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## Measuring Winds From Space to Reduce the Uncertainty in the Southern Ocean Carbon Fluxes: Science Requirements and Proposed Mission

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# 1 **Measuring Winds from Space to Reduce the Uncertainty in the Southern Ocean** 2 **Carbon Fluxes: Science Requirements and Proposed Mission**

3  
4 **Joellen L. Russell<sup>1</sup>, David G. Long<sup>2</sup>, Paul S. Chang<sup>3</sup>, Madeline Cowell<sup>4</sup>, Enrique Curchitser<sup>5</sup>, Michael S. Dinniman<sup>6</sup>,**  
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13

14  
15 **Keywords: Observing System Design, Surface Vector Winds, Scatterometer, Southern Ocean, Air-Sea Carbon Flux**

## 16 17 **Key points:**

- 18 **1) The** current wind observing system samples Southern Ocean storms infrequently and is unlikely to directly observe the  
19 highest winds and variability  
20 **2) Southern Ocean winds are critical to the global air-sea exchange of carbon and heat**  
21 **3) Adding a carefully targeted scatterometer to the observing constellation will reduce the uncertainty in the global carbon**  
22 **budget by focusing on the SO where the largest fraction of the air-sea exchange happens and where the current uncertainties**  
23 **are largest.**

## 24 25 26 **Plain Language Summary**

27 The Southern Ocean is the windiest place in the world, with frequent intense storms. The winds in these storms drive large  
28 fluxes of carbon and heat between the ocean and the atmosphere. Unfortunately, these fluxes can't be observed directly from  
29 space; we rely on wind measurements and climate reanalyses to determine them, Our space-based observing network,  
30 however, only captures winds over the Southern Ocean twice per day at best, so our estimates of the SO winds and air-sea  
31 fluxes are uncertain and about 50% of the global uncertainty in air-sea carbon exchange is associated with the Southern Ocean.  
32 We show that higher winds are consistent with reduced uptake of atmospheric carbon by the Southern Ocean. We describe our

33 observing system design experiment to determine the best additional scatterometer to add to the wind-observing constellation  
34 to capture more of the high winds and reduce the uncertainty in the Southern Ocean carbon budget

35

36

37

## 38 **Abstract**

39

40 Strong winds in Southern Ocean storms drive air-sea carbon and heat fluxes. These fluxes are integral to the global climate  
41 system and wind speeds that drive them are increasing. The current scatterometer constellation measuring vector winds  
42 remotely undersamples these storms and the higher winds within them, leading to potentially large biases in Southern Ocean  
43 wind reanalyses and the carbon and heat fluxes that derive from them. This observing system design study addresses these  
44 issues in two ways. First, we describe an addition to the scatterometer constellation, called Southern Ocean Storms–Zephyr, to  
45 increase the frequency of independent observations, better constraining high winds. Second, we show that potential reanalysis  
46 wind biases over the Southern Ocean lead to uncertainty over the sign of the net winter carbon flux. More frequent  
47 independent observations per day will capture these higher winds and reduce the uncertainty in estimates of the global carbon  
48 and heat budgets.

49

## 50 **1) Introduction**

51

52 The Southern Ocean is the windiest ocean basin in the world; storms play an important role in mass and heat transport and  
53 precipitation (Wei & Qin, 2016) and drive air-sea fluxes of carbon and heat, which scale non-linearly with wind speed. These  
54 strong winds, coupled with the unique geography and upper ocean processes around Antarctica, forge a connection where  
55 carbon dioxide (and heat) are readily exchanged between the atmosphere, the oceanic mixed layer and the deep ocean (Russell  
56 et al. 2006).

57

58 The World Meteorological Organization (WMO) recognizes the need for global wind sampling every 6 hours (4 x per day);  
59 preferably every 3 hours for ocean and climate applications (Bourassa et al. 2019; Stoffelen et al. 2019). This is not achieved by  
60 the existing scatterometer constellation; undersampling is acute in the Southern Ocean (SO, hereafter, Hell et al., 2020) where  
61 fast-moving storms drive an increase in carbon exchange (Matear & Lenton, 2008). Storms are frequent but inadequately  
62 sampled (only 1-2 times per day at any location), limiting independent assessment of model-based wind reanalyses. Belmonte

63 Rivas and Stoffelen (2019) show large SO reanalysis biases in mean and eddy flow; additional uncertainty is associated with  
64 reduced precision and accuracy of high wind speeds (Stoffelen et al. 2020), and the lack of coincident rain determination (Xu &  
65 Stoffelen, 2020). Uncertainties at high wind speeds and short storm durations (Wentz et al. 2017, Chang et al. 2009, Hell et al.  
66 2020) suggest that the current satellite-based wind observations are insufficient. Given the small spatial scales of the SO storms  
67 and their fluctuating intensities, it is likely that current satellite wind speed observations are biased low, especially in winter.

68  
69 Scatterometer, radiometer, and altimeter observations of SO winds, ocean wave height, and ocean power over the last decade  
70 indicate that all are increasing (Young et al. 2011, 2017; Young & Ribal, 2019; Reguero et al. 2019). Wei and Qin (2016) note  
71 increasing SO storms during each season, although the increase was only statistically significant in summer. Verhoef et al.  
72 (2017) show increasing global winds in reanalyses but decreasing winds in collocated QuikSCAT data. Stronger winds bring  
73 more carbon-rich deep water to the surface; this decreases uptake and increases outgassing by changing the air-sea gradient,  
74 as observed by autonomous biogeochemical floats in the SO (Gray et al. 2018).

75  
76 Several studies report significant uncertainties and potential biases in wind reanalysis products over the SO, especially in the  
77 highest winds (Marseille et al., 2017; Risien & Chelton, 2008; Arduin et al. 2011; Chawla et al. 2013, Verezemskaya et al.  
78 2017). Sampe and Xie (2007) found that >5% of QuikSCAT winds (Spencer et al. 2000) exceeded 20 m/s over large areas south  
79 of 40°S during winter (June–August, JJA). Comparable calculations from the ERA5 reanalysis (5<sup>th</sup> reanalysis from the ECMWF;  
80 Hersbach et al. 2020) for 2018–2019 find that <1% of winter wind speeds exceed the 20 m/s threshold. Tetzner et al. (2019)  
81 found that ERA-Interim (Dee et al. 2011) and ERA5 reanalyses (Hersbach et al. 2020) underestimated monthly-mean winds  
82 over the Antarctic Peninsula by >1 m/s and partly attribute this to higher-frequency observations by the meteorological  
83 stations. Verezemskaya et al. (2017) compared QuikSCAT wind speeds in SO mesocyclones during winter (June–September;  
84 Ricciardulli & Wentz, 2015) to four different reanalysis products (ERA-Interim, Dee et al. 2011; NCEP CFSR, Saha et al. 2010;  
85 JRA55, Kobayashi et al. 2015; MERRA2, Bosilovich et al. 2016), showing that mean wind speed was underestimated in each by  
86 1–7 m/s and the 75<sup>th</sup> percentile was underestimated by 5–10 m/s. A significant underrepresentation in the higher winds will  
87 impact the trend.

88  
89 Air-sea fluxes of CO<sub>2</sub> and heat are not directly observable from space; we rely on bulk formulae, experiments and simulations to  
90 determine these quantities. Current estimates of the ocean's role in the global carbon budget indicate that >50% of the  
91 anthropogenic uptake of carbon from the atmosphere by the global ocean (1.4 PgC/yr in the SO of the 2.6 PgC/yr global) and  
92 50% of the uncertainty ( $\pm 0.3$  PgC/yr) in air-sea CO<sub>2</sub> exchange occurs in the SO (Friedlingstein et al. 2020). Uncertainties in the

93 SO winds contribute to significant uncertainties in the global and regional carbon budgets; this uncertainty hampers prediction  
94 and challenges our carbon emission reduction projections to stabilize global atmospheric CO<sub>2</sub> levels.

95  
96 Current estimates of the net global carbon flux (Friedlingstein et al. 2020; Iida et al. 2015; Landschutzer et al. 2016; Takahashi  
97 et al. 2014, Wanninkhof et al. 2013) rely on a method based on the observed net invasion of bomb-<sup>14</sup>C to scale the gas  
98 exchange rate equation, assuming *a priori* that gas exchange scales to the square of the winds (Sweeney et al. 2007). This  
99 process depends on spatial and temporal resolution of the “observed” wind speeds (Naegler et al. 2006). Sweeney et al. (2007)  
100 note that, “no single (scaling) value can be applied for all wind products”; other parameterizations based on isotopic evidence  
101 have been proposed (e.g. Krakauer et al. 2006). Wanninkhof and Triñanes, 2017 found that a different gas exchange  
102 parameterization (Wanninkhof et al. 2009) with increased exchange above 14 m/s and below 5 m/s (relative to the standard  
103 square of wind speed) adequately represents the net invasion of bomb-<sup>14</sup>C. Alternative approaches to carbon flux  
104 parameterization using high resolution surface roughness estimates (e.g. Frew et al. 2007) have not been explored in the SO. A  
105 coherent observing system with detailed calibration and validation will allow a more precise estimate of the gas exchange rate  
106 and therefore the carbon flux in the SO.

107  
108 To assess the effects of missing high winds and/or increasing winds over the SO, we take advantage of a unique and powerful  
109 tool, the Biogeochemical SO State Estimate (**BSOSE**, Verdy & Mazloff, 2017). The state estimate is constrained with physical  
110 and biogeochemical observations while maintaining closed budgets and obeying dynamical and thermodynamic balances. The  
111 ocean state estimate solves for the model initial and **boundary conditions** (i.e. surface heat fluxes, freshwater and carbon)  
112 that minimize the weighted least squares sum of model-observation misfits.

113  
114 When we compare net carbon flux that occurs under high winds (>10 m/s in ERA5 reanalysis) to total flux in the daily solutions  
115 from BSOSE for 2013–2018 (forced with ERA5 hourly winds), we find that >60% of the carbon flux happens under winds  
116 greater than 10 m/s, although the fraction of the SO (south of 30°S) under these high wind speeds is ~35% of the total area  
117 (Supp. Fig. S1). **We show that the air-sea carbon fluxes and upwelling consistent with stronger winds (imposed as**  
118 **part of an idealized experiment) indicate that the SO will change from a net carbon sink into a net carbon source**  
119 **during austral winter.** This change is consistent with findings of strong outgassing between the polar front and sea ice edge  
120 based on the biogeochemical float array (Gray et al. 2018). Bronselaer et al. 2020 showed that the float observations noted by  
121 Gray et al. 2018 are not reproducible without imposing stronger winds.

122

123 As proposed, SOS-Zephyr addresses key Decadal Survey questions (NASEM 2018): How can we reduce the uncertainty in the  
 124 carbon cycle feedback (carbon budget), by up to a factor of 2? And how large are variations in the global carbon cycle? SOS-  
 125 Zephyr reduces uncertainty in the global carbon budget by focusing on the SO where a large fraction of the air-sea carbon  
 126 exchange takes place and where the uncertainties are largest; the two biggest sources of uncertainty are: 1) “Are we (now)  
 127 capturing the surface vector wind field sufficiently with our observing constellation?”, and 2) is our uncertainty about the vector  
 128 wind field concealing a trend? All indicators point to surface winds strengthening over the SO; SOS-Zephyr’s contribution to the  
 129 wind field refines our uncertainty estimates of the vector wind field and the statistics of the number, size and strength of SO  
 130 Storms and indicates the presence or absence of significant trend.

131  
 132 The second source of uncertainty is that while wind speed determines the gas exchange rate, vector wind fields determine  
 133 upwelling and mixed layer depth and therefore air-sea carbon gradient. Quantifying time-varying air-sea carbon flux in the SO  
 134 **requires** numerical simulations to quantify underlying the ocean circulation; these simulations of biogeochemistry and air-sea  
 135 carbon flux in the SO vary widely. Accordingly, SOS-Zephyr proposes a scatterometer mission to capture vector winds rather  
 136 than a radiometer which can only determine wind speeds.

137  
 138 **Reducing uncertainty in SO wind speed and variability improves estimates of air-sea CO<sub>2</sub> exchange in this critical**  
 139 **region. More frequent, finely-resolved measurements allow us to better quantify the SO’s role in the global**  
 140 **carbon cycle and the climate system; enhancing our ability to predict the evolution of the carbon system over the**  
 141 **near term.**

142  
 143 This modeling study, where faster winds are assimilated into BSOSE, indicate that stronger winds lead to significantly increased  
 144 carbon outgassing along the seasonal sea ice zone in winter and enhanced outgassing during most seasons at most latitudes,  
 145 likely due to increased upwelling. Heat fluxes were enhanced by stronger winds but did not change sign. We conduct an  
 146 observing system simulation experiment (OSSE) within the state estimation to illustrate how adding a satellite to the existing  
 147 constellation reveals a change in magnitude and potentially the sign of present-day SO air-sea CO<sub>2</sub> flux estimates. The study is  
 148 as follows: Section 2 describes the current scatterometer constellation, the tools we use to assess performance, and the  
 149 Biogeochemical SO State Estimate; Section 3 evaluates orbital and performance specifications of the scatterometer  
 150 constellation, without and with the proposed SOS-Zephyr mission. Section 4 describes our experiment in BSOSE, where surface  
 151 wind speeds are increased by 20% and compares the seasonal carbon and heat fluxes in the two simulations; and Section 5  
 152 presents our conclusions.

153

154 **2) Data and Methods**

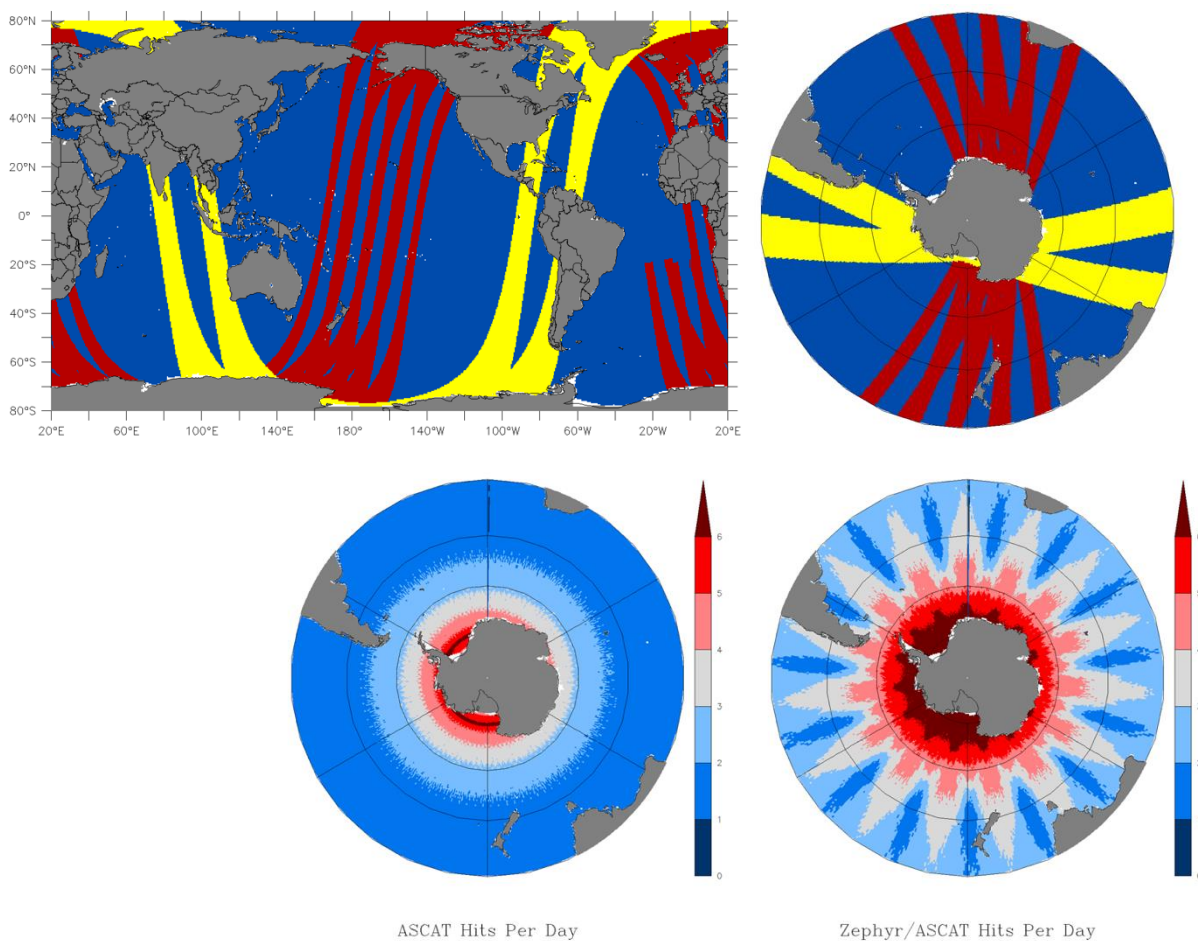
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156 We first assess how often per day and at what spatial resolution the existing scatterometer constellation measures SO winds.

157 We determine the orbital and sampling details needed for an additional satellite, to reduce the uncertainty in the net air-sea  
 158 exchange of CO<sub>2</sub> over the SO by >30% to ±0.2 PgC/yr or less.

159

160



161

162 Figure 1: (A) Locations of ground swaths during a “typical” period (3-6am GMT) for ASCAT-2 and ASCAT-3 (red) and SOS-Zephyr  
 163 (yellow) with a  $\Delta$ RAAN of approximately 90° and  $\Delta$ LTAN of about 6 hours. (B) Polar plot of the same data; (C) Number of  
 164 “independent” observations (defined as observations not in the same hour) per day for the constellation of ASCAT-2 and ASCAT-3;  
 165 and (D) independent observations for proposed constellation (ASCAT plus SOS-Zephyr) where most locations over the Southern  
 166 Ocean will be revisited 3 to 5 times per day—a 2x to 3x improvement providing the necessary temporal/spatial coverage to capture  
 167 storms.

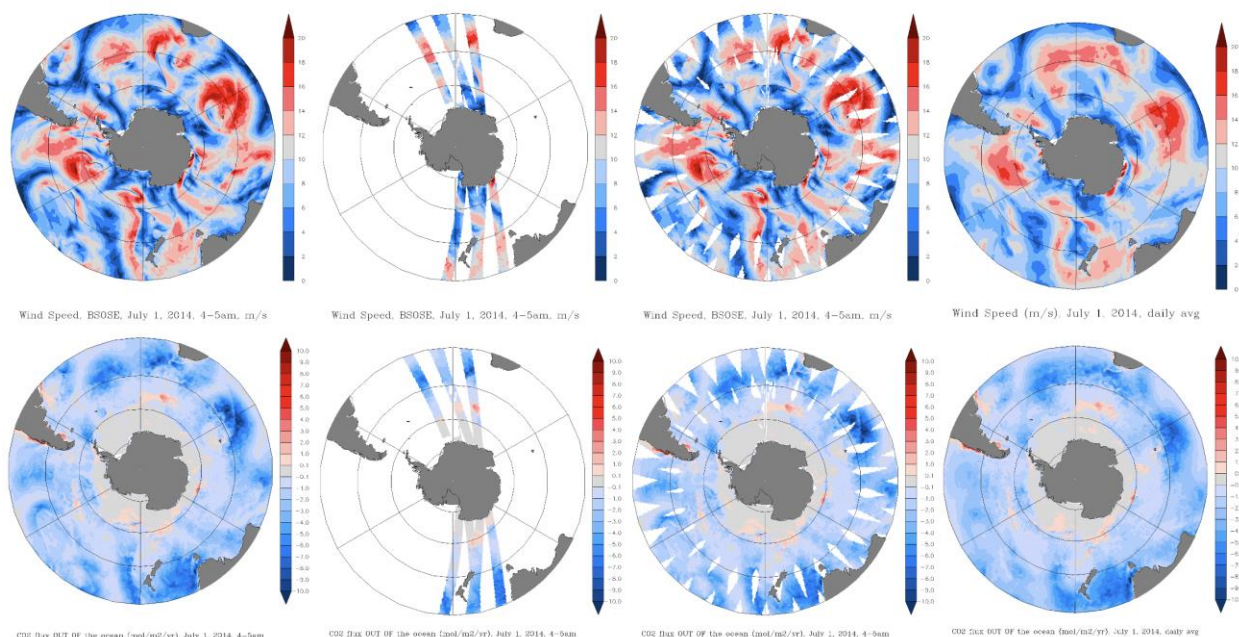


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## 2.1 Satellite-borne Scatterometers (ASCAT-1, ASCAT-2 & ASCAT-3)

The operational scatterometers constellation consists of three European-launched satellite missions: ASCAT-1 (Metop-A, until 2022), ASCAT-2 (Metop-B) and ASCAT-3 (Metop-C). There are three additional scatterometers currently on orbit: OSCAT2 (SCAT-SAT1; Indian Space Research Organisation, ISRO) and HY-2B/C and CFOSAT launched by China. OSCAT2 largely duplicates the ASCAT coverage (Bhowmick et al., 2019). The HY-2B satellite is in a sun-synchronous 6am/6pm orbit, while CFOSAT is a sun-synchronous 7am/7pm orbit. The temporal separation between the ASCATs and the ISRO and Chinese missions is insufficient for proper temporal sampling; they are not included in our analysis. ASCAT-2 and ASCAT-3 will still be on orbit when SOS-Zephyr is launched (2027-2028); with no knowledge of additional scatterometers in that time frame, we limit our analysis to ASCATs 2 and 3 and SOS-Zephyr.

Figure 1A and 1B show ground swaths from the ASCATs during a 3-hour period (3-6 am GMT on Day 1). During each hour, ~9% of the SO is directly observed by the ASCAT satellites and ~6.4% of the total carbon flux is “seen” directly. Figure 1C shows the daily satellite revisit cadence; for the ASCATs, only locations south of ~70°S have 4 unique visits per day, but areas north of ~53°S have 2 or fewer visits per day (12-hour return time at best). Adding ScatSat or ASCAT-3 does not change the twice-daily clustering of overpasses.



186

187 Figure 2: (Top row, A) Wind speed (m/s) for the BSOSE solution (2013-2018) for July 1, 2014, at 4-5am (from ERA5 hourly data);  
188 (B) wind speed “seen” at 4-5am by the ASCAT-only constellation (~9% of the area); (C) wind speed “seen” by all visits of the ASCAT  
189 constellation during the day (24 hours) applied to the same wind field (~85% of the area); (D) daily average wind speed from ERA5  
190 for July 1, 2014. (Bottom row, E) Carbon flux (mol/m<sup>2</sup>/yr) consistent with the above winds from BSOSE at the same day/time; (F)  
191 flux “seen” by ASCAT constellation during the hour; (G) flux “seen” by all visits of the ASCAT constellation during the day (24 hours)  
192 applied to the same flux field; (H) daily average of the carbon flux from BSOSE.

193  
194 We determined where and when the constellation of satellites (ASCAT-2, ASCAT-3) observe the ocean over the course of 7 days  
195 (168 hours). We projected these observations onto hourly and daily grids of ¼°, ½° and 1° spacing, creating a series of 168  
196 hourly “coverage maps” indicating whether a location was observed at least once by the constellation during that hour or not.  
197 We will refer to these coverage maps as “masks” because they hide the results of the model that are *unseen* by the satellites.  
198 Our results were insensitive to mask resolution; the rest of this study describes results using the ½° hourly masks. Daily masks  
199 were calculated from hourly masks (Figure 2C, 2G). We note that applying these “daily” masks to *individual hours* is more  
200 representative than applying them to the *daily average* of any particular field.

201

## 202 **2.2 Biogeochemical SO State Estimate**

203

204 The Biogeochemical SO State Estimate (BSOSE, Verdy & Mazloff, 2017) at 1/6° horizontal grid (~18km), January 2013 to  
205 December 2018, is used ([http://sose.ucsd.edu/BSOSE6\\_iter133\\_solution.html](http://sose.ucsd.edu/BSOSE6_iter133_solution.html)). BSOSE assimilates observations from shipboard  
206 sensors, profiling floats, satellites and reanalyses (wind speeds, SST, SSS, biogeochemical data, etc.) into a numerical model,  
207 producing a state estimate for the SO. In BSOSE, the MIT general circulation model (MITgcm) is fully coupled to a  
208 Biogeochemistry with Light, Iron, Nutrients, and Gases (BLING) model (Galbraith et al. 2015). Please refer to Verdy and Mazloff  
209 (2017) for additional details.

210

211 The BSOSE solution assimilates ERA5 hourly wind speed data, so we are able to assess the ocean state consistent with any wind  
212 regime. To gauge the effects of either a low bias in the reanalysis winds and/or increasing wind speeds on the ocean (e.g. the  
213 mixed-layer depth, the surface temperature, the air-sea fluxes of carbon and heat, etc.), we ran a *perturbation* experiment  
214 where BSOSE winds are increased by 20%. This approach is similar to the idealized perturbation experiments recently published  
215 by Bronselaer et al. 2018, 2020 in which a fixed zonal wind forcing anomaly was applied to the SO surface to assess the effect of  
216 possible biases in wind stress and latitudinal position. We chose a 20% increase to envelope the effects of the possible missing

217 winds. This experiment addresses two specific points: how do surface fluxes over the SO change in response to stronger winds,  
218 and how often must we sample the SO winds to capture either the missing winds or the trend. All other parameters for the  
219 2013-2018 simulation were held constant from the control experiment. Increasing the winds has two direct effects on the  
220 ocean; mixed layers deepen, exposing a larger volume of water to the atmosphere, and air-sea fluxes that depend on wind  
221 speed will be greater. Either or both could alter the air-sea exchange.

222

### 223 **3) Adding SOS-Zephyr to the Constellation**

224

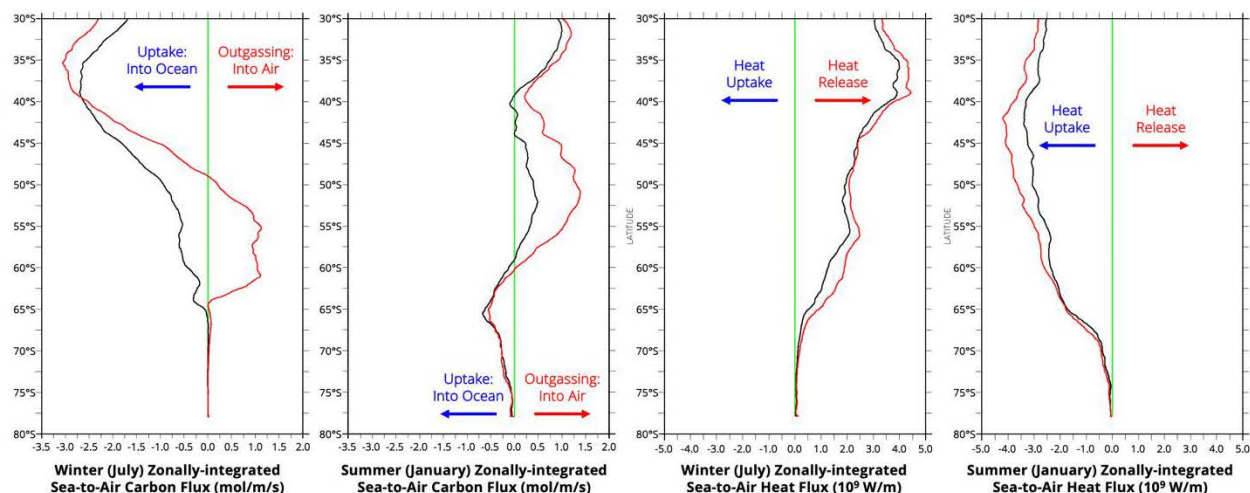
225 SOS-Zephyr will be a sun synchronous, conical scan, single swath instrument similar to SeaWinds on QuikSCAT (Spencer et al.,  
226 2000). Having a wider swath with overlap at lower latitudes was one of the big advantages of QuikSCAT over the ASCAT design:  
227 QuikSCAT visited 93% of the global ocean each day while the ASCAT constellation only observes 77% each day (Verspeek &  
228 Stoffelen, 2009). Many orbital details proposed for SOS-Zephyr are found in the Supplemental Methods section; the essential  
229 parameters are the swath-width of 1225km and the RAAN/LTAN of  $\sim 152^\circ$  and  $\sim 3:30/15:30$  respectively. The size and timing of  
230 SOS-Zephyr's ground track decreases the average revisit to less than 6 hours south of  $65^\circ\text{S}$  (Fig 1D, 4 per day at most  
231 longitudes) and less than 8 hours south of about  $50^\circ\text{S}$  (3 per day). The relative swath positions of SOS-Zephyr in our optimal  
232 orbit (Fig 1A & 1B) show excellent separation from the ASCAT swaths. Including the SOS-Zephyr coverage in the constellation  
233 increased the area observed from 9% per hour with ASCAT alone to more than 14% per hour. Fast transient changes will be  
234 better tracked by adding SOS-Zephyr; inclusion into the constellation increases the fraction of integrated carbon flux retrieved  
235 from 6.4% with ASCAT-only to 11.2% per hour (75% increase).

236

237 To quantify the net improvement per day by the augmented constellation, the daily mask of all locations visited that day by  
238 each constellation was applied to both the hourly retrievals and the daily sum of the hourly fluxes. The fraction of net flux  
239 captured by each constellation was similar in both methods; the differences between ASCAT and ASCAT+SOS-Zephyr are clear,  
240 with increases of daily capture at 96%, compared to 75% for carbon and 86% for heat for ASCAT-only.

241





242  
 243 *Figure 3: Comparison of carbon fluxes and heat fluxes consistent with standard ERA5 wind speeds and with 20% higher wind*  
 244 *speeds. Carbon Fluxes (zonally-integrated) during (A) July 2014 for BSOSE-ERA5x1.0 (black), BSOSE-ERA5x1.2 (red), and (B)*  
 245 *January 2014 for BSOSE-ERA5x1.0 (black), and BSOSE-ERA5x1.2 (red); and Heat Fluxes (zonally-integrated) for (C) July 2014 and*  
 246 *(D) January 2014 with the same color convention. Positive (negative) values are out of (into) the ocean. Note that carbon fluxes in*  
 247 *January of the ERAx1.0 run (panel B, black line) are generally out of the ocean except at 40°S and south of 58°S, while in the*  
 248 *ERAx1.2 run (red line), these fluxes are more strongly out of the ocean (degassing) between 60°S and 40°S, mirroring the strong*  
 249 *outgassing seen between 62°S and 50°S during July (A, red line) under increased winds compared to the uptake at these latitudes in*  
 250 *July under standard winds (A, black line).*

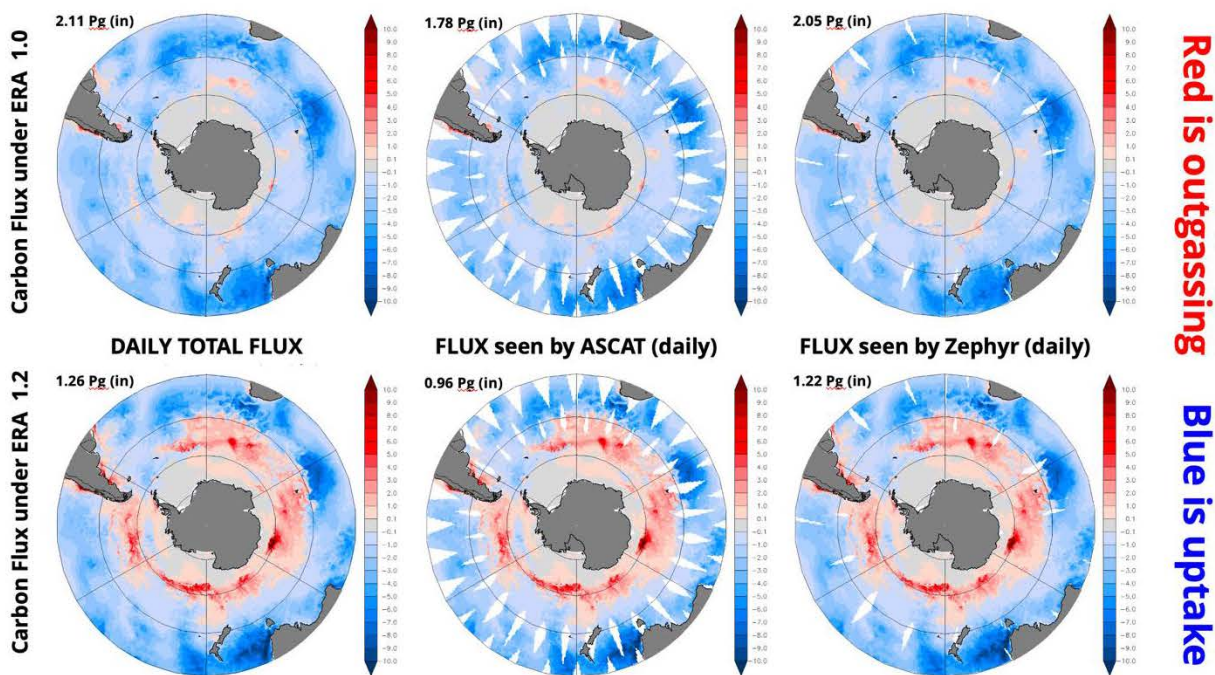
251  
 252 **4) The Experiment: A State Estimate with Stronger Wind Speeds**

253  
 254 To assess potential benefits of adding SOS-Zephyr to our scatterometer constellation, we pose two questions: 1) “If reanalysis  
 255 winds are biased low, how would this affect the carbon and heat fluxes?” and 2) “Would adding an additional satellite capture  
 256 more of these higher winds?”.

257  
 258 Figure 3 shows zonally-integrated carbon fluxes (A,B) and total heat fluxes (C,D) for July (A,C) and January (B,D) under standard  
 259 ERA5 winds (black) and stronger winds (red) in response to increasing the wind speeds. In the SO, south of about 50°S, the  
 260 vertical carbon gradient in winter is strong; increased stirring brings more carbon-enriched deep water to the surface in a  
 261 region of divergence where it can escape to the atmosphere. Enhanced mixing of deep carbon changes the sign of the air-sea  
 262 gradient and turns the region south of 50°S from a net sink (Fig 3A, black line) taking up of 0.024 PgC for the month to a net  
 263 source (red line) releasing 0.044 PgC for the month – a change of 0.067 PgC. Increased gas exchange in uptake regions at lower

264 latitudes increase the net uptake there, but stronger divergence in the latitudes of Drake Passage (63°S-55°S) under higher  
 265 winds ventilates older, deeper carbon-rich water, and turns the SO from a strong net sink taking up 0.175 PgC into a weaker net  
 266 sink, only taking up 0.096 PgC. Outgassing in this region in winter near the ice edge has been documented by  
 267 biogeochemically-sensored floats (Gray et al. 2018). Carbon fluxes in January are not as uniform; there is uptake at the highest  
 268 latitudes adjacent to the continent, but most of the region is outgassing except along the northern edge of the Antarctic  
 269 Circumpolar Current. Increasing winds turn the summer SO, south of 30°S, from a weak outgassing region with a net release of  
 270 0.020 PgC over the month into a strong outgassing region releasing 0.074 PgC. The average monthly change implies an annual  
 271 change of  $\sim 0.84$  PgC/yr less uptake, representing a 33% decrease in the total uptake by global ocean (2.5 PgC, and an  
 272 additional atmospheric increase of  $\sim 0.4$  ppm per year) or about 60% of the annual US emissions (1.4 PgC/yr in 2018,  
 273 Friedlingstein et al. 2019).

274  
 275 This experiment illustrates that carbon fluxes respond differently to increasing winds than do heat fluxes. Heat fluxes (both in  
 276 and out) are enhanced by stronger winds, while stronger winds release more carbon out of the ocean throughout the year.  
 277



278  
 279 *Figure 4 (Top row, A,B,C) Simulated carbon fluxes on July 1, 2014 from BSOSE-ERA5x1.0; (Bottom row, D,E,F) Simulated carbon*  
 280 *fluxes from BSOSE-ERA5x1.2. In each panel, red (positive) is out of the ocean while blue (negative) is into the ocean. The left column*  
 281 *(A,D) shows the total from BSOSE; the middle column (B,E) shows what is captured by the ASCAT constellation; and the right*

282 *column (C,F) shows what is captured by the addition of SOS-Zephyr. The total fluxes (PgC/yr) are indicated in the upper left corner*  
283 *of each panel.*

284

#### 285 **4a) Carbon Flux captured by the Satellite Constellation**

286

287 We next look at the differences between carbon and heat fluxes captured. On an hourly basis, ASCAT sees ~9% of the area and  
288 6.4% of the carbon flux, while ASCAT+SOS-Zephyr sees ~14% of the area and 11.2% of the carbon. Over the course of each 24-  
289 hour interval, the ASCAT constellation visits ~88% of the SO (south of 30°S) while adding SOS-Zephyr increases that area to  
290 97%. This increase has significant repercussions for the total fluxes of carbon and heat observed.

291

292 Figure 4 shows total surface fluxes of carbon from BSOSE assimilations for July 1, 2014. The hourly output from BSOSE was  
293 averaged over the entire day; the mask for each constellation includes locations that were visited at least once during the day.  
294 Most of the carbon flux is into the ocean except for the highest latitudes near the ice edge and the coastal regions of South  
295 America. The net carbon flux for the month is uptake of ~0.17 PgC, equivalent to ~2.1 PgC/yr. The daily average for the ASCAT-  
296 constellation represents 81% of the total flux (1.7 Pg/yr, less than the relative area covered) whereas the addition of SOS-  
297 Zephyr increases the net flux captured to 96% (2.0 Pg/yr). As can be seen, the gaps in the coverage by the ASCAT-only  
298 constellation coincide with the larger uptake fluxes, biasing the total toward the low end.

299

300 Monteiro et al (2015) support the importance of temporal resolution, noting that pCO<sub>2</sub> observations less than two days apart  
301 are required to reduce the annual uncertainty of the SO carbon flux below 10%. They conclude that “the synoptic period and  
302 the spatial scale of the wind stress, particularly the magnitude and phasing of storm events, make a significant contribution to  
303 reducing the uncertainty of the flux.” Trindade et al. (2020) show that reanalysis differences with scatterometers can be  
304 reduced by 20% by subtracting local biases that are constant over 5 days, indicating that these biases are associated with the  
305 local ocean state rather than with the local weather. Local ocean states vary on the ocean eddy scale of a few km; we believe  
306 that the higher spatial resolution of SOS-Zephyr reduces this aspect of our uncertainty (Lindsley et al. 2016).

307

#### 308 **5) Discussion**

309

310 SO winds are the strongest on average globally, but are distinctly spatially and temporally heterogeneous due to the presence  
311 of long-lasting, fast-moving storms. These winds stir the surface ocean, driving strong carbon and heat fluxes between

312 atmosphere and ocean, especially in winter. Significant shortcomings and assumptions associated with determining the air-sea  
 313 carbon fluxes over the SO persist. 1) Our current wind observing system samples these storms infrequently (once or twice per  
 314 day), and is unlikely to directly observe the highest winds and variability. 2) Uncertainty in precision and accuracy of existing  
 315 scatterometers are large at the highest wind speeds. 3) Climate reanalyses underestimate the mean winds by 1–7 m/s and the  
 316 75<sup>th</sup> percentile by 5–10 m/s compared to scatterometer data (Vezeremskaya et al. 2017). It is these reanalysis winds that  
 317 determine the SO and global carbon fluxes and budgets. 4) Determination of the wind-dependent air-sea gas exchange  
 318 parameterization relies on these uncertain winds to determine the global formulation. And 5) coupled climate models  
 319 consistently simulate wind speeds over the SO that are weaker and more equatorward than observed, which has a large impact  
 320 on the simulated fluxes (Russell et al. 2006; Bracegirdle et al. 2013; Russell et al. 2018; Beadling et al. 2020).

321  
 322 By paying careful attention to the orbital parameters, this design OSSE addresses most of the above issues. 1) SOS-Zephyr  
 323 increases temporal resolution to 3–6 observations per day, south of 45°S. 2) Increased spatial resolution using new processing  
 324 algorithms increases precision and accuracy at the highest wind speeds and provides data close to coasts and sea ice edges, and  
 325 coincident radiometer observations reduce the confounding effects of coincident rain. And 3) new wind observations and new  
 326 attention to the gas exchange parameterization will refine this critical component of our carbon budget estimates. The “best”  
 327 estimate of the global carbon budget (Friedlingstein et al. 2020) indicates that more than half of the net air-sea carbon flux  
 328 occurs in the SO and half of the global uncertainty in the air-sea carbon flux is in the SO.

329  
 330 An additional, targeted scatterometer achieves our main goal of reducing the uncertainty in the global carbon budget by  
 331 focusing on the SO where the largest fraction of the air-sea exchange happens and where the current uncertainties are largest.  
 332 If successful, SOS-Zephyr will become a pathfinder for additional instruments that could provide a trove of new data, closing  
 333 many of the holes in our understanding and quantification of the carbon and heat budgets due to weathered ocean-scale air-  
 334 sea interaction.

335  
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344

345 **Data availability statement.**

346

347 The B-SOSE Iteration 133 output used in this analysis is available at Scripps Institution of Oceanography:

348 [http://sose.ucsd.edu/BSOSE6\\_iter133\\_solution.html](http://sose.ucsd.edu/BSOSE6_iter133_solution.html).

349

350 **References**

351

352 Arduin, F., Hanafin, J., Quilfen, Y., Chapron, B., Queffelec, P., Obrebski, M., et al. (2011). Calibration of the IOWAGA global  
 353 wave hindcast (1991–2011) using ECMWF and CFSR winds. In *Proc. 12th International Workshop of Wave Hindcasting and*  
 354 *Forecasting*, Hawaii. Joint Technical Commission for Oceanography and Marine Meteorology Technical Report No. 67,  
 355 Kohala Coast, Hawaii.

356 Beadling, R.L., Russell, J.L., Stouffer, R.J., Mazloff, M., Talley, L.D., Goodman, P.J., et al. (2020). Representation of Southern  
 357 Ocean properties across Coupled Model Intercomparison Project generations: CMIP3 to CMIP6, *J. Climate*, **33(15)**, 6555-  
 358 6581. <https://doi.org/10.1175/JCLI-D-19-0970.1>

359 Belmonte Rivas, M. & Stoffelen, A. (2019). Characterizing ERA-Interim and ERA5 surface wind biases using ASCAT. *Ocean*  
 360 *Science*, **15**, 831–852. <https://doi.org/10.5194/os-15-831-2019>

361 Bhowmick, S.A., Cotton, J., Fore, A., Kumar, R., Payan, C., Rodriguez, E., et al. (2019). An assessment of the performance of  
 362 ISRO's SCATSAT-1 Scatterometer. *Current Science*, **117**, 959. doi: 10.18520/cs/v117/i6/959-972.

363 Bosilovich, M.G., Lucchesi, R. & Suarez, M. (2016). MERRA-2: File Specification. GMAO Office Note No. 9 (Version 1.1), 73 pp.  
 364 [Available at [http://gmao.gsfc.nasa.gov/pubs/office\\_notes/](http://gmao.gsfc.nasa.gov/pubs/office_notes/).]

365 Bourassa, M.A., Meissner, T., Cerovecki, I., Chang, P.S., Dong, X., Chiara, G.D., et al. (2019). Remotely Sensed Winds and Wind  
 366 Stresses for Marine Forecasting and Ocean Modeling. *Frontiers in Marine Science*, **6**, 443.  
 367 <https://doi.org/10.3389/fmars.2019.00443>

368 Bracegirdle, T.J., Shuckburgh, E., Sallee, J.-B., Wang, Z., Meijers, A.J.S., Bruneau, N., et al. (2013). Assessment of surface winds  
 369 over the Atlantic, Indian, and Pacific Ocean sectors of the Southern Ocean in CMIP5 models: historical bias, forcing  
 370 response, and state dependence, *J. Geophysical Research-Atmosphere*, **118**, 547–562, doi:10.1002/jgrd.50153.



- 371 Bronselaer, B., Winton, M., Griffies, S.M., Hurlin, W.J., Rodgers, K.B., Sergienko, O.V. et al. (2018). Change in future climate due  
372 to freshwater from Antarctic ice melt, *Nature*, **564**, 53–58. <https://doi.org/10.1038/s41586-018-0712-z>
- 373 Bronselaer, B., Russell, J.L., Winton, M., Williams, N.L., Key, R.M., Dunne, J.P. et al. (2020). Importance of wind and meltwater  
374 for observed chemical and physical changes in the Southern Ocean, *Nature Geosciences*, **13**, 35–42.  
375 <https://doi.org/10.1038/s41561-019-0502-8>
- 376 Chang, P.S., Jelenak, Z., Sienkiewicz, J., Knabb, R., & Brennan, M. (2009). Operational Utilization and Impact of Satellite  
377 Remotely-Sensed Ocean Surface Vector Winds in the Marine Warning and Forecasting Environment. *Oceanography*  
378 *Magazine*, **22**, 194–207. <https://doi.org/10.5670/oceanog.2009.49>
- 379 Chawla, A., Spindler, D.M. & Tolman, H.L. (2013). Validation of a thirty-year wave hindcast using the Climate Forecast System  
380 Reanalysis winds. *Ocean Modelling*, **70**, 189–206. doi: 10.1016/j.ocemod.2012.07.005
- 381 Dee, D.P., Uppala, S.M., Simmons, A.J., Berrisford, P., Poli, P., Kobayashi, S., et al. (2011). The ERA-Interim reanalysis:  
382 configuration and performance of the data assimilation system. *Quarterly Journal of the Royal Meteorological Society*, **137**,  
383 553–597. <https://doi.org/10.1002/qj.828>
- 384 Frew, N.M., Glover, D.M., Bock, E.J. & McCue, S.J. (2007). A new approach to estimation of global air-sea gas transfer velocity  
385 fields using dual-frequency altimeter backscatter, *J. Geophysical Research*, **112**, C11003, doi:[10.1029/2006JC003819](https://doi.org/10.1029/2006JC003819)
- 386 Friedlingstein, P., Jones, M.W., O'Sullivan, M., Andrew, R.M., Hauck, J., Peters, G., et al. (2019). Global Carbon Budget 2019,  
387 *Earth System Science Data*, **11**, 1783–1838. <https://doi.org/10.5194/essd-11-1783-2019>
- 388 Friedlingstein, P., O'Sullivan, M., Jones, M.W., Andrew, R.M., Hauck, J., Olsen, A. et al. (2020). Global Carbon Budget 2020. *Earth*  
389 *System Science Data*, **12**, 3269–3340. <https://doi.org/10.5194/essd-12-3269-2020>
- 390 Galbraith, E.D., Dunne, J.P., Gnanadesikan, A., Slater, R.D., Sarmiento, J.L., Dufour, C.O. et al. (2015), Complex functionality with  
391 minimal computation: Promise and pitfalls of reduced-tracer ocean biogeochemistry models, *J. Advances in Modeling Earth*  
392 *Systems*, **7**, 2012–2028, doi:10.1002/2015MS000463.
- 393 Gray, A.R., Johnson, K.S., Bushinsky, S.M., Riser, S.C., Russell, J.L., Talley, L.D., et al. (2018). Autonomous Biogeochemical Floats  
394 Detect Significant Carbon Dioxide Outgassing in the High-Latitude Southern Ocean. *Geophysical Research Letters*, **45**.  
395 <https://doi.org/10.1029/2018GL078013>
- 396 Hell, M.C., Gille, S.T., Cornuelle, B.D., Miller, A.J., Bromirski, P.D., & Crawford, A.D. (2020). Estimating Southern Ocean Storm  
397 Positions With Seismic Observations. *Journal of Geophysical Research: Oceans*, **125(4)**.  
398 <https://doi.org/10.1029/2019jc015898>
- 399 Hersbach, H, Bell, B, Berrisford, P, Hirahara, S., Horányi, A., Muñoz-Sabater, J., et al. (2020). The ERA5 global reanalysis.  
400 *Quarterly Journal of the Royal Meteorological Society*, **146**, 1999–2049. <https://doi.org/10.1002/qj.3803>

- 401 Iida, Y., Kojima, A., Takatani, Y., Nakano, T., Sugimoto, H., Midorikawa, T., & Ishii, M. (2015). Trends in pCO<sub>2</sub> and sea-air CO<sub>2</sub> flux  
 402 over the global open oceans for the last two decades. *Journal of Oceanography*, **71**, 637–661.  
 403 <https://doi.org/10.1007/s10872-015-0306-4>
- 404 Kobayashi, S., Ota, Y., Harada, Y., Ebata, A., Moriya, M., Onoda, H., et al. (2015), The JRA-55 reanalysis: General specifications  
 405 and basic characteristics, *Journal of the Meteorological Society of Japan. Series II*, **93(1)**, 5–48.  
 406 <https://doi.org/10.2151/jmsj.2015-001>
- 407 Krakauer, N.Y., Randerson, J.T., Primeau, F.W., Gruber, N., & Menemenlis, D. (2006). Carbon isotope evidence for the latitudinal  
 408 distribution and wind speed dependence of the air-sea gas transfer velocity. *Tellus B*, **58**, 390–417, doi: 10.1111/j.1600-  
 409 0889.2006.00223.x.
- 410 Landschützer, P., Gruber, N. & Bakker, D.C.E. (2016). Decadal variations and trends of the global ocean carbon sink, *Global*  
 411 *Biogeochemical Cycles*, **30**, 1396–1417. doi:[10.1002/2015GB005359](https://doi.org/10.1002/2015GB005359).
- 412 Lindsley, R.D., Blodgett, J.R. & Long, D.G. (2016). Analysis and Validation of High-Resolution Wind from ASCAT, *IEEE*  
 413 *Transactions on Geoscience and Remote Sensing*, **54(10)**, 5699–5711. doi:10.1109/TGRS.2016.2570245
- 414 Marseille, G.J., Stoffelen, A., van den Brink, H. & Stepek, A. (2017). WISC Intermediate Bias Derivation and Uncertainty  
 415 Assessment, Copernicus Climate Change Service (C3S) Wind Information Service (WISC) report, KNMI, de Bilt, the  
 416 Netherlands, REF.: (C3S\_441\_Lot3\_WISC\_SC2-D3.3-CGI-RP-17-0071),  
 417 [https://wisc.climate.copernicus.eu/wisc/documents/shared/C3S\\_WISC\\_Intermediate\\_Bias\\_Derivation\\_and\\_Uncertainty](https://wisc.climate.copernicus.eu/wisc/documents/shared/C3S_WISC_Intermediate_Bias_Derivation_and_Uncertainty_Assessment_v1-0.pdf)  
 418 [\\_Assessment\\_v1-0.pdf](https://wisc.climate.copernicus.eu/wisc/documents/shared/C3S_WISC_Intermediate_Bias_Derivation_and_Uncertainty_Assessment_v1-0.pdf)
- 419 Matear, R. J., & Lenton, A. (2008). Impact of Historical Climate Change on the Southern Ocean Carbon Cycle, *Journal of Climate*,  
 420 **21(22)**, 5820–5834. <https://journals.ametsoc.org/view/journals/clim/21/22/2008jcli2194.1.xml>
- 421 Monteiro, P.M.S., Gregor, L., Lévy, M., Maenner, S., Sabine, C.L. & Swart, S. (2015). Intraseasonal variability linked to sampling  
 422 alias in air-sea CO<sub>2</sub> fluxes in the Southern Ocean, *Geophysical Research Letters*, **42**, 8507–8514.  
 423 doi:[10.1002/2015GL066009](https://doi.org/10.1002/2015GL066009).
- 424 Naegler T., Ciais P., Rodgers K. & Levin I. (2006). Excess radiocarbon constraints on air-sea gas exchange and the uptake of CO<sub>2</sub>  
 425 by the oceans. *Geophysical Research Letters*, **33**: L11802, doi:10.1029/2005GL025408.
- 426 National Academies of Sciences, Engineering, and Medicine. 2018. *Thriving on Our Changing Planet: A Decadal Strategy for Earth*  
 427 *Observation from Space*. Washington, DC: The National Academies Press. doi: <https://doi.org/10.17226/24938>
- 428 Reguero, B.G., Losada, I.J. & Méndez, F.J. (2019). A recent increase in global wave power as a consequence of oceanic warming.  
 429 *Nature Communications*, **10**, 205. <https://doi.org/10.1038/s41467-018-08066-0>

- 430 Ricciardulli, L., & Wentz, F.J. (2015). A Scatterometer Geophysical Model Function for Climate- Quality Winds: QuikSCAT Ku-  
 431 2011. *J. Atmospheric and Oceanic Technology*, **32**, 1829-1846. DOI: 10.1175/JTECH-D-15-0008.1
- 432 Risien, C.M., & Chelton, D.B. (2008). A Global Climatology of Surface Wind and Wind Stress Fields from Eight Years of QuikSCAT  
 433 Scatterometer Data. *J. Phys. Oceanogr.*, **38**, 2379-2413. <https://doi.org/10.1175/2008JPO3881.1>
- 434 Russell, J.L., Dixon, K.W., Gnanadesikan, A., Stouffer, R.J. & Toggweiler, J.R. (2006). The Southern Hemisphere Westerlies in a  
 435 Warming World: Propping Open the Door to the Deep Ocean. *J. Climate*, **19(24)**, 6382-6390.  
 436 <https://doi.org/10.1175/JCLI3984.1>
- 437 Russell, J.L., Kamenkovich, I., Bitz, C., Ferrari, R., Gille, S.T., Goodman, P.J. et al. (2018). Metrics for the Evaluation of the  
 438 Southern Ocean in Coupled Climate and Earth System Models, *J. Geophysical Research – Oceans*, **123**, 3120-3143.  
 439 <https://doi.org/10.1002/2017JC013461>
- 440 Saha, S., Moorthi, S., Pan, H., Wu, X., Wang, J., Nadiga, S., Tripp, P., et al. (2010). The NCEP Climate Forecast System Reanalysis,  
 441 *Bulletin of the American Meteorological Society*, **91(8)**, 1015-1058. <https://doi.org/10.1175/2010BAMS3001.1>
- 442 Sampe, T., & Xie, S. (2007). Mapping High Sea Winds from Space: A Global Climatology, *Bulletin of the American Meteorological*  
 443 *Society*, **88(12)**, 1965-1978. <https://journals.ametsoc.org/view/journals/bams/88/12/bams-88-12-1965.xml>
- 444 Spencer, M.W., Wu, C., & Long, D.G. (2000). Improved resolution backscatter measurements with the SeaWinds pencil-beam  
 445 scatterometer. *IEEE Transactions on Geoscience and Remote Sensing*, **38(1)**, 89-104. <https://doi.org/10.1109/36.823904>
- 446 Stoffelen A., Kumar R., Zou J., Karaev V., Chang P.S. & Rodriguez E. (2019). Ocean Surface Vector Wind Observations. In: Barale  
 447 V., Gade M. (eds) *Remote Sensing of the Asian Seas*. Springer, Cham. [https://doi.org/10.1007/978-3-319-94067-0\\_24](https://doi.org/10.1007/978-3-319-94067-0_24)
- 448 Stoffelen, A., Mouche, A., Polverari, F., van Zadelhoff, G.-J., Sapp, J., Portabella, M., et al. (2020). C-band High and Extreme-  
 449 Force Speeds (CHEFS), EUMETSAT project report, EUMETSAT ITT 16/166, <https://www.eumetsat.int/CHEFS>;  
 450 <https://www.eumetsat.int/media/45432>
- 451 Sweeney, C., Gloor, E., Jacobson, A.R., Key, R.M., McKinley, G., Sarmiento, J.L., & Wanninkhof, R. (2007), Constraining global  
 452 air-sea gas exchange for CO<sub>2</sub> with recent bomb <sup>14</sup>C measurements, *Global Biogeochemical Cycles*, **21**, GB2015,  
 453 doi:[10.1029/2006GB002784](https://doi.org/10.1029/2006GB002784)
- 454 Takahashi, T., Sutherland, S.C., Chipman, D.W., Goddard, J.G., Ho, C., Newberger, T. et al. (2014). Climatological distributions of  
 455 pH, pCO<sub>2</sub>, total CO<sub>2</sub>, alkalinity, and CaCO<sub>3</sub> saturation in the global surface ocean, and temporal changes at selected  
 456 locations. *Marine Chemistry*, **164**, 95-125, <https://doi.org/10.1016/j.marchem.2014.06.004>
- 457 Trindade, A., Portabella, M., Stoffelen, A., Lin W. & Verhoef, A. (2020). ERAstar: A High-Resolution Ocean Forcing Product, *IEEE*  
 458 *Transactions on Geoscience and Remote Sensing*, **58(2)**, 1337-1347, doi: 10.1109/TGRS.2019.2946019

- 459 Verdy, A. & Mazloff, M.R. (2017). A data assimilating model for estimating Southern Ocean biogeochemistry, *J. Geophysical*  
 460 *Research-Oceans*, **122**, 6968–6988, doi:10.1002/2016JC012650
- 461 Verezemskaya, P., Tilinina, N., Gulev, S., Renfrew, I.A. & Lazzara, M. (2017). Southern Ocean mesocyclones and polar lows from  
 462 manually tracked satellite mosaics, *Geophysical Research Letters*, **44**, 7985–7993, doi:10.1002/2017GL074053
- 463 Verhoef, A., Vogelzang, J., Verspeek, J. & Stoffelen, A. (2017). Long-Term Scatterometer Wind Climate Data Records, *IEEE*  
 464 *Journal of Selected Topics in Applied Earth Observations and Remote Sensing*, **10(5)**, 2186–2194. doi:  
 465 10.1109/JSTARS.2016.2615873
- 466 Verspeek, J., & Stoffelen, A. (2009). ASCAT tandem coverage, EUMETSAT Ocean and Sea Ice (OSI) Satellite Application Facility  
 467 (SAF) report, v0.8,  
 468 [https://cdn.knmi.nl/system/data\\_center\\_publications/files/000/068/323/original/ascat\\_tandem\\_coverage.pdf?149562](https://cdn.knmi.nl/system/data_center_publications/files/000/068/323/original/ascat_tandem_coverage.pdf?149562)  
 469 1136
- 470 Wanninkhof, R., Asher, W.E., Ho, D.T., Sweeney, C.S. & McGillis, W.R. (2009). Advances in quantifying air-sea gas exchange and  
 471 environmental forcing. *Annual Reviews of Marine Science*, **1**, 213–244, doi:10.1146/annurev.marine.010908.163742.
- 472 Wanninkhof, R., Park, G.-H., Takahashi, T., Sweeney, C., Feely, R., Nojiri, Y., et al. (2013). Global ocean carbon uptake:  
 473 magnitude, variability and trends. *Biogeosciences*, **10**, 1983–2000. <https://doi.org/10.5194/bg-10-1983-2013>
- 474 Wanninkhof, R. & Trīñanes, J. (2017). The impact of changing wind speeds on gas transfer and its effect on global air-sea CO<sub>2</sub>  
 475 fluxes. *Global Biogeochemical Cycles*, **31**, 961–974, doi:10.1002/2016GB005592
- 476 Wei, L., & Qin, T. (2016). Characteristics of cyclone climatology and variability in the Southern Ocean. *Acta Oceanologica Sinica*,  
 477 **35**, 59–67, doi: 10.1007/s13131-016-0913-y
- 478 Wentz, F., Ricciardulli, L., Rodriguez, E. Stiles, B., Bourassa, M., Long, D. et al. (2017). Evaluating and Extending the Ocean Wind  
 479 Climate Data Record. *IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing*. **99**, 2165–2185. doi:  
 480 10.1109/JSTARS.2016.2643641
- 481 Xu, X. & Stoffelen, A. (2020). Improved Rain Screening for Ku-Band Wind Scatterometry, *IEEE Transactions on Geoscience and*  
 482 *Remote Sensing*, **58:4**, 2494–2503. doi: 10.1109/TGRS.2019.2951726
- 483 Young, I.R., & Ribal, A. (2019). Multiplatform evaluation of global trends in wind speed and wave height. *Science*, **364(6440)**,  
 484 eaav9527. <https://doi.org/10.1126/science.aav9527>
- 485 Young, I.R., Sanina, E., & Babanin, A.V. (2017). Calibration and Cross Validation of a Global Wind and Wave Database of  
 486 Altimeter, Radiometer, and Scatterometer Measurements. *Journal of Atmospheric and Oceanic Technology*, **34(6)**, 1285–  
 487 1306. <https://doi.org/10.1175/jtech-d-16-0145.1>

488 Young, I.R., Zieger, S., & Babanin, A.V. (2011). Global Trends in Wind Speed and Wave Height. *Science*, **332(6028)**, 451–455.

489 <https://doi.org/10.1126/science.1197219>

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