

1 **Offset between profiling float and shipboard oxygen observations at depth imparts bias on**
2 **float pH and derived $p\text{CO}_2$**

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14 **Abstract**

15 Profiles of oxygen measurements from Argo profiling floats now vastly outnumber
16 shipboard profiles. Air calibration of a float’s oxygen optode upon surfacing enables accurate
17 measurements in the upper ocean but does not necessarily provide similar accuracy at depth. In
18 this study we use a quality controlled shipboard dataset to show that, on average, the entire Argo
19 oxygen dataset is offset relative to shipboard measurements (float minus ship) at pressures of 1450
20 to 2000 db by $-1.9 \pm 4.7 \mu\text{mol kg}^{-1}$ (95% confidence interval around the mean of $\{-2.3, -1.5\}$) and
21 air calibrated floats are offset by $-3.1 \pm 5.3 \mu\text{mol kg}^{-1}$ (95% CI: $\{-3.7, -2.4\}$). The difference
22 between float and shipboard oxygen is most likely due to offsets in the float oxygen data and not
23 due to oxygen changes at these depths or biases in the shipboard dataset. In addition to posing
24 problems for the calculation of long-term ocean oxygen changes, these float oxygen offsets impact
25 the adjustment of float nitrate and pH measurements and therefore bias important derived
26 quantities such as the partial pressure of CO_2 ($p\text{CO}_2$) and dissolved inorganic carbon. Correcting
27 floats with air-calibrated oxygen for the float-ship oxygen offsets changes float pH by 3.2 ± 3.8
28 mpH and float-derived surface $p\text{CO}_2$ by $-3.3 \pm 4.1 \mu\text{atm}$. This adjustment to float $p\text{CO}_2$ represents
29 half, or more, of the bias in float-derived $p\text{CO}_2$ reported in studies comparing float $p\text{CO}_2$ to
30 shipboard $p\text{CO}_2$ measurements.

31

32 **Plain Language Summary**

33 Oxygen has historically been measured using chemical titrations on water collected by
34 ships at sea. Over the past 20 years, sensors that measure oxygen have been deployed on robotic
35 profiling floats. Measurements by oxygen sensors on profiling floats now greatly exceed those
36 collected by ships. Here we compare all float oxygen data collected to shipboard measurements in
37 deep waters (1450 to 2000 m depth) where we do not expect oxygen to be changing in the ocean.
38 We find a difference between float and shipboard data. If left uncorrected, this difference would
39 give the false impression of a long-term oxygen change. This difference also impacts float-
40 measured pH and float-estimated carbon dioxide, both of which rely on float oxygen
41 measurements. Correcting oxygen, and therefore float pH and carbon dioxide, would largely
42 address a widely-studied bias in float measurements of these parameters.

43

44 **Key Points**

- 45 1. Air-calibrated float oxygen measurements are lower than shipboard data by $3.1 \mu\text{mol kg}^{-1}$
46 at pressures of 1450 to 2000 db.
- 47 2. Correcting float oxygen for this offset would increase float pH by 3.2 mpH and lower float-
48 derived $p\text{CO}_2$ by $-3.3 \mu\text{atm}$.
- 49 3. This float oxygen offset would improve float and ship $p\text{CO}_2$ comparisons, removing most
50 or all of observed biases.

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52

53 1. Introduction

54 Measurements of oxygen in the ocean are critical, as the ocean is losing oxygen due to
55 warming, respiration, and stratification-induced changes to ventilation (Helm et al., 2011; Levin,
56 2018; Schmidtko et al., 2017; Stramma & Schmidtko, 2021). Measurements of ocean oxygen also
57 can be used to understand the balance between photosynthesis and respiration in the surface and
58 deep ocean (Bushinsky & Emerson, 2015; Emerson, 1987; Hennon et al., 2016; Yang et al., 2017).
59 Historically, oxygen was primarily measured by Winkler titrations of water sampled from the
60 ocean (Carpenter, 1965; Dickson, 1994). These titrations require reliable standards and trained
61 operators to achieve high accuracy and precision. Winkler titrations have been supplemented by
62 electrochemical and optical sensors attached to CTDs but have remained the gold standard of
63 accurate oxygen measurement in the ocean.

64 Oxygen measurements on autonomous profiling floats are transforming our ability to
65 observe the ocean at unprecedented levels of detail. The first Argo oxygen data was from floats
66 deployed in the early 2000s equipped with Clark-cell electrodes (Figure 1) that provided fast
67 response times but could drift rapidly and in unpredictable ways (Gruber et al., 2007). Oxygen
68 optodes that measure the partial pressure of oxygen through an oxygen-sensitive luminophore have
69 now become the standard oxygen sensor deployed on floats (Claustre et al., 2020; Gruber et al.,
70 2009; Körtzinger et al., 2005; Tengberg et al., 2006) (Figure 1). Over 1800 Argo oxygen floats
71 have been deployed as of 2023, with increasing numbers due to a mix of many small deployments
72 by individual research groups and the development of a few projects deploying large numbers of
73 floats (e.g., the Southern Ocean Carbon and Climate Observations and Modeling project,
74 SOCCOM, (Johnson et al., 2017; Sarmiento et al., 2023); Global Ocean Biogeochemistry Array,
75 GO-BGC (Roemmich et al., 2021; Schofield, O. A. et al., 2022)). Optodes drift significantly prior
76 to deployment, but the advent of calibration using atmospheric oxygen has increased accuracy of
77 surface data to better than 1% (Bittig, Körtzinger, et al., 2018; Bushinsky et al., 2016; D'Asaro &
78 McNeil, 2013; Johnson et al., 2015). Floats calibrated using atmospheric data primarily use a
79 single multiplicative gain correction based on the difference between float air measurements and
80 calculated atmospheric oxygen that is then applied to the whole float profile (Figure 2). This
81 approach assumes that the response of the oxygen optode at different oxygen levels and
82 temperatures changes uniformly over time, and that the zero reading of the optode remains
83 unchanged.

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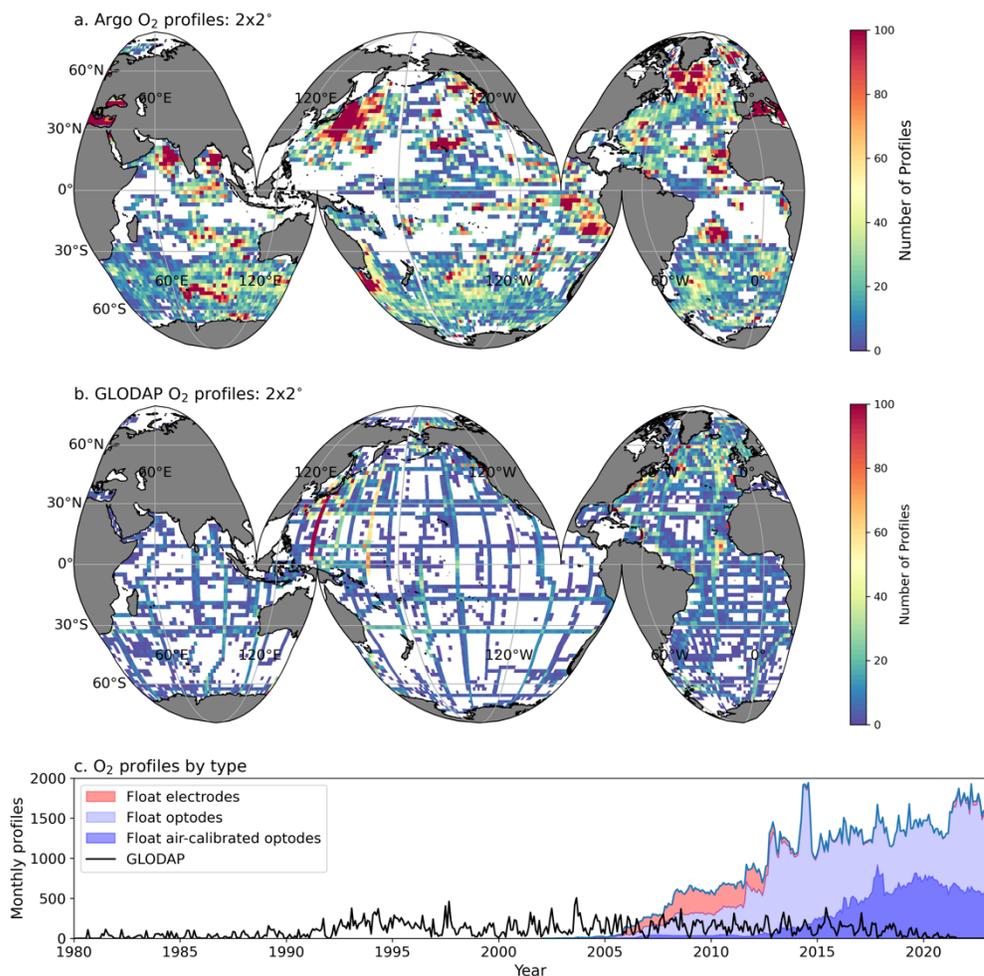


Figure 1. Observational density of float and ship oxygen and change in float sensor type over time. Float (a.) and GLODAP (b.) oxygen profile density on a $2 \times 2^\circ$ grid. (c.) Total number of oxygen profiles per month, with the contribution of float sensor type shown (Clark cell electrodes (red) and optodes (blue), and the subset of optodes calibrated with in-air measurements (dark blue)), and total number of GLODAP profiles that contain oxygen per month (black line).

85 The Global Ocean Data Analysis Project (GLODAP; Key et al., 2015; Olsen et al., 2016,
 86 2020) is an on-going international synthesis effort that evaluates surface-to-bottom ocean
 87 biogeochemical bottle data for outliers and internal consistency, which has been crucial to
 88 improving the accuracy and usability of shipboard data. A similar effort, the Surface Ocean CO₂
 89 Atlas (SOCAT) collects and assesses surface $p\text{CO}_2$ measurements for accuracy prior to inclusion
 90 in an annual data product (Bakker et al., 2016). These efforts have been instrumental in our
 91 understanding of ocean biogeochemistry. There is currently no comparable, on-going, post-

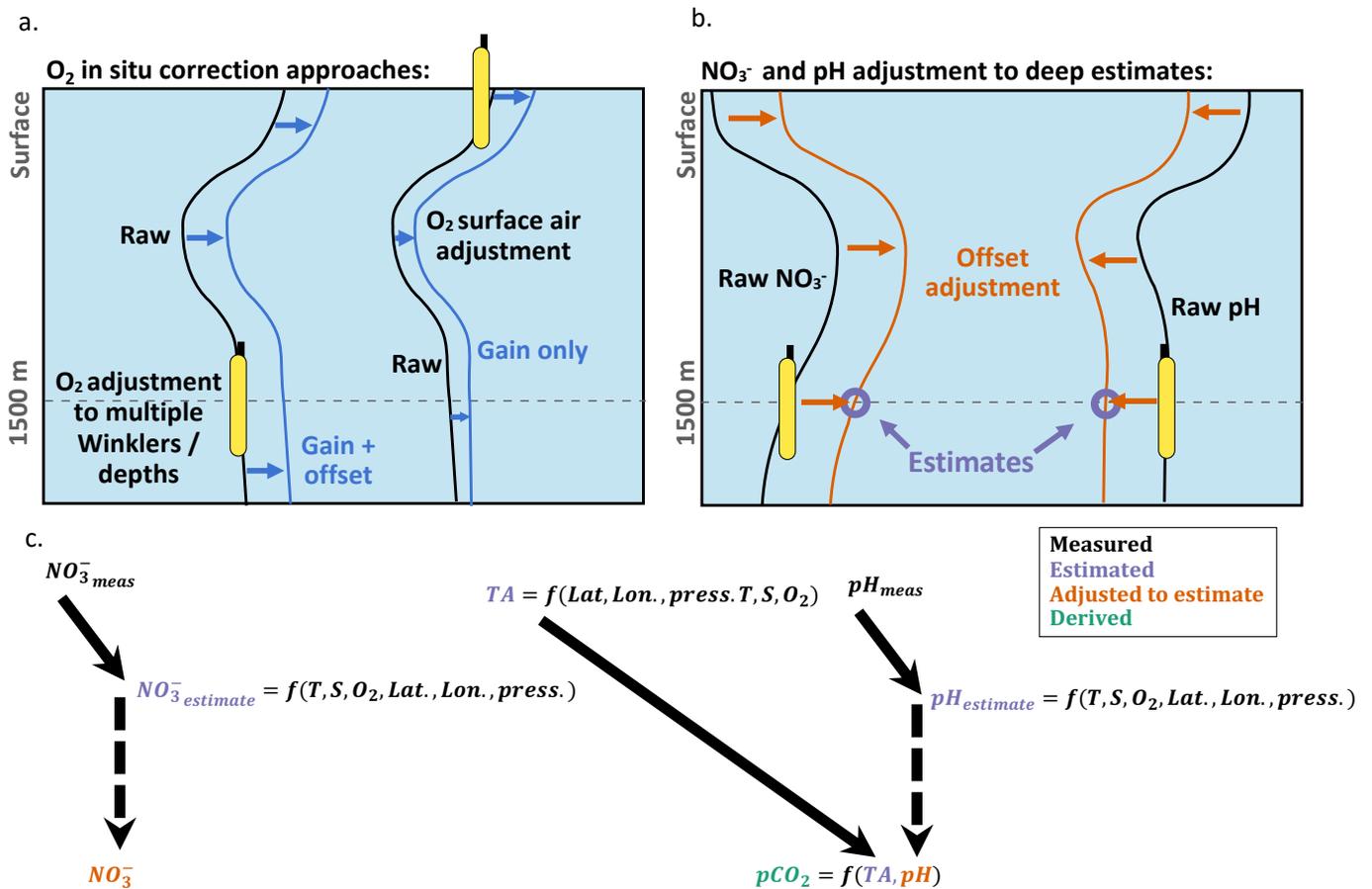


Figure 2. Schematic of the two primary in-situ oxygen calibration approaches and how the calibrated oxygen data are used to adjust float pH and nitrate measurements. (a.) Oxygen data collected on floats are typically calibrated using a gain and offset correction based on in-situ data, typically collected at float deployment, or a gain-only correction based on air-calibration measurements made upon float surfacing throughout its lifetime. (b.) Float nitrate and pH measurements are adjusted to algorithmic estimates of those parameters at 1500 db in a way that impacts the whole profile. (c.) Variable inputs, including oxygen, to the nitrate and pH algorithms, which are trained on shipboard data. Offsets between the float and ship oxygen will propagate through these algorithms into the adjusted nitrate and pH data.

92 deployment census of float biogeochemical data to assess consistency within the float dataset or
 93 between float and shipboard data. Most studies that have used Argo oxygen data and assessed their
 94 accuracy have focused on surface data or analyzed changes measured by individual floats, thereby
 95 avoiding comparisons between different float measurements (Bushinsky & Emerson, 2015;
 96 Johnson et al., 2015; Martz et al., 2008; Wolf et al., 2018). As the float array expands and
 97 researchers begin using the entire dataset as a whole, or combining float and shipboard datasets to

98 create global interior ocean oxygen products (e.g., World Ocean Atlas (Garcia et al., 2010);
99 Gridded Ocean Biogeochemistry from Artificial Intelligence – Oxygen (Sharp et al., 2022)),
100 attention must be paid to the accuracy of float oxygen data at depth.

101 Largescale comparisons of float and ship datasets indicate that, to a first order, float oxygen
102 data have reached a comparable level of accuracy as ship-board measurements (Bushinsky et al.,
103 2017; Johnson et al., 2017; Maurer et al., 2021). However, two float-to-ship comparisons of deep
104 (1500-2000 m) oxygen data (Bushinsky et al., 2016; Drucker & Riser, 2016) indicate that surface
105 calibration may not be a sufficient adjustment for the entire float oxygen profile. There is some
106 indication that this could be due to inadequate calibration of the optode temperature response
107 (Bittig, Körtzinger, et al., 2018), but Bushinsky et al. (2016) re-calibrated the optode temperature
108 response for 11 floats in the lab prior to deployment, which did not address the difference in deep
109 data, so this approach does not seem to fully resolve the observed drift.

110 The accuracy of oxygen data throughout the water column is critical for understanding
111 long-term changes in ocean oxygen content. At depth, the accuracy of quality-controlled float
112 oxygen data is especially critical due to its use in adjusting other biogeochemical sensor data from
113 Argo floats, which has downstream impacts on derived carbonate system parameters. Nitrate and
114 pH sensors are now being deployed in large numbers (Claustre et al., 2020) and also require in-
115 situ adjustment to correct sensor drift (Maurer et al., 2021). The nitrate and pH measurements are
116 adjusted using estimates of these parameters at 1500 db that are derived from multiple linear
117 regression or neural network algorithms that were trained on the GLODAP shipboard database
118 (Bittig, Steinhoff, et al., 2018; Carter et al., 2016, 2021; Williams et al., 2016). These algorithmic
119 estimates use inputs of temperature, salinity, depth, latitude, longitude, and, importantly, oxygen.
120 Due to sensor response characteristics, adjustments to the nitrate and pH sensor data are applied
121 almost uniformly to the entire profile, so offsets at 1500 m directly impact surface measurements
122 (Maurer et al., 2021).

123 Float measurements of pH are widely used to estimate $p\text{CO}_2$, and other carbonate system
124 parameters, using an algorithm-based estimate of total alkalinity (TA) and a carbonate system
125 calculator. Many studies apply an additional adjustment to the quality controlled pH data prior to
126 estimating $p\text{CO}_2$ that is meant to correct for an empirical pH-dependent pH bias (Carter et al.,
127 2013, 2018; Williams et al., 2017). The accuracy of float $p\text{CO}_2$ estimates is critical, as studies
128 relying on float $p\text{CO}_2$ have identified significant differences between seasonal cycles of $p\text{CO}_2$, and

129 wintertime air-sea CO₂ fluxes from studies that rely on shipboard *p*CO₂ alone (e.g. Bushinsky et
 130 al., 2019; Gray et al., 2018; Williams et al., 2016). Floats measure year-round, including during
 131 winter months when rough weather makes shipboard observations rare, which provides immense
 132 observational value, if accurate. A number of studies have directly compared float *p*CO₂ estimates
 133 to shipboard observations (Bushinsky & Cerovečki, 2023; Coggins et al., 2023; Fay et al., 2018;
 134 Gray et al., 2018; Williams et al., 2017), while other studies have indirectly compared float *p*CO₂
 135 and pH through assessment of other carbonate system parameters or CO₂ fluxes (e.g., Long et al.,
 136 2021; Mackay & Watson, 2021; Wu et al., 2022). A recent meta-analysis of float *p*CO₂ accuracy
 137 found biases are likely between 6-9 μatm (float *p*CO₂ high), with direct comparisons yielding
 138 lower biases (2-5 μatm) than indirect comparison (Wu & Qi, 2023).

139 Here we use crossover comparisons between ship and float data to quantify differences in
 140 deep oxygen values and calculate the impact those offsets would have on adjusted and derived
 141 parameters. We refer to oxygen “offset”, without strict attribution of the source of the error. Given
 142 the long-history and extensive use of Winkler titrations and the relatively short time-history of
 143 oxygen sensors and float-mounted oxygen sensors, we assume that the GLODAP values are likely
 144 correct and will present evidence later that supports this assumption.

145

146

147 **2. Methods**

148 *2.1 Float and shipboard datasets*

149 Biogeochemical float data were downloaded on June 20, 2023 from the Argo Data
 150 Assembly Centers (DACs, closest snapshot: 2023-06-09 (Argo, 2023)) according to the list of
 151 floats with oxygen, nitrate, or pH sensors in the Argo Global DACs Synthetic-Profile Index file.
 152 1,839 Argo floats deployed between 2002 and 2023 were included in this dataset. Of these floats,
 153 1,830 measured oxygen, of which 151,880 out of 270,654 profiles (56%) contained valid delayed
 154 mode “ADJUSTED” oxygen data, indicating the data had been checked and/or corrected post
 155 deployment (median difference between uncorrected and adjusted data was 11 μmol kg⁻¹, adjusted
 156 data higher). 582 floats measured nitrate, with 43,280 delayed mode, adjusted profiles out of
 157 67,505 total (64%). 492 floats measured pH, of which 19,137 profiles had delayed mode, adjusted
 158 data out of 44,407 total (43%). Only delayed mode, adjusted float data flagged as “good” were
 159 used for this analysis. Float oxygen sensor calibration type for floats with valid crossovers was

160 determined by reading the “SCIENTIFIC_CALIB_COMMENT” field (198 unique comments,
 161 Table S1) in float “Sprof” files and were categorized as: air, non-air, and bad/no calibration.

162 Shipboard bottle measurements of salinity, temperature, oxygen, nitrate, total CO₂ (DIC),
 163 or pH flagged as “good” from the GLODAP v2.2022 (Olsen et al., 2020) were used for comparison
 164 with float observations. The GLODAP dataset was chosen because it includes a secondary quality
 165 control and adjustment to shipboard data for overall accuracy and internal consistency. Shipboard
 166 pH measurements in the GLODAP dataset include a variety of measurement approaches. Carter et
 167 al. 2021 and 2018 “homogenized” the GLODAP pH dataset to be consistent with
 168 spectrophotometric pH measurements using purified meta-cresol purple (Liu et al., 2011) prior to
 169 training of the LIPHR (Locally Interpolated PH Regression)/ESPER (Empirical Seawater Property
 170 Estimation Routine) algorithms. To recreate this homogenized dataset, we used ESPER to
 171 calculate GLODAP pH on the total scale normalized to 25°C (pH_{25-T}) for every datapoint where a
 172 “good” pH measurement was present. By using the algorithms at the same datapoints on which
 173 they were trained, we recreated the homogenized dataset and used this data for the pH crossover
 174 comparison.

175

176 *2.2 Crossover comparisons*

177 Criteria for crossover comparisons between float and shipboard measurements were
 178 established using distance, pressure, potential density, and spiciness. For each float profile, we first
 179 found all GLODAP bottle measurements within a 100 km radius. Float data from 1450 to 2000 db
 180 were interpolated to a 1 db grid, with any gaps of over 125 db between successive float
 181 measurements removed from the interpolated profiles. Potential density (σ_θ) and spiciness (τ)
 182 relative to 0 db were calculated for both the float and shipboard data using the Gibbs SeaWater
 183 Oceanographic Toolbox of TEOS-10 for Python (McDougall & Barker, 2011). For each GLODAP
 184 bottle measurement between 1400 and 2100 db within the 100 km distance range, crossovers were
 185 determined by looking for interpolated float data with differences of less than $\pm 0.005 \text{ kg m}^{-3} \sigma_\theta$,
 186 $\pm 0.005 \tau$, and $\pm 100 \text{ db}$ from the GLODAP sample properties. These difference thresholds were
 187 selected by analyzing levels of environmental oxygen noise in comparisons of individual floats
 188 against themselves using a range of density, spiciness, and distance thresholds (Text S1, Figure
 189 S1). Crossovers from any point in time were allowed. Mean property offsets (e.g., ΔC_{off} , for a
 190 given property “C”) were calculated for floats with at least 20 oxygen crossovers present and used

191 in the results shown here (Figure S2 for float crossover examples). On average, offsets in the 1450
192 – 2000 db range did not differ significantly as a function of depth or concentration (Figure S3).
193 While adjusting the filter criteria does impact the number of crossovers found for each float and
194 can impact the mean offset calculated for an individual float, the overall results presented in this
195 manuscript are relatively insensitive to the exact criteria used.

196

197 *2.3 Impact of oxygen offsets on derived parameters*

198 The impact of oxygen offsets (e.g., ΔC_{imp} , for a given property C) on float nitrate and pH
199 adjustments and float estimated $p\text{CO}_2$ and DIC ($\Delta\text{NO}_3^-_{\text{imp}}$, $\Delta\text{pH}_{25-\text{T,imp}}$, $\Delta p\text{CO}_{2,\text{imp}}$, and $\Delta\text{DIC}_{\text{imp}}$,
200 respectively) was determined for each float with valid oxygen and nitrate, or pH data and with a
201 valid GLODAP crossover comparison. As previously described, oxygen offsets impact estimated
202 $p\text{CO}_2$ and DIC through the effect of oxygen on the pH adjustment at 1500 m (Figure 2). While
203 oxygen is also used in the algorithmic estimation of total alkalinity, which is required for $p\text{CO}_2$
204 and DIC estimation, only a surface oxygen offset would impact the surface total alkalinity
205 estimate, and subsequently the surface $p\text{CO}_2$ and DIC estimates, which are the foci of this work.
206 Using temperature, salinity, and oxygen data at 1500 m from each profile as inputs to the
207 calibration algorithms, we calculated pH and nitrate, both with and without adjusting for the mean
208 float oxygen offset relative to GLODAP ($\Delta\text{O}_{2,\text{off}}$). We then calculated the differences in (impacts
209 on) pH and nitrate with and without the $\Delta\text{O}_{2,\text{off}}$ correction ($\Delta\text{pH}_{25-\text{T,imp}}$ and $\Delta\text{NO}_3^-_{\text{imp}}$) and applied
210 these differences to the adjusted, full float profiles. This approach allows us to determine the
211 impact a mean oxygen correction would have without attempting to replicate any step changes or
212 non-linear adjustments that may have been applied during the original data adjustment procedure
213 (Maurer et al., 2021). For nitrate, a uniform adjustment is applied to the entire nitrate profile. For
214 pH, the adjustment at 1500 m is scaled relative to the difference in temperature between each depth
215 and 1500 m, following the protocol used in the original pH measurement adjustment (Johnson et
216 al., 2023). $\Delta p\text{CO}_{2,\text{imp}}$ and $\Delta\text{DIC}_{\text{imp}}$ were calculated using CO2SYS first with the original pH as an
217 input and then with mean $\Delta\text{pH}_{25-\text{T,imp}}$ applied to the float profile and calculating the difference.

218 Floats equipped with pH and nitrate sensors have been deployed by many groups
219 throughout the world. The majority have been deployed as part of SOCCOM or GO-BGC and
220 adjusted by the data management teams of SOCCOM and the Monterey Bay Aquarium Research
221 Institute (MBARI). Following adjustment approaches used by SOCCOM/MBARI, total alkalinity

222 was calculated using LIARv2, pH using ESPER (ESPER-mixed, an average of a neural network-
 223 based approach and an MLR; Carter et al., 2021) or LIPHR (Carter et al., 2018), and carbonate
 224 system calculations using PyCO2SYS (v1.8.1; Humphreys et al., 2022, 2023). Both ESPER and
 225 LIPHR were used because SOCCOM pH data at the time of download have been adjusted to one
 226 of the two algorithms, depending on when the float was last active. Floats active prior to April
 227 2023 were adjusted to LIPHR pH estimates, while floats active past this date are adjusted to
 228 ESPER pH. Figures and results shown in the main text rely on ESPER-based adjustments while
 229 the supplement includes results that rely on LIPHR-based adjustments, but average differences
 230 between the two are of a second order.

231 One complication is the presence of a pH-dependent pH correction (Williams et al., 2017)
 232 used by the SOCCOM/GO-BGC groups when calculating $p\text{CO}_2$. This correction accounts for the
 233 difference between float ISFET measured pH, which has been shown to align with
 234 spectrophotometric pH measurements (Takeshita et al., 2020), and pH values calculated from
 235 measurements of TA and DIC (Carter et al., 2013; 2018). It is currently unclear how to best apply
 236 a global correction similar to the one developed in Williams et al. (2017) and a recently published
 237 paper by a working group focused on inter-consistency in carbonate system measurements
 238 recommended removing this correction until a suitable correction for all float pH measurements
 239 can be developed (Carter et al., 2023). We have avoided dealing with this issue by looking at the
 240 difference between calculations with and without the oxygen offset impacts included. Any changes
 241 in this pH-dependent bias correction will represent a different, additional impact to float $p\text{CO}_2$
 242 estimates. However, the impacts of the oxygen offset should be very similar for estimated $p\text{CO}_2$
 243 with or without this additional pH-dependent bias correction.

244
 245

246 **3. Results**

247 For floats where oxygen offsets could be determined, 93% of the offsets were statistically
 248 significant using a 1 sample t-test and a p-value threshold of 0.01 (Figures S2A and S2B for
 249 examples with significant and non-significant crossovers). Our goal is to quantify the potential
 250 impact of float oxygen offsets on other parameters, so we include all oxygen offset estimates,
 251 including insignificant ones, when calculating the mean oxygen offset and all floats with pH in the
 252 subsequent impact on derived parameters. Only including floats with a statistically significant

253 oxygen offset would overstate the magnitude of the mean dataset offset. However, if these
 254 crossover comparisons were used in the future to correct float oxygen data it would be important
 255 to only adjust those floats with significant offsets so as not to over-adjust already good data.

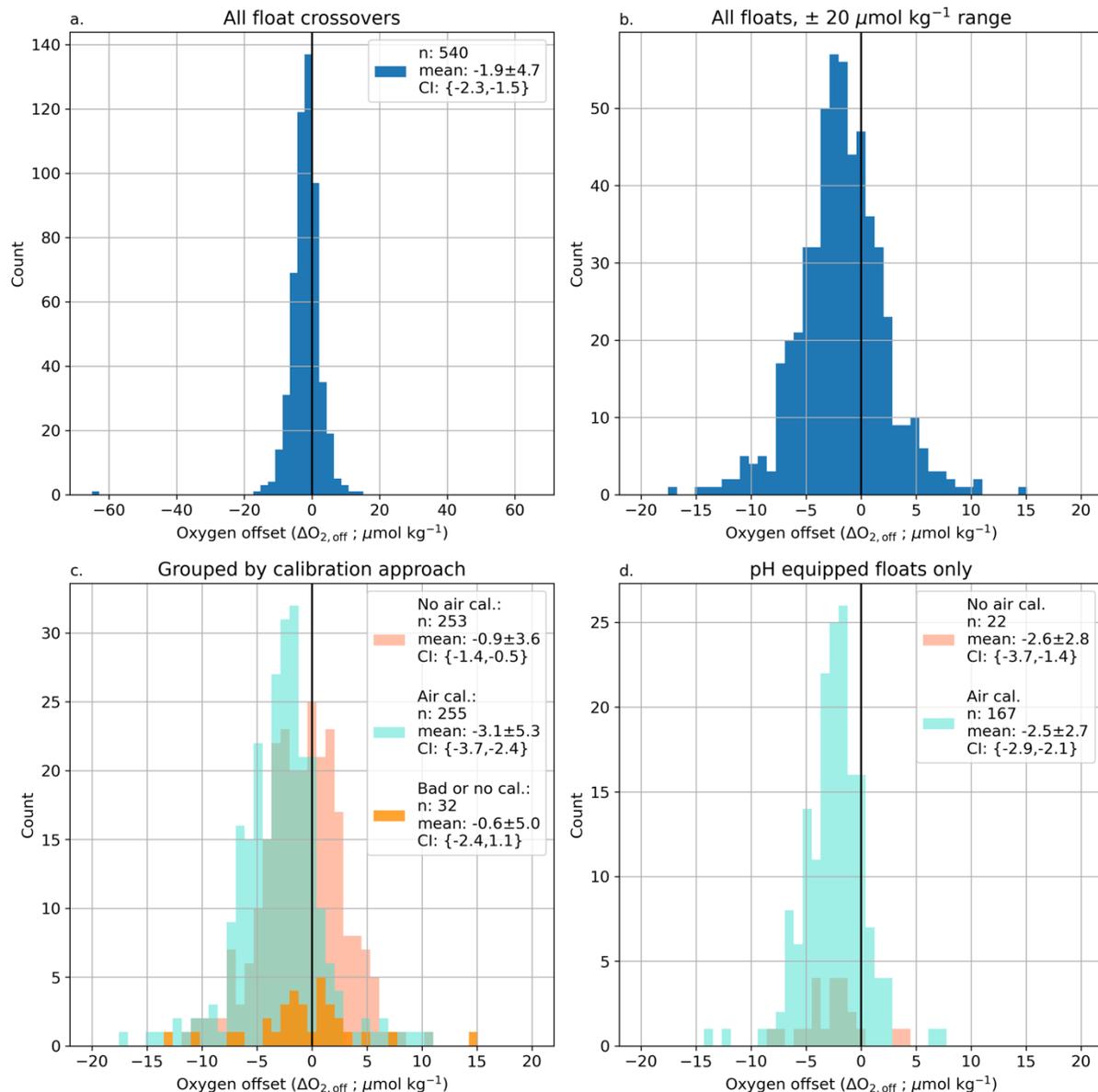


Figure 3. Histograms of float oxygen offsets relative to shipboard measurements. Float minus ship mean offsets between 1450 and 2000 db for all floats (a) with crossovers to GLODAP data and within $\pm 0.005 \text{ kg m}^{-3} \sigma_{\theta}$, $\pm 0.005 \tau$, and $\pm 100 \text{ db}$. (b) same as (a) but with a restricted x-axis range of $\pm 20 \mu\text{mol kg}^{-1}$. (c) Offsets grouped by calibration type: non-air calibration listed (light red), air-calibrated (turquoise), and no calibration or bad calibration, though still marked as good data (orange). (d) same as (c) but only showing data from non-air and air calibrated floats equipped with pH sensors. Figure legends list the number of floats, mean offsets $\pm 1 \text{ SD}$, and 95% confidence intervals for each calibration category.

256 The mean oxygen offset for all floats is -1.9 ± 4.7 (1 SD) $\mu\text{mol kg}^{-1}$ (n=540, float minus
 257 GLODAP, Figure 3, Table S2), with a 95% confidence interval around the mean of -2.3 to -1.5
 258 $\mu\text{mol kg}^{-1}$. Of the float oxygen sensors with valid crossovers, 253 had a non-air calibration method
 259 listed (offset of -0.9 ± 3.6 , 95% CI $\{-1.4, -0.5\}$ $\mu\text{mol kg}^{-1}$), 255 were air calibrated (offset of -3.1
 260 ± 5.3 , 95% CI $\{-3.7, -2.4\}$ $\mu\text{mol kg}^{-1}$), and 32 had bad calibration or no calibration listed, though
 261 they were still flagged as good data (offset of -0.6 ± 5.0 , 95% CI $\{-2.4, 1.1\}$ $\mu\text{mol kg}^{-1}$) (Figure 3).
 262 For floats equipped with pH, non-air calibrated floats had a mean oxygen offset of -2.6 ± 2.8 μmol
 263 kg^{-1} (n=22, 95% CI $\{-3.7, -1.4\}$ $\mu\text{mol kg}^{-1}$) and air-calibrated floats had a mean oxygen offset
 264 of -2.5 ± 2.7 $\mu\text{mol kg}^{-1}$ (n=167, 95% CI $\{-2.9, -2.1\}$ $\mu\text{mol kg}^{-1}$).

265 Offsets were also calculated between GLODAP and float measurements of nitrate and pH
 266 and between float estimates of DIC and GLODAP measurements (Figure 4, blue shaded
 267 histograms). The mean difference between float and GLODAP nitrate measurements is 0.2 ± 0.4
 268 $\mu\text{mol kg}^{-1}$ ($\Delta\text{NO}_3^-_{\text{off}}$, n=232, 95% CI $\{0.1, 0.2\}$ $\mu\text{mol kg}^{-1}$). The mean difference between float and
 269 GLODAP pH (normalized to 25°C, total pH scale) is -4.5 ± 7.7 mpH ($\Delta\text{pH}_{25-T,\text{off}}$, n=113, 95% CI
 270 $\{-5.9, -3.1\}$ mpH). The mean difference between DIC estimated from float pH and LIARv2
 271 alkalinity and GLODAP DIC measurements is 2.9 ± 6.1 $\mu\text{mol kg}^{-1}$ ($\Delta\text{DIC}_{\text{off}}$, n=154, 95% CI $\{1.9,$
 272 $4.0\}$ $\mu\text{mol kg}^{-1}$, full statistics for nitrate, pH_{25-T} , and DIC crossovers in Table S3).

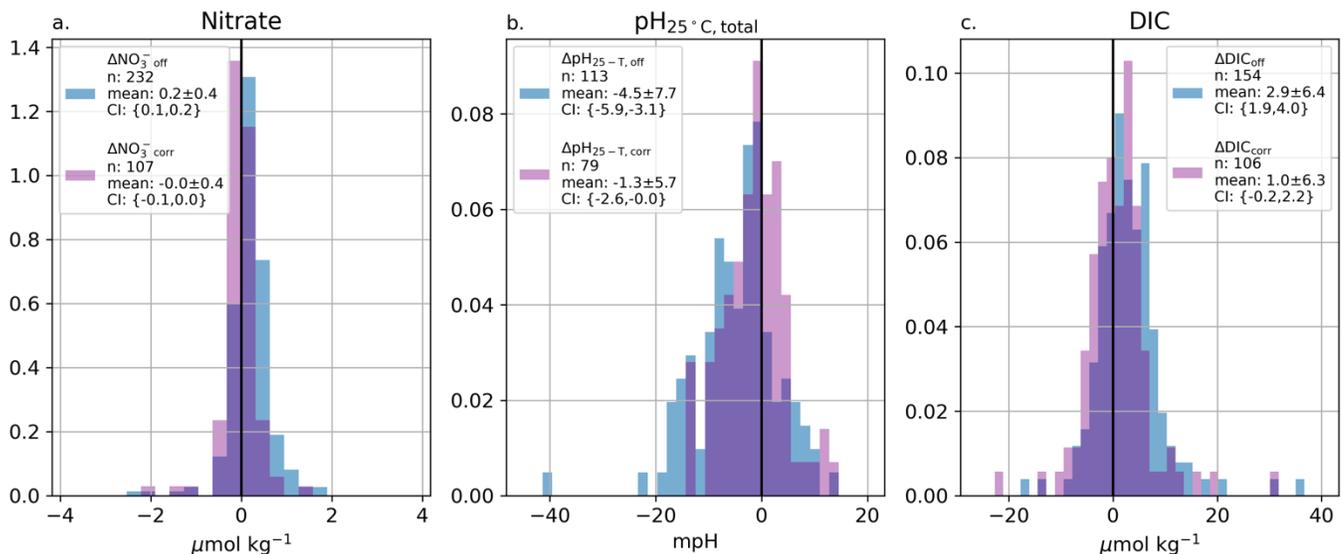


Figure 4. Frequency distributions of original nitrate, pH, and DIC offsets relative to GLODAP crossovers ($\Delta\text{NO}_3^-_{\text{off}}$, $\Delta\text{pH}_{\text{off}}$, $\Delta\text{DIC}_{\text{off}}$, blue shaded histograms) and crossover comparisons after the impact of correcting for the oxygen offset has been applied ($\Delta\text{NO}_3^-_{\text{corr}}$, $\Delta\text{pH}_{\text{corr}}$, $\Delta\text{DIC}_{\text{corr}}$, purple shaded histograms). Correcting for the observed oxygen offset at depth fully corrects the nitrate offset relative to GLODAP and improves the pH and DIC crossover comparisons by 3.2 mpH and 1.9 $\mu\text{mol kg}^{-1}$, respectively. Full statistics in Tables S3 and S4.

273

274

275 **4. Discussion**

276 *4.1 Oxygen offsets*

277 The magnitude of the mean offset is larger for air-calibrated floats ($-3.1 \mu\text{mol kg}^{-1}$) than
278 non-air calibrated floats ($-0.9 \mu\text{mol kg}^{-1}$). This likely reflects that some non-air calibrated floats
279 are corrected using both deep and near-surface shipboard values or a full oxygen profile from a
280 cast made at the deployment location (Figure 2) (Drucker & Riser, 2016; Takeshita et al., 2013),
281 while air calibrated floats are primarily adjusted using a gain value derived from surface
282 measurements of atmospheric oxygen over the float's lifetime (Bushinsky et al., 2016; Johnson et
283 al., 2015, 2017; Maurer et al., 2021). The offsets shown in Figure 3 are small relative to the original
284 correction from raw to "adjusted" oxygen (median difference between raw and adjusted float
285 oxygen of $-11 \mu\text{mol kg}^{-1}$), but the mean offset for all comparisons other than the "Bad / no. cal" is
286 significantly different from zero (95% confidence intervals, Figure 3 and Table S2) and, as we will
287 discuss below, can have significant impacts on interpretation and use of this data.

288 The offset between float and shipboard data could reflect either that the float oxygen
289 measurements are low or ship-based Winkler measurements are high. We will discuss both
290 possibilities. It is important to recognize that we are considering approximately 12 different
291 oxygen sensor models that utilize two different measurement principles made by three different
292 manufacturers. The earliest oxygen sensors deployed on floats were initially Clark-cell electrodes
293 (various SeaBird 43 models) while most current sensors are oxygen optodes made by multiple
294 manufacturers, but with the same basic sensing approach and chemistry (Figure 1). Here we
295 primarily focus on possible offsets for oxygen optodes rather than Clark cell electrodes, and on
296 air-calibrated optodes specifically, as these are the current state of the art sensors and represent the
297 bulk of floats deployed with pH sensors.

298 If the offset between float and shipboard oxygen is due to low-biased float oxygen
299 measurements, three possible causes of the offsets are: (i) an in-situ difference in ocean oxygen
300 content, (ii) a residual uncorrected pressure response, or (iii) a non-linear concentration-dependent
301 drift in the sensor response. Basin-scale comparisons of float oxygen to shipboard measurements
302 have indicated overall good float sensor accuracy in the surface ocean. A comparison of SOCCOM
303 float oxygen data relative to GLODAP on pressure surfaces above and below the thermocline

304 indicated that the air-calibrated float data at depth may be low by 2-3 $\mu\text{mol kg}^{-1}$ (Bushinsky et al.,
 305 2017). Johnson et al. (2017) assessed SOCCOM float data relative to the respective float
 306 deployment cruises, across the full depth range, and against GLODAP crossovers within 20 km
 307 and below 300 m, finding that float oxygen was lower than GLODAP by 3.7 and 3.2 $\mu\text{mol kg}^{-1}$ at
 308 “Midrange”, or approximately 250 $\mu\text{mol kg}^{-1}$ [O_2]. Maurer et al. (2021) updated the Johnson et al.
 309 (2017) GLODAP comparison, finding a 3.6 to 3.8 $\mu\text{mol kg}^{-1}$ low oxygen offset.

310 While these earlier studies included shallower waters and compared data on pressure
 311 surfaces instead of the combined σ_θ , τ , and pressure criteria of this study, all found similar
 312 magnitude and direction of differences. Maurer et al. (2021) attribute the mean [O_2] difference to
 313 a mean age difference of 18.6 years between the GLODAP and SOCCOM datasets due to the
 314 linear declines in Southern Ocean interior oxygen concentrations found in Helm et al. (2011). In
 315 Helm et al. (2011) the Southern Ocean has the largest region of oxygen change in the upper ocean
 316 (100-1000 m) with the south Pacific and south Indian basins, seeing changes of up to $-0.7 \mu\text{mol l}^{-1}$
 317 yr^{-1} between 1970 and 1992. However, deeper in the water column where we are conducting our
 318 crossover comparison (1500 – 2000 m), changes are of a smaller magnitude and appear to primarily
 319 be between 0 to $-0.1 \mu\text{mol l}^{-1} \text{yr}^{-1}$ in the Southern Ocean and between -0.2 and $+0.2 \mu\text{mol l}^{-1} \text{yr}^{-1}$
 320 across the global ocean. To rule out true oxygen changes as the source of offsets between the float
 321 and GLODAP datasets, we can assess the GLODAP dataset for long-term oxygen changes and
 322 compare that oxygen change to the magnitude of float oxygen offsets.

323 If true oxygen changes at depth are responsible for the offsets found in our present study,
 324 we would expect the offset for a given float relative to GLODAP to be larger when compared to
 325 older cruise data and decrease in magnitude (typically becoming less negative) the closer in time
 326 between the float and GLODAP measurements. We therefore fit regressions to the float-GLODAP
 327 offsets as a function of time, calculating a 95% confidence interval around the regression, to
 328 determine if the regression \pm CI included a zero offset at the midpoint time of the float deployment
 329 (see Figure S2A/B for examples of the regression and CI). 66 float offsets (12%) could be a result
 330 of observed change in oxygen concentration as determined by a trend in the GLODAP dataset.
 331 However, in many of these cases, there is simply too much uncertainty in the GLODAP oxygen
 332 regression with time, or little to no difference between the float and shipboard data. While actual
 333 ocean oxygen change in the 1450 – 2000 db range remains a possible contributing factor to the
 334 differences seen between the float and shipboard oxygen, it does not seem to be the main cause.

335 The optode pressure correction combines a sensor pressure response with the pressure
 336 effect on oxygen solubility. Significant effort has been made to determine the appropriate pressure
 337 correction between optode response and oxygen partial pressure (e.g., Bittig et al., 2015; Uchida
 338 et al., 2008). We primarily focus on the mean oxygen offset for each float, averaging all crossover
 339 data from 1450 – 2000 db. However, if we bin the data by depth rather than pressure, we do not
 340 see a depth dependency in the float offsets in this depth range. While this may still exist, it does
 341 not seem to be a first order factor in the deep oxygen offset (Figure S3). A related issue is the lag
 342 in optode oxygen measurements due to the sensor response time (Bittig et al., 2014; Bittig &
 343 Körtzinger, 2017). Oxygen gradients at these depths are small, so is not likely to be a first order
 344 issue but may contribute to the offset in some regions.

345 Optodes have been shown to not change response at zero oxygen (Johnson et al., 2015) and
 346 multiple calibrations over time have indicated relatively linear drift rates (Bittig & Körtzinger,
 347 2015), lending support for the use of a gain correction across entire oxygen profiles. Bushinsky et
 348 al. (2016) measured greater drift rates at lower oxygen concentration and postulated that the faster
 349 drift rate at low oxygen concentrations represents a deformation of the oxygen calibration surface,
 350 such that neither a gain nor an offset can be used to fully correct the range of oxygen measurements.
 351 Drucker and Riser (2016) show data from eight floats indicating that a near-surface gain correction
 352 leaves a negative offset at depth, similar to Bushinsky et al. (2016), but they did not provide an
 353 explanation. Both Bushinsky et al. (2016) and Drucker and Riser (2016) compared float data to
 354 bottle oxygen measurements from deployment casts, so oxygen change at depth did not play a
 355 factor. While we are still uncertain as to the mechanism causing low float oxygen values at depth
 356 relative to Winkler data, our current results from the entire oxygen Argo dataset indicate that this
 357 does not seem to be an issue limited to a small number of floats and the possibility of non-linear
 358 drift in the oxygen calibration surface remains.

359 An alternative to the float oxygen measurement being biased low, is that bottle
 360 measurements of oxygen using Winkler titrations are biased high due to contamination by
 361 atmospheric oxygen or impurities in reagents (Schmidtke et al., 2017). Sampling of oxygen and
 362 subsequent Winkler titration involves careful isolation of the water from atmospheric
 363 contamination. Incomplete flushing or trapped bubbles can add a significant bias to Winkler data
 364 given that the low solubility of oxygen in water means that in equal volumes of air and water, the
 365 air will hold 50 times more oxygen than the water. GLODAP data has been QC'd and adjusted for

366 internal consistency, but it is possible a bias is present in the deep data, especially if, on average,
367 this bias is present in either all shipboard observations or the shipboard observations used as a
368 reference for GLODAP adjustments.

369 Regardless of the source of the offset or mechanism for its existence, a systematic offset
370 between float and shipboard oxygen measurements presents a problem for the current use of
371 oxygen in float nitrate and pH parameter adjustment and derived parameter calculations. For all
372 mechanisms other than a true change in ocean oxygen content, these offsets also complicate
373 determination of long-term ocean oxygen changes. Given the mean difference in float and
374 GLODAP dataset ages and that float oxygen measurements are now made in far greater numbers
375 than shipboard data, a negative offset in the float data would appear in a combined data product as
376 an increase in the true ocean oxygen loss signal. For the rest of this discussion, we focus on the
377 impact of an oxygen offset on water properties derived from float measured data.

378

379 *4.2 Impact of oxygen offsets on pH*

380 As described earlier, float oxygen measurements at 1500 m are used to correct for drift in
381 the pH sensor data which is then used with TA estimates to derive $p\text{CO}_2$ (Williams et al., 2017).
382 We only consider pH-equipped floats with air-calibrated oxygen here, with equivalent figures and
383 tables for all pH-equipped floats provided in the supplement. The mean impact of correcting float
384 pH for observed oxygen offsets is 3.2 ± 3.8 mpH (n=119, 95% CI of 2.5 to 3.9 mpH, Figure 5,
385 Table 1). The impact of oxygen offsets on pH corrections can be understood through the
386 relationship between oxygen and inorganic carbon. A negative oxygen offset means that float
387 oxygen is lower than the expected value, so correcting the oxygen by a positive amount would
388 result in a corresponding reduction in the apparent remineralization signature of the water mass.
389 Higher oxygen and less remineralization would then imply lower dissolved inorganic carbon and
390 therefore higher pH.

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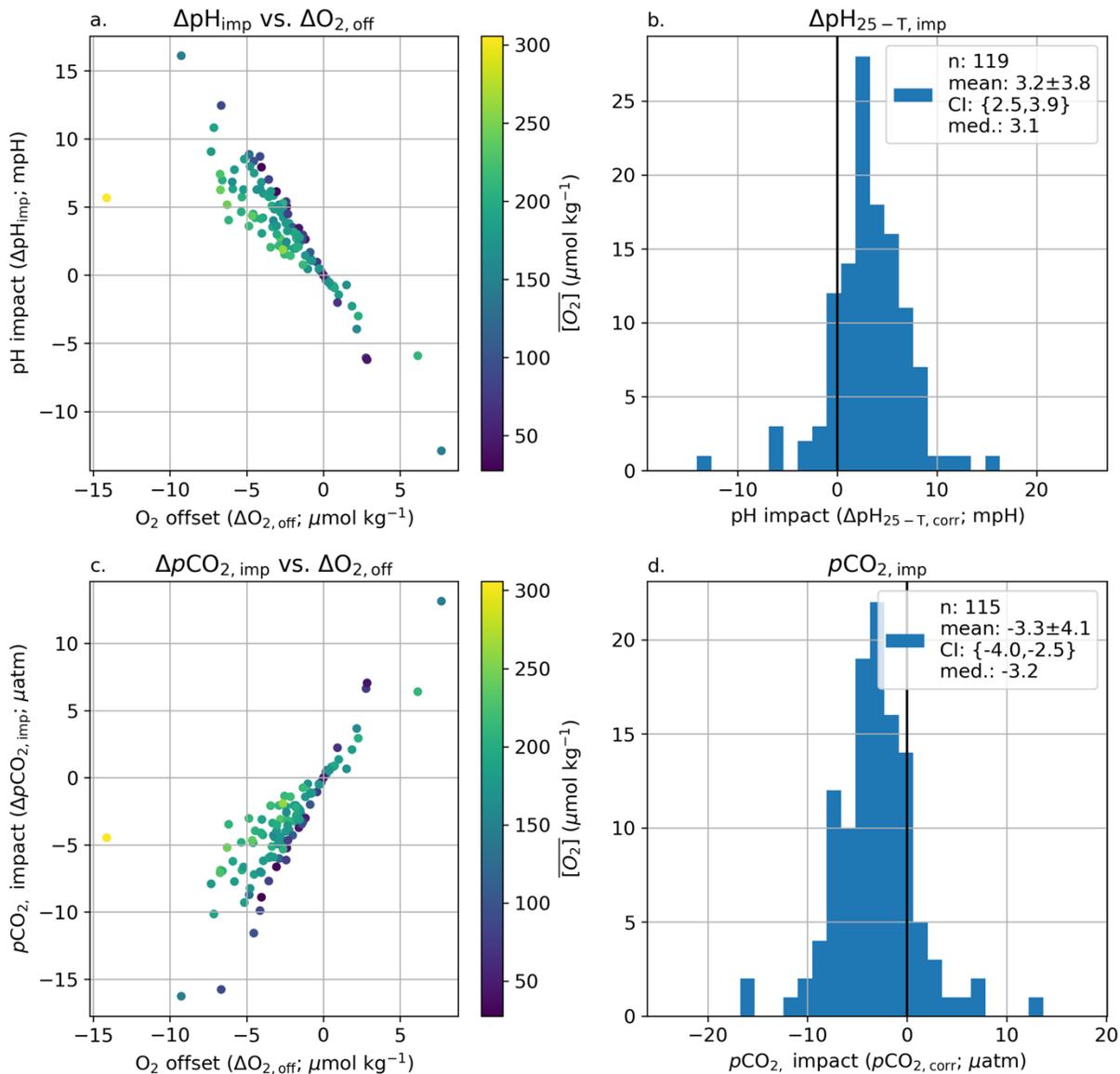


Figure 5. 1500 m pH and surface $p\text{CO}_2$ impact from associated oxygen offset. The calculated impact of correcting pH (top panels) and $p\text{CO}_2$ (bottom panels) for observed oxygen offsets. (a) and (c) are scatter plots of the change in pH and $p\text{CO}_2$ for a given oxygen offset, with the points colored by the mean oxygen concentration of the float crossover comparisons. Correcting a float oxygen sensor that is low of correct would increase the float pH and decrease derived $p\text{CO}_2$. (b) and (d) are histograms of the pH and $p\text{CO}_2$ impacts, with zero marked with a black line and mean $\pm 1\text{SD}$, 95% confidence intervals around the mean, and median values listed in the figure legends. pH impacts shown are at 1500 m, while $p\text{CO}_2$ impacts are from surface values. Results shown here are calculated using air-calibrated floats and the ESPER-mixed pH algorithm, equivalent results for LIPHR in Supplemental Figure S4 and for all pH-equipped floats in Figures S5 and S6.

399

400 **Table 1. Impact on pH at 1500 db and derived surface $p\text{CO}_2$ of observed oxygen offsets.**

	Count	Mean	SD	P value ²	95.0% CI {low, high}	median	min	max
pH impact ($\Delta\text{pH}_{25\text{-T,imp}}$, mpH) ¹	119	3.2	3.8	<0.001	{2.5, 3.9}	3.1	-12.9	16.1
$p\text{CO}_2$ impact ($\Delta p\text{CO}_{2,\text{imp}}$, μatm)	115	-3.3	4.1	<0.001	{-4.0, -2.5}	-3.2	-16.3	13.1

401 ¹Impacts for pH calculated using ESPER-mixed. Impacts shown here are for air-calibrated floats
402 only. Equivalent numbers for LIPHR in Table S5.

403 ²P-value testing the hypothesis that the mean impact is different from 0 at a 95% confidence
404 level.

405
406 The sensitivity of pH impact ($\Delta\text{pH}_{25\text{-T,imp}}$) to oxygen offset (represented as $\Delta\text{pH}_{25\text{-T,imp}}/\Delta\text{O}_{2,\text{off}}$) is between -0.4 and -2.3 mpH/($\mu\text{mol kg}^{-1}$) (Figures 5, 6). The largest $\Delta\text{pH}_{25\text{-T,imp}}$ values
407 are observed in the Southern and Pacific Oceans, though the oxygen offsets do not show a similar
408 spatial pattern. Instead, there is a spatial pattern to the $\Delta\text{pH}_{25\text{-T,imp}}/\Delta\text{O}_{2,\text{off}}$ that corresponds to the
409 crossover oxygen concentration. The pH impact sensitivity (slope of the pH impact to O_2 offset)
410 is greatest at low oxygen concentrations (Figure 5), with the mean crossover oxygen concentration
411 explaining 61% of the variance in calculated $\Delta\text{pH}_{25\text{-T,imp}}/\Delta\text{O}_{2,\text{off}}$ (Figure 6).
412

413 This relationship can be understood by considering the changes in ocean chemistry as
414 respiration takes place in a parcel of water. For example, we can take a parcel of water with initial
415 TA and DIC of newly formed Subantarctic Mode Water from the southeast Pacific Ocean (Carter
416 et al., 2014). If we then calculate the impact of organic matter respiration on oxygen, DIC, and
417 TA, we can calculate the change in pH for every mole of oxygen respired. Initially, the $\Delta\text{pH}_{25\text{-T,imp}}/\Delta\text{O}_{2,\text{off}}$
418 is -2 mpH/($\mu\text{mol kg}^{-1}$), but it drops to almost -2.8 mpH/($\mu\text{mol kg}^{-1}$) after 250 μmol
419 kg^{-1} of oxygen have been respired (Figure S10), as the buffer capacity of the water is eroded with
420 increasing DIC; a situation analogous to surface ocean acidification. In the real ocean, regional
421 differences in ocean interior biogeochemistry, including the buffer capacity, will cause regional
422 differences in the sensitivity of pH to oxygen change. This likely accounts for larger spread in the
423 relationship between pH impact and oxygen offset for points in the Southern Ocean (Figure 6e),
424 where there is significant mixing of different water masses.

425

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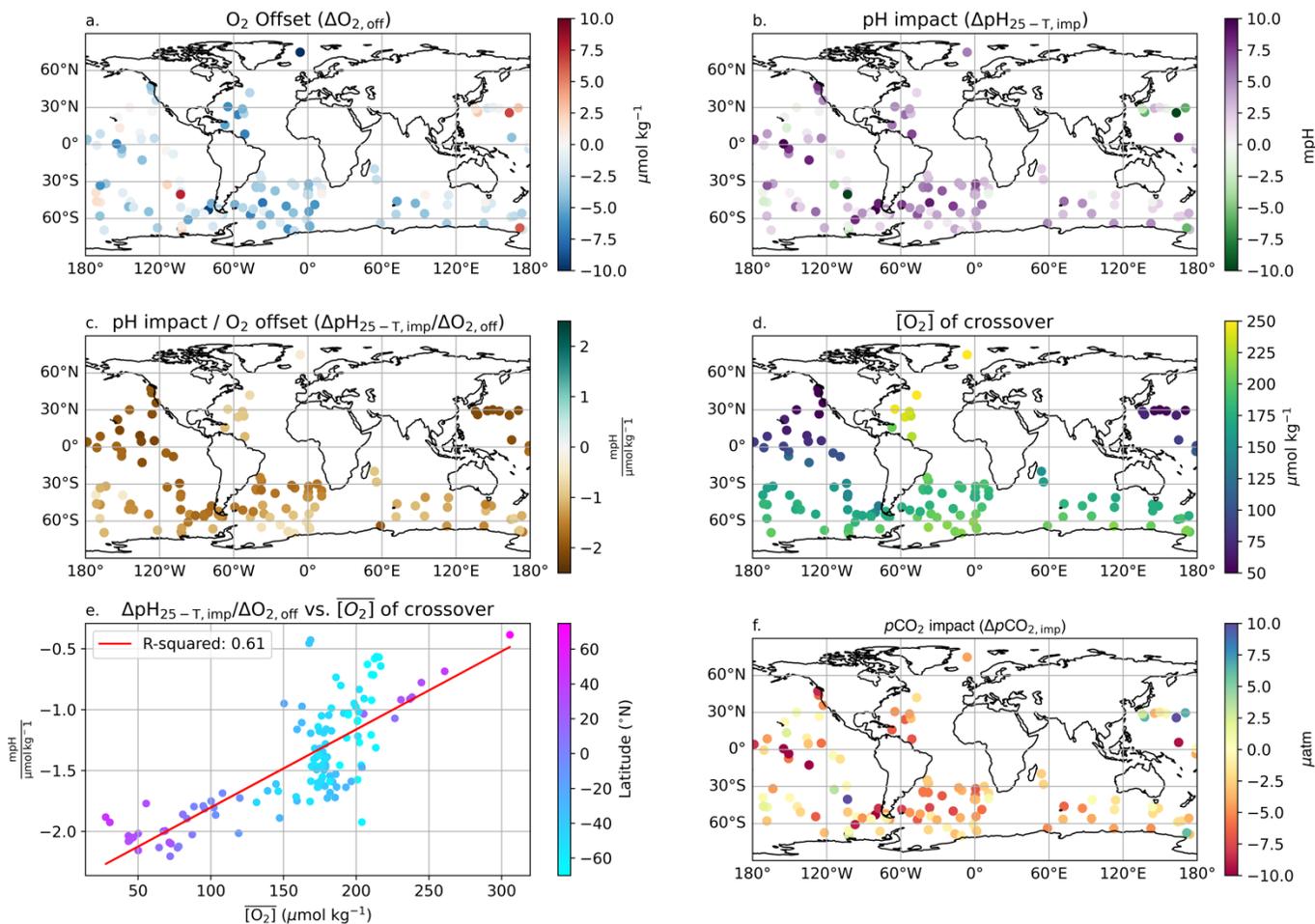


Figure 6. Relationships between oxygen offset, pH impact, mean oxygen concentration at crossover, and $p\text{CO}_2$ impact. Map of O_2 offset (a.) demonstrates no obvious spatial pattern in the magnitude of offsets while the impact of correcting for the O_2 offsets on pH (b.) tends to be greater in the Pacific and subpolar Southern Ocean. The ratio of the pH impact to O_2 offset ($\Delta\text{pH}_{25-T,\text{imp}}/\Delta\text{O}_{2,\text{off}}$, c.) is greatest in the north Pacific and subpolar Southern Ocean, reflecting the mean oxygen concentration at crossover ($[\text{O}_2]$, d.). Plotting $\Delta\text{pH}_{25-T,\text{imp}}/\Delta\text{O}_{2,\text{off}}$ against $[\text{O}_2]$ (e.) and calculating a linear fit (red line) indicates that variations in $[\text{O}_2]$ explain $\sim 61\%$ of the variance in $\Delta\text{pH}_{\text{imp}}/\Delta\text{O}_{2,\text{off}}$. Much of the deviation from the linear fit occurs in the Southern Ocean (light blue points). This response leads to stronger $p\text{CO}_2$ impacts (f.) in the Pacific and subpolar Southern Ocean than in the North Atlantic or polar Southern Ocean. pH impacts shown are at 1500 m, while $p\text{CO}_2$ impacts are from surface values. Results shown here are calculated using floats with air-calibrated oxygen and the ESPER-mixed pH algorithm, equivalent results for LIPHR in Supplemental Figure S7 and for all pH-equipped floats in Figures S8 and S9.

427 4.3 Impact of oxygen offsets on derived $p\text{CO}_2$

428 The mean impact on float $p\text{CO}_2$ ($\Delta p\text{CO}_{2,\text{imp}}$) for correcting observed oxygen offsets is -3.3
 429 $\pm 4.1 \mu\text{atm}$ (air-calibrated floats only, 95% CI of -4.0 to $-2.5 \mu\text{atm}$, Figure 5, Table 1). A reduction

430 of float derived $p\text{CO}_2$ by this magnitude would account for a large portion of the apparent bias in
 431 float $p\text{CO}_2$ described in Wu and Qi (2023). For many of the studies with direct crossover
 432 comparisons, a mean adjustment of $-3.3 \mu\text{atm}$ would effectively eliminate the observed differences
 433 between float and shipboard $p\text{CO}_2$. It should be noted that the range in impacts is much greater
 434 than the mean (a range of $p\text{CO}_2$ impact between -16.3 and $13.1 \mu\text{atm}$), with the impact on
 435 individual floats and regions differing from the mean impact. Following pH, some of the greatest
 436 $p\text{CO}_2$ impacts are found in the Southern Ocean and Pacific (Figure 6). Similar results are found if
 437 LIPHR is used to calculate pH impacts instead of ESPER, though with a slightly greater mean
 438 $p\text{CO}_2$ impact magnitude (-3.6 ± 4.7 , 95% CI $\{-4.4, -2.7\} \mu\text{atm}$, Table S5) and differences for
 439 individual floats.

440

441 *4.4 Impacts of oxygen offset on nitrate and derived DIC*

442 As described above, relative to GLODAP float nitrate is offset high ($0.2 \pm 0.4 \mu\text{mol/kg}$),
 443 pH is offset low ($-4.5 \pm 7.7 \text{ mpH}$), and DIC is offset high ($2.9 \pm 6.4 \mu\text{mol/kg}$, Table S3). These
 444 offsets are in approximately the correct ratios and directions for a biological signal, either real or
 445 due to an offset in the oxygen measurement that is then propagated to pH and DIC. This indicates
 446 that the oxygen offset is most likely not due to a problem with the Winkler titrations.

447 The calculated impact on nitrate of the oxygen offset ($\Delta\text{NO}_3^-_{\text{imp}}$) is small (mean -0.2 ± 0.2 ,
 448 95% CI $\{-0.22, -0.14\} \mu\text{mol kg}^{-1}$, Figure S11, Table S6), in keeping with Redfield stoichiometry
 449 of $-16 \text{ N} : 154 \text{ O}_2$ (Hedges et al., 2002) multiplied by an oxygen offset of $\sim 2 \mu\text{mol kg}^{-1}$. The impact
 450 on DIC at 1500 m of correcting for oxygen offsets is $-1 \pm 1.2 \mu\text{mol kg}^{-1}$ (CI $\{-1.3, -0.8\}$, Figures
 451 S12, S13, Table S7), which is the slightly smaller than multiplying the oxygen offset by a Redfield
 452 ratio of $-106 \text{ C} : 154 \text{ O}_2$.

453 As a check that the mean impacts ($\Delta\text{NO}_3^-_{\text{imp}}$, $\Delta\text{pH}_{25-\text{T,imp}}$) calculated from the oxygen offset
 454 would, in fact, improve the crossover comparisons with GLODAP data, we also re-ran the
 455 crossover comparison after applying the $\Delta\text{O}_{2,\text{off}}$, $\Delta\text{NO}_3^-_{\text{imp}}$ and $\Delta\text{pH}_{25-\text{T,imp}}$ to the original data. The
 456 resulting crossovers ($\Delta\text{NO}_3^-_{\text{corr}}$, $\Delta\text{pH}_{25-\text{T,corr}}$, $\Delta\text{DIC}_{\text{corr}}$, Figure 4, purple shaded histograms,
 457 statistics in Table S4) indicate that, on average, correcting the nitrate for the oxygen offset
 458 eliminates the entire nitrate offset, 3.2 mpH of the original -4.5 mpH pH offset, and $1.9 \mu\text{mol kg}^{-1}$
 459 of the original $2.9 \mu\text{mol kg}^{-1}$ DIC offset.

460 The improvement in, but not full correction of, float-derived DIC and measured pH relative
461 to the GLODAP crossovers provides an independent assessment that correcting the float data for
462 this deep O₂ offset does, in fact, improve the pH data and subsequent carbonate system derived
463 parameters. Furthermore, the fact that the nitrate bias appears to be fully corrected while the DIC,
464 pH, and *p*CO₂ impacts only partially correct for the differences between float values and crossover
465 or indirect comparisons gives an indication that the deep oxygen offset is not the only source of
466 bias in the derived float carbonate parameters. This could be due to additional biases in the float
467 pH, biases in the estimated TA, penetration of the ocean acidification signal to these depths,
468 internal consistency issues with the marine carbonate system, or some other factor. It appears that
469 correcting the oxygen may resolve a large fraction of the differences, but additional work remains
470 to fully separate *p*CO₂, pH, and DIC biases in the float data from true trends.

471 Float oxygen crossovers with shipboard data are not available for all floats, making it
472 difficult to determine the magnitude of an oxygen offset for all pH-equipped floats at this time.
473 One option to reduce the possibility of an oxygen-induced bias in pH and derived *p*CO₂ is to correct
474 float pH using an algorithm that does not use oxygen. Removing oxygen from the ESPER
475 algorithm yields a 4.2 ± 6.0 mpH and -4.3 ± 6.4 μ atm *p*CO₂ impact, somewhat larger than the 3.2
476 ± 3.8 mpH and -3.3 ± 4.1 μ atm impact we calculate from applying the observed oxygen offset
477 relative to GLODAP (Figure S14). Plotting the ESPER pH and *p*CO₂ impacts due to removing
478 oxygen or correcting for the observed offset against one another yields a cluster of points around
479 the 1:1 lines, though with considerable spread (Figure S15). This approach may indeed improve
480 derived parameters for floats with no GLODAP oxygen crossover for comparison, but is less
481 accurate than if an oxygen correction is possible.

482

483

484 **5. Conclusions**

485 Here we identify an offset between float and ship-board oxygen measurements between
486 1450 and 2000 db. The magnitude of this offset is significant for studies assessing long-term ocean
487 oxygen changes and for the use of float oxygen in adjusting pH and nitrate measurements and in
488 subsequent calculated derived carbonate system quantities.

489 Correcting oxygen offsets of -2.5 μ mol kg⁻¹ in pH-equipped, air-calibrated floats results in
490 mean pH changes of 3.2 mpH and *p*CO₂ changes of -3.3 μ atm. These differences are of similar

491 direction and magnitude as many of the direct in-situ comparisons between float $p\text{CO}_2$ estimates
492 and underway $p\text{CO}_2$ measurements and therefore represent a first-order bias that needs to be
493 addressed in the biogeochemical float dataset. We do not definitively identify whether the oxygen
494 offset is present in the float or ship-board dataset, though the fact that correcting float oxygen
495 would improve the nitrate, DIC, and pH crossover comparisons to shipboard data are a strong
496 indication that the issue lies with the float observations.

497

498 Based on our findings we offer the following recommendations:

- 499 1. The oxygen offsets described here represent an empirical correction that must be
500 investigated to determine the underlying mechanism.
- 501 2. Float oxygen data at depth should be adjusted to historical shipboard data until our
502 mechanistic understanding of the causes behind the float – ship differences is sufficient
503 such that air calibration or other adjustments do not require a secondary correction.
- 504 3. Care should be used in combining float and ship data, with an understanding that small
505 biases may be present in either dataset that could impact the usability of the data
506 compilation to answer some scientific questions. The difference between the average age
507 of the float and GLODAP datasets and the shift to float profile numbers greatly exceeding
508 shipboard profiles in the 2000's mean that any offset between the datasets will appear as a
509 spurious change in ocean oxygen content. Additionally, individual floats may have
510 significantly greater magnitude biases than the mean and data should be assessed prior to
511 any use relying on absolute accuracy.
- 512 4. Standardization of float sensor calibration comments and equations will make future
513 studies of overall biogeochemical Argo float performance easier to perform.

514

515 **Data availability**

516 The “argo_synthetic-profile_index.txt” file used to determine biogeochemical Argo float WMO
517 numbers and data locations was downloaded from <ftp.ifremer.fr/ifremer/argo/dac>. GLODAP data
518 is available at <https://glodap.info/index.php/merged-and-adjusted-data-product-v2-2022/>. The
519 analysis and plotting code used for this manuscript are available at: [10.5281/zenodo.10866941](https://doi.org/10.5281/zenodo.10866941)
520 (Bushinsky et al., 2024).

521

522

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539

540

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