 1:1 line given their stated

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uncertainties, these comparisons reveal the large range of pCO_2 captured by high-frequency shipboard measurements in a relatively small region and illustrates that this range cannot be fully captured by floats surfacing only once every 10 days. Further investigation of crossovers in the entire Southern Ocean region is warranted. While the DPT provides the most likely occurrence for this, other regions with frequent ship traffic could provide additional comparisons.

While autonomous biogeochemical floats can sample the larger Southern Ocean across all seasons, float sensor calibrations must be corrected initially after deployment by reference to deep (near 1500 m) pH values, which are estimated from multiple linear regression equations fitted to high quality, spectrophotometric pH observations made on repeat hydrography cruises [Williams et al., 2016; 2017; Johnson et al., 2016; 2017]. In addition, empirical algorithms for alkalinity must be used to estimate pCO_2 from float-based pH [Carter et al. 2016; Williams et al. 2016]. A thorough analysis of all sources of uncertainty estimated the total uncertainty in float-based pCO_2 to be as high as 11 µatm, although crossover comparisons with underway ship data collected close to the first float profile found a mean difference of only 3.7 µatm [Williams et al. 2017]. However, it is expected that the sensors will drift or require adjustments during their 4-5 year lifespan. Ship-based programs like the DPT should be utilized for post-deployment quality control assessments or data quality checks, both with the underway pCO_2 data from the surface (as shown in Figure 8), and more thoroughly if hydrocast observations were planned to occur in the vicinity of a passing biogeochemical float. Such coordinated efforts would advance monitoring of the carbon cycle in the Southern Ocean.

6. Conclusions

The Drake Passage Time-series illustrates the large variability of surface ocean pCO_2, and exemplifies the value of sustained observations in understanding changing ocean carbon uptake in the Southern Ocean. This is the only location where carbon measurements throughout the entire annual cycle in the subpolar Southern Ocean have been made regularly over the past two decades. With this complete coverage we find seasonal amplitudes in the SPSS to be smaller than subpolar regions in the Northern Hemisphere, and controlled by a combination of temperature and deep water mixing effects. Uncertainties in the seasonality

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remain considerable given the dynamic nature of this region and the short time-series considered. Specifically, a lack of winter data in all years limits the conclusions for differences between the Drake Passage and the larger SPSS biome where we see a discrepancy in the timing of the winter maxima. These findings can direct specific goals for future observations. Specifically, insufficient wintertime data in regions outside of the Drake Passage limits our assessment of how representative Drake Passage data is of the larger region.

The magnitude of interannual variability is comparable for SOCAT pCO_2 data within and outside of the Drake Passage region of the SPSS biome, a finding that conflicts with results from previous modeling and analysis of the SOM-FFN product. A clear idea of whether the Drake Passage is more or less variable in pCO_2 will require increased data, particularly during the austral winter outside of the Drake Passage. Given these data restrictions, representativity of the larger SPSS biome is also investigated using the SOM-FFN product. Within this gap-filled data product, monthly anomalies in the Drake Passage region are representative of broad swaths of the Southern Ocean, specifically regions upstream of the Drake Passage, but also regions in the Indian Ocean sector of the Southern Ocean. Consistent with this finding, estimates of long-term trends do not change substantially if observations in the Drake Passage are removed from the SOM-FFN analysis. Across approaches to data analysis, trends in annual oceanic pCO_2 trends for 2002-2015 are less than the atmospheric pCO_2 trend, confirming previous findings that the Southern Ocean has been a growing sink for atmospheric carbon since 2002.

Comparisons between underway DPT and SOCCOM float measurements show general agreement over the Drake Passage and a fine-scale crossover investigation demonstrates their correspondence given uncertainty ranges for SOCCOM float pCO_2 estimates. Employing the high-temporal measurements of the DPT and frequent hydrocasts as comparisons could aid in reducing the uncertainty on the float pCO_2 measurements by helping to identify problematic float sensors. Coordinated monitoring efforts that combine a well-calibrated array of autonomous biogeochemical floats with a robust ship-based observational network will improve and expand monitoring of the carbon cycle in the Southern Ocean in the future.

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Figure Captions

Figure 1

Map of Fay and McKinley [2014] biomes that are defined at 1°x1° resolution. Subpolar seasonally stratified (SPSS) biome shown in teal. The red line represents the mean location of the Antarctic Polar Front [Freeman and Lovenduski, 2016], interpolated to a 1°x1° grid. The black box represents the Drake Passage region considered in this analysis.

Figure 2

Mean surface ocean pCO_2 seasonal cycle estimate for years 2002-2015, for the SPSS biome from each dataset, shown on an 18-month cycle, calculated from a time-series with the atmospheric trend removed (1.95 μatm yr^{-1}). Shading represents 1 standard error for biome-scale monthly means. Bar plot indicates the number of years containing observations in a given month (maximum of 14 years) for the SOCAT-DP SOCAT-noDP, and SOCAT-all datasets.

Figure 3

Data density of pCO_2 observations from the SOCATv4 dataset within each 1^ox1^o gridcell. Data is restricted to years 2002-2015. Salinity values outside of 33.5-34.5 psu and observations within 50 km of land are omitted. (a) data from all months of the year; (b) data from only June, July, and August (austral winter).

Figure 4

(a) Temporal evolution of deseasonalized, detrended monthly SOCAT-DP pCO_2 anomalies (gray bars) over 2002-2015, with 12-month running averages (black line) overlain. (b) Correlation between monthly SOCAT-DP pCO_2 anomalies and the pCO_2 anomalies estimated from the SOM-FFN-noDP product (created without the inclusion of Drake Passage data), for years 2002-2015 at each 1^ox1^o grid cell. Gray shading represents areas where the correlation does not pass significance t-tests at $p<0.05$.

Figure 5

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Surface ocean pCO_2 trends in the SPSS biome for years 2002-2015 (μatm yr^{-1}): SOCATv4 data within the Drake Passage box (gray); SOCATv4 data excluding data from the Drake Passage box (green); SOCATv4 (blue); SOM-FFN product (magenta); SOM-FFN pCO_2 product sampled as SOCATv4 data in the Drake Passage box (light pink). Figure includes annual trends (left), summer trends (center) and winter trends (right). SOCAT-noDP winter trend omitted because it did not contain a JJA value for every year of the time-series. For reference, the atmospheric pCO_2 trend during the 2002-2015 period (1.95 μatm yr^{-1}) is shown as a horizontal black line.

Figure 6

(a) Sea-air CO_2 flux and (b) pCO_2 averaged over the Southern Ocean (south of 35°S) from the SOM-FFN pCO_2 product (blue) and that of the SOM-FFN-noDP product created without the inclusion of Drake Passage data (red). Trends and uncertainty values in corresponding colors.

Figure 7

(a) 2002-2017 underway DPT pCO_2 observations (circles) and surface pCO_2 estimates from SOCCOM floats overlain (diamonds; μatm), plotted versus latitude. (b) Trajectories of Drake Passage-transiting SOCCOM floats included in this analysis. Colored dots represent the location of surface measurements for each float. Data from floats collected east of 55°W and west of 90°W are not included in this analysis. Gray dots represent observations from the DPT. (c) Same as (a) but plotted as October 2015 to September 2017.

Figure 8

(a) Map of SOCCOM floats with DPT crossovers within 75km, 3 days, and 0.3°C SST from coincident surface observations. (b) Calculated pCO_2 from SOCCOM float (x-axis) versus DPT underway pCO_2 observations (y-axis) for crossover float locations, with 1:1 line. Colors correspond to float number in Figure 7. Horizontal width of shading represents SOCCOM relative standard uncertainty which is estimated at 11μatm; vertical shading is 2 μatm uncertainty around DPT observations. Black 'x' and squares indicated crossovers within a smaller window (50km/2day/0.3°C SST and 25km/1day/0.3°C SST respectively).

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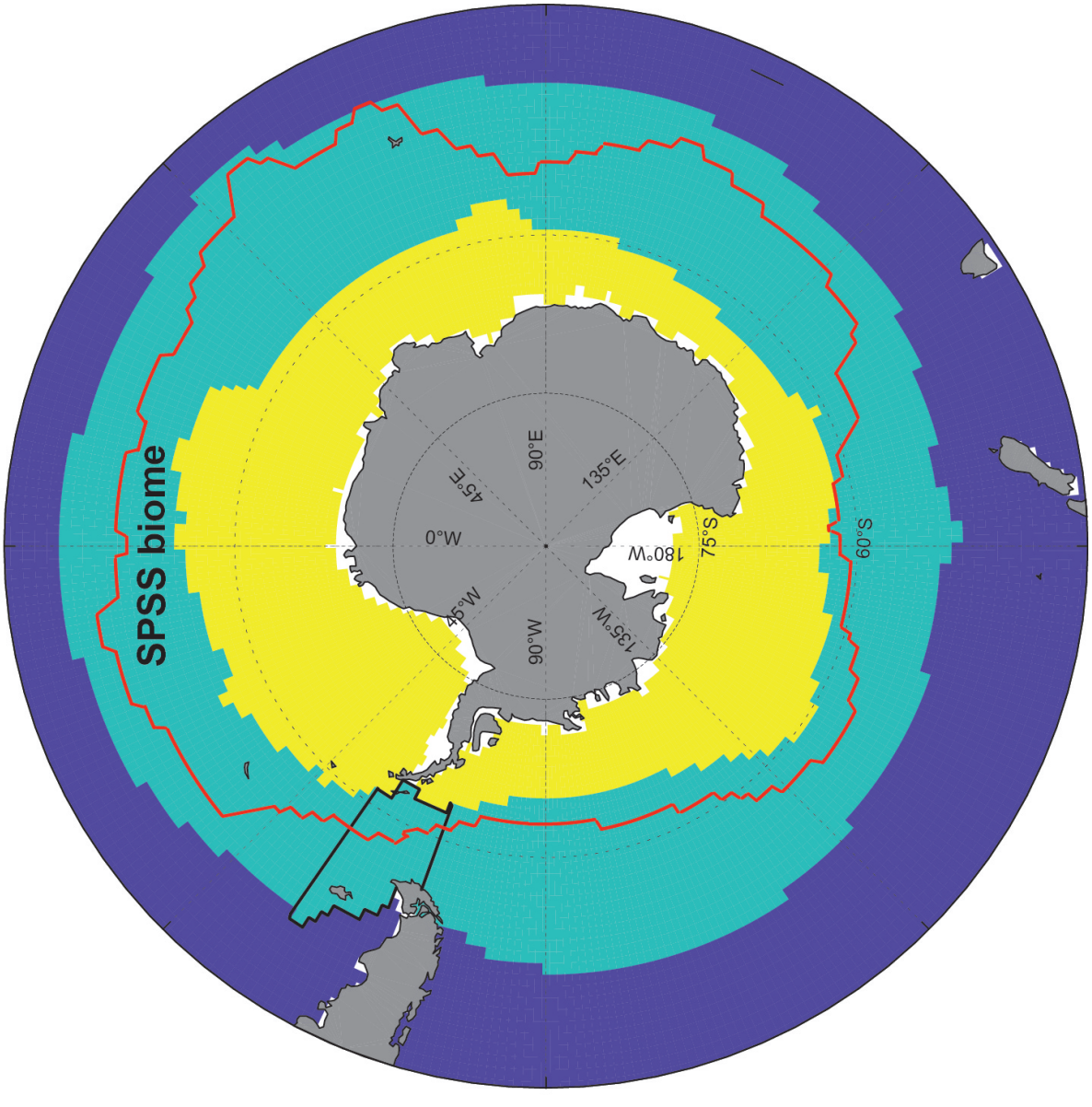

Figure 1

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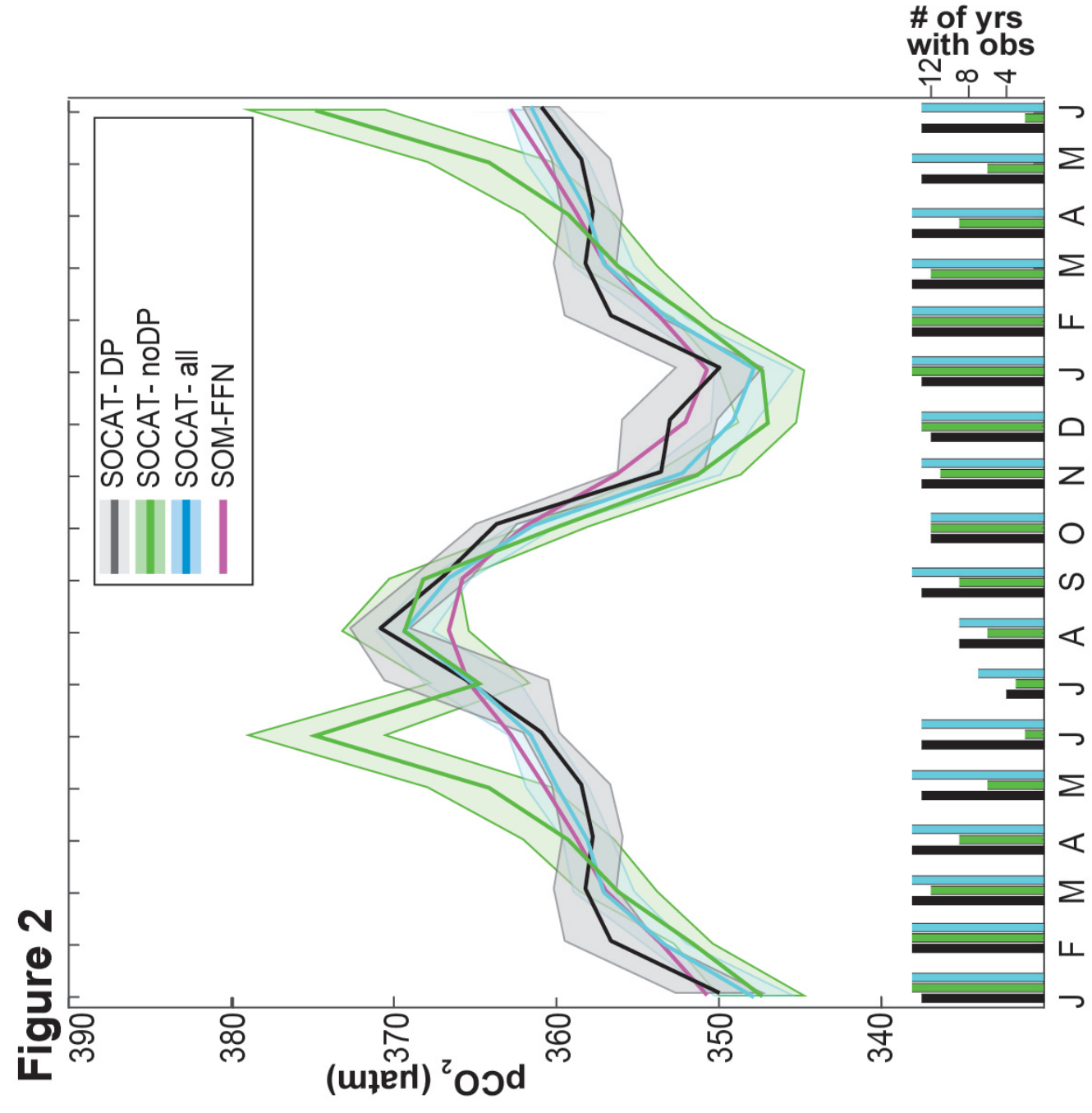

Figure 2

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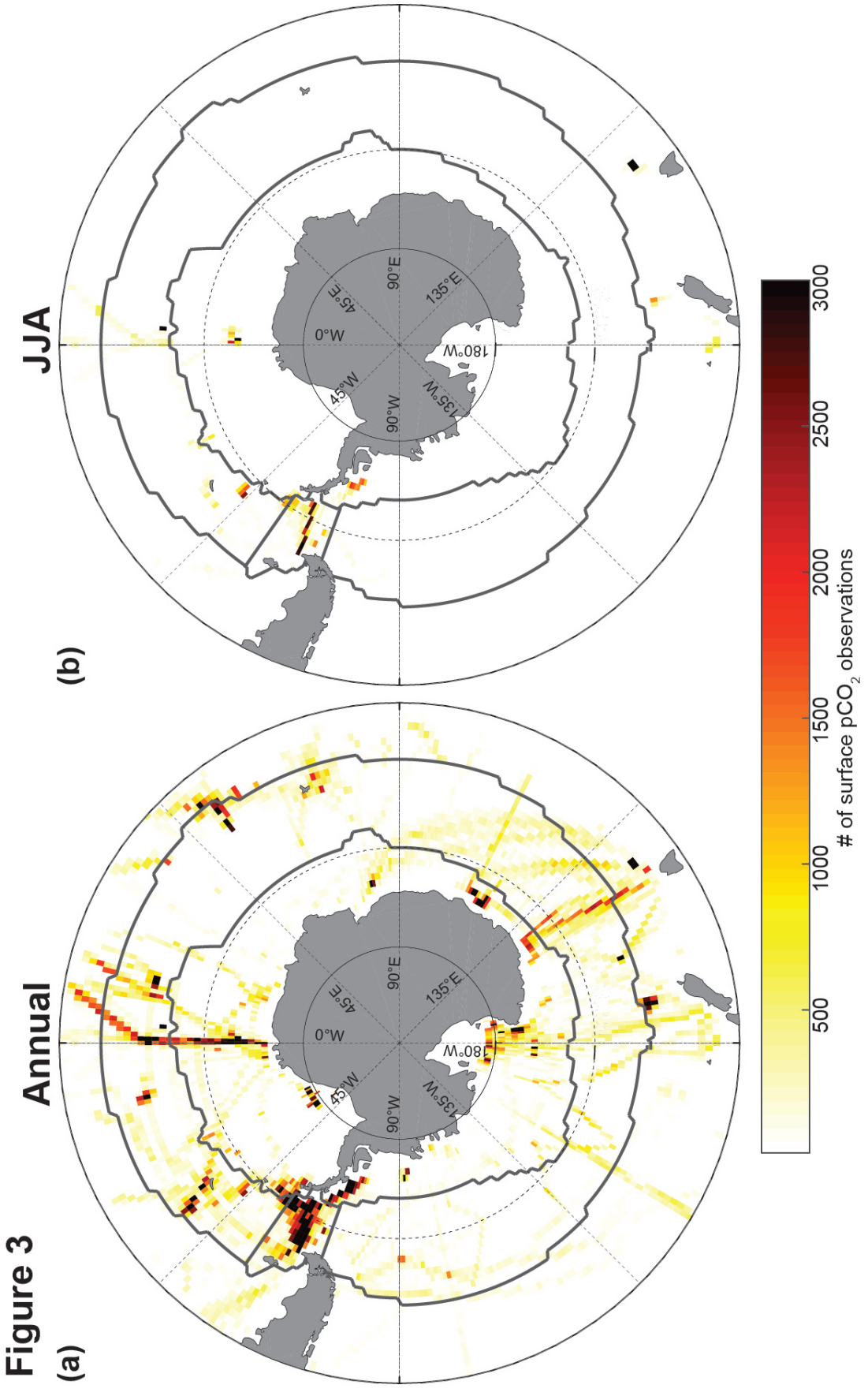

Figure 3

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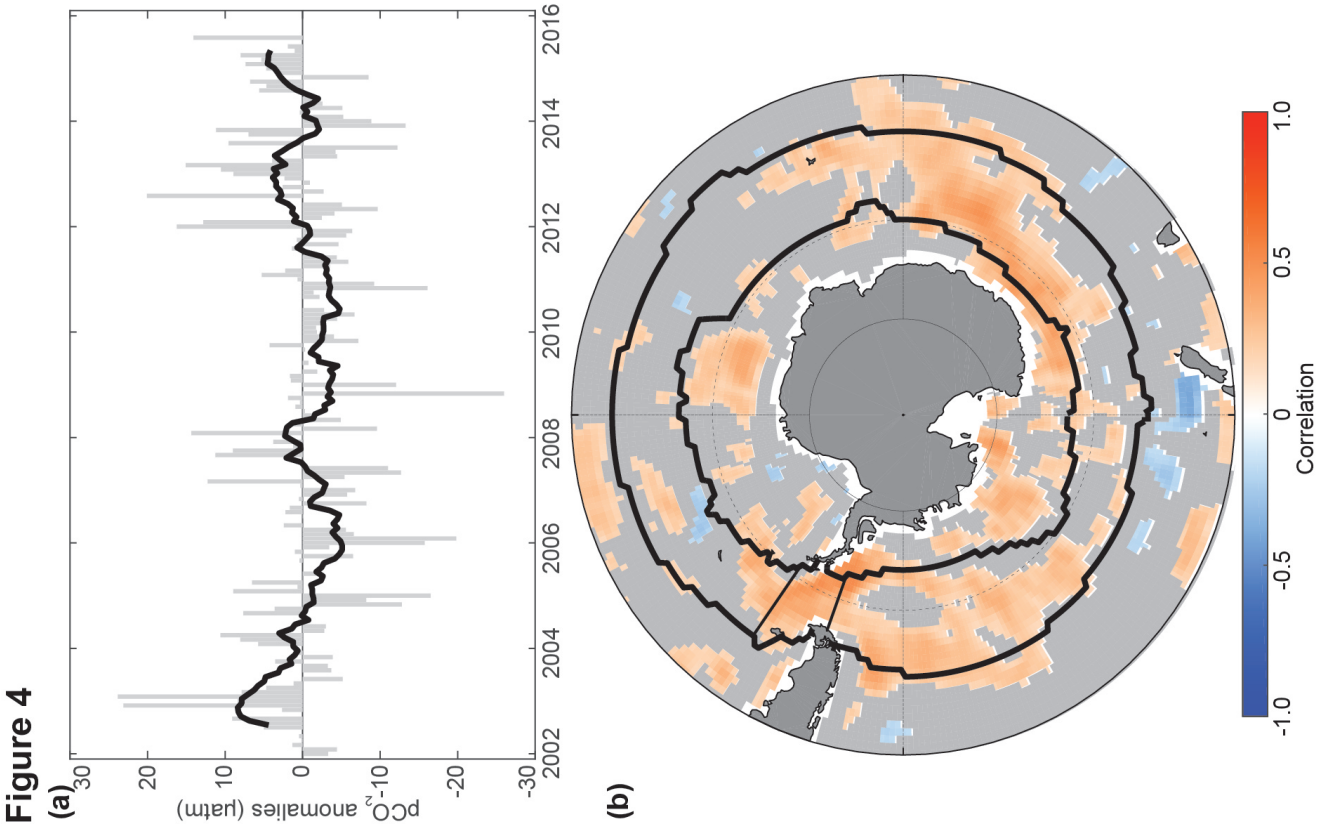

Figure 4

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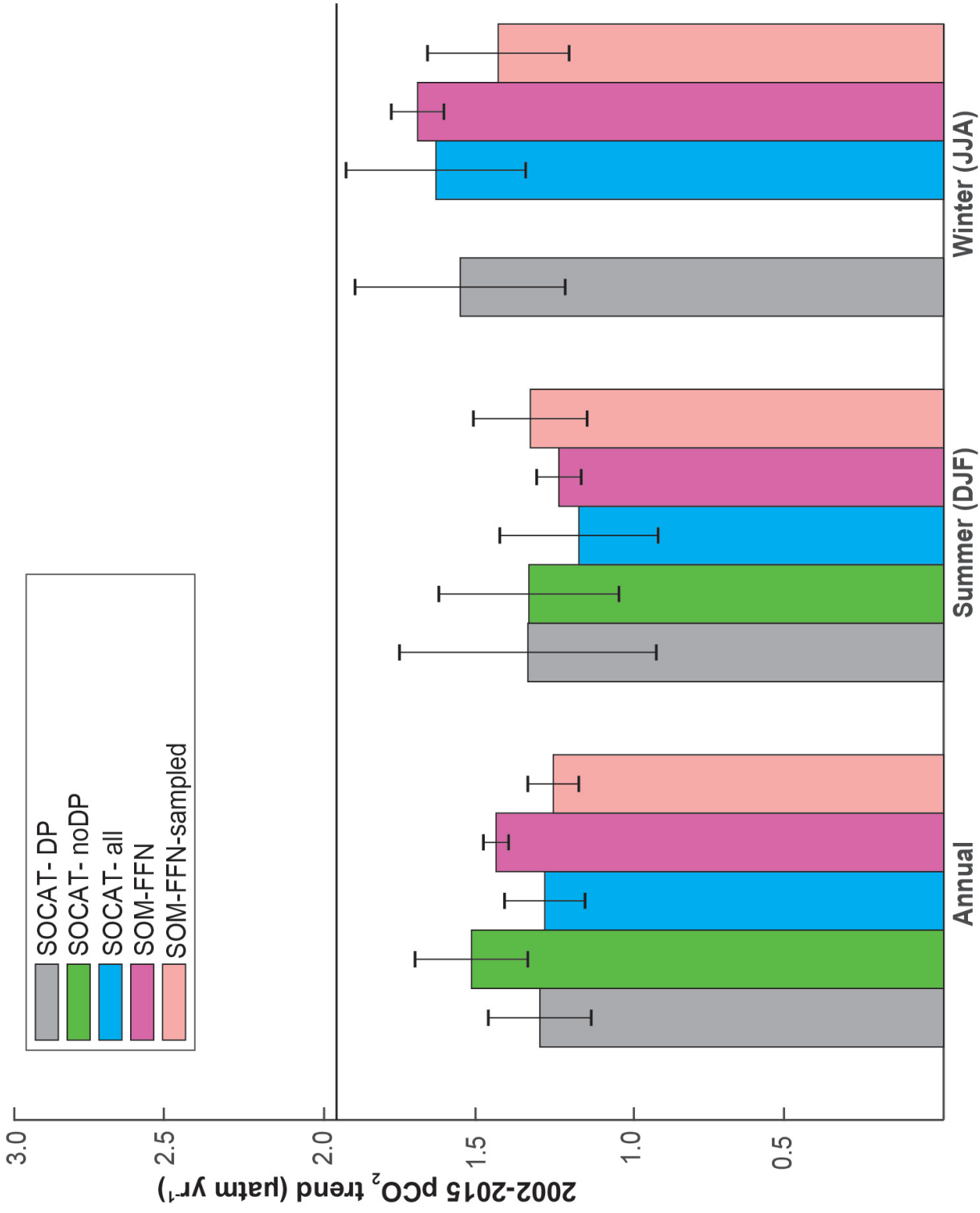

Figure 5

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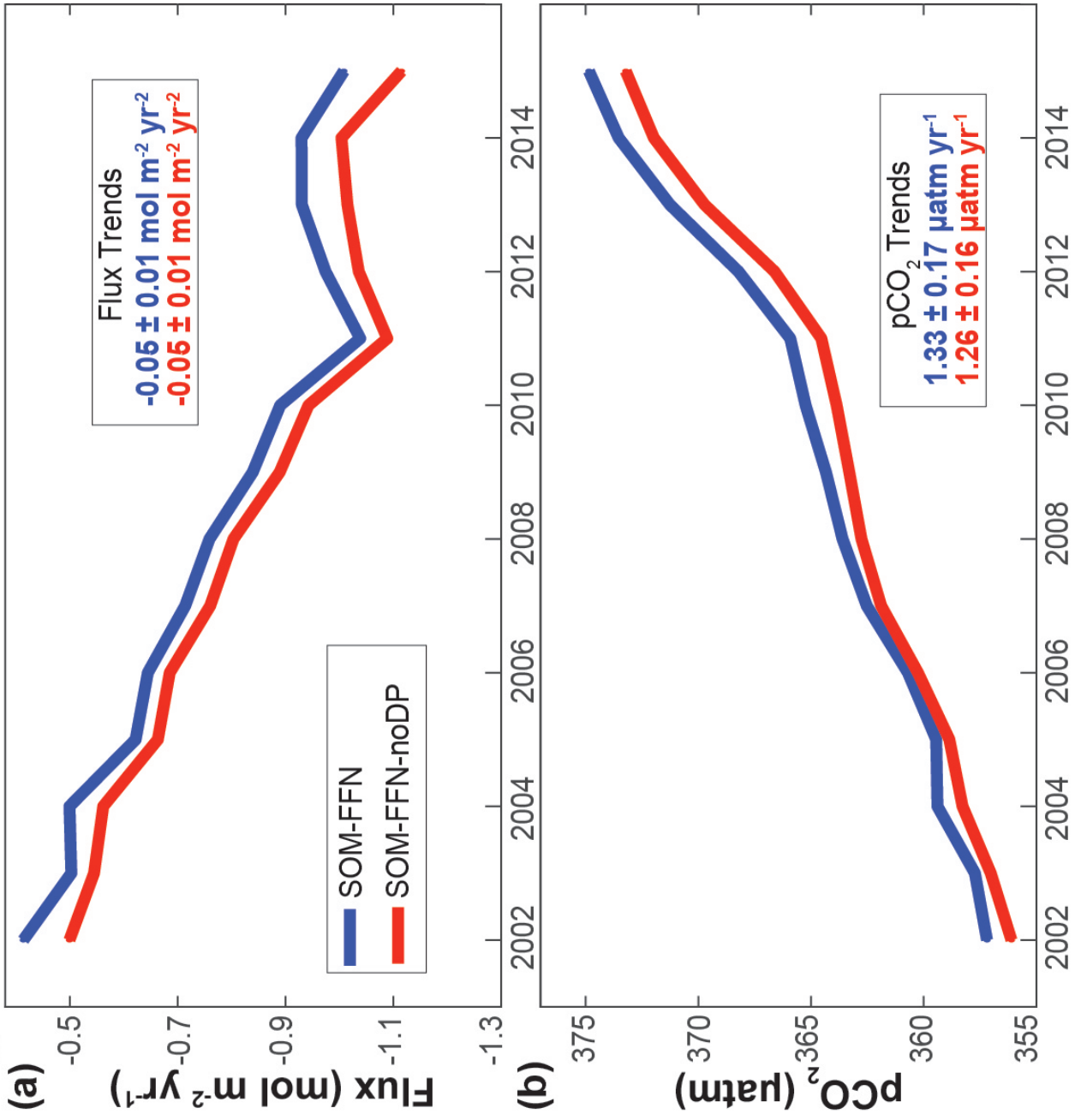
Figure 6



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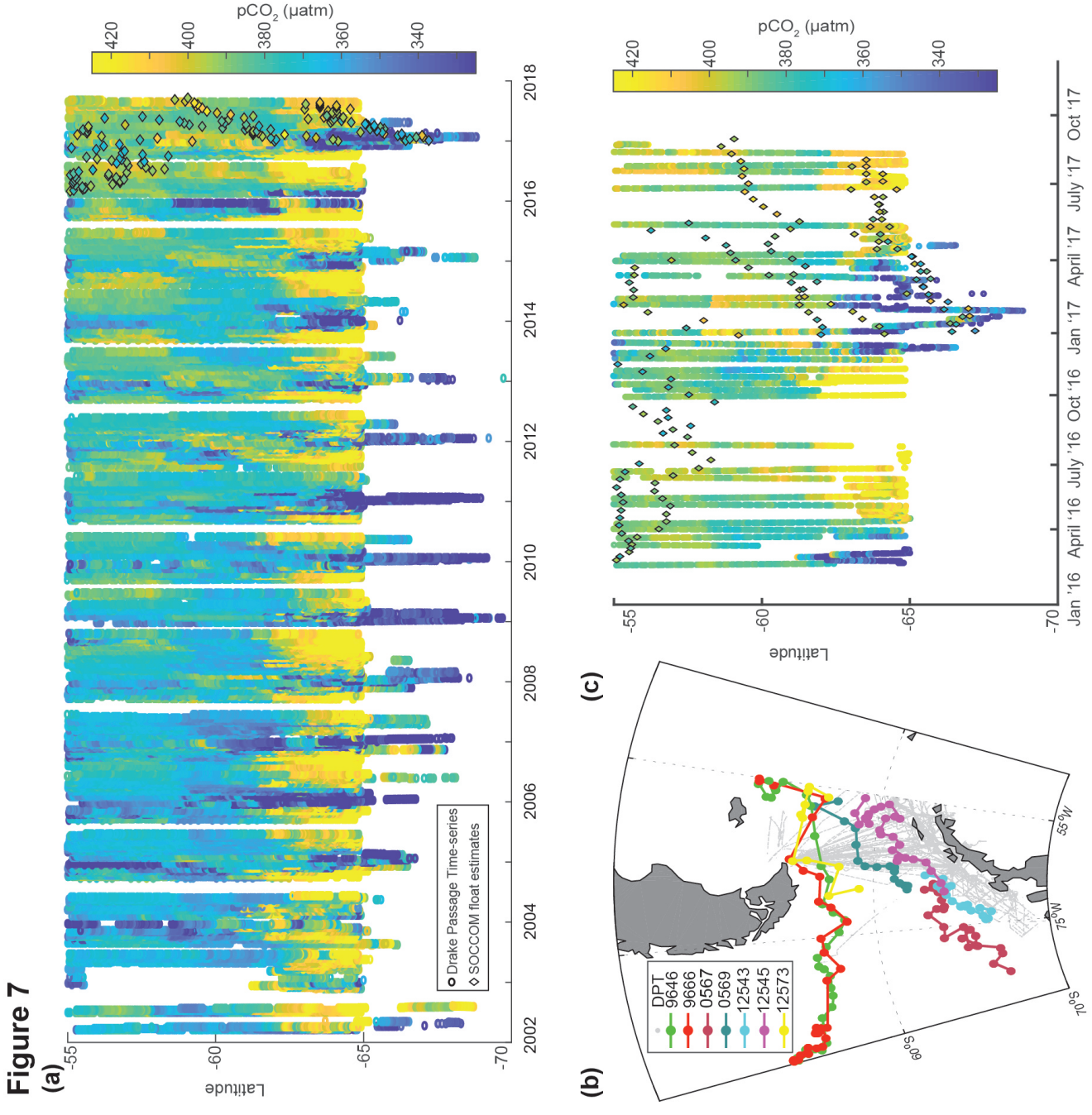

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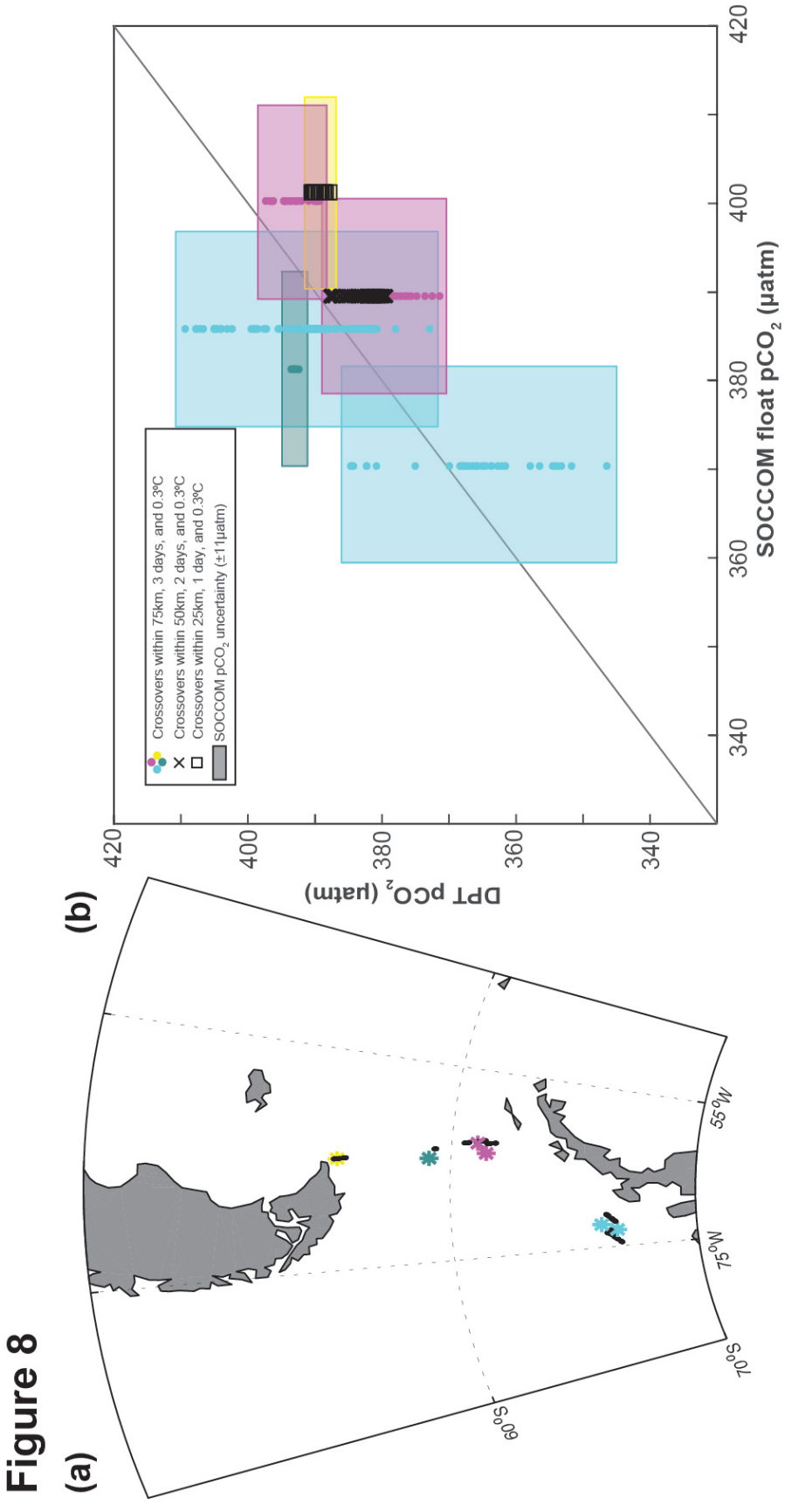

Figure 8