

Controls on Polar Southern Ocean Deep Chlorophyll Maxima: Viewpoints from Multiple Observational Platforms

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Abstract

Deep Chlorophyll Maxima (DCMs) are ubiquitous in low-latitude oceans, and of recognized biogeochemical and ecological importance. DCMs have been observed in the Southern Ocean, initially from ships and recently from profiling robotic floats, but with less understanding of their onset, duration, underlying drivers, or whether they are associated with enhanced biomass features. We report the characteristics of a DCM and DBM (Deep Biomass Maximum) in the Inter-Polar-Frontal-Zone (IPFZ) south of Australia from CTD profiles, shipboard-incubated samples, a towbody, and a BGC-ARGO float. The DCM and DBM were ~20 m thick and co-located with the nutricline, in the vicinity of a subsurface ammonium maximum characteristic of the IPFZ, but ~100 m shallower than the ferricline. Towbody transects demonstrated that the co-located DCM/DBM was broadly present across the IPFZ. Large healthy diatoms, with low iron requirements, resided within the DCM/DBM, and fixed up to 20 mmol C m⁻² d⁻¹. The BGC-ARGO float revealed the DCM/DBM persisted for >3 months. We propose a dual environmental mechanism to drive DCM/DBM formation and persistence within the IPFZ: sustained supply of both recycled iron within the subsurface ammonium maxima and upward silicate transport from depth. DCM/DBM cell-specific growth rates were considerably slower than those in the overlying mixed layer, implying that phytoplankton losses are also reduced, possibly as a result of heavily silicified diatom frustules. The light-limited seasonal termination of the observed DCM/DBM did not result in a ‘diatom dump’, rather ongoing diatom downward export occurred throughout its multi-month persistence.

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Controls on Polar Southern Ocean Deep Chlorophyll Maxima: Viewpoints from Multiple Observational Platforms

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35 Deep Chlorophyll Maxima (DCMs) are ubiquitous in low-latitude oceans, and of recognized
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38 understanding of their onset, duration, underlying drivers, or whether they are associated with
39 enhanced biomass features. We report the characteristics of a DCM and DBM (Deep
40 Biomass Maximum) in the Inter-Polar-Frontal-Zone (IPFZ) south of Australia from CTD
41 profiles, shipboard-incubated samples, a towbody, and a BGC-ARGO float. The DCM and
42 DBM were ~20 m thick and co-located with the nutricline, in the vicinity of a subsurface
43 ammonium maximum characteristic of the IPFZ, but ~100 m shallower than the ferricline.
44 Towbody transects demonstrated that the co-located DCM/DBM was broadly present across
45 the IPFZ. Large healthy diatoms, with low iron requirements, resided within the DCM/DBM,
46 and fixed up to 20 mmol C m⁻² d⁻¹. The BGC-ARGO float revealed the DCM/DBM persisted
47 for >3 months. We propose a dual environmental mechanism to drive DCM/DBM formation
48 and persistence within the IPFZ: sustained supply of both recycled iron within the subsurface
49 ammonium maxima and upward silicate transport from depth. DCM/DBM cell-specific
50 growth rates were considerably slower than those in the overlying mixed layer, implying that
51 phytoplankton losses are also reduced, possibly as a result of heavily silicified diatom
52 frustules. The light-limited seasonal termination of the observed DCM/DBM did not result in
53 a ‘diatom dump’, rather ongoing diatom downward export occurred throughout its multi-
54 month persistence.

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57

58 Plain language summary

- 59 • DCMs and DBMs are typically observed in the low latitude ocean where they
60 contribute to regional ecology and biogeochemistry.

- They are cryptic features not observable from satellites.
- They are being more frequently observed in the Southern Ocean due to increased deployments of robotic profilers.
- The mechanisms that lead to their formation are not well understood in the Southern Ocean.
- Little is known about their seasonality or biogeochemical role.
- We use multiple observational platforms to address these issues.

1. Introduction

92 Deep Chlorophyll Maxima (DCMs) were initially observed in the low-latitude oligotrophic
93 ocean, where they were conspicuous in vertical fluorescence profiles at the base of the
94 seasonal thermocline and upper portion of the nitracline (Cullen, 1982; Cullen, 2015; Hogle
95 et al., 2018). These features have subsequently been observed in other basins, including the
96 Southern (S.) Ocean (Holm-Hansen and Hewes 2004; Parslow et al., 2001; Trull et al., 2001),
97 during oceanographic surveys such as WOCE (World Ocean Circulation Experiment). In the
98 last decade, the deployment of robotic profiling floats has revealed that DCMs are
99 widespread features across the global ocean (Cornec et al., 2021a). The frequent sampling by
100 such floats has provided insights into the seasonality of DCMs (Cornec et al., 2021a; Bock et
101 al., 2022).

102

103 DCMs are best characterized in the low-latitude ocean, often using a comparison of physical,
104 chemical and bio-optical vertical profiles (Cullen, 2015). Other insights have come from
105 discrete sampling of the subsurface feature and shipboard manipulation experiments to
106 elucidate their environmental controls (Hopkinson et al., 2005; Hogle et al., 2018). This
107 multi-faceted research allowed the determination of several factors controlling DCMs: a well-
108 stratified seasonally-stable thermocline, sufficient irradiance for phytoplankton growth along
109 with contact with the nitracline, often via internal waves (Cullen, 2015). Under the
110 classification of DCMs developed by Cornec et al. (2021a), these low-latitude persistent
111 features are termed Typical Stable Water Systems (see Cullen, 2015). Low-latitude DCM
112 habitats are dominated by specialised phytoplankton groups such as picophytoplankton
113 (Cullen, 2015). These communities typically exploit the episodic supply of additional
114 nutrients and hence can play both an important ecological and biogeochemical role, such as
115 in fuelling additional downward export flux (Pollehne et al., 1993).

116

117 In the last decade, the deployment of profiling robotic floats with a range of bioptical sensors
118 (such as chlorophyll (Chl) fluorescence and backscatter) in oligotrophic and other oceanic
119 regions has enhanced our ability to classify these subsurface features (Cornec et al., 2021a;
120 Strutton et al., 2023). Some DCMs have co-located Deep Biomass Maxima (DBMs) whereas
121 others have no DBM but result from a photoacclimatory increase in cellular Chl to harvest
122 light at depth. The ocean-wide coverage of robotic profiling floats has also provided insights
123 into the geographical distribution and typology of DCM/DBMs (Cornec et al., 2021a; Bock et
124 al., 2022).

125

126 For other DCM categories reported in Cornec et al. (2021a), a diverse range of drivers has
127 been developed from both observational and experimental studies, that differ from the
128 classical model of light/nitrate and picophytoplankton for the oligotrophic ocean (Cullen,
129 2015). For example, (new) iron and light are key controls on the resident picoeukaryotes and
130 diatoms in DCM/DBMs in the North Pacific (Hopkinson et al., 2005). The supply of
131 regenerated nutrients has also been invoked as a driver for (diatom-dominated) DCM/DBMs
132 in the Mediterranean Sea (Marañón et al., 2019). For other regional diatom-dominated
133 DCM/DBMs, silicate and/or iron supply from underlying waters have been proposed as
134 candidate drivers (Hopkinson & Barbeau, 2008; Allen et al., 2005; Yool & Tyrrell, 2003).
135 Mesoscale eddies can also play a role in DCM/DBM formation (Cornec et al., 2021b;
136 Strutton et al., 2023). In some oligotrophic regions, photoacclimation alone can be the driver
137 that underpins the presence of DCMs (Barbieux et al., 2019). For the S. Ocean, Pinkerton et
138 al. (2021), using data from three BGC-ARGO floats, advocate using a new metric - the
139 irradiance at the base of the mixed layer - to explain the magnitude of DCMs.

140

141 In the S. Ocean, proposed drivers of DCM/DBM formation include silicate resupply from the
142 nutricline (Parslow et al., 2001), and ‘irregular fertilization’ by iron (Cornec et al., 2021a),
143 potentially via eddies (Uchida et al., 2020) since the DCM/DBM depth is typically shallower
144 than that of the ferricline (Klunder et al., 2011). S. Ocean DCM/DBMs also differ from those
145 in other regions in that they are only observed - by floats - over a few months during austral
146 summer (see Figure 4 in Cornec et al., 2021a) and their magnitudes are typically smaller (see
147 S-Figs. 20 and 21 in Cornec et al., 2021a). These puzzling features have been classified as
148 ‘Ghost Zones’ by Cornec et al. (2021a) because a suite of outstanding questions remains
149 regarding the drivers of initiation, longevity, fate, and biogeochemical roles of S. Ocean
150 DCM/DBMs. Here, we employ 3 distinctive approaches: ship Conductivity–Temperature–
151 Depth (CTD) profiles and rosette sampling, towbody surveys, and high temporal resolution
152 BGC-ARGO profiles to jointly explore the underpinning mechanisms, spatial bounds,
153 environmental controls, links to the DBM and seasonality of the S. Ocean DCM. This, in turn,
154 enables us to begin to probe the biogeochemical and ecological roles of S. Ocean
155 DCM/DBMs.

156

157

158 **2.1 Materials and Methods**

159 The data presented here were obtained during the 42 day SOLACE (Southern Ocean Large
160 Area Carbon Export) voyage on the RV Investigator (IN2020_V08) from 6 December 2020
161 to 15 January 2021 to the S. Ocean, along with several months of observations from a robotic
162 profiling BGC-ARGO float deployed at a polar site (55.48°S 138.5°E) during this voyage.
163 SOLACE occupied three sites, one in the subantarctic (47.1°S, 141.4°E) near the Southern
164 Ocean Time Series (SOTS) station, and two south of the Polar Front (55.8°S 138.5°E, 57.8°S
165 141.5°E, S-Figure 1). The results presented here focus only on the two polar sites, both
166 sampled in a quasi-Lagrangian mode following the deployment of a holey-sock drogue at the

167 mid-depth of the seasonal mixed layer. The drogue drift trajectory over 10 days at the 55.8°S
168 site is presented in S-Figure 2. The trajectory was typical of the low advective regimes we
169 sought, and was similar to that observed at the southern site.

170

171 At each polar site, vertical oceanographic profiles were obtained using a Sea-Bird SBE911-
172 plus CTD unit (conductivity, temperature, and depth) that was linked to calibrated
173 fluorometer (Chelsea Aqua-Tracker Mk3), oxygen (SBE 43 electrode), photosynthetically
174 active radiation (i.e., PAR, Biospherical Laboratories) and transmissometer (Wetlabs C-Star
175 700 nm) sensors. Mixed Layer Depths were computed for each CTD profile using the mean
176 of a density threshold and density gradient algorithm. For the threshold, we followed Boyer
177 Montegut et al.'s (2004) criteria (via Holte and Talley, 2009): a density difference of 0.03 kg
178 m⁻³ referenced to the closest measurement to 10 dbar. For the mixed layer gradient, we
179 followed Dong et al. 2007 (via Holte and Talley, 2009) where the gradient criterion was
180 0.0005 kg m⁻³ dbar⁻¹.

181

182 The CTD and associated instruments were mounted within the frame of a 24 bottle (12 L)
183 rosette sampler. The CTD sensor package was calibrated after Kwong et al. (2020). Seawater
184 was sampled from the rosette at selected depths for nutrients and rate measurements
185 (including iron uptake, see later). Dissolved macronutrients were analysed following
186 procedures in Rees et al. (2018). Seawater samples for trace metal and isotope determination
187 were collected using acid-cleaned, Teflon-coated, externally-sprung, 12 L Niskin bottles
188 attached to an autonomous rosette equipped with a Sea-Bird SBE911-plus CTD unit
189 following methods detailed in Ellwood et al. (2020a,b). Particulate trace metal samples were
190 collected in situ onto acid-leached 0.2-µm PVDF (142 mm diameter) filters (Sterlitech) using
191 six large-volume dual-head pumps (McLane Research Laboratories), deployed at various

192 water depths (Ellwood et al., 2020a,b). Elemental analysis for dissolved and particulate trace
 193 metals followed procedures in Ellwood et al. (2020b). Discrete Particulate Organic Carbon
 194 (POC) samples were analysed following Trull et al. (2018). The POC data were used to
 195 calibrate the CTD transmissometer. In-situ values from the instrument were averaged across
 196 all depths within 5 m (above or below) of the Niskin bottles from which the discrete POC
 197 samples were obtained. Beam attenuation, c (m^{-1}) was computed from the transmissometer as
 198
$$c = -(1/.25) * \ln(\text{trans}/100)$$

 199 where trans is the beam transmittance (%). The beam attenuation from particulates (c_p) is
 200 estimated by subtracting out the attenuation due to the intrinsic properties of seawater (c_{sw}),
 201 $c_p = c - c_{sw}$.
 202 c_{sw} is set using the minimum value measured by the sensor at depth, assuming particle-free
 203 seawater. An estimate of the proportion of detrital (i.e., non-phytoplankton) POC was
 204 obtained by assuming a carbon (C) to Chl ratio of 30 (g:g) in living phytoplankton (Strutton
 205 et al., 2023), such that
 206 Detrital Fraction = $POC - 30 * Chl$.
 207
 208 Water from the trace metal rosette was also obtained for biological and biogeochemical
 209 metrics. Extracted Chl, photochemical efficiency (F_v/F_m), and the functional absorption cross
 210 section (σ_{PSII} ; nm^2 reaction centre (RC) $^{-1}$) of photosystem II (PSII) were measured after Boyd
 211 et al. (2022). Biogenic silica (BSi) was determined by measuring silicic acid
 212 spectrophotometrically after converting BSi to silicic acid through leaching with 0.1 M
 213 sodium hydroxide at 85°C for 2.25 h (Paasche 1973). Samples from multiple depths across
 214 the seasonal mixed layer and DCM/DBM were incubated in shipboard temperature-controlled
 215 (± 0.5 °C) seawater incubators, with light depths mimicked using a range of neutral density
 216 screening. Daily rates of Net Primary Production (NPP) and iron uptake were measured for

217 0.2-2 μm , 2-20 μm , >20 μm size fractions and the community (>0.2 μm) following
 218 procedures in Boyd et al. (2022). NPP was calculated from non-titanium-washed filters, as
 219 titanium decreased carbon (C) uptake rates by ~ 15%. However, iron (Fe) and Fe:C uptake
 220 rates were calculated using titanium-washed Fe and C samples, and so are intracellular. Six
 221 light depths were chosen to provide coverage across the mixed layer and within the
 222 underlying DCM. The 1% I_0 (surface irradiance) ranged from 83-92 m depth (with an
 223 attenuation coefficient (K_d) ~0.05).
 224
 225 The Triaxus towbody (MacArtney A/S, Esbjerg, Denmark) was towed at ~9 knots (using ~
 226 800 m of conducting core cable). It was undulated from ~15–200 m depth to observe the co-
 227 located DCM and DBM. We investigated measurements from a suite of sensors on the
 228 towbody including nitrate (SUNA UV-spectrometer, SBE), oxygen (SBE 43 electrodes
 229 plumbed in line with the CTD intakes) duplicate Sea-Bird SBE911 CTDs and a calibrated
 230 Sea-Bird ECO-Triplet FLBB2K measuring Chl fluorescence (470/695nm
 231 excitation/emission), optical backscatter (700nm), and dissolved organic matter fluorescence
 232 (370/460 nm – not discussed here) (Sea-Bird Electronics, Bellevue, USA). All data from
 233 these instruments were integrated over 2-s intervals. The estimation of the mixed layer depth
 234 was as for the CTD profiles. Profiles from each up/down Triaxus profile were smoothed with
 235 a 10 m moving average. A DCM was identified when the maximum Chl concentration was
 236 below the mixed layer depth (MLD) and >10% greater than the mixed layer depth Chl mean
 237 value. The thickness of the DCM is based on the region with at least 50% of the difference
 238 between the MLD mean and maximum Chl value. This method was also applied to the
 239 identification of a DBM using the POC field measured by the transmissometer using the same
 240 calibration as described for the CTD. We employ the term ‘deep enhancement’, which is
 241 defined as the percentage increase of the DCM mean (averaged across the thickness of DCM)

relative to the MLD mean. Deep enhancement of POC and C:Chl are computed within the DCM, rather than independently defining a DBM and D(C:Chl)M, respectively, with potentially different vertical boundaries.

A BGC-ARGO robotic profiling float (Provor-CTS5 float (NKE)), WMO 5906624, was deployed at the 56°S site during our voyage. It had the following sensor constellation: a SBE41 CTD (Sea-Bird); an ECO-Triplet composed of a Chl *a* fluorometer (excitation at 470 nm; emission at 695 nm), a Colored Dissolved Organic Matter (CDOM) fluorometer, and an optical backscattering sensor at 700 nm and angle of 124° (bbp); an OCR-504 (Satlantic) radiometer measuring PAR integrated over 400-700 nm; a SUNA-V2 nitrate sensor (Satlantic); a Seafet pH sensor (Sea-Bird); an Anderaa optode-4330 for dissolved oxygen, and an Underwater Vision Profiler (UVP) version 6. The float was programmed to profile every 2-4 days from December to late March and thereafter every 10 days, with parking depths of 500 or 1000 m. Following Argo protocols, hydrological data collected by the SBE41 Seabird CTD sensors were processed and quality-controlled, as described by Wong et al. (2023). Bio-optical adjusted data were used after quality-control following Schmechtig et al. (2014) for Chl fluorescence, and Schmechtig et al. (2019) for the bbp. Chlorophyll *a* values were multiplied by a S. Ocean specific correction factor of 0.3 following Ardyna et al. (2019). The bbp was converted to POC using the S. Ocean specific relationship reported in Johnson et al. (2017). Phytoplankton carbon (C) was then derived assuming a contribution to POC of 30% (Behrenfeld et al. 2005). Chlorophyll *a* and bbp were partitioned into 4 components following Briggs et al. (2020): small, labile fluorescing (chl_{a_s}) and backscattering (bbp_s) particles; and large, fast-sinking fluorescing (chl_{a_l}) and backscattering (bbp_l) particles. The division between small and large corresponds approximately to a particle chlorophyll content of 60 pg for chl_{a_s} versus chl_{a_l} and a particle diameter of 100 μm for bbp_s.

267 versus bbp₁. Data are available through the Coriolis database
268 (<ftp://ftp.ifremer.fr/ifremer/argo>; Argo, 2000). The float data were collected and made freely
269 available by the International Argo Program and the national programs that contribute to it
270 (<https://argo.ucsd.edu>, <https://www.ocean-ops.org>). The Argo Program is part of the Global
271 Ocean Observing System.

272

273 **2. Results**

274 *3.1 Ship-based sampling*

275 A combination of data from CTD profiles and discrete chemical sampling provides a broader
276 oceanographic context with which to interpret the location of the DCM/DBM feature. Two
277 sites were occupied for multiple days at 55.48°S 138.34°E (hereafter referred to as 56°S) and
278 further to the SE at 58°S 141°E (hereafter referred to as 58°S) in late December 2020 and
279 early January 2021 during the SOLACE voyage (S-Figure 1). Each site was selected using 3
280 day composite satellite maps of Chl concentrations overlaid on sea surface height anomaly
281 (S-Figure 1b), and low advective sites with elevated Chl stocks were sought. At 56°S, the
282 water column was characterised by temperature/salinity properties of the IPFZ (Parslow et al.,
283 2001), including a temperature minimum (T_{min}) layer between 100 and 300 m depth (Figure
284 1a).

285

286 A DCM was evident at 56°S as a >20 m thick feature in Chl fluorescence (Figure 1d) co-
287 located with the upper strata of the T_{min} layer and associated with low underwater
288 irradiances (Figures 1a, 1c). The DCM was co-located with a DBM across all 10 profiles,
289 indicative of biomass accumulation (Figure 1e), however, a coincident decrease in the C:Chl
290 ratio points to photoacclimation at depth as well (Figure 1f). The proportion of detrital POC
291 was ~0.9 in the mixed layer and decreased to ~0.7 in DCM/DBM (Figure 1g). This
292 subsurface feature was observed at the base of the seasonal thermocline in the zone where

both nitrate (from 25 to $\sim 28 \mu\text{mol L}^{-1}$) and silicate (from 4 to $>10 \mu\text{mol L}^{-1}$) concentrations increased with depth (Figures 2b and 2e). However, the DCM was not co-located with the ferricline ($\sim 0.2 \text{ nmol kg}^{-1}$ dissolved Fe (dFe) in the DCM c.f. $>0.4 \text{ nmol kg}^{-1}$ at depth, Figure 2a). The DCM/DBM feature was coincident with a subsurface ammonium maximum in all profiles where ammonium was sampled (Figure 2c). The Tmin layer, a relict feature from winter water, is often associated with a subsurface ammonium maximum that is present during winter in the IPFZ (Mdutyana et al., 2021).

Discrete samples from the CTD rosette were analysed for biological metrics such as BSi (Figure 2h), floristics (not shown), F_v/F_m (Figure 2i), and NPP/Fe uptake rates (Figures 2k and 2l). Extracted Chl measurements confirmed the presence of a DCM ($>0.7 \text{ mg m}^{-3}$ c.f. 0.2 mg m^{-3} within the mixed layer, Figure 2g). At the 56°S site BSi was measured at $\sim 0.1 \mu\text{mol L}^{-1}$ in the mixed layer, but increased to $0.2 \mu\text{mol L}^{-1}$ within the DCM – indicative of a diatom-dominated subsurface feature (Figure 2h). The DCM/DBM was collocated with a deep particulate phosphorus (P) maximum (80 nmol kg^{-1} c.f. $\sim 30 \text{ nmol kg}^{-1}$ in the mixed layer, data not shown) but was only associated with a small increase in particulate Fe stocks (0.1 nmol kg^{-1} in the DCM, c.f. $<0.1 \text{ nmol kg}^{-1}$ in the mixed layer, data not shown).

Light microscopy revealed that the DCM/DBM was dominated by large diatoms comprising many species (S-Figure 3). Cells in the subsurface feature had an F_v/F_m of ~ 0.5 , whereas those in the mixed layer had either equivalent or lower values (Figure 2i). The functional absorption cross section of PSII (σ_{PSII}) was variable and ranged from $600\text{--}1500 \text{ nm}^2 \text{ RC}^{-1}$ across two profiles (Figure 2j). Carbon (i.e., NPP) and Fe (by phytoplankton and heterotrophic bacteria) uptake profiles (Figures 2k, 2l) exhibited low iron uptake rates within the DCM/DBM ($\sim 2 \text{ pmol L}^{-1} \text{ d}^{-1}$, c.f. up to $40 \text{ pmol L}^{-1} \text{ d}^{-1}$ in the mixed layer) with large cells

318 contributing ~60% to the community integrated rate at depth (Figure 3). In contrast, NPP was
 319 $\sim 0.3 \mu\text{mol L}^{-1} \text{d}^{-1}$ in the DCM/DBM (c.f. $0.7\text{-}0.8 \mu\text{mol L}^{-1} \text{d}^{-1}$ in the mixed layer, Figure 2k).
 320 Large cells ($>20 \mu\text{m}$) dominated C uptake in both the mixed layer and DCM (Figure 3),
 321 resulting in low Fe:C uptake ratios ($3.3\text{-}4.5 \mu\text{mol}:\text{mol}$), indicative of cells in steady-state.
 322
 323 In contrast, at the 58°S site there was no evidence of a DCM or DBM until almost the end of
 324 our site occupation (Figure 4d, 4f), with relatively high Chl stocks (0.6mg m^{-3} (extracted
 325 value) within the seasonal mixed layer (Figure 5g and S-Figure 4). From a physical
 326 perspective, ship-based sampling revealed that the water column had a colder ($1\text{-}1.2^\circ\text{C}$) and
 327 deeper ($225\text{-}275\text{m}$ depth, Figure 4a) T_{min} feature than at the 56°S site ($1.75\text{-}2.0^\circ\text{C}$ and
 328 $\sim 200\text{m}$ depth, Figure 2a). Importantly, both features overlie a 2.5°C layer of Upper
 329 Circumpolar Deep Water (UCDW) suggesting similar winter water mass initial composition
 330 (data not shown). Biogeochemically, detrital POC made up a smaller proportion (~ 0.8) in the
 331 surface mixed layer at 58°S (Figure 4g) relative to the 56°S site (Figure 2g). As at the 56°S
 332 site, a subsurface ammonium maximum was evident below the mixed layer (Figure 5c) and
 333 coincided with the upper stratum of the T_{min} layer (Figure 5a). At the 58°S site, BSi was 0.2-
 334 $0.3 \mu\text{mol L}^{-1}$ within the surface mixed layer (Figure 5h), particulate P was $80\text{-}120 \text{nmol kg}^{-1}$
 335 in the mixed layer (data not shown) and particulate Fe was variable with depth ($0.1\text{-}0.4 \text{nmol}$
 336 kg^{-1} , data not shown). Phytoplankton cells exhibited F_v/F_m of ~ 0.45 in the surface mixed
 337 layer (Figure 5i) and a σ_{PSII} of $>800 \text{nm}^2 \text{RC}^{-1}$ (Figure 5j) in this stratum. NPP rates were
 338 higher than at the 56°S site (Figure 3a, 3b), but community Fe uptake rates were comparable
 339 (Figure 3c, 3d). As observed for the 56°S site, cells $<2 \mu\text{m}$ dominated Fe uptake while
 340 cells $>20 \mu\text{m}$ dominated NPP (Figure 3).

341

342

3.2 Spatial and temporal patterns in the DCM feature around 56°S and 58°S

The spatial extent of the DCM/DBM and the relationship with environmental drivers of this feature around the two sites were explored using Triaxus towbody surveys of around 30-40 miles comprising three sections at each site (S-Figure 2c and Figures 6 and 7). An initial Triaxus tow of ~35 miles (55.75°S 138.65°E to 138.3°E, S-Figure 2) to the west of the site under darkness (to avoid non-photochemical quenching (NPQ)) exhibited constancy in both the IPFZ water mass characteristics and the location of the DCM (Figure 6). Towbody observations also revealed the presence of a coincident DBM of ~20 m thickness located at 80 to >100 m depth. The POC:Chl ratios (note POC will contain non-phytoplankton cells) were typically lower (~40) within the DCM/DBM than in the overlying mixed layer (~80) reflecting the greater contribution of Chl to this feature relative to POC (Figure 6 c.f. 1f).

Several additional tows at the 56°S site further corroborated that the DCM was a more widespread feature beyond our study site (Figure 6). However, there was some spatial variability along each leg of the Triaxus tows in both the depth, thickness and magnitude of the DCM. The relationship with the depth and thickness of the DCM relative to that of the DBM provides clues as to the environmental forcing of this feature on short temporal and spatial scales. The depth of the DCM and DBM were well correlated and generally co-located (within ~5 m) during all tows that identified both a DCM and DBM. However, the DCM was consistently slightly deeper (~5 m) than the DBM, suggesting the increasing role of photoacclimation with depth. The thickness of the DCM and DBM were also well correlated, with the DCM typically ~5 m thicker than the DBM. The absolute magnitude of the DCM and DBM were generally well correlated, however the deep enhancement of the DCM was greater than that of the DBM (data not shown).

368 At the 58°S site, there was evidence of temporal evolution of a co-located DCM and DBM
369 near the study site. This emerging feature is conspicuous on January 11 2021 on tow 2 (i.e.,
370 the S-N return leg to the 58°S study site (Figure 7 and S-Figure 2c). During the first
371 deployment at 58°S, the DCM thickness was much more variable than that of the DBM. A
372 comparison of the features at both sites revealed that the absolute magnitudes of the DCM
373 and DBM were larger at 58°S than 56°S, whereas the deep enhancement of the DCM and
374 DBM was substantially larger at 56°S compared to 58°S (S-Figure 4). At 56°S Chl was
375 enhanced by 1 to 4 fold across the DCM relative to the surface mixed layer, coincident with a
376 smaller but substantial 20-60% enhancement of POC. In contrast, at 58°S deep enhancement
377 of Chl and C did not exceed ~25% in any profile. If the emerging DCM/DBM observed at the
378 58°S is to be interpreted as a precursor to the more established feature observed as 56°S then
379 this suggests that subsurface biomass accumulation already exists below the mixed layer at
380 58°S (even more so than at 56°S) but does not emerge as a maximum relative to the surfacer
381 layer until overlaying phytoplankton stocks are grazed to levels lower than in the subsurface
382 feature.

383
384 The seasonality and downward export potential of the DCM observed in the IPFZ at the 56°S
385 site were explored using the BGC-ARGO float. The float datasets extended the week-long
386 shipboard observations for 3-4 months within the IPFZ water mass (S-Figure 2a) and thus can
387 be cautiously linked to shipboard trends presented in Figures 1,2 and 5. The float's multi-
388 sensor constellation provides insights into temporal evolution of physical (Figure 8) and bio-
389 optical (Figure 9) properties over the ensuing months from austral summer into autumn/fall
390 2021, allowing us to track changes in the characteristics of the DCM/DBM (thickness,
391 POC:Chl, depth) and its environment. The distinctive DCM/DBM feature we observed from
392 CTD profiles (Figure 1) and the Triaxus tow-body (Figure 7) was also evident from the BGC-

393 ARGO float observations for ~3 additional months. The joint presence of the DCM and DBM
394 spanned late December 2020 to late March 2021 (Figure 9a,b) and exhibited a comparable
395 gradient in C:Chl ratios, which decreased with depth (Figure 9c,d) as observed with the
396 towbody (Figure 6). There was no marked change in the POC:Chl ratio in the DCM over
397 several months (Figure 9c), which we interpret as indicative of a persistent healthy population
398 of large diatoms, based on the float profiles obtained during our shipboard occupation of this
399 site.

400

401

402 The magnitude ($\sim 0.6 \mu\text{g L}^{-1}$, Figure 2g, c.f. Figure 1d and (a), depth (80-100 m) and thickness
403 (20-25 m) of the subsurface feature were largely consistent for 3 months (Figure 9) despite
404 pronounced changes in the depth of the surface mixed layer, which varied from <50 m to
405 ~ 100 m depth (Figure 8). The DCM/DBM decreased in amplitude and thickness in late
406 March, which coincided with a programmed change in the sampling frequency of the float
407 from 2 to 5 days (for several profiles) and followed by a shift to 10 day intervals (i.e., ARGO
408 standard protocol). The cause of the demise of the DCM/DBM feature is unclear but may be
409 linked to the threefold seasonal decrease in incident irradiance in April 2021 that is reflected
410 in underwater PAR of $<2 \mu\text{mol quanta m}^{-2} \text{ s}^{-1}$ within the subsurface feature (S-Figure 5).

411

412 The fate of the large diatoms within this feature is also unclear. There was no evidence of a
413 distinct downward particle pulse in either the BCG-ARGO Chl or POC time-series associated
414 with the decline of the DCM/DBM feature (Figure 10). However, there is some evidence of a
415 small but constant flux of particles, from January to March 2021, from the backscatter sensor
416 on the float (Figure 10b) that is less conspicuous in the float fluorometer time-series (Figure

10a). This observation suggests that the diatoms residing within the subsurface features may have sunk to depth intact as both cells and empty frustules.

4. Discussion

The different observational modes we employed to study the DCM within the IPFZ along with the diverse range of metrics, from biogeochemical to photo-physiological, enable us to probe many facets of this polar subsurface feature. We explore potential drivers for the DCM formation, then compare and contrast its characteristics with the biogeochemical fluxes we measured. Next, we further interpret towbody and BGC-ARGO observations to examine its wider-scale spatial and temporal distribution. The float data also enable us to address questions about its longevity and fate. Together, these multiple lines of examination provide insights into the DCM's ecological and biogeochemical role in the S. Ocean.

4.1 Drivers of DCM/DBM formation

We observed the DCM feature in late December after arriving at the 56°S site, but prior studies have recorded a springtime DCM (Parslow et al., 2001), suggesting that the 56°S feature may have formed before December. The earliest seasonally reported DCM in the S. Ocean was in November 1995 at 53°S i.e., at the northern edge of the IPFZ, the most southern station sampled by Parslow et al., 2001). They reported a diatom-dominated feature at ~65 m depth, that was not present in a prior October 1991 transect in the IPFZ. Parslow et al. (2001) reported data on Chl and pigments but not for backscatter or transmissivity so it is not known if there was also a DBM in the spring 1995 feature. However, they did present values of alpha (the slope of the phytoplankton photosynthesis-irradiance curve) that were two-fold higher in the DCM phytoplankton community compared to overlying waters, suggesting a low light-acclimated phytoplankton population, and hence potentially no DBM. The November 1995 feature Parslow et al. observed had 0.7 $\mu\text{g Chl L}^{-1}$ (c.f. 0.3 $\mu\text{g L}^{-1}$ in the

443 overlying surface mixed layer) and it was present at a time when mixed layer silicate and
 444 nitrate were close to winter reserve concentrations (i.e., likely not limiting).
 445
 446 Here, we attempt a space-for-time substitution to explore whether the 58°S site, which was at
 447 an earlier stage of the seasonal productivity cycle (Figure 2 c.f. Figure 5; S-Figure 6) can be
 448 viewed as a potential precursor for DCM formation. The 58°S site which had similar IPFZ
 449 physical characteristics, such as the Tmin layer (Figure 4a), may provide insights regarding
 450 what factors, such as resource limitation, led to the formation of a DCM/DBM (see Lande et
 451 al., 1989). In contrast, at our polar sites which were more southerly (56°S and 58°S) than that
 452 studied by Parslow et al. (2001) in November 1995, silicate concentrations were low and
 453 vanishingly low in the surface mixed layer of the 56°S and 58°S, respectively (Figures 2 and
 454 5). Parslow et al. (2001) also reported low silicate concentrations (along with DFe of 0.2
 455 nmol kg⁻¹) in DCMs near 54°S (i.e., within the IPFZ) in January over several different years.
 456 At both our sites, DFe was ~0.2 nmol kg⁻¹ (Figures 2 and 5) suggesting Fe stress, based on
 457 the relationship between DFe concentration and F_v/F_m reported for the polar S. Ocean in
 458 Boyd and Abraham (2001). Furthermore, at the 56°S and 58°S sites, Chl and (NPP) in the
 459 mixed layer were 0.3 mg m⁻³ (~600 mg C m⁻² d⁻¹) and 0.6 mg m⁻³ (~1000 mg C m⁻² d⁻¹)
 460 (Figures 2 and 5), respectively, supporting the conclusion from the ocean colour remote-
 461 sensing (S-Figure 6) that the 58°S site was at an earlier stage of development in its seasonal
 462 primary productivity cycle.
 463
 464
 465 At the 58°S site, based on drawdown in silicate between the two profiles (obtained while
 466 tracking a holey sock drogue, and so quasi-Lagrangian), 4 days apart (Figure 5h), the demand
 467 for silicate is 0.176 μmol L⁻¹ d⁻¹, which is ~5-fold lower than the rate measured for the Pacific

sector of the S. Ocean, $\sim 1 \mu\text{mol L}^{-1} \text{d}^{-1}$ (Sigmon et al., 2002) at a similar latitude. This, along with low and decreasing silicate stocks, suggests that cells at this site are close to Si limitation. Thus, it is likely that the 58°S site would be on the verge of transitioning to a decline in phytoplankton stocks and NPP driven by silicate and/or Fe limitation. These conditions may have enabled the development of a DCM/DBM (see DCM/DBM in S-N tow on 11 January 2021 in Figure 7) around mid-January 2021 (i.e., at the end of our ship-based observational record at the 58°S site).

How did the subsurface feature develop and where was it initiated within the water column? The gradual enhancement of the subsurface features evident in S-Figure 4, assuming it was in the same water mass, suggest that a DCM and DBM evolved at depth at a time when there is high chl in overlying waters and a correspondingly high light attenuation coefficient. As such it suggests the hypothesis put forward by Cornec et al. (2021a) on DCM formation - in which there is *in situ* enhancement of the DCM/DBM driven by reduced light attenuation at depth due to the decline of the stocks in the mixed layer - does not fit this S. Ocean scenario. Furthermore, in the surface mixed layer the estimated phytoplankton turnover times based on POC stocks and NPP (S-Table 1) are higher than in the DCM, despite the onset of Fe and/or Si limitation. This suggests that the build-up of the subsurface feature must require low loss terms, in particular low loss rates due to herbivory. The resident large diatoms present at the 56°S site have highly silicified frustules (S-Figure 3) thought to be an evolutionary mechanism to prevent/minimize grazing (Smetacek, 2001) and evident in their ability to resist salp herbivory (S-Figure 7). Thus, a combination of bottom-up (onset of silicate and/or Fe limitation in the surface mixed layer) and top-down (low loss terms to grazers) may lead to the onset of DCM/DBM formation, but whether this formation takes place at depth, or originates within the mixed layer via the relocation of a subset of the phytoplankton

493 population (the large diatoms) via slow sinking/buoyancy regulation , remains an open
494 question.

495

496 In the next section, we explore key characteristics of the DCM observed at the 56°S site such
497 as phytoplankton species composition and Fe uptake rates to further explore whether the
498 conditions at the 58°S site, at the time of occupation, led to DCM/DBM formation.

499

500

501 *4.2 DCM/DBM characteristics and biogeochemical fluxes*

502 The feature at 56°S had several distinctive characteristics that enable us to further probe the
503 validity of silicate and/or Fe limitation as key environmental triggers in the initiation of a
504 DCM. The subsurface phytoplankton assemblage differed from that in the overlying water
505 column (S-Figure 3). Based on light microscopy, the DCM/DBM was dominated by large
506 diatoms, many >200 µm in length, comprising multiple species (see S-Figure 3). Multiple
507 diatom species have also been recorded in a DCM in the Indian sector of the S. Ocean by
508 Gomi et al. (2010). At our 56°S site, observations from microscopy are supported by a >3-
509 fold higher BSi concentration in the DCM relative to the overlying mixed layer (Figure 2h).

510 Size-fractionated NPP and Fe uptake revealed that the large cells (>20 µm fraction)
511 dominated NPP within the DCM ($0.1 \mu\text{mol L}^{-1} \text{d}^{-1}$) (Figure 3), had a relatively high
512 photosynthetic competence (F_v/F_m , Figure 2i c.f. theoretical maximum of 0.65 see Boyd and
513 Abraham, 2001), and very low Fe requirements at 56°S (Figure 3b). These low Fe
514 requirements for large polar diatoms are also observed in lab cultures and are attributed to the
515 cells' ability to increase the size of their light-harvesting antenna under low light conditions
516 (with implications for self-shading, see later) rather than increase the number of photosystem
517 units in the chloroplast, which has an added Fe cost for effective light harvesting under low

518 irradiances (Strzepek et al., 2012). Irradiances at the base of the DCM were low during the
519 daytime ($1\text{--}20\ \mu\text{mol photons m}^{-2}\text{ s}^{-1}$, Figure 1c and S-Figure 5b) suggesting that large polar
520 diatoms may be particularly well suited to persist in the poorly-lit DCM relative to other
521 species with higher iron requirements at such low irradiances.

522

523 The findings of a shipboard perturbation experiment conducted at the 56°S site in which dFe,
524 manganese and irradiance were amended either alone or in combination (Latour et al., in
525 prep.) reveal some evidence of Fe limitation of the resident cells within the DCM/DBM.
526 Although some of the treatments, such as increasing both Fe and irradiance, do not reflect
527 conditions within the overlying mixed layer at 56°S, these perturbations do provide valuable
528 insights into the physiological status of the cells within the DCM/DBM. The transfer of
529 resident cells to more optimal conditions (high irradiance and high Fe) led to a major
530 upregulation in their physiology, as evidenced by marked increases in Chl, POC and BSi
531 stocks (relative to a high light only treatment). Thus, diatoms are probably subsisting in the
532 DCM/DBM with sufficient resources for low rates of NPP (Figure 3) in a subsurface niche
533 that enables them to continue to be productive for months. However, the perturbation
534 experiments by Latour et al. (in prep.) strongly suggest that these cells remain primed for
535 more optimal conditions (such as nutrient replete and high light, where they could grow faster
536 (S-Table 1)), as is observed in high-latitude polar regions of the Arctic (Hoppe, 2021) and
537 Antarctic (Kennedy et al., 2019).

538

539 Other characteristics of the 56°S site provide insights into what might lead to the initiation of
540 a DCM/DBM as a niche for large diatoms. The ferricline at the 56°S site was >100 m deeper
541 than the seasonal mixed layer (Figure 1a c.f. 2a), indicating that the observed persistence of
542 the DCM/DBM for months (Figure 9) likely requires another source of Fe, since the $\sim 4\ \text{pmol}$

543 $\text{L}^{-1} \text{d}^{-1}$ Fe demand by large cells would lead to a cumulative demand of $>0.1 \text{ nmol L}^{-1} \text{ month}^{-1}$
544 (assuming this observed Fe uptake rate (Figure 3b) was applicable beyond our site occupation
545 in late December 2020). Where could this Fe be supplied from? Subsurface ammonium
546 maxima reflect the signature of microbial remineralisation in many locales including the S.
547 Ocean (see Mdutyana et al., 2021). So, is it possible that the co-location of the DCM/DBM
548 with the upper zone of the subsurface ammonium maximum (Figure 2) indicates a role in for
549 a recycled Fe iron supply to the diatoms within the DCM/DBM?

550

551 Prior measurements of ammonium and dFe recycling made during an *in situ* particle
552 remineralisation study at 180 m depth in a subantarctic site revealed that $0.78 \text{ nmol L}^{-1} \text{ dFe}$
553 was released per $0.38 \text{ } \mu\text{mol L}^{-1}$ of ammonium produced, equating to a resupply ratio of 2.06
554 $\text{nmol L}^{-1} \text{ dFe per } \mu\text{mol L}^{-1}$ of ammonium released (Bressac, unpublished). The subsurface
555 ammonium maximum was $\sim 0.6 \text{ } \mu\text{mol L}^{-1}$ at the 56°S (Figure 2c) and approximates steady-
556 state based on three profiles within 9 days. Assuming a conservative turnover time of 100
557 days for the subsurface ammonium maximum (c.f. Mdutyana et al., 2020), this feature could
558 release $\sim 12 \text{ pmol dFe L}^{-1} \text{ d}^{-1}$, more than meeting the measured diatom Fe requirements
559 (Figure 3b). The subsurface ammonium feature that characterises the Tmin layer (Figures 2c
560 and 5c) is present over winter when it is already dynamic as reported for the IPFZ in the
561 Atlantic sector by Mdutyana et al. (2021). In other systems, Fe recycling within the
562 DCM/DBM is reported to play a key role, for example in sustaining the diatom-dominated
563 feature in the Mediterranean Sea (Marañón et al., 2019).

564

565 Another candidate mechanism for DCM/DBM formation is the alleviation of diatom silicate
566 limitation, as silicate was at low and vanishingly low levels at the 56°S and 58°S sites,
567 respectively, and the DCM was co-located with a subsurface peak in BSi (Figures 2e, 2h and

Figures 5e, 5h). At 90 m depth, the base of the DCM at 56°S, silicate was present at ~10 $\mu\text{mol L}^{-1}$ (Figure 2e). As the DCM persisted for months after our site occupation (Figure 9), a continuing source of silicate is likely required for this feature's ongoing presence. S. Ocean diatoms have been reported to have a low affinity for silicate, especially south of the Polar Front. For example, Nelson et al. (2001) reported half-saturation constants of $> 10 \mu\text{mol L}^{-1}$ for some species north of the Ross Sea during the AESOPS Joint Global Ocean Flux Study (JGOFS) process study. In the lab, Meyerink et al. (2017) measured a half-saturation constant of $11 \mu\text{mol L}^{-1}$ for the diatom *Proboscia inermis* and $9 \mu\text{mol L}^{-1}$ for *Eucampia antarctica* when grown under Fe-replete conditions, so silicate availability may be an issue for larger diatoms that reside in the DCM (S-Figure 3). Thus, increased silicate availability at depth may be a driver, along with Fe supply via recycling, for the formation of a DCM in the IPFZ. Our proposed drivers combine prior suggestions for a role of silicate resupply (Parslow et al., 2001) and ‘irregular fertilization’ of Fe (Cornec et al., 2021a), but go one step further by more clearly identifying a mechanism for sustained Fe supply via recycled rather than new Fe (from the ferricline) that is linked to the presence of the subsurface ammonium maximum.

583

4.3 Wider distribution of DCMs/DBMs

DCMs/DBMs are typically sampled opportunistically, and hence most observational records are based on a small number of CTD profiles (see Review by Baldry et al., 2021), along with a wider extrapolation of oceanographic snapshots of DCM features across regions (e.g., Parslow et al., 2001). The availability of both the towbody (night-time only) and BGC-ARGO observations enable us to assess the wider distribution of the DCM/DBM, both around our sampling sites, and also for the BGC-ARGO float after the vessel departed the sites. The tow-body sections reveal that the water mass associated with the IPFZ extended by at least a 15 km radius around our sampling site at ~56°S (Figure 6). There is a strong

593 coherence along each towbody section in the depth and thickness (~20 m) of both the DCM
594 and DBM. Any small variations in the DCM's depth or thickness were mirrored by that for
595 the DBM, likely reflecting small variations in the depth of the seasonal mixed layer in this
596 region. The C:Chl ratio of the subsurface feature was also relatively constant along each
597 section and was several-fold lower than in the overlying waters. The ratios in the upper ocean
598 were typical of those observed in the seasonal mixed layer (Riemann et al., 1989), whereas
599 the values in the DCM were typical of regions with more subsurface carbon at depth than Chl
600 (Taylor et al., 1997). At the 58°S site, the presence of subsurface features were more variable,
601 reflecting their development towards the end of our site occupation (Figure 7 and S-Figure 4).

602
603 The wider distribution of both subsurface features can also be explored, in part, using the
604 BGC-ARGO high-resolution time-series (Figures 8 and 9) as the float remained both in the
605 vicinity of the 56°S site (S-Figure 1a) and within the water mass characteristics of the IPFZ.
606 For example, the Tmin layer at depth is conspicuous in the float time-series observations
607 (Figure 8a). Again, a coherent DCM co-located with a DBM is evident for several months
608 (Figures 9a, 9b). As for the towbody, lower C:Chl ratios were evident in the subsurface
609 feature when compared to those in the overlying waters from profiles obtained under
610 darkness (which were interspersed with noon profiles, as is evident from Figures 9c and 9d).
611 The multi-month float record also provides insights into the longevity and eventual decline of
612 the DCM.

613

614 *4.4 Fate of the DCM/DBM*

615 Most prior studies of DCMs/DBMs in the S. Ocean have been opportunistic 'snapshots' (e.g.,
616 Parslow et al., 2001; Trull et al., 2001). Insights into the lifetime of such features have
617 therefore come from inference. For example, Parslow et al. (2001) observed DCMs from

618 November to March, but they are prescribed profiles as part of WOCE and JGOFS transects
619 that straddled multiple years. A recent compilation of DCMs from Southern Ocean BGC-
620 ARGO floats reveals several cases in which a DCM/DBM was repeatedly observed (Cornec
621 et al. 2021a; this study Figures 11 and 12). These studies provide more examples of extended
622 observations of the DCM and DBM to compare with those from January 2021 to May 2021
623 when the decline of the DCM was evident (Figure 9).

624

625 The sampling of a DCM in March within the IPFZ, south of Australia, by Parslow et al.
626 (2001) pointed to a feature in decline, as evinced by empty diatom frustules in the DCM
627 (Kopczynska et al., 2001), and also no difference between the photosynthetic metric alpha
628 (slope of the PE curve) within the DCM relative to the overlying waters. In contrast, higher
629 alpha values (indicative of photoacclimation) were reported in January (summer) DCMs
630 sampled by Parslow et al.. A major unknown from the Parslow et al. (2001) study is whether
631 the DCMs they observed were also representative of DBMs, but there are some suggestions
632 from the relatively high NPP within the DCM features that they may also have been DBMs.
633 The longer time records from Cornec et al. (2021a) reveal for two floats within the IPFZ
634 (Figures 11 and 12) that both DCMs and DBMs were evident in BGC-ARGO time-series
635 observations below the seasonal mixed layer to a depth of ~80 m (i.e., 30 m thick features) in
636 the vicinity of 120°E (WMO # 6901581) for ~55 days (30 December 2016 to 24 February
637 2017) and near 165°E (WMO # 6901004) for ~60 days (29 Dec 2016 to 03 March 2017). The
638 fate of these features – a decline in late March and no evidence of a particle export pulse -
639 appears similar to that of the DCM/DBM recorded by the float near the 56°S site in the
640 present study (Figure 9 c.f. Figure 12).

641

642 At the 56°S site, the subsurface feature persisted until mid-April 2021, with coherence
 643 between the thickness and depth strata of the DCM and DBM, along with little change in
 644 C:Chl ratios in the subsurface feature (Figure 9). The latter is indicative of a healthy
 645 population of diatoms and hence a strong indication of a region in which of NPP persisted,
 646 albeit at lower rates (see Figure 3). The decline of the DCM was relatively abrupt (likely
 647 driven by vanishingly low light levels, S-Figure 5b), and there was no evidence of a late-
 648 season fall-out of the large diatoms to depth, as has been speculated by Queguiner (2013) and
 649 Kemp (2000). The decline was likely driven by a decrease in underwater solar radiation,
 650 which declines markedly in this polar region to $<3 \mu\text{mol photons m}^{-2} \text{ d}^{-1}$ (S-Figure 5). Prior to
 651 April, there was no clear trend in the column-integrated irradiances recorded on profiles by
 652 the float at 56°S (S-Figure 5a). What was the fate of the large diatoms within the DCM?
 653

654 During our occupation of the 56°S site in late December 2020/early January 2021, there was
 655 evidence of grazing by salp swarms but no change in the DCM characteristics over this
 656 period. Microscopic analysis of dissected salp guts revealed some large diatoms, but they
 657 were intact and likely passed through the gut (S-Figure 7). The likely fate of the diatoms
 658 within the DCM may have been a slow but continuous export of a fraction of the assemblage,
 659 given that the feature appeared stable and viable for months (Figure 9), as opposed to an
 660 export pulse which would have been conspicuous from the bio-optical sensors on the float
 661 (see Figure 10). Such a constant and low export flux may have been driven by self-regulation
 662 of the thickness and integrated Chl (a community response analogous to the cellular self-
 663 shading ‘package effect’) within the DCM (see Lande et al., 1989). As stated earlier, the
 664 ability of large polar diatoms to increase their light-harvesting antennae (a mechanism that
 665 requires no additional Fe, Strzepek et al., 2012, 2019) may have exacerbated this Chl
 666 ‘package’ effect leading to their vertical export. There is some evidence of such a low but

constant export flux from Chl fluorescence and backscatter from January to April 2021 (Figure 10). However, these downward fluxes are more evident for backscatter than for Chl fluorescence suggesting chlorotic cells with declining Chl relative to carbon. Such chlorotic cells would be linked to their senescence after less than a week (Strzepek et al., 2012), based on observations of lab-cultured S. Ocean polar diatoms under high Fe but low light conditions (i.e., reflecting the environment within the DCM/DBM). These observations help inform on the wider functional role of the DCM and DBM.

4.5 Ecological and biogeochemical roles of the DCM/DBM

Recent reviews of S. Ocean NPP (Pinkerton et al., 2021) and biogeochemistry (Henley et al., 2021) suggest DCMs play important ecological and/or biogeochemical roles based on particle export. Our suite of datasets from diverse observational platforms offers insights into the wider roles of DCMs/DBMs. The co-location of both the DCM and DBM, which is mainly associated with diatoms, along with its multi-month persistence suggests that it is a subsurface niche that develops as a result of the decline of the surface mixed layer phytoplankton community (S-Figure 4 and S-Table 1) following resource limitation by both silicate and Fe. The surface waters appear, based on the BGC-ARGO float records (Figure 9), to have low and constant Chl and C concentrations, that characterise a seasonal High-Nutrient Low-Chlorophyll province (Boyd et al., 2000; Boyd and Law 2001; Arrigo et al., 2003). The development of the subsurface diatom community will have ramifications for the cycles of Fe, silicate and C in particular. The diatom community appears to be driven by the availability of silicate below the seasonal mixed layer along with Fe derived from recycling rather than new sources. NPP is relatively low – we measured $0.2 \mu\text{mol L}^{-1} \text{d}^{-1}$ in the DCM. Other studies have estimated NPP from DCMs, but these are based on snapshots from short station occupations. Parslow et al. (2001) reported a maximum rate of NPP of $0.25 \mu\text{mol L}^{-1} \text{d}^{-1}$

692 (equivalent to the daily ‘production’ of 4×10^4 (*E. antarctica*) to 5.5×10^4 (*P. inermis*)
 693 diatom cells L^{-1} (based on S-materials in Strzepek et al., 2019) in the DCM in October and
 694 January, decreasing to $<0.1 \mu\text{mol } L^{-1} \text{ d}^{-1}$ in March.
 695
 696 Prior NPP estimates (Parslow et al., 2001) did not take into consideration the thickness of the
 697 stratum associated with the DCM/DBM. Based on robust estimates, from our three
 698 observational approaches, we can extrapolate this NPP rate over the ~25 m thick feature
 699 (Figure 9) resulting in a column integral of $5.0 \text{ mmol } m^{-2} \text{ d}^{-1}$. Further extrapolation, based on
 700 little change in C:Chl ratios which is indicative of relatively healthy cells, to a month
 701 suggests that an NPP of $150 \text{ mmol } m^{-2}$ monthly could be contributed by this feature which
 702 persisted for 3 months (Figure 9). The fate of this additional carbon is unknown, but based on
 703 the bio-optical sensor time-series (Figure 10), could be a ‘slow trickle’ of exported particles
 704 to depth. Herbivory data during the ship occupation of the 56°S site suggest that salps can
 705 ingest but not consume these large diatoms (S-Figure 7). Thus, it is possible that most losses
 706 can be attributed to export rather than secondary consumption, leading to a ‘slow trickle’ of
 707 up to $150 \text{ mmol } \text{POC } m^{-2}$ each month from ~90 m depth.
 708
 709 Is there a biogeographic province for S. Ocean DCM/DBMs? Our findings, along with those
 710 from Parslow et al. (2001) south of Australia, and several of the floats featured in the Cornec
 711 et al. (2021a) global DCM analysis, but re-examined in detail here (Figure 11), suggest that
 712 the IPFZ may be such a region. This region can provide both silicate at depth and *in situ* Fe
 713 recycling by microbes associated with the subsurface ammonium maximum. However,
 714 additional insights come from observations from the waters north and south of the IPFZ. To
 715 the north, in the subantarctic, which also has seasonal silicate limitation (Hutchins et al.,
 716 2001), there is no evidence of DCM or DBM, suggesting that alleviation of similar limitation

717 at depth alone may not result in a DCM/DBM. To the south of the IPFZ, the SOIREE site
718 (Trull et al., 2001) was south of the southern branch of the Polar Front, in eastward flowing
719 Antarctic Circumpolar Current waters. This site was characterized by a Tmin layer (but there
720 are no ammonium data), and Figure 9 in Trull et al. (2001) reveals that silicate most likely is
721 never fully depleted in surface waters at 61°S. Thus, the physico-chemical characteristics of
722 the IPFZ may play a key role by being both silicate and Fe deplete in surface waters, yet
723 being able to provide both nutrients in the subsurface, but via different mechanisms – from
724 the nutricline for silicate and via recycling for Fe. The IPFZ thus provides an interesting
725 testbed to see if it represents a province in which both DCM and DBM are co-located, as
726 opposed to other regions where only DCMs comprising photoacclimated cells are evident
727 (Carranza et al., 2018; Baldry et al., 2021; Cornec et al., 2021a).

728

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982 Figure captions

983 Figure 1 Vertical profiles for the 56°S station from calibrated CTD sensors. a. temperature, b.
984 salinity, c. irradiance (PAR), d. Chl fluorescence, e. transmissometer POC, f. POC:Chl ratio,
985 g) proportion of detrital fraction. MLD denotes the mean Mixed Layer Depth for all profiles
986 with +/- 1 standard deviation. Dashed lines labelled DCM and DBM denote the mean
987 position of these subsurface features. Dotted lines in d. and e. denote the mean vertical extent
988 of each feature. In Figure 1d. and e. the location of each subsurface feature is identified by
989 smoothing each profile with a 10 m moving mean then identifying the maximum. The
990 maximum is 10% larger than the mixed layer mean value to qualify. The vertical extent of
991 each feature is defined as the region with 50% of the difference between the MLD mean and
992 maximum concentration. Days since arriving the 56°S station on 24 December 2020, for each
993 profile are denoted on the color bar.

994

995 Figure 2 Vertical profiles for the 56°S station from CTD rosette water samples. Dissolved Fe
996 samples were sampled from the trace metal clean rosette. a. dissolved Fe (dFe), b. nitrate, c.
997 ammonium, d. nitrite, e. silicate, f. phosphate, g. extracted Chl, h. biogenic silica, i. F_v/F_m , j.
998 σ_{PSII} , k. community carbon fixation and l. community iron uptake. MLD and color bar are as
999 for Figure 1.

1000

1001 Figure 3 Size- partitioned C and Fe uptake rates for three size classes and their sum (all sizes)
1002 at 56°S (solid lines 20 December 2020; dashed lines 26 December 2020) and 58°S (solid
1003 lines 29 December 2020, dashed lines 7 January 2021).

1004

1005 Figure 4 Vertical profiles for the 58°S station from calibrated CTD sensors. Panels are as for
1006 Figure 1, as is the MLD definition and the color bar. Arrival on station (day 0) was 1 January
1007 2021) Note, no DCM or DBM was located using our algorithm (see Methods) at 58°S.

1008

1009 Figure 5 Vertical profiles for the 58°S station from and CTD rosette water samples.
1010 Dissolved Fe samples were sampled from the trace metal clean rosette. Panels are as for
1011 Figure 2 and MLD and color bar are as for Figure 3.

1012

1013 Figure 6 Triaxus towbody sections in the vicinity of the 56°S station (see S-Figure 4 for
1014 towbody maps that relate to the direction of the tow presented above the panels for Chl) for
1015 Chl, POC and C:Chl ratio. The red vertical line in each panel denotes the mixed layer depth.

1016 The DCM and DBM peak (i.e., maximum concentration) and vertical extent are calculated as
1017 per Figure 1 for each profile of the towbody and denoted with black lines.

1018

1019 Figure 7 Triaxus towbody sections in the vicinity of the 58°S station. As per Figure 6. Note,
1020 discontinuities in DCM/DBM time-series indicate no DCM/DBM was located using our
1021 algorithm for that profile.

1022

1023 Figure 8 Time-series of BGC-ARGO physical observations (semi-log plots) in the vicinity of
1024 the 56°S site. a. temperature; b. salinity; c. potential density; and d. Brunt–Väisälä frequency
1025 (i.e., buoyancy frequency). MLD denotes the seasonal mixed layer depth (white line).

1026

1027 Figure 9 Time-series of BGC-ARGO biological observations (semi-log plots) in the vicinity
1028 of the 56°S site. a. concentration of small fluorescing particles chl_{a_s} and b. small
1029 backscattering particles bbp_l , c. POC: chl_{a_s} ratio and d. algal C: chl_{a_s} ratio (see Methods).
1030 MLD denotes the seasonal mixed layer depth (white line).

1031

1032 Figure 10 Time-series of BGC-ARGO biological observations in the vicinity of the 56°S site.
1033 a. concentration of large fluorescing particles chl_{a_l} and b. large backscattering particles bbp_l .
1034 The black line denotes the seasonal mixed layer depth.

1035

1036 Figure 10 Time-series of BGC-ARGO biological observations in the vicinity of the 56°S site
1037 presented in Figure 9a and b, but replotted with a linear (rather than log) colormap to better
1038 assess the potential export of Chl and C into the oceans' interior. The black line denotes the
1039 seasonal mixed layer depth.

1040

1041 Figure 11 Indo-Pacific sectors of the S. Ocean overlaid with composite of the locations of
1042 BGC-ARGO float profiles presented in Cornec et al. (2021a). Blue small symbols denote
1043 float profiles where DCM and DBMs were observed. Green symbols represent where only
1044 DCMs (but no DBM) were recorded. Gray symbols represent where no DCMs were observed.
1045 Two floats that recorded persistent DCM features are highlighted with light blue circles at
1046 120°E and 165°E. The two polar sites (56°S 138.5°E, 58°S 141.5°E) featured in our study are
1047 denoted by red crosses. The SR3 line (from Tasmania to E. Antarctica) along which Parslow
1048 et al. (2021) recorded DCMs, only within the IPFZ, over multiple years during WOCE and
1049 JGOFS transects is represented by a yellow dashed line. The purple and red lines denote the
1050 fronts which bound the IPFZ.

1051

1052 Figure 12 Time-series observations of the DCM and DBM from Cornec et al. (2021) for the
1053 two floats within the IPFZ featured in Figure 11. The sampling frequency for both floats was

every 2 days before March 2017, 4 days during March 2017, and 5 days after March 2017.
The mixed layer depth is denoted with a white line.

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1057

1058 S-Figures

1059 S-Figure 1 Locations of stations occupied during the 2020/21 SOLACE voyage
1060 (IN2020_V08) south of Tasmania, Australia. The left hand panel shows the locations of all
1061 three sites and locations of the Triaxus undulating towbody tows, superimposed on the
1062 voyage track. The right hand panel features only the polar 1 (56°S) and 2 (58°S) sites
1063 overlaid on a map of ocean color Chl and sea surface height (SSH) anomaly from early
1064 January 2021 (courtesy of Benoit Legresy, CSIRO, Australia). The two sites were located in
1065 low flow regions with low and intermediate Chl concentrations, respectively.

1066 S-Figure 2 Location of a) the BGC-ARGO float relative to the 56°S site (red circle) from its
1067 launch in Dec 2020 to June 2021 (solid symbols, just N of 54S, W of 140E). B) drift
1068 trajectory (miles) of holey-sock drogue at 56°S polar site (denoted by red circle). Examples
1069 of Triaxus towbody routes at c) 56°S and d) 58°S.

1070 S-Figure 3 Overview of SOLACE DCM large diatom species based on a photomicrograph
1071 using a 20-fold concentrate from the DCM at the 56S site. Species include: *Fragilariopsis*
1072 *keruelensis*, *Fragilariopsis* sp. (*cylindrus/curta*), *Pseudo-nitzschia* spp., *Proboscia* sp. (*alata*
1073 */ inermis / truncata*), *Dactyliosolen antarctica*, *Cylindrotheca* spp., *Corethron* spp.,
1074 *Chaetoceros atlanticus*, *Asteromphalus hookeri*, *Thalassiosira oliverana / tumida*.

1075 S-Figure 4 The temporal evolution of the DCM and DBM at the 58°S site. a) Chl and d)
1076 POC profiles from Fig 3d and 3e are shown, zoomed in on upper 100 m. The associated
1077 temporal evolution of the b, e) magnitude and c, f) enhancement relative to the mean MLD
1078 concentration for the b, c) DCM and e, f) DBM are plotted. Note, the ‘DBM/DCM’
1079 magnitude and enhancement are shown even if they do not technically qualify as a
1080 ‘DBM/DCM’ based on our threshold criteria (See Methods).

1081 S-Figure 5 a) Depth-integrated irradiance from the BGC-ARGO float over the duration of the
1082 observed DCM/DBM. White line denotes mixed layer depth. b) Time-series of PAR at the
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1084 resolution, MODIS) over period of late 2020 and early 2021 for c) 55.5°S – 56.5°S, 137.5°E
1085 – 138.5°E and d), 57.5°S-58.5°S, 140.5°E to 141.8°E.

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1087 development of a, b) surface Chlorophyll and c, d) the depth of the SML is show for the a, c)
1088 56°S and b, d) 58°S sites. For each, we plotted shipboard measurements (black) atop the full
1089 seasonal cycle from the a, b) remote sensing or c, d) reanalysis record (red). For the later we
1090 show the 2020-2021 cycle (solid) and the climatologic cycle (dashed). Remote sensing
1091 chlorophyll is from the MODIS-GSM ocean color record and reanalysis SML depths are
1092 from HYCOM, both downloaded from [Ocean Productivity \(oregonstate.edu\)](https://oceanproductivity.oregonstate.edu/) .. Both are
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1094 mean position of the occupation. Remote sensing chlorophyll is correct by a factor of 1.73 per
1095 Johnson et al. (2013).

1096 S-Figure 7 Photomicrographs of intact diatoms within the (dissected) gut of a salp at the
1097 58°S site suggests that diatoms are ingested but not consumed by herbivores.

1098

1099 S-Table 1 Phytoplankton specific growth rates in different features. Division rates are
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1103 Chlorophyll are averaged across the specified depth range for each feature, with the surface
1104 mixed layer, DBM and DCM defined as in Figures 1-4. At 58S no DCM or DBM was
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Figures 1 to 12.

Fig.1

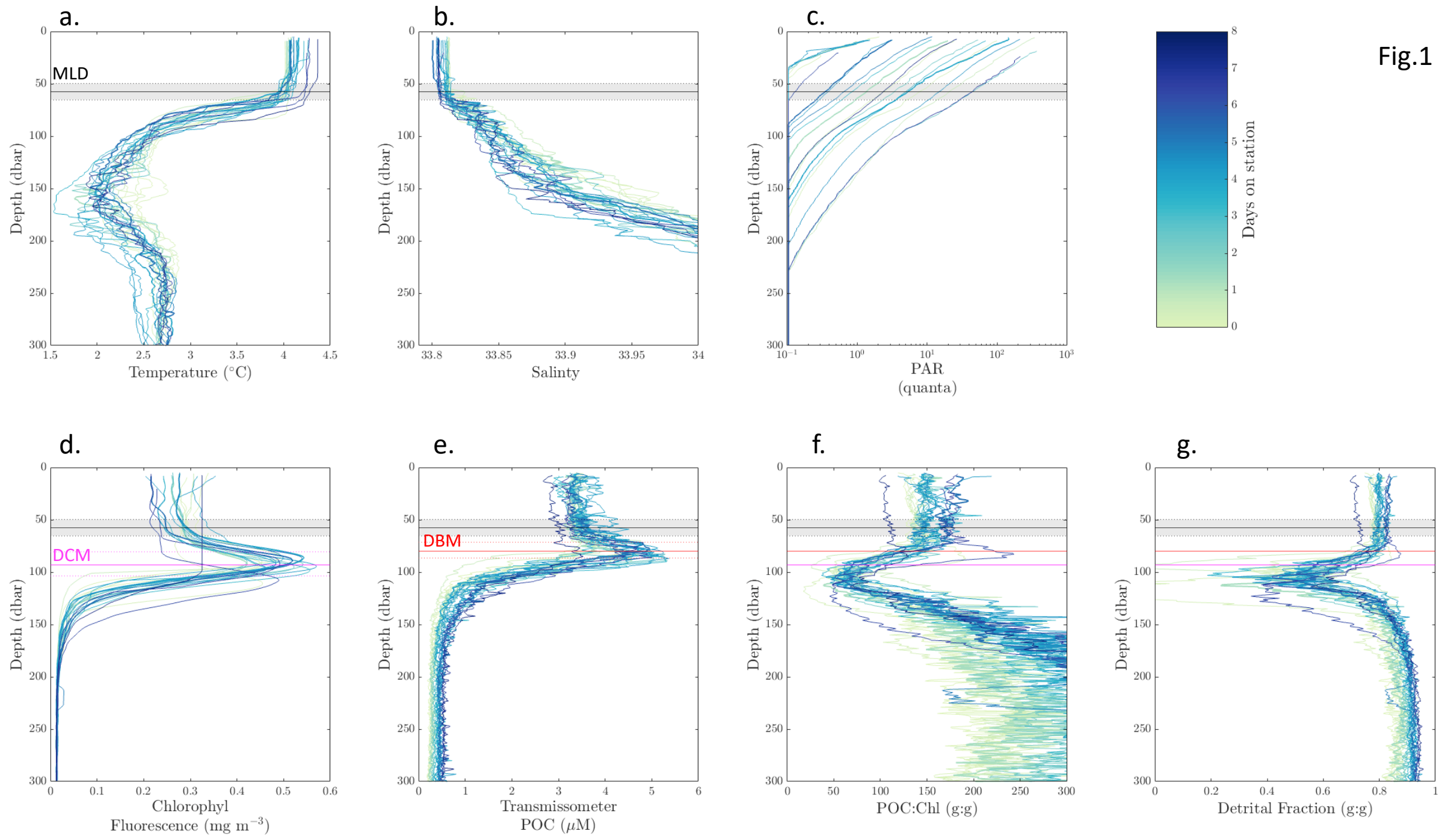
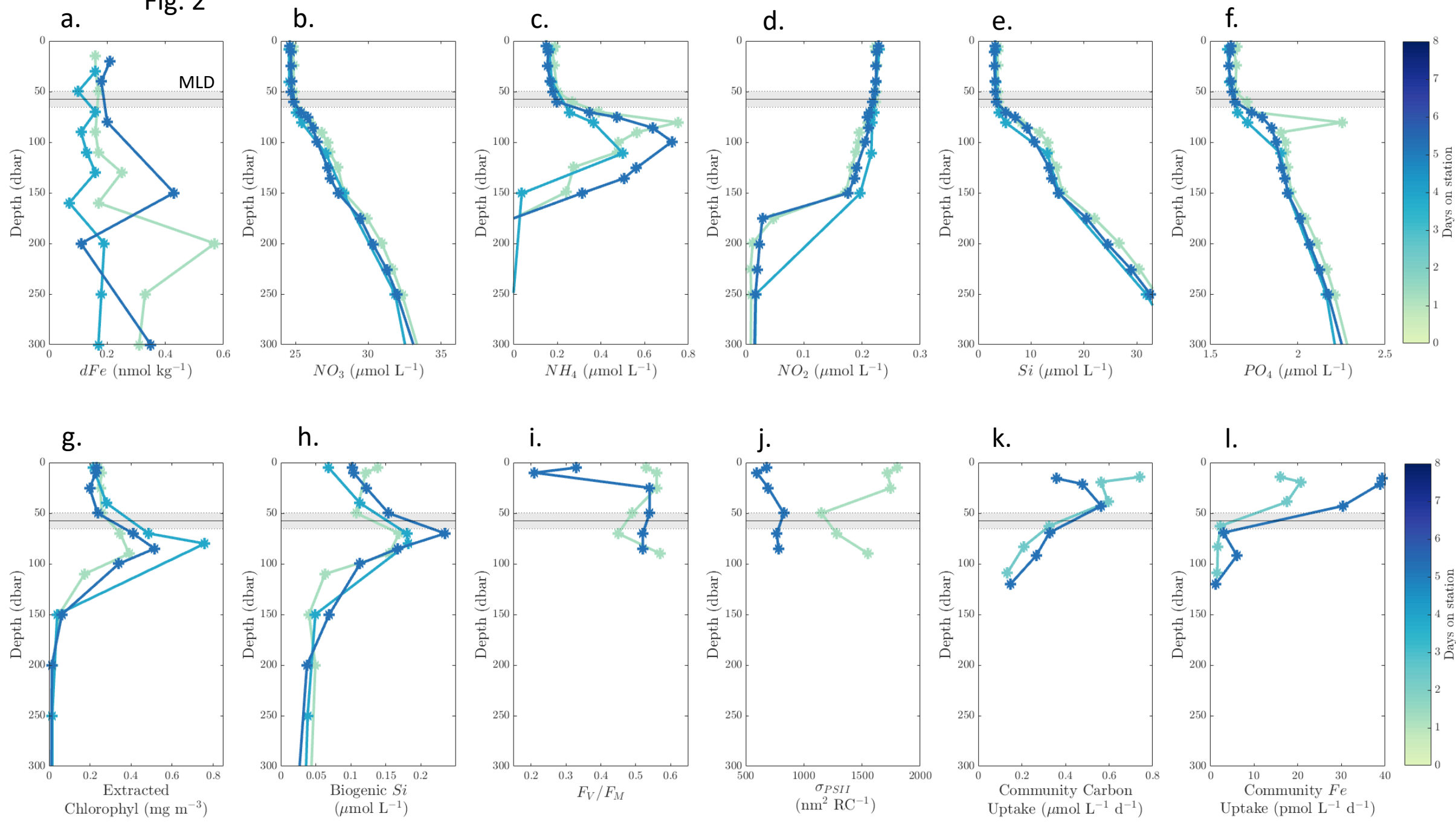


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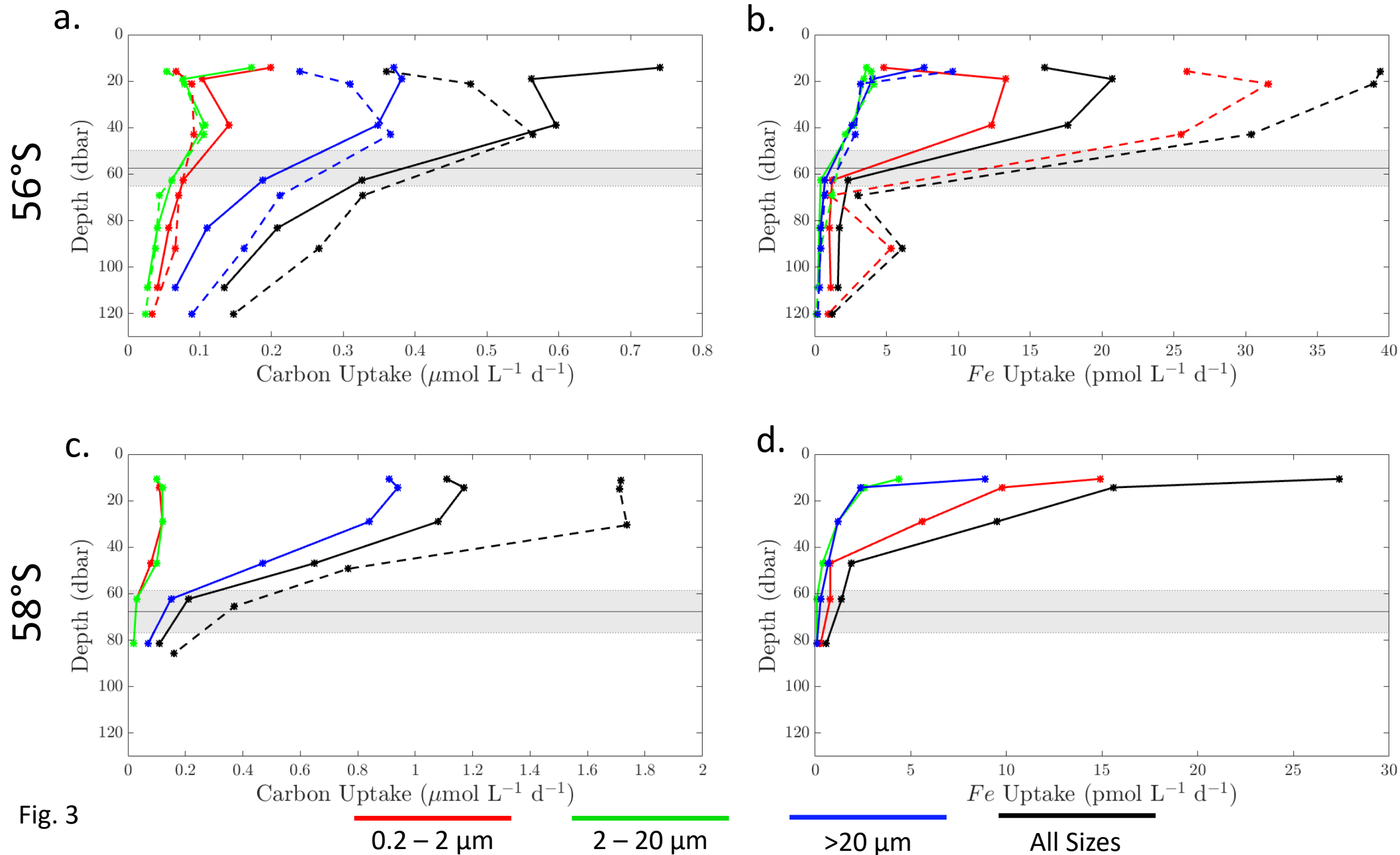


Fig. 3

Fig. 4

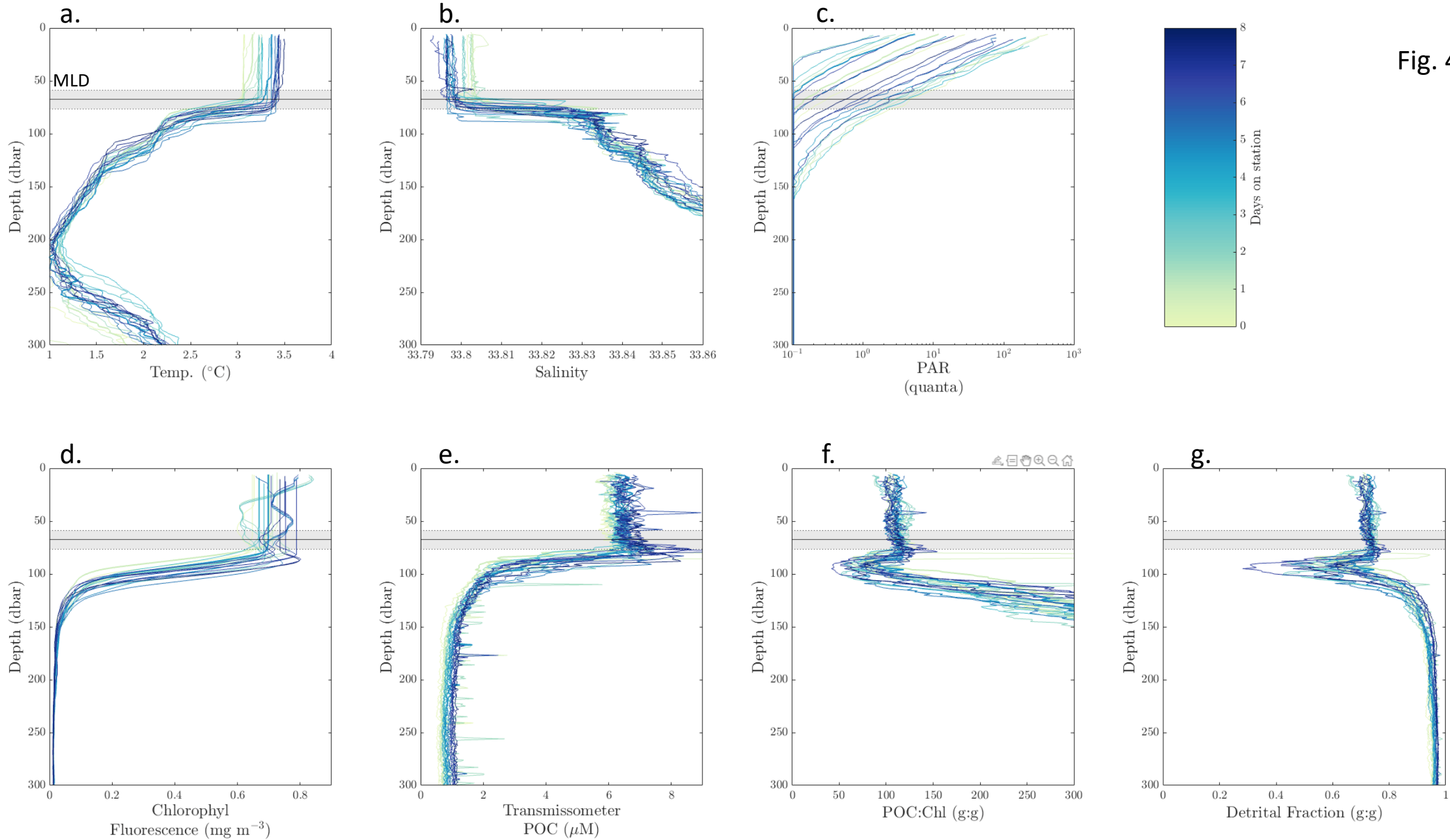


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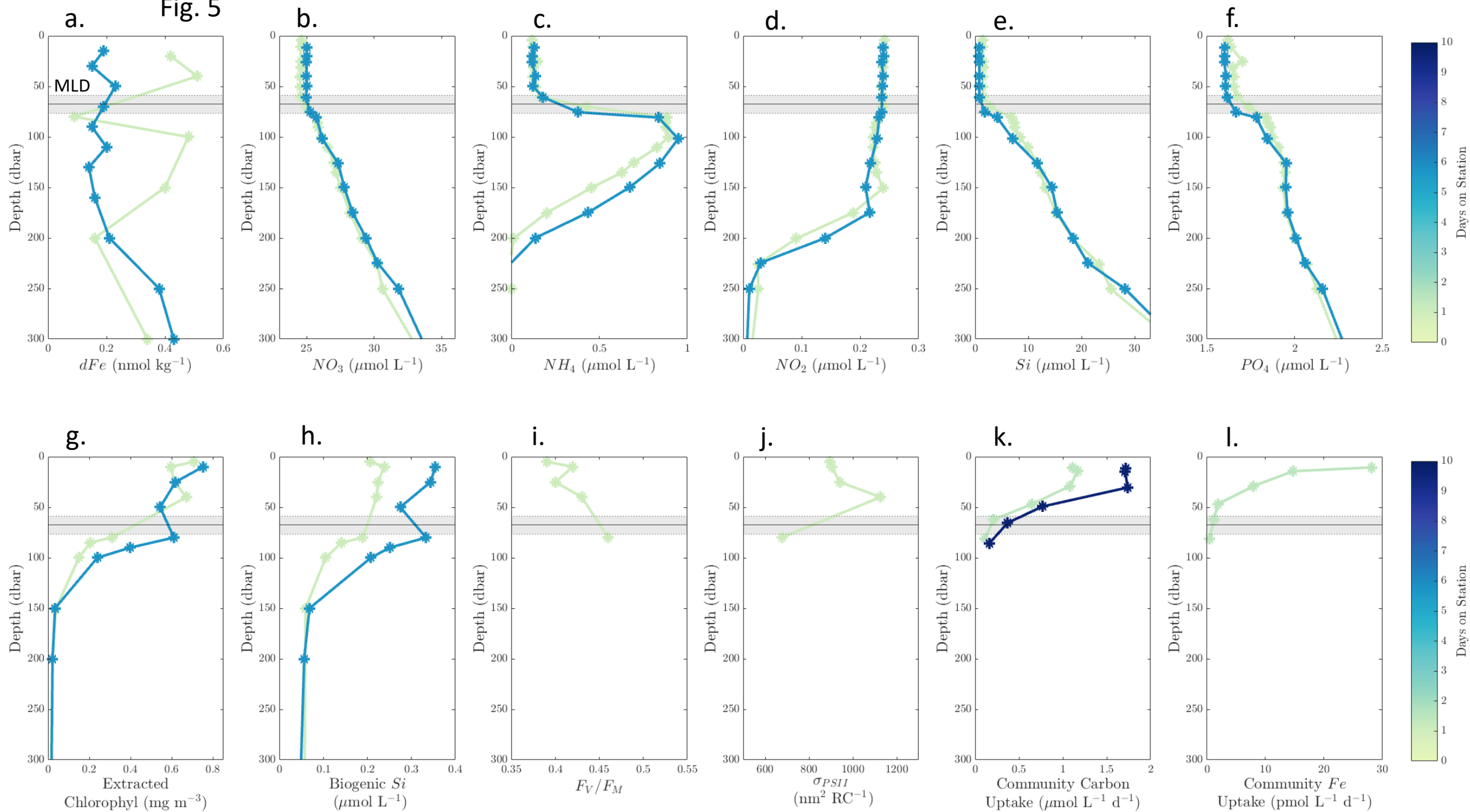
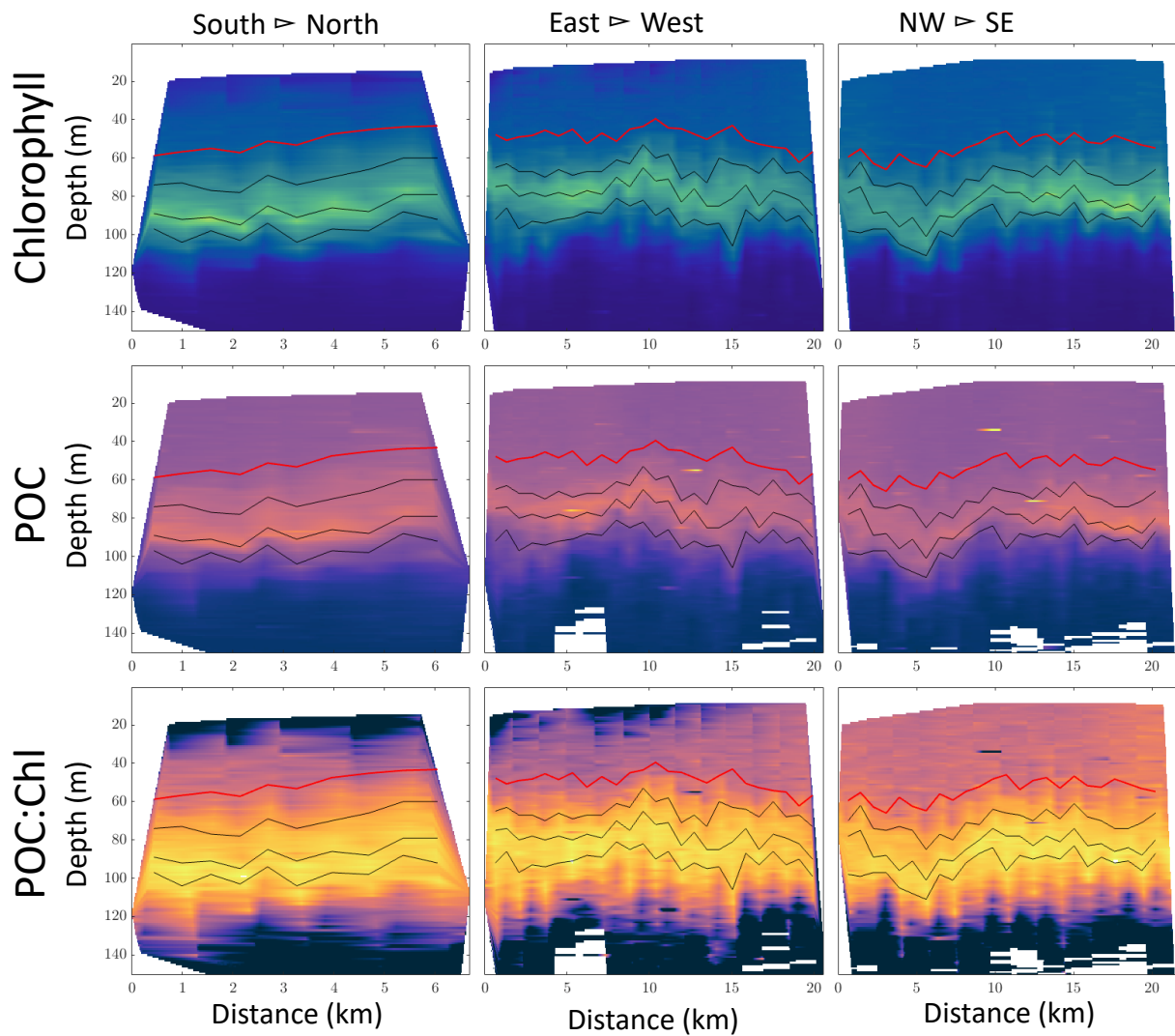


Fig. 6

56°S: Tow 1-3: Dec 29



56°S: Tow 4-6: Dec 30

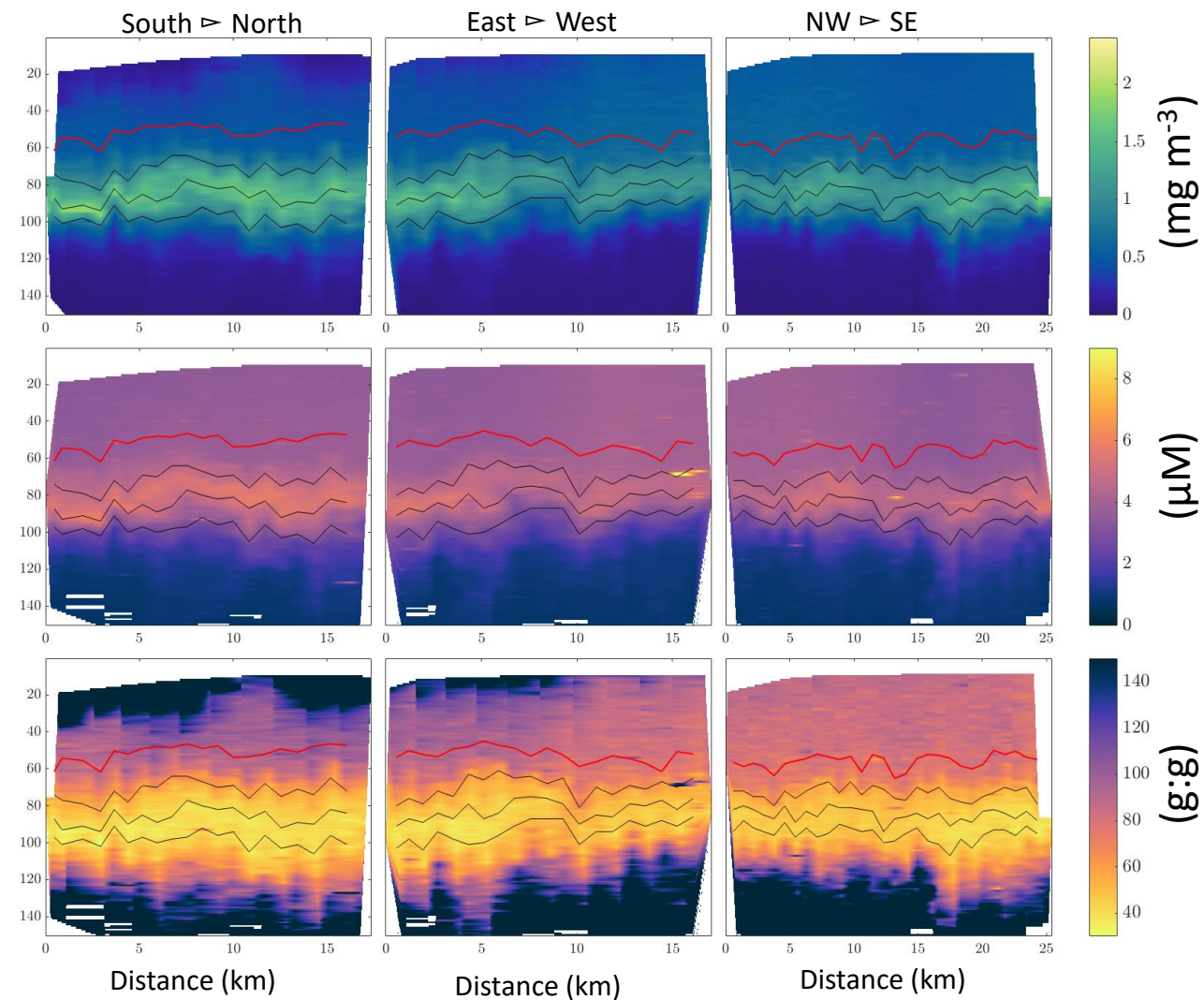


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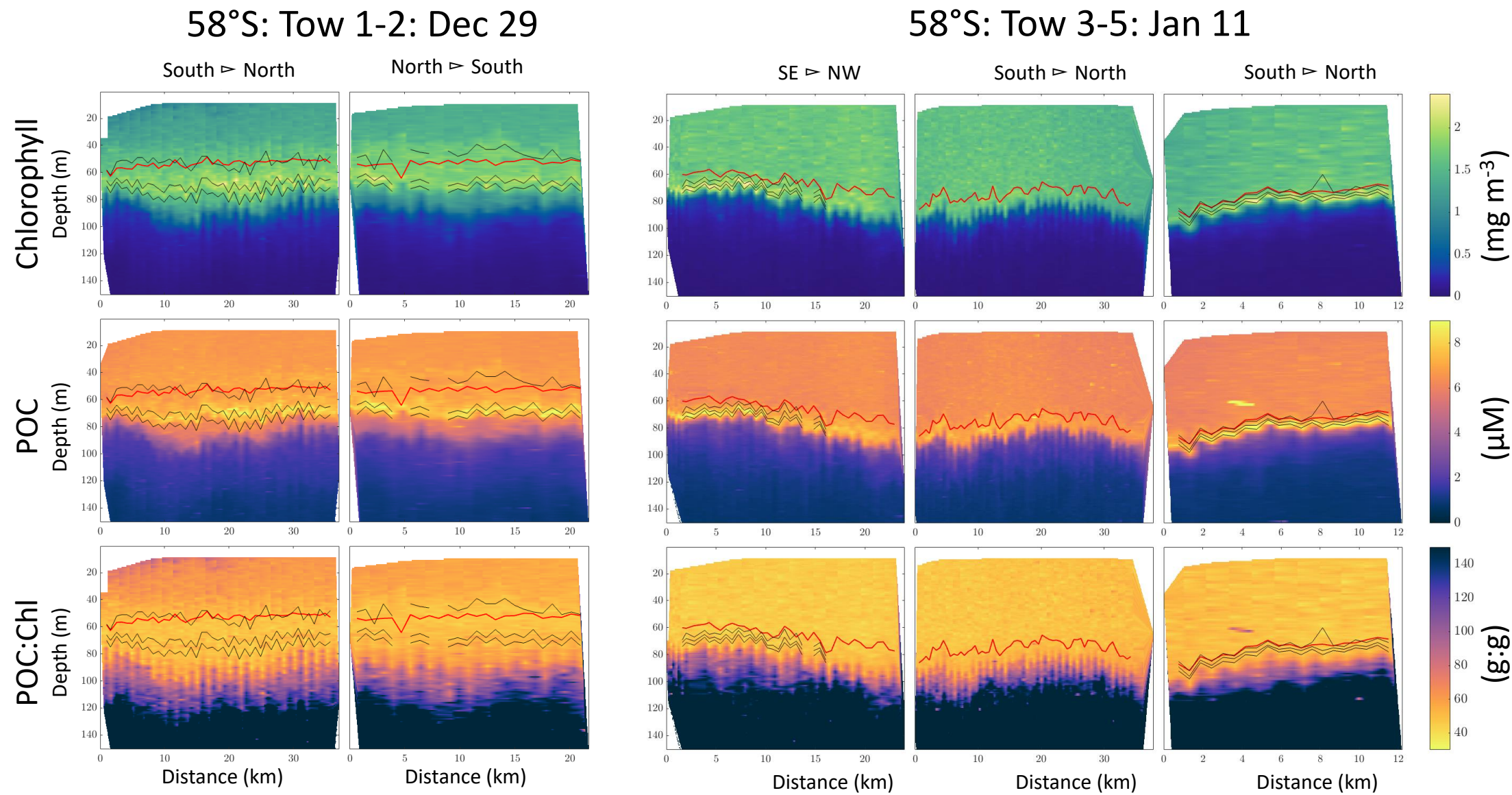


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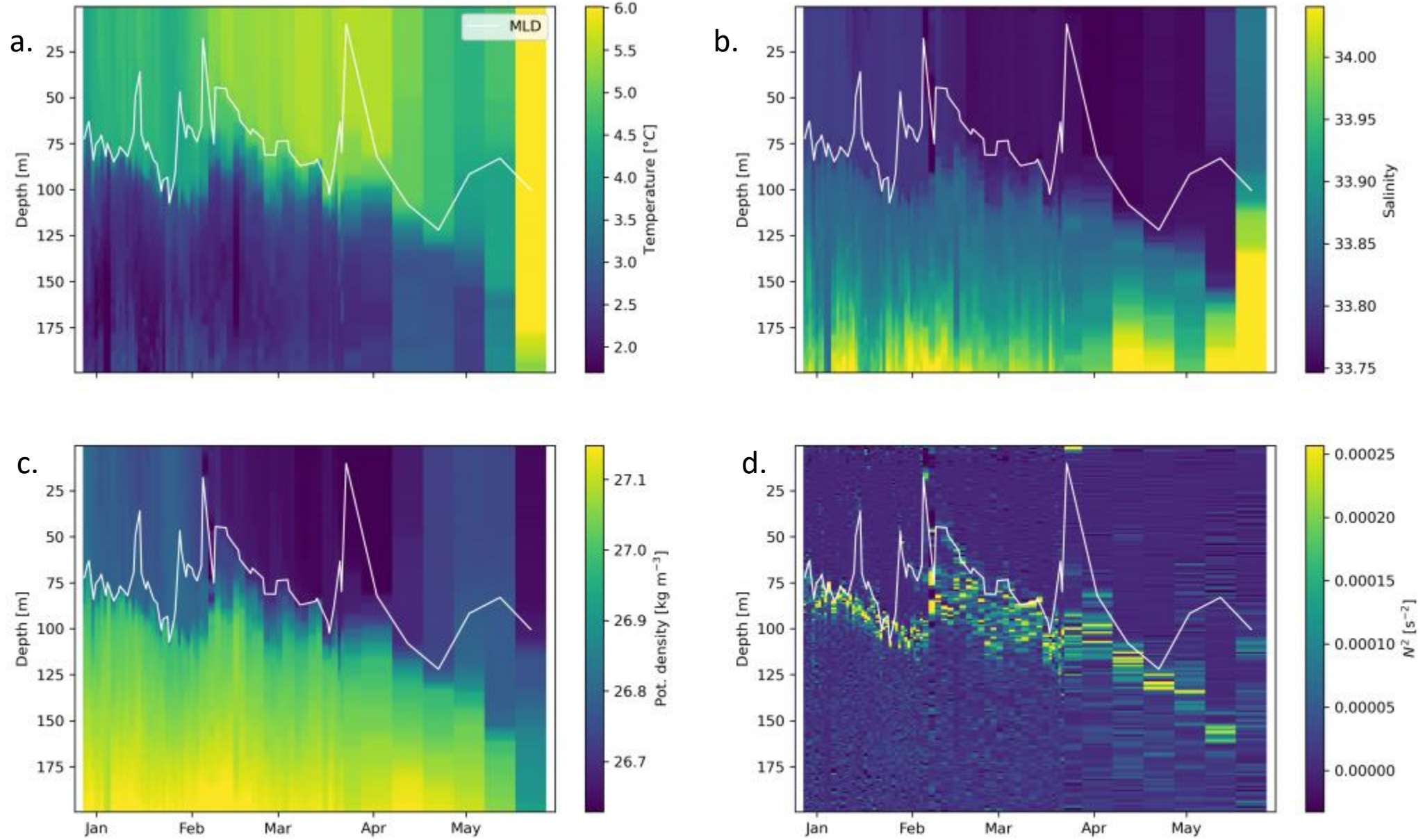


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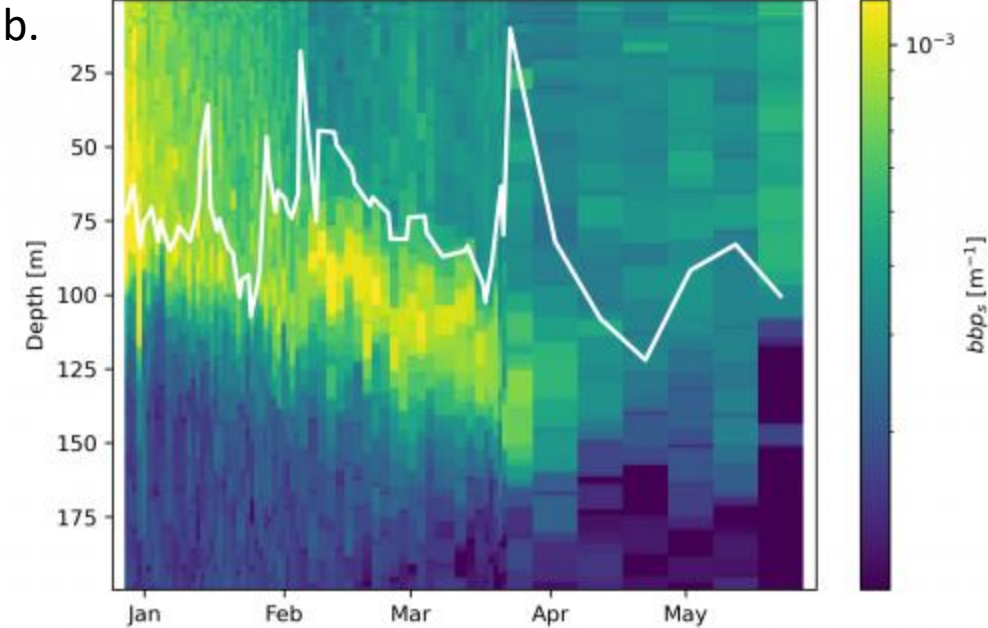
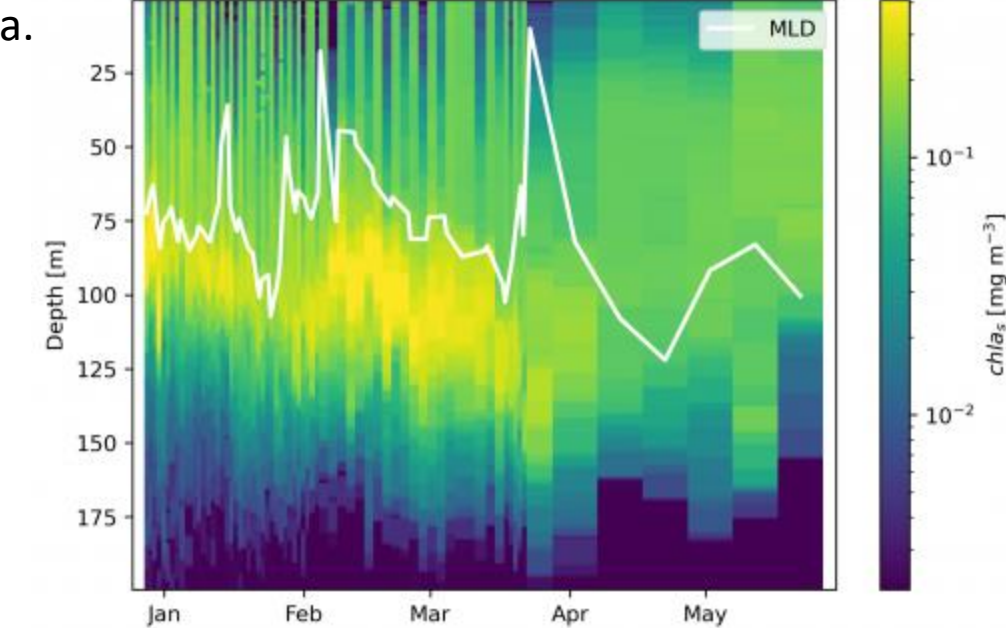


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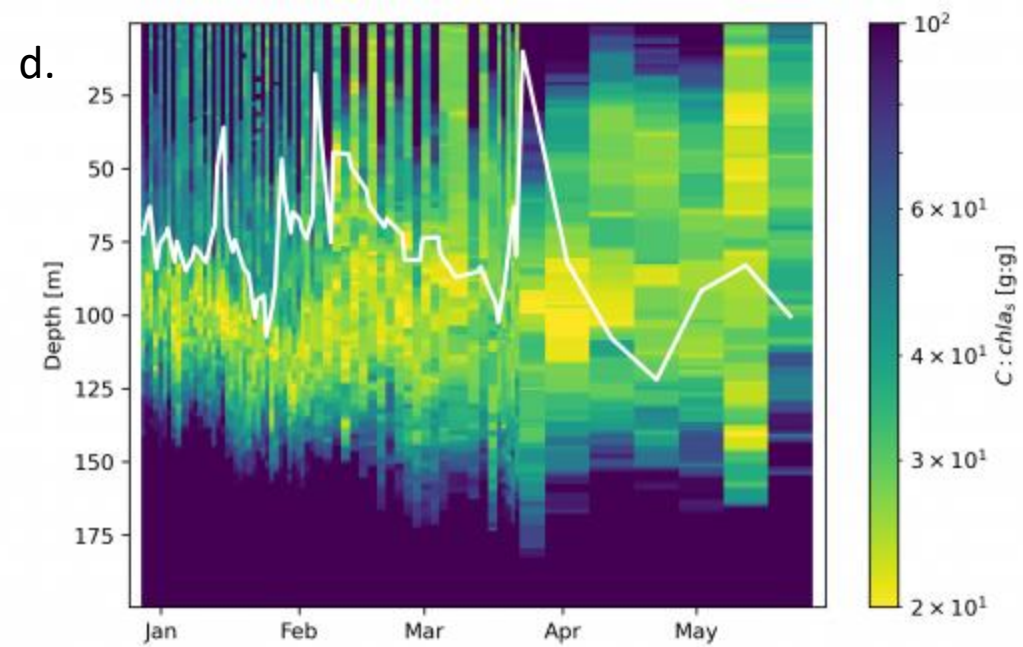
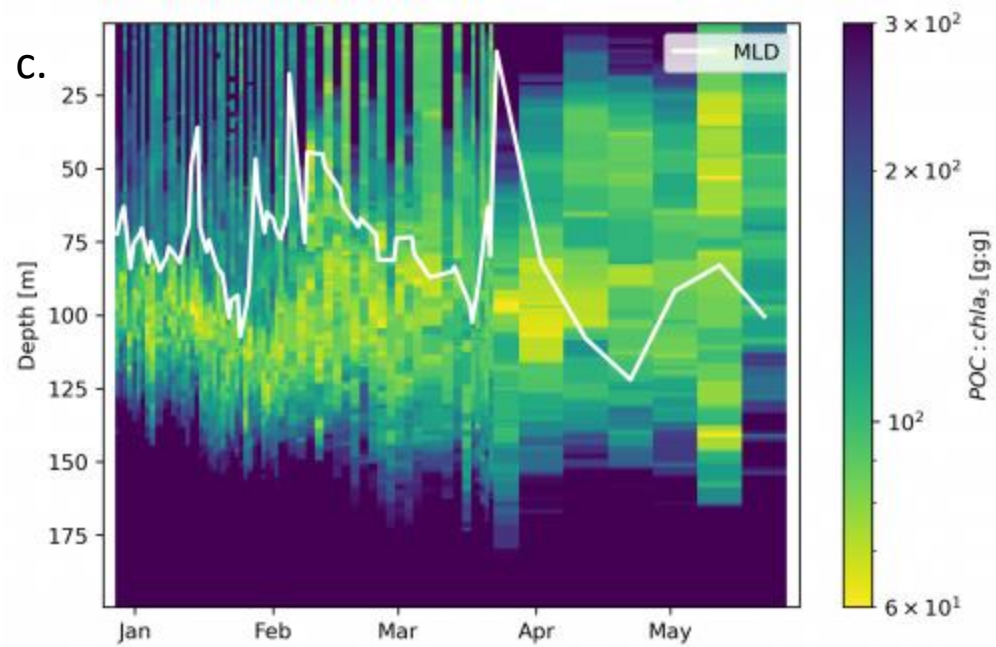
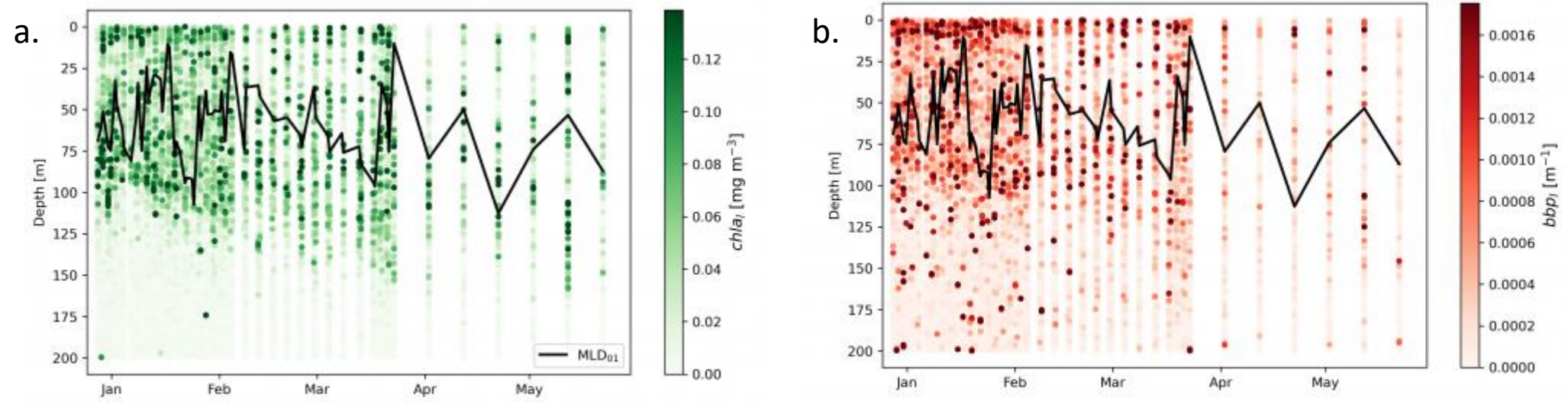


Figure 10



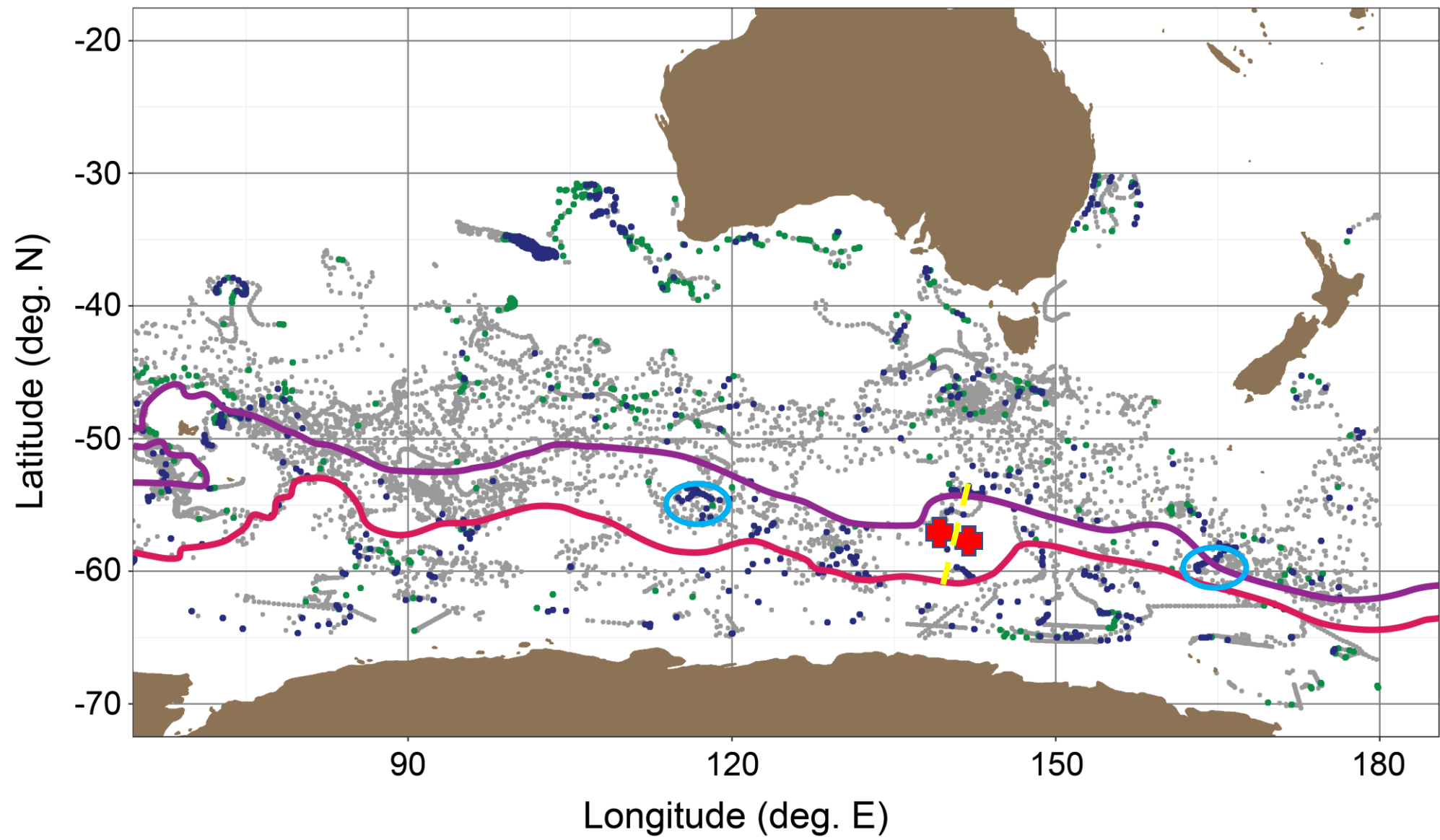


Figure 11

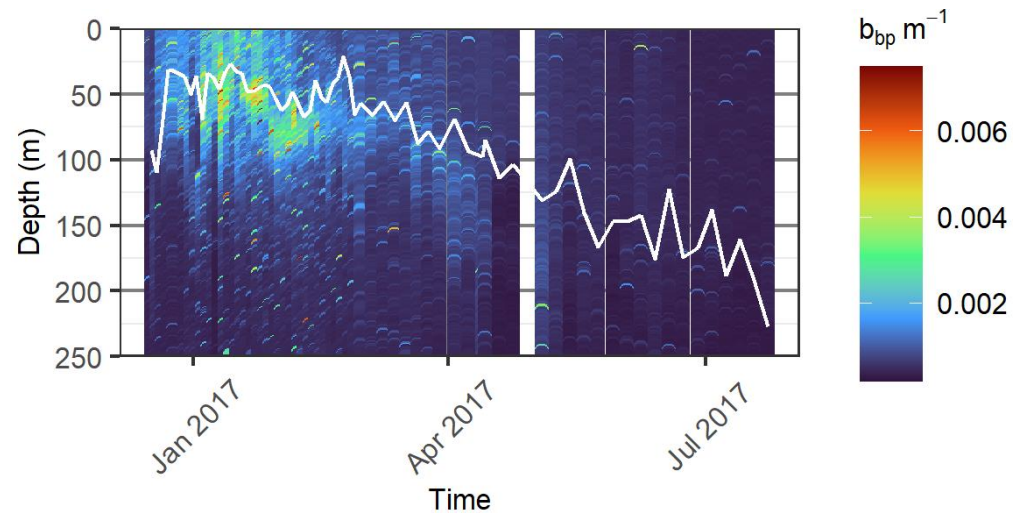
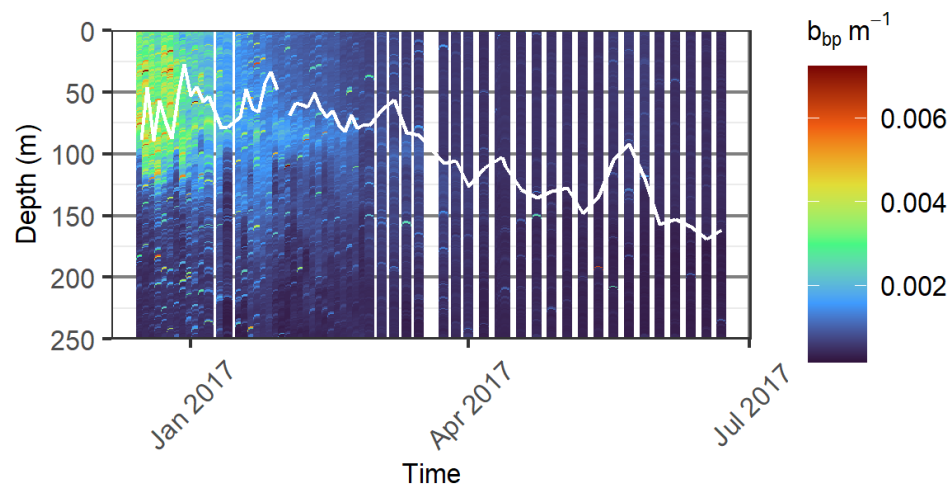
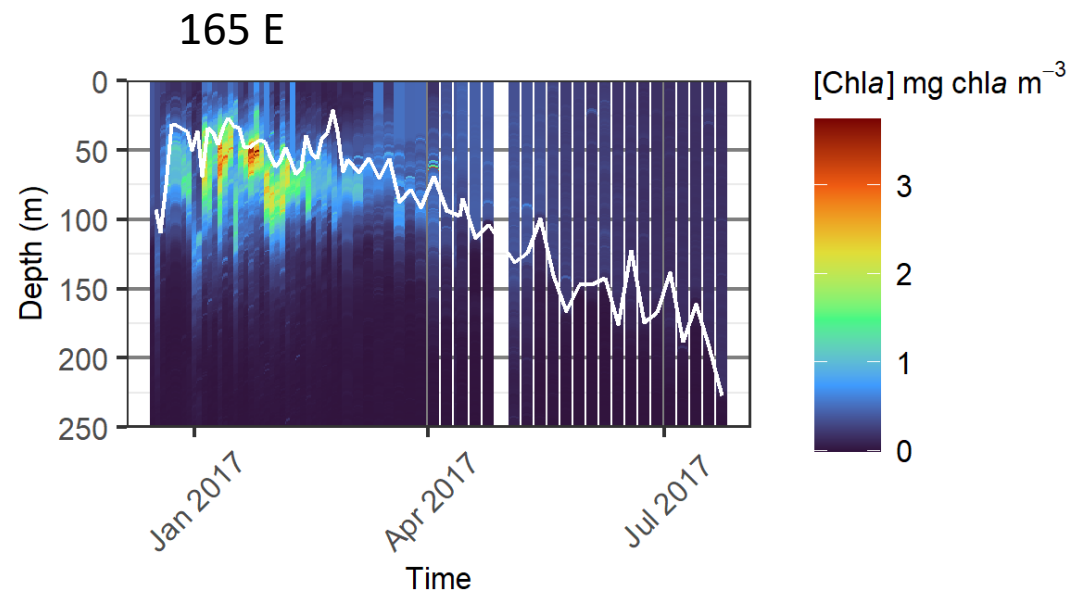
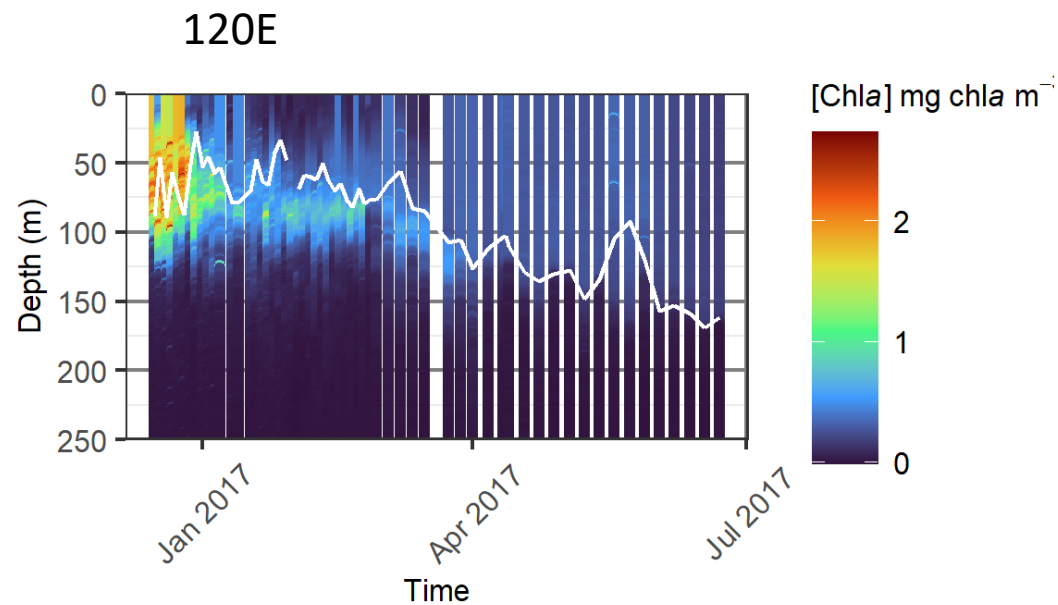


Figure 12

Fig.1

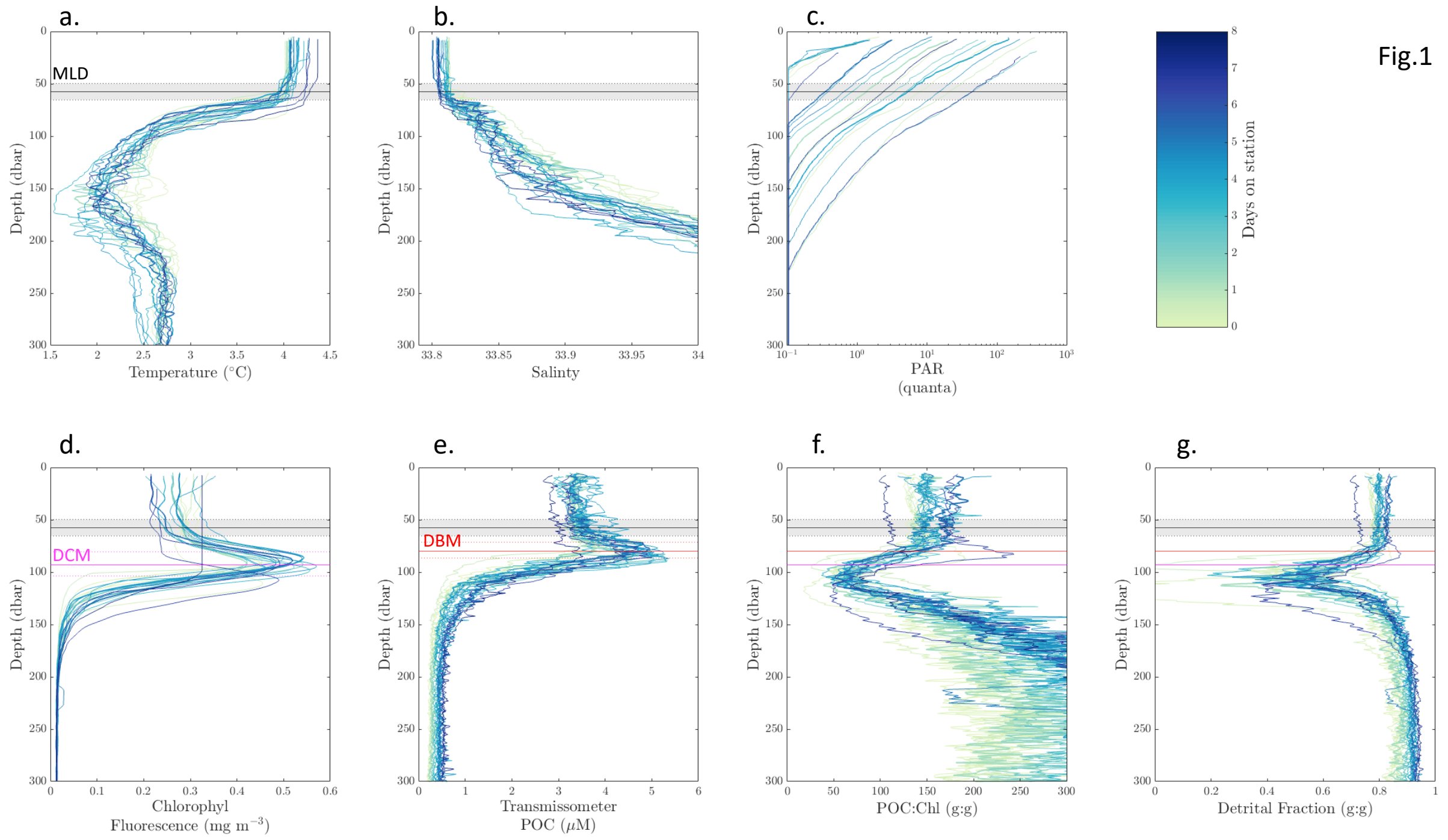
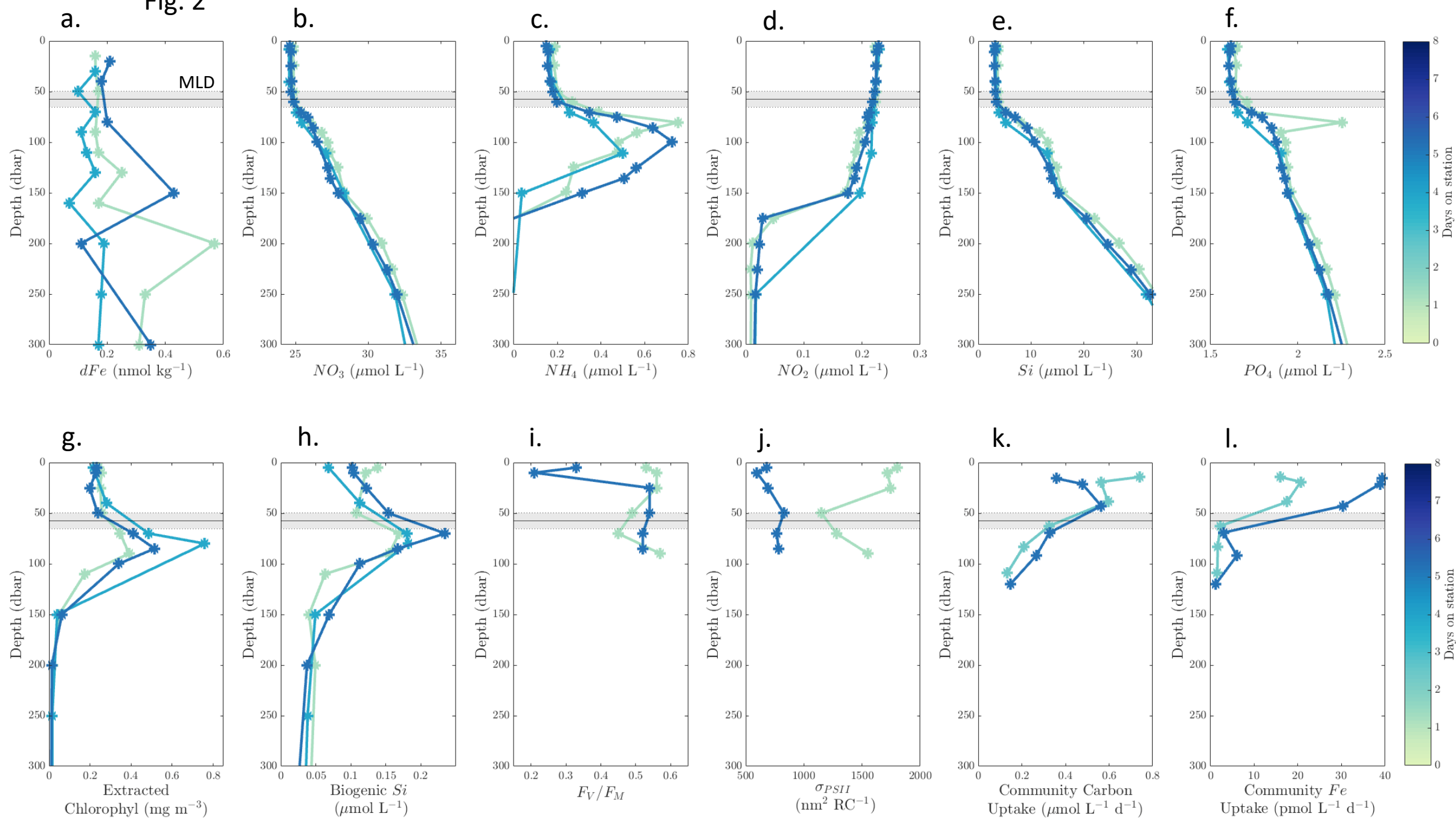


Fig. 2



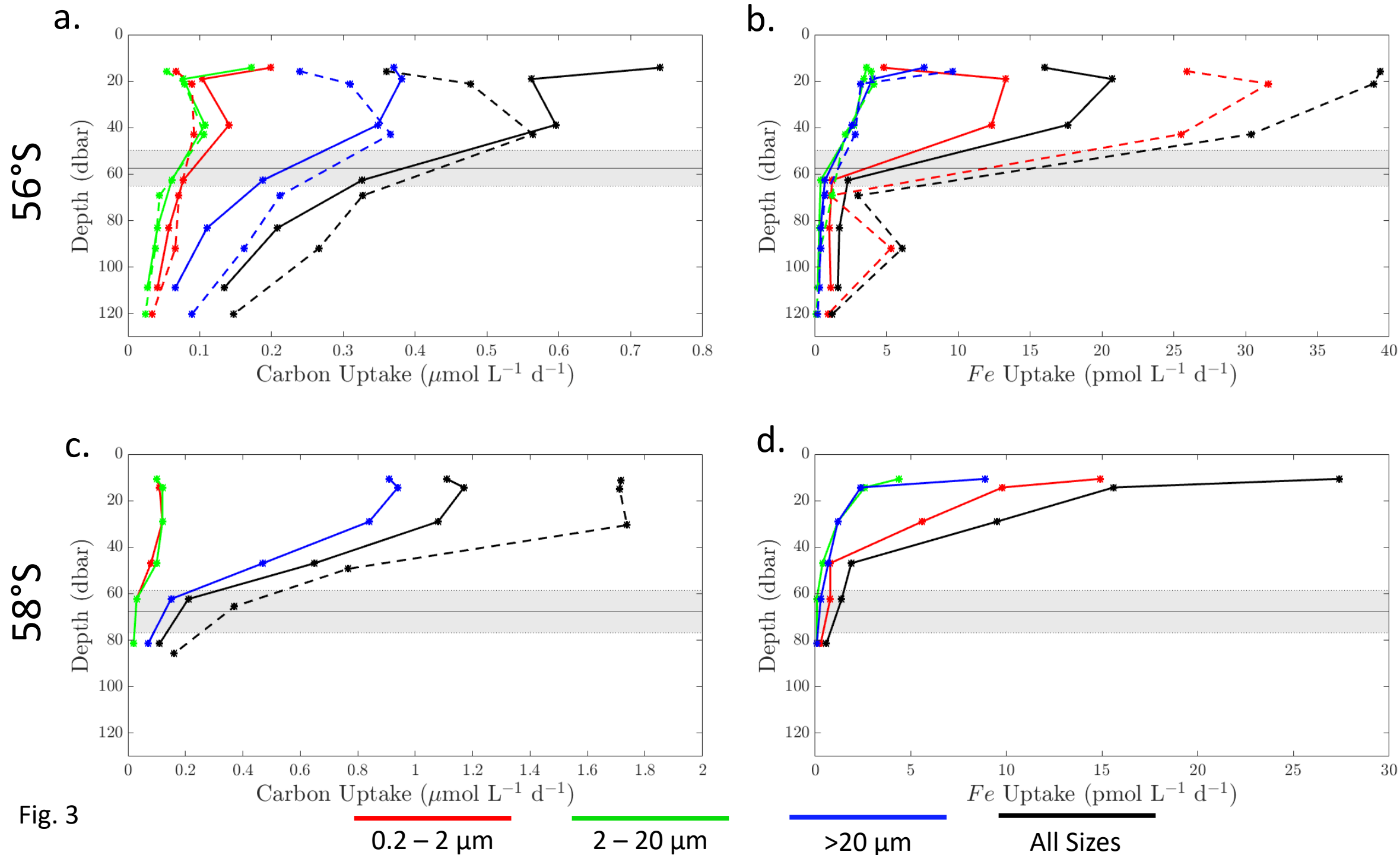


Fig. 3

Fig. 4

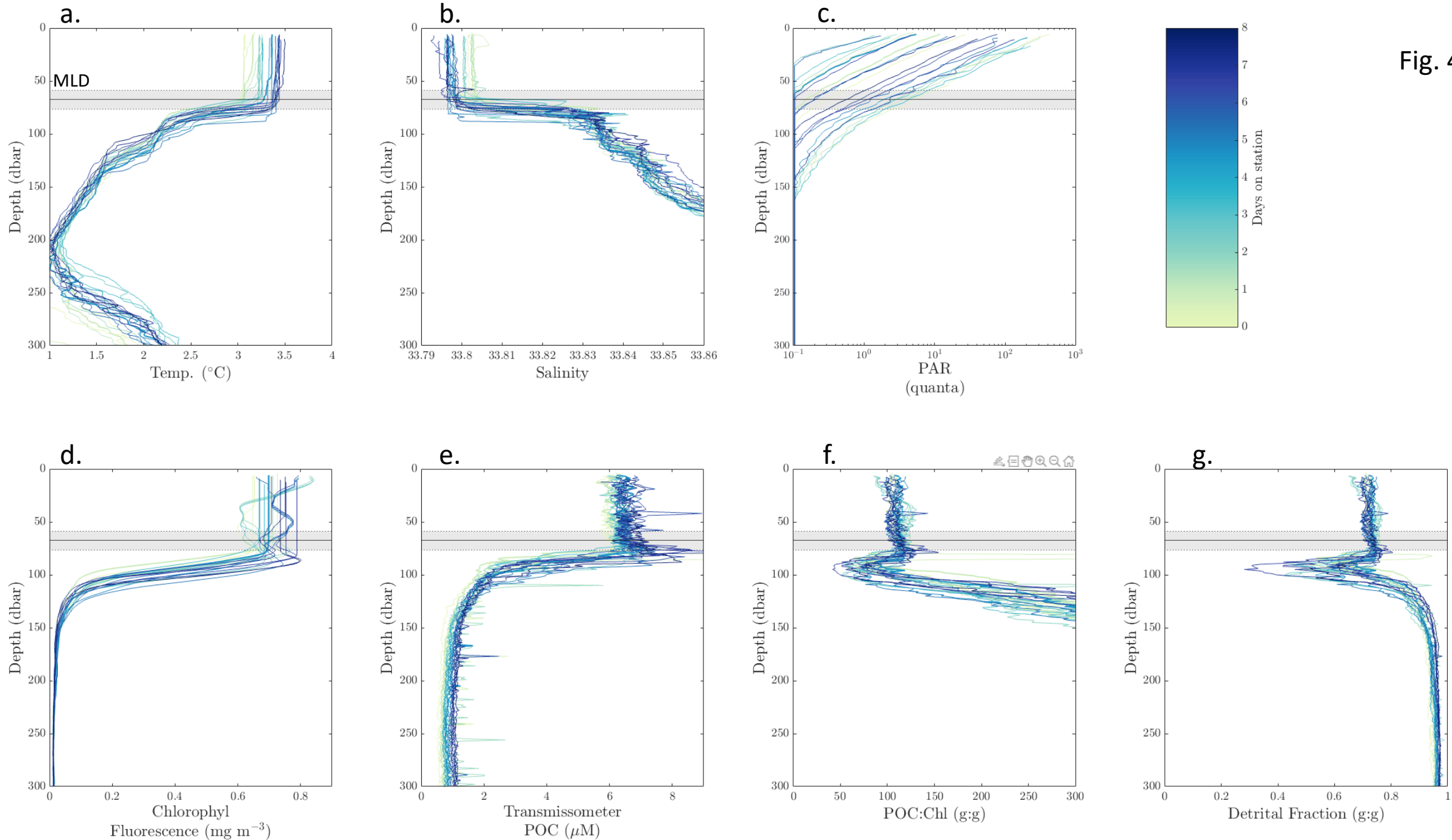


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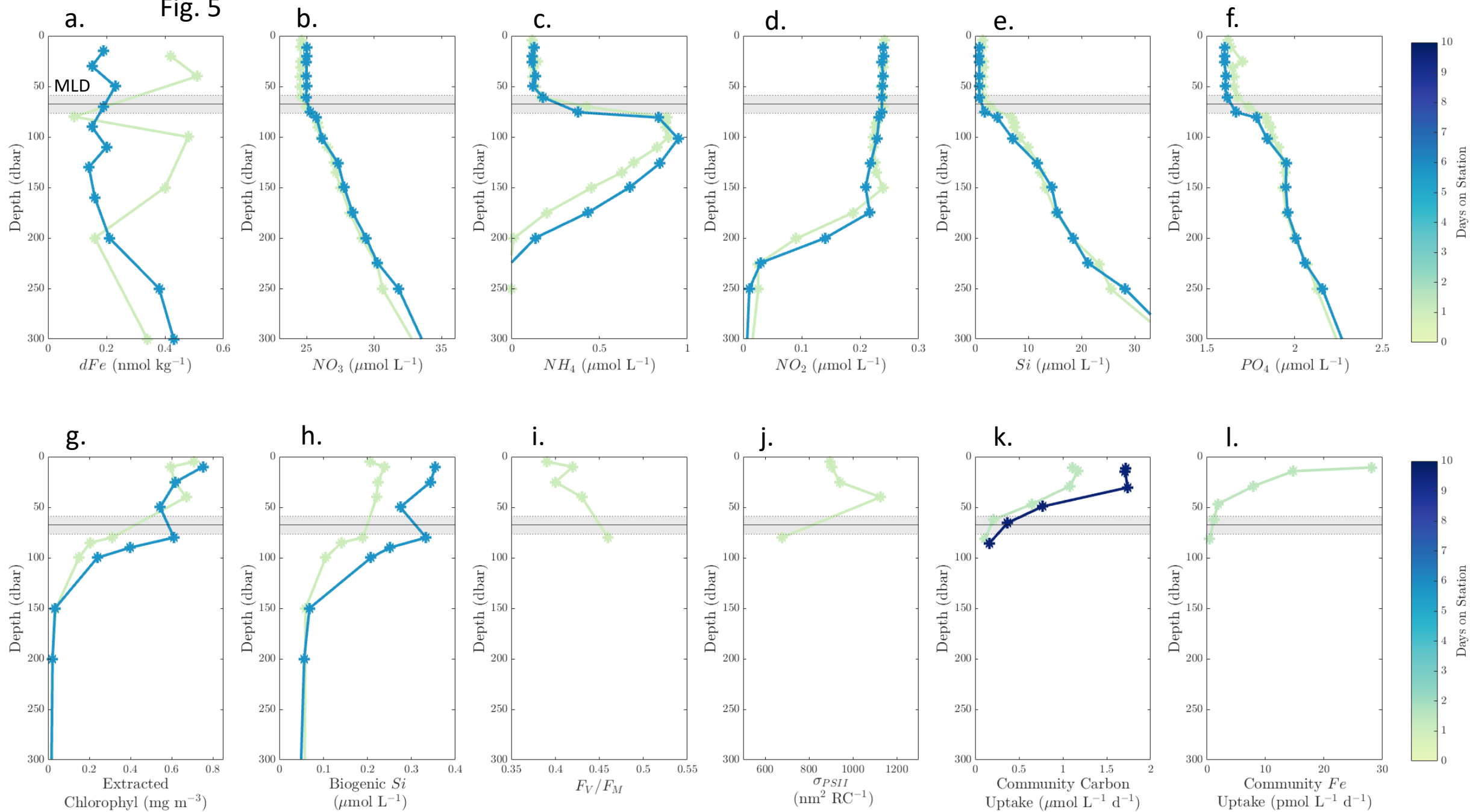
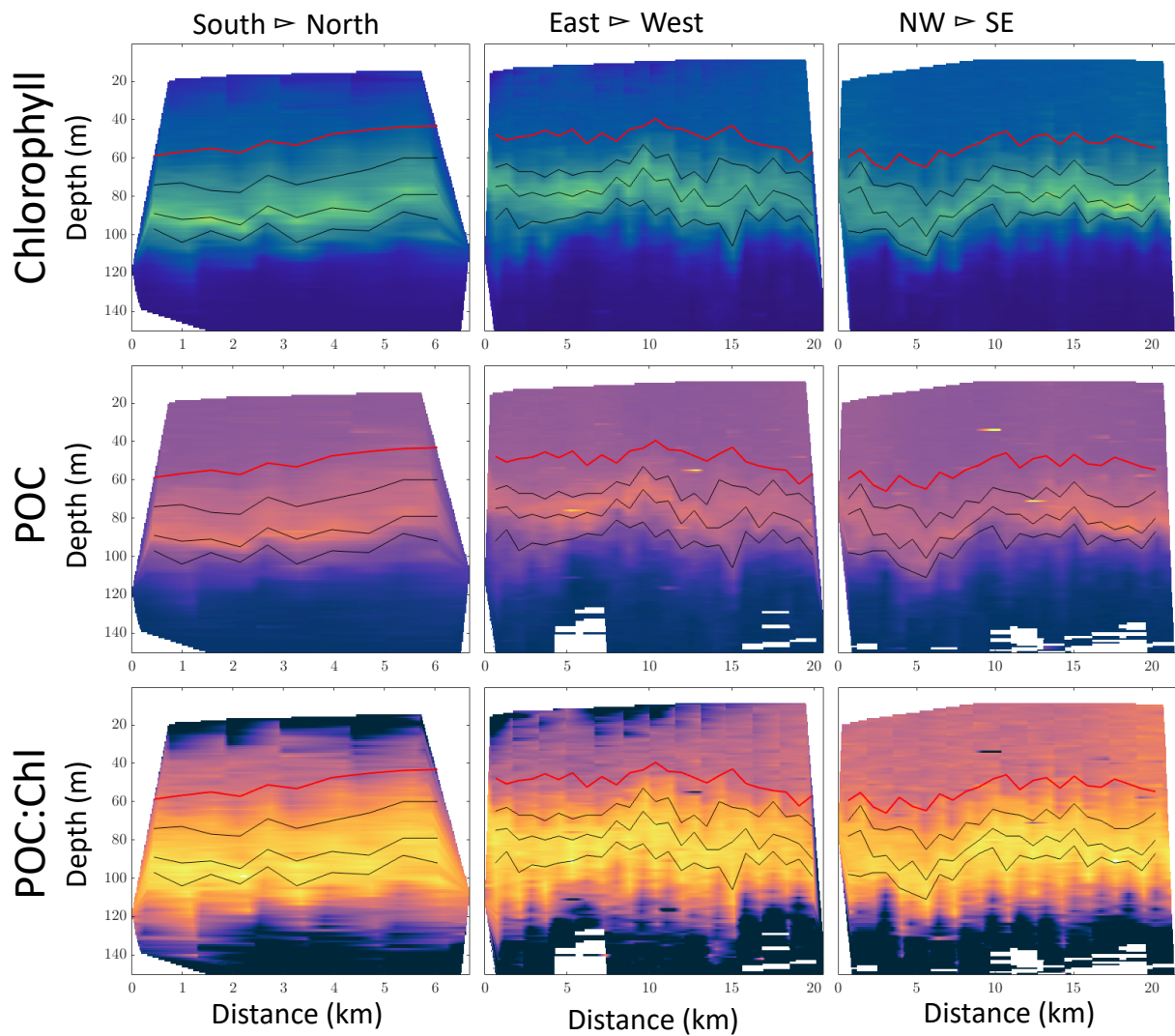


Fig. 6

56°S: Tow 1-3: Dec 29



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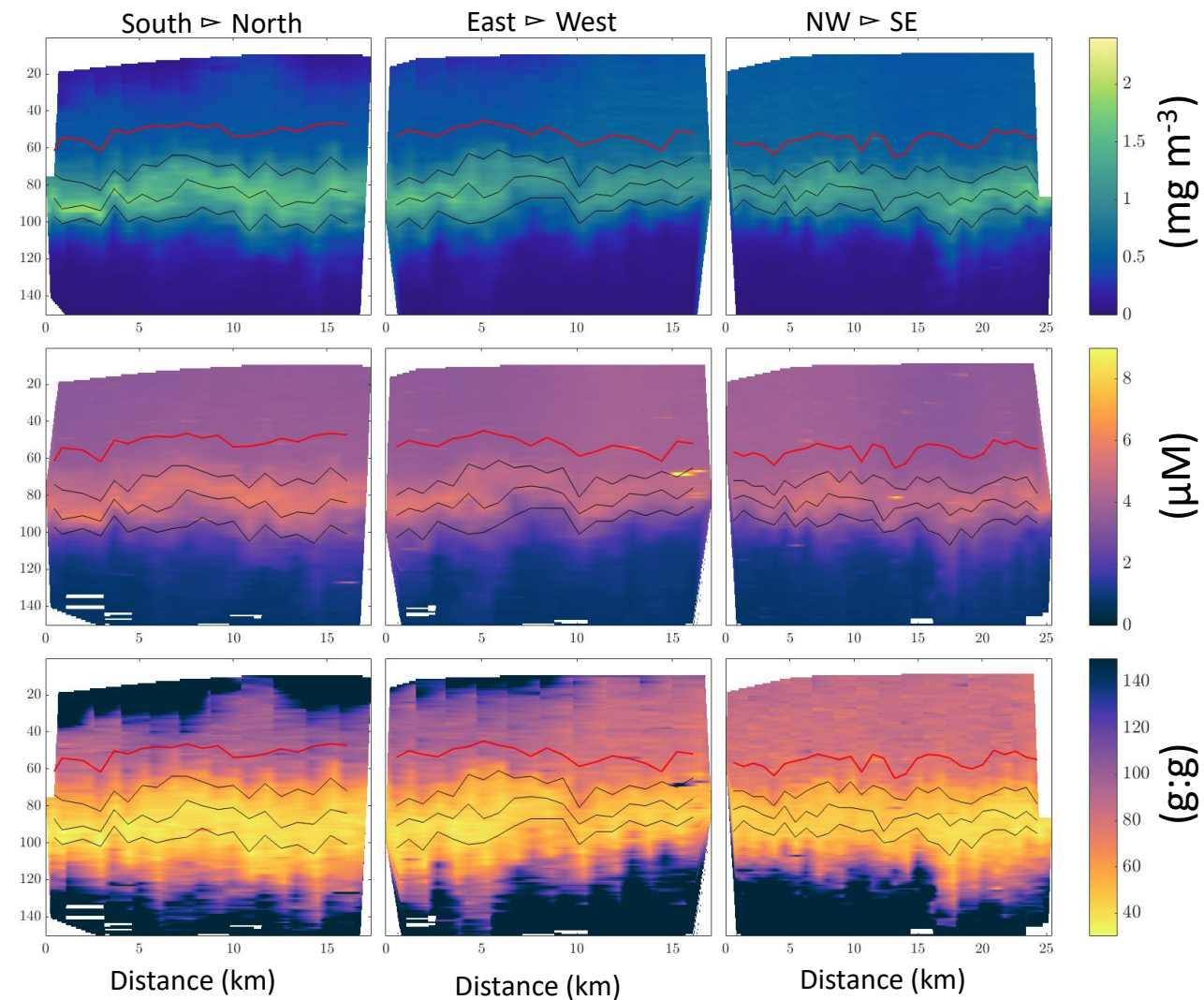


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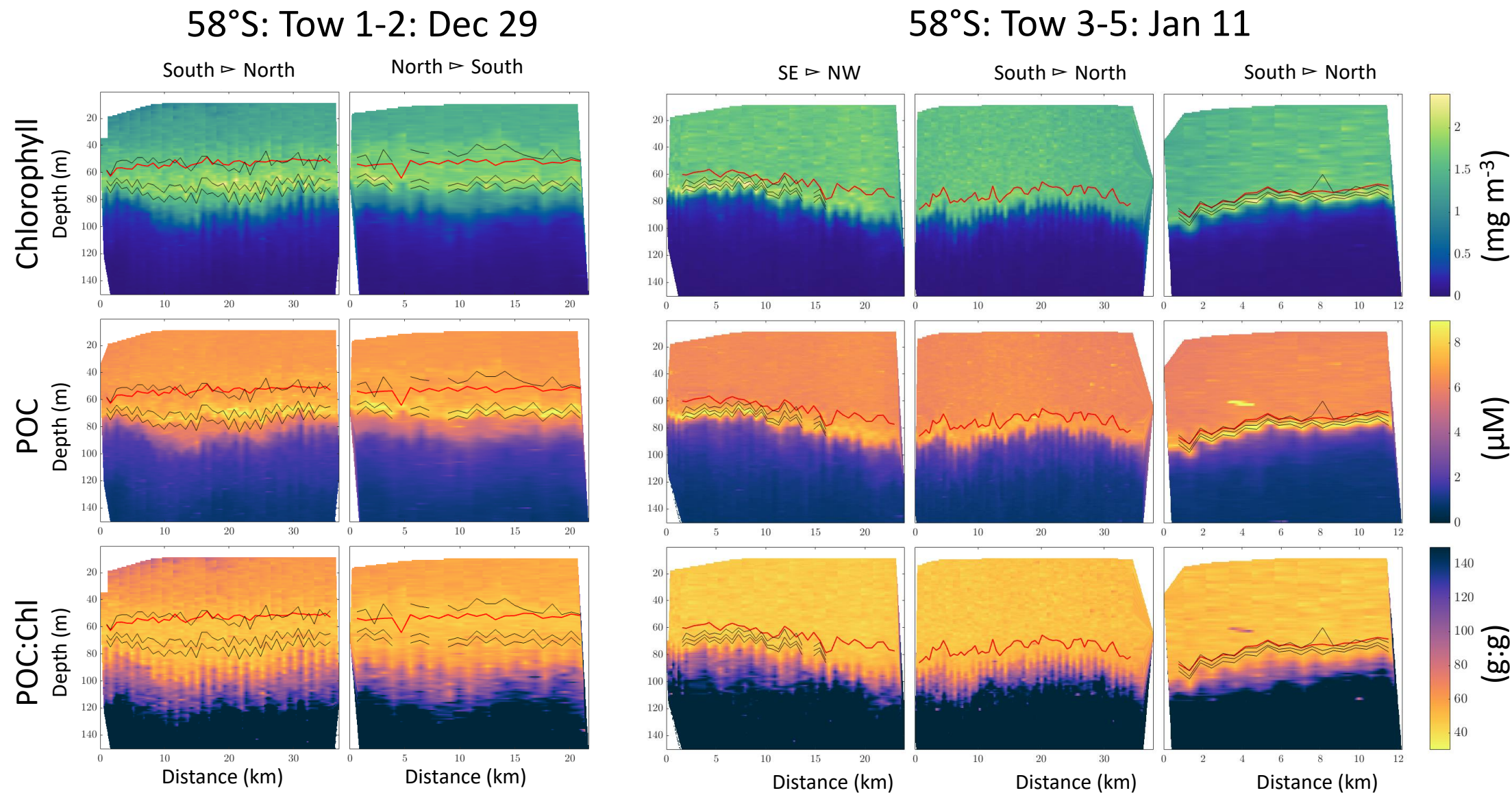


Figure 8

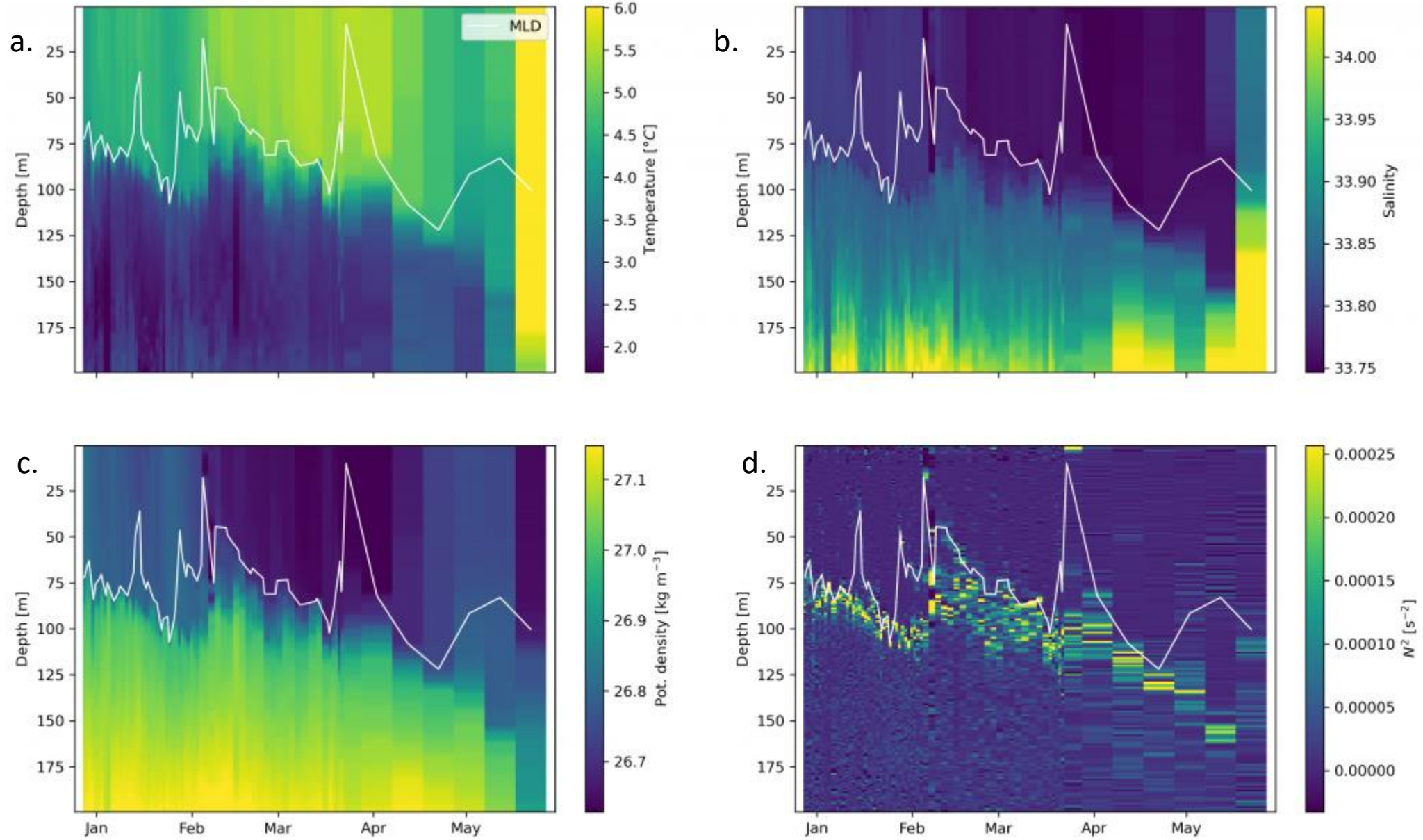


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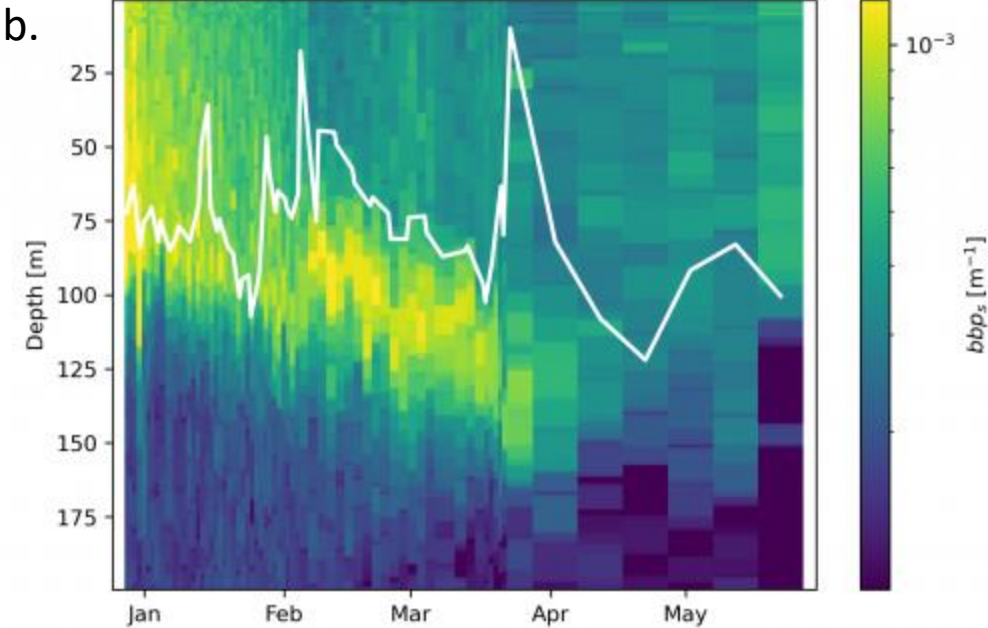
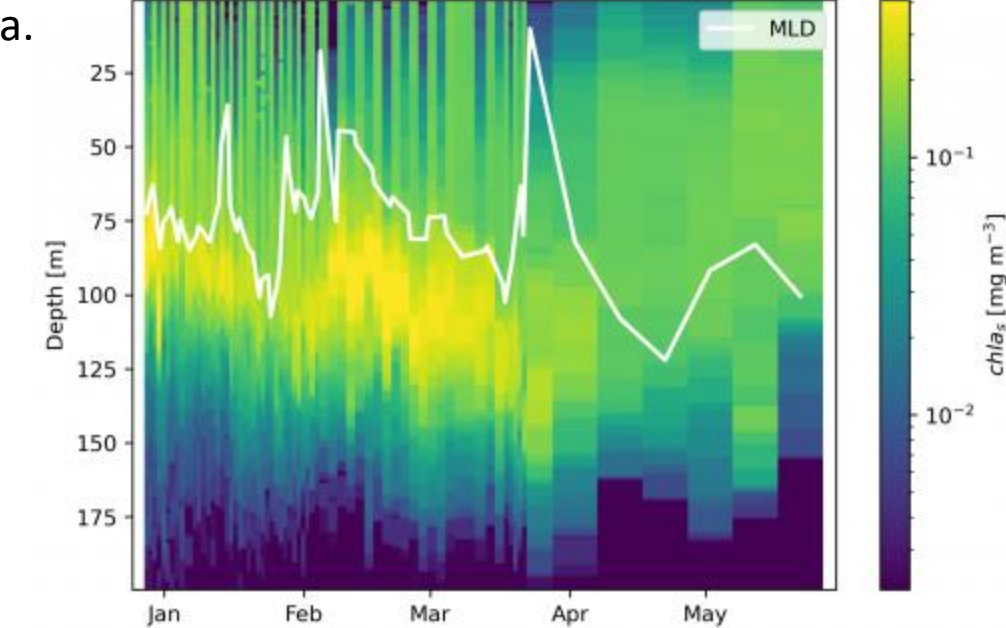


Figure 9 (cont)

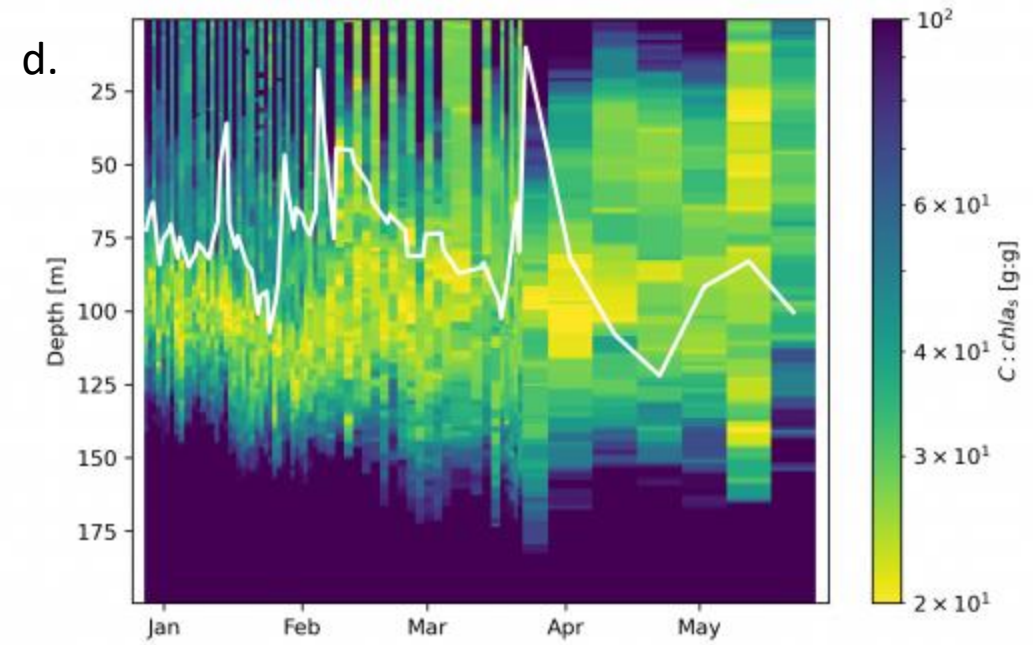
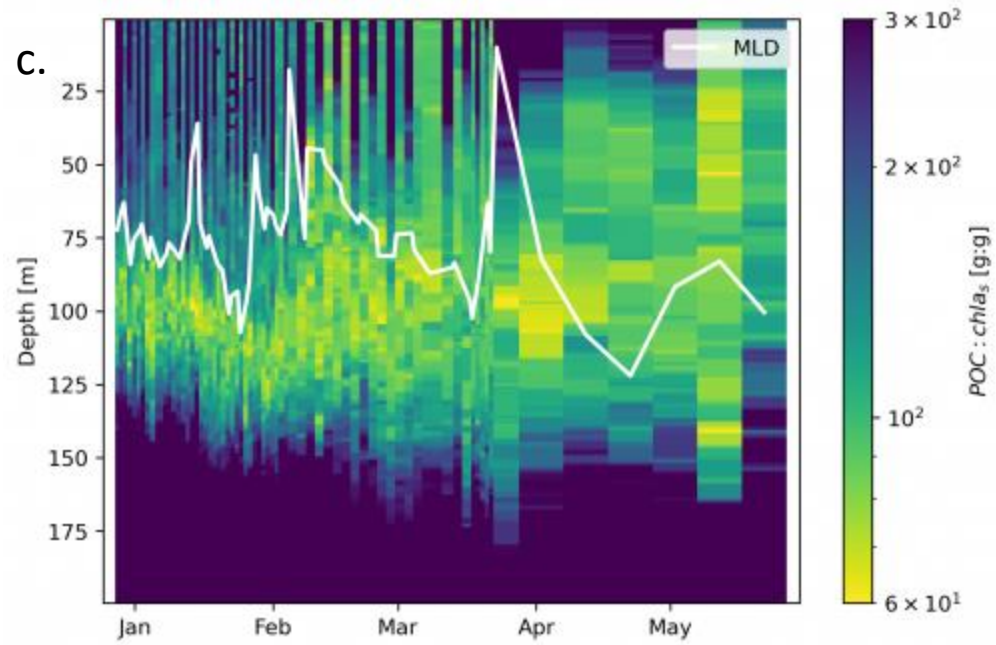
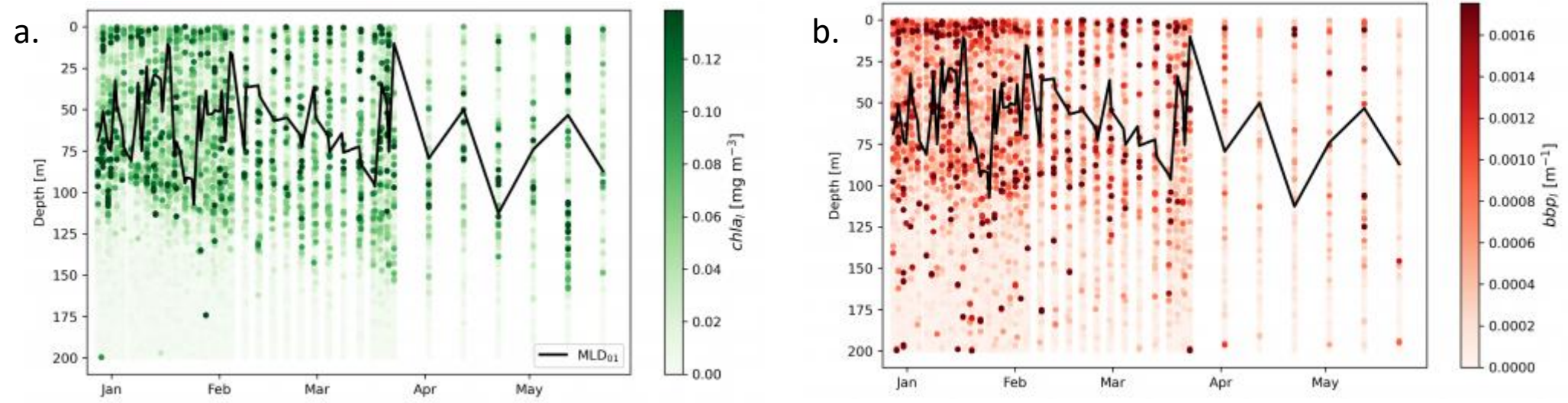


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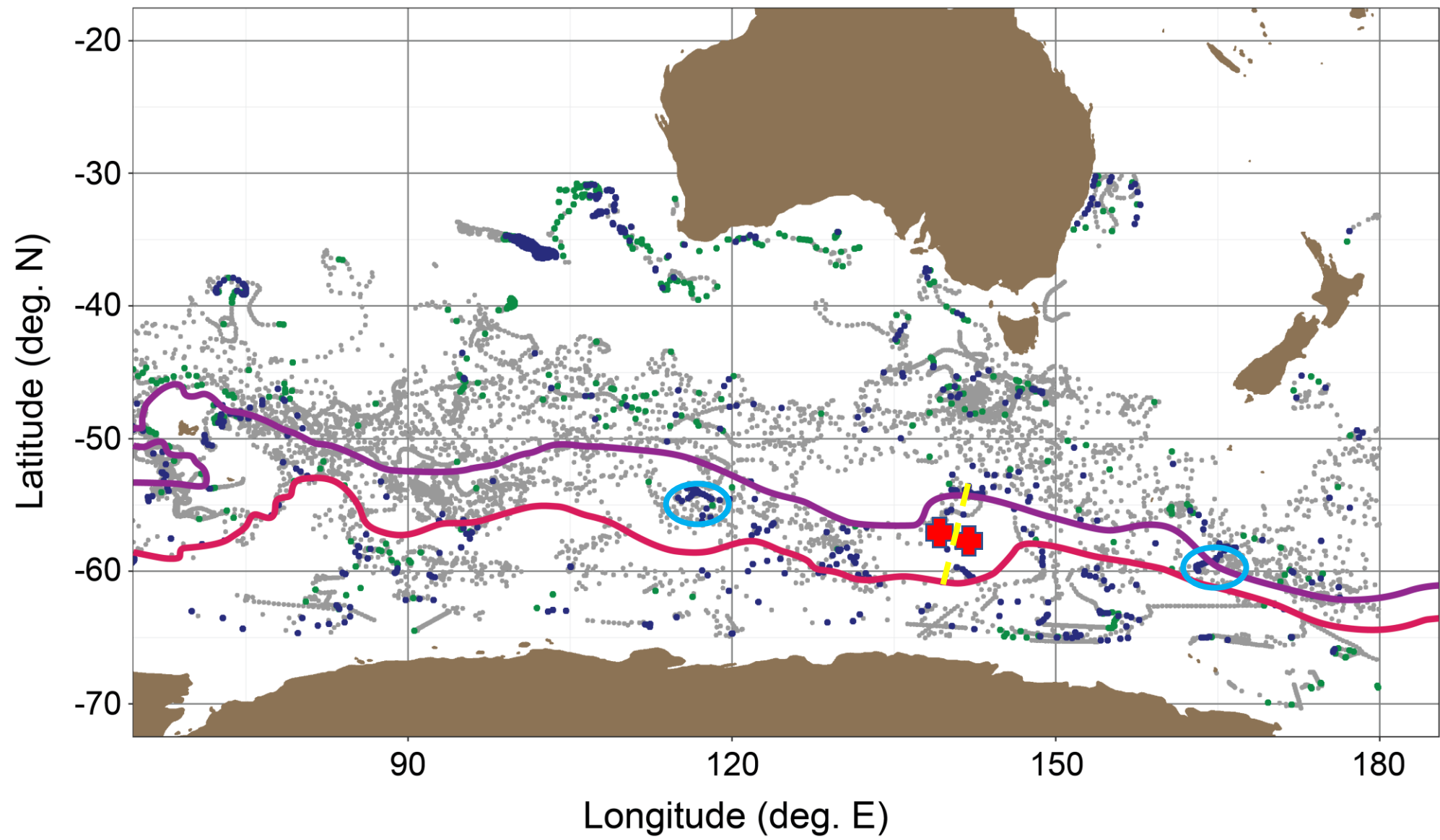


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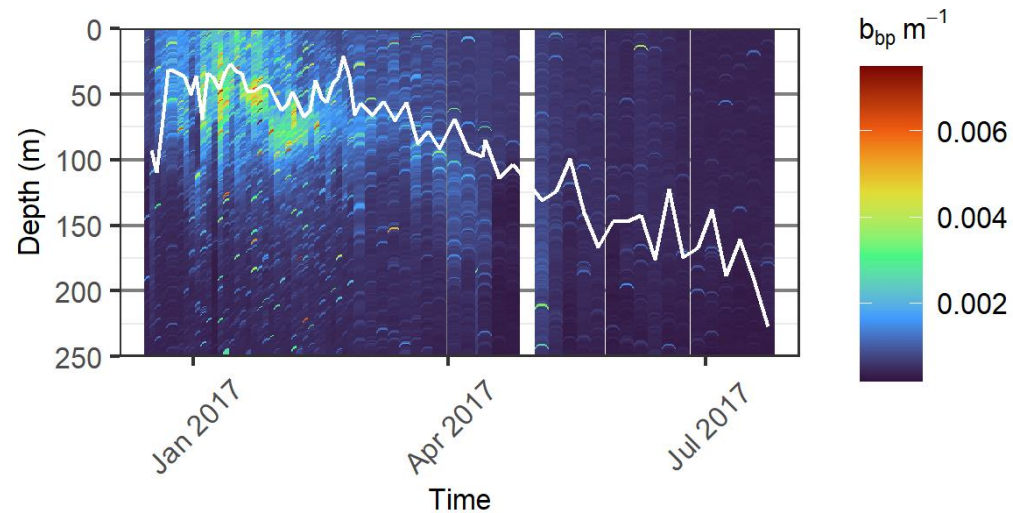
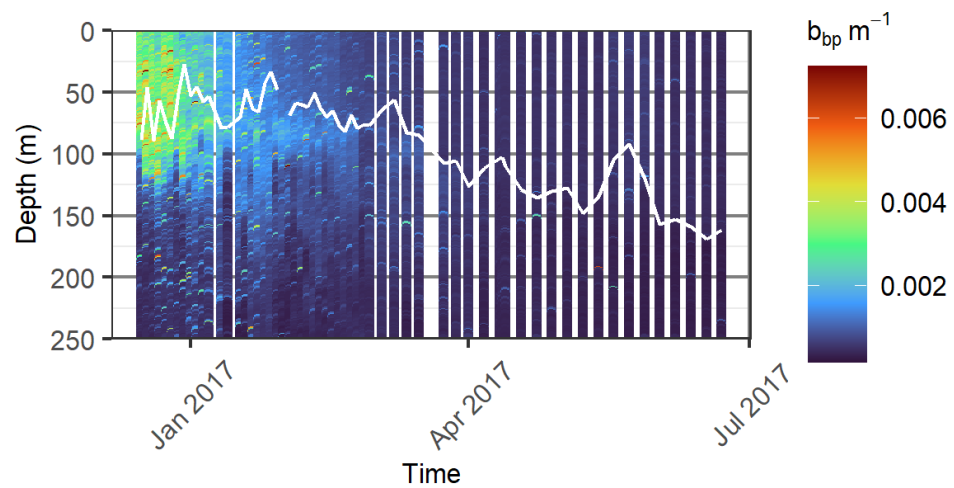
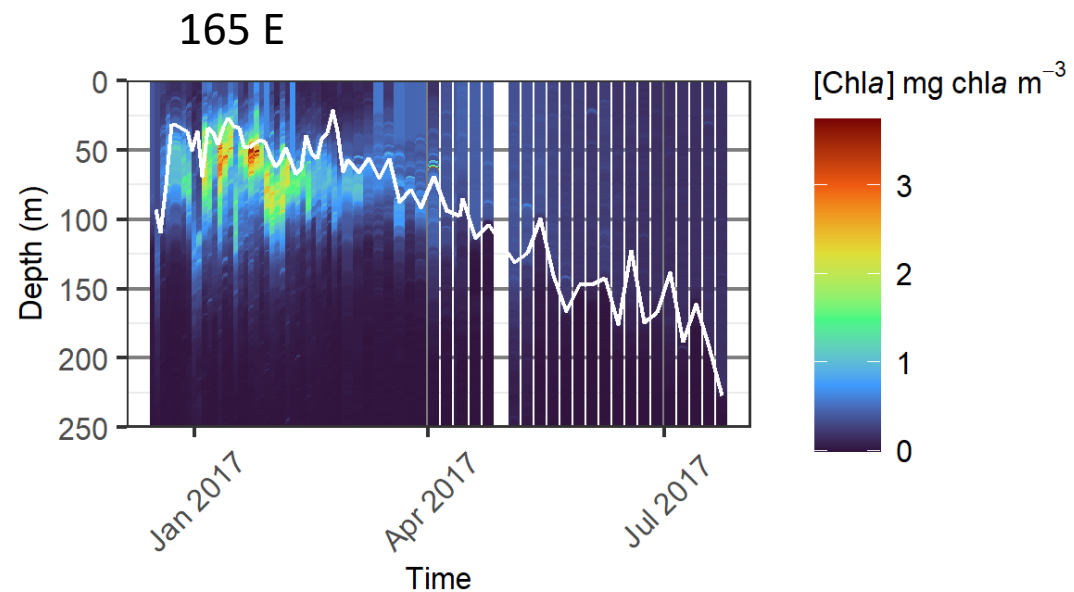
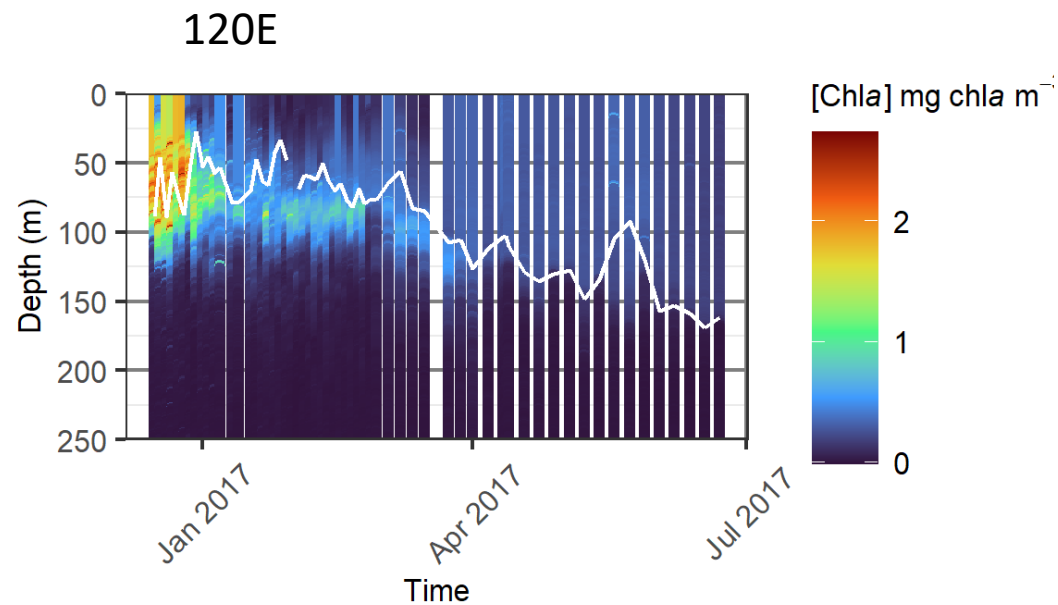
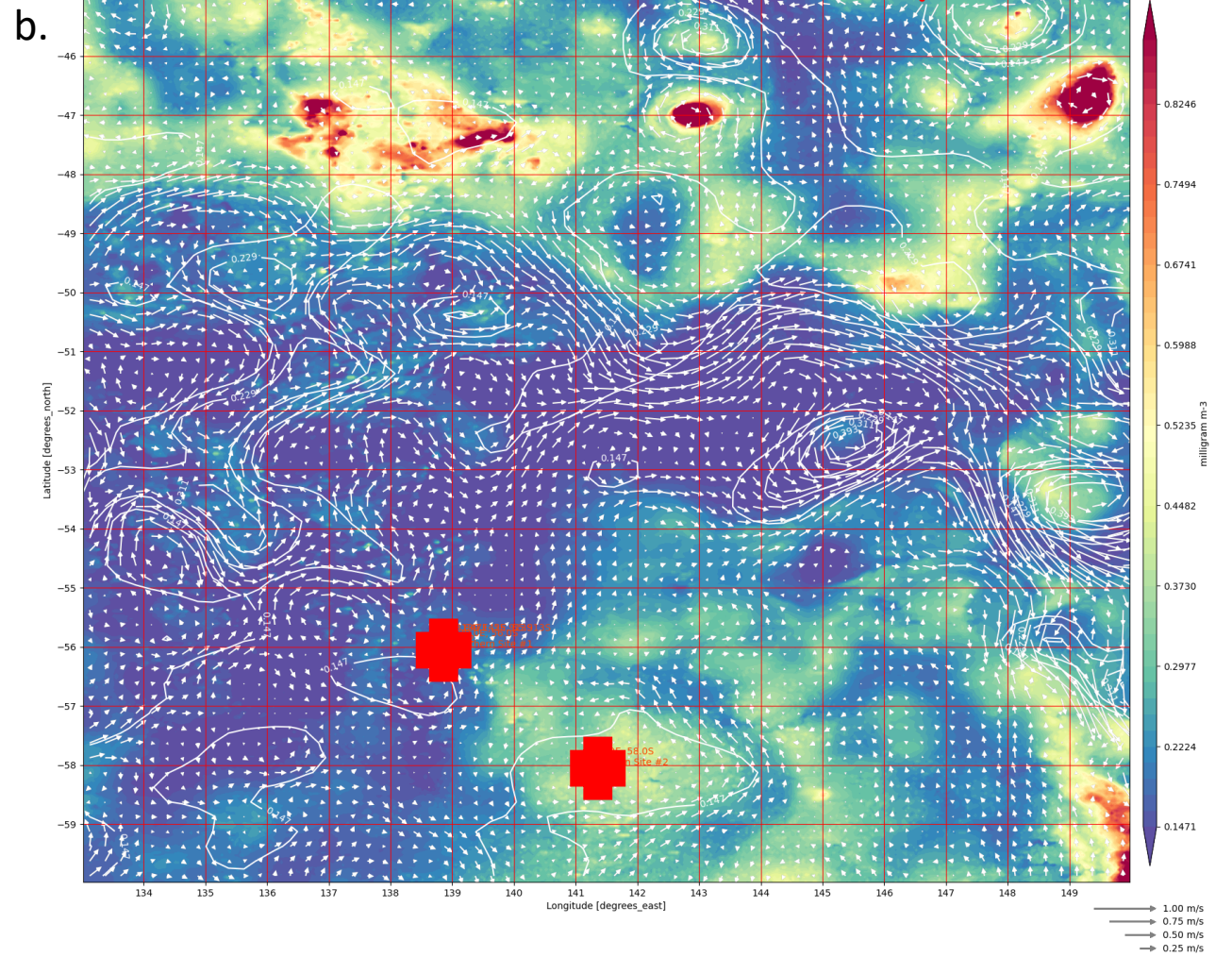
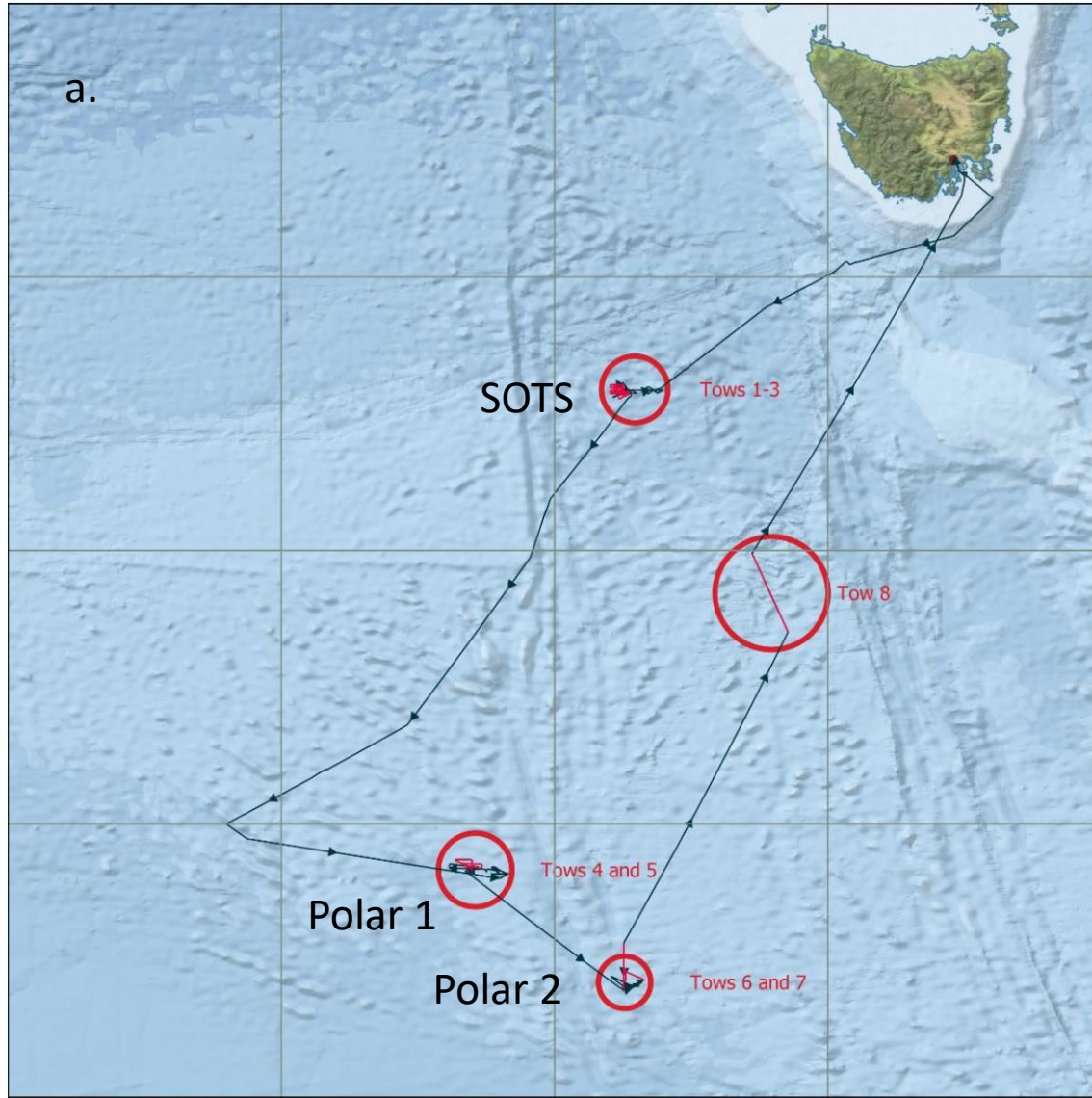
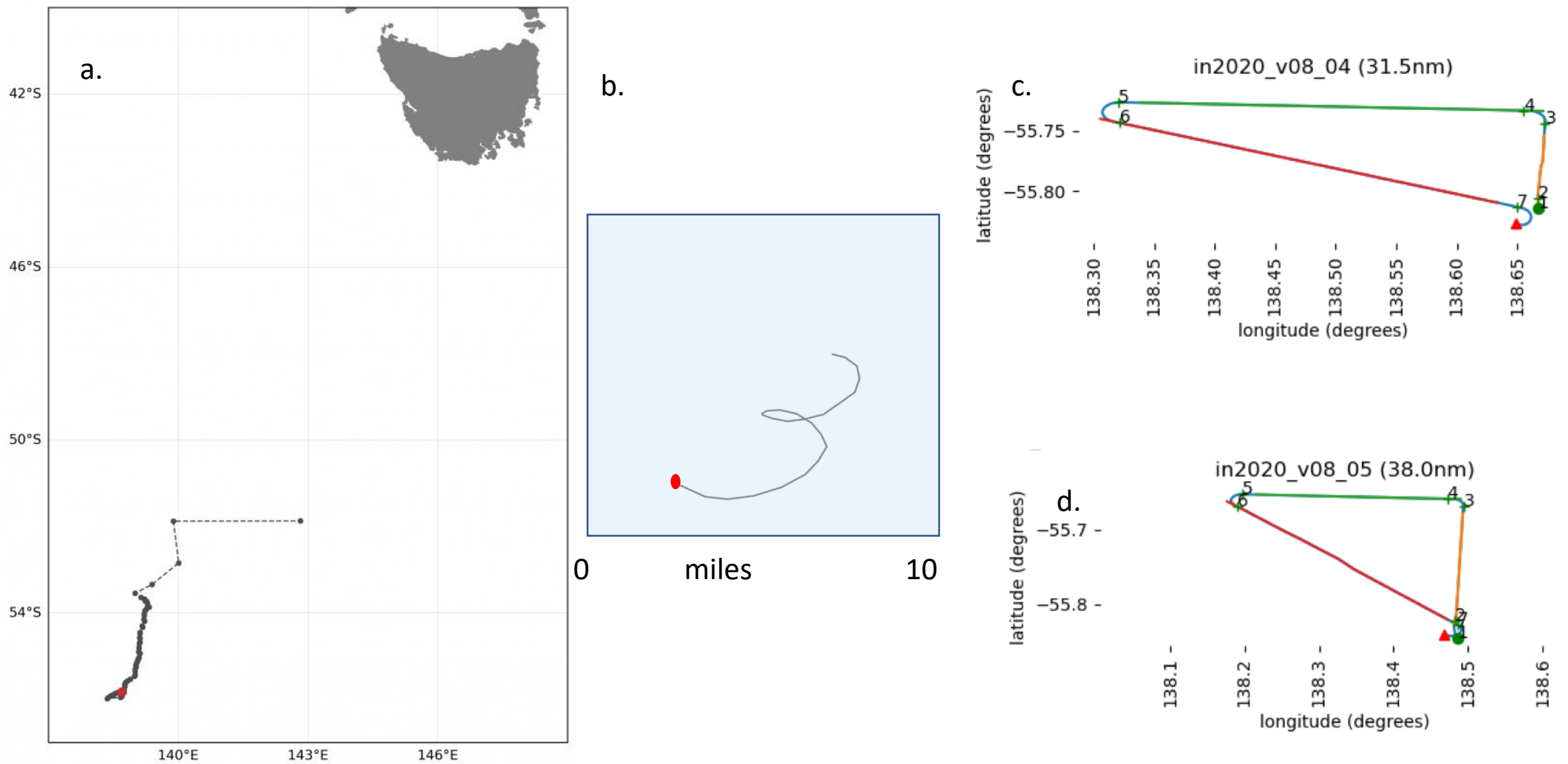


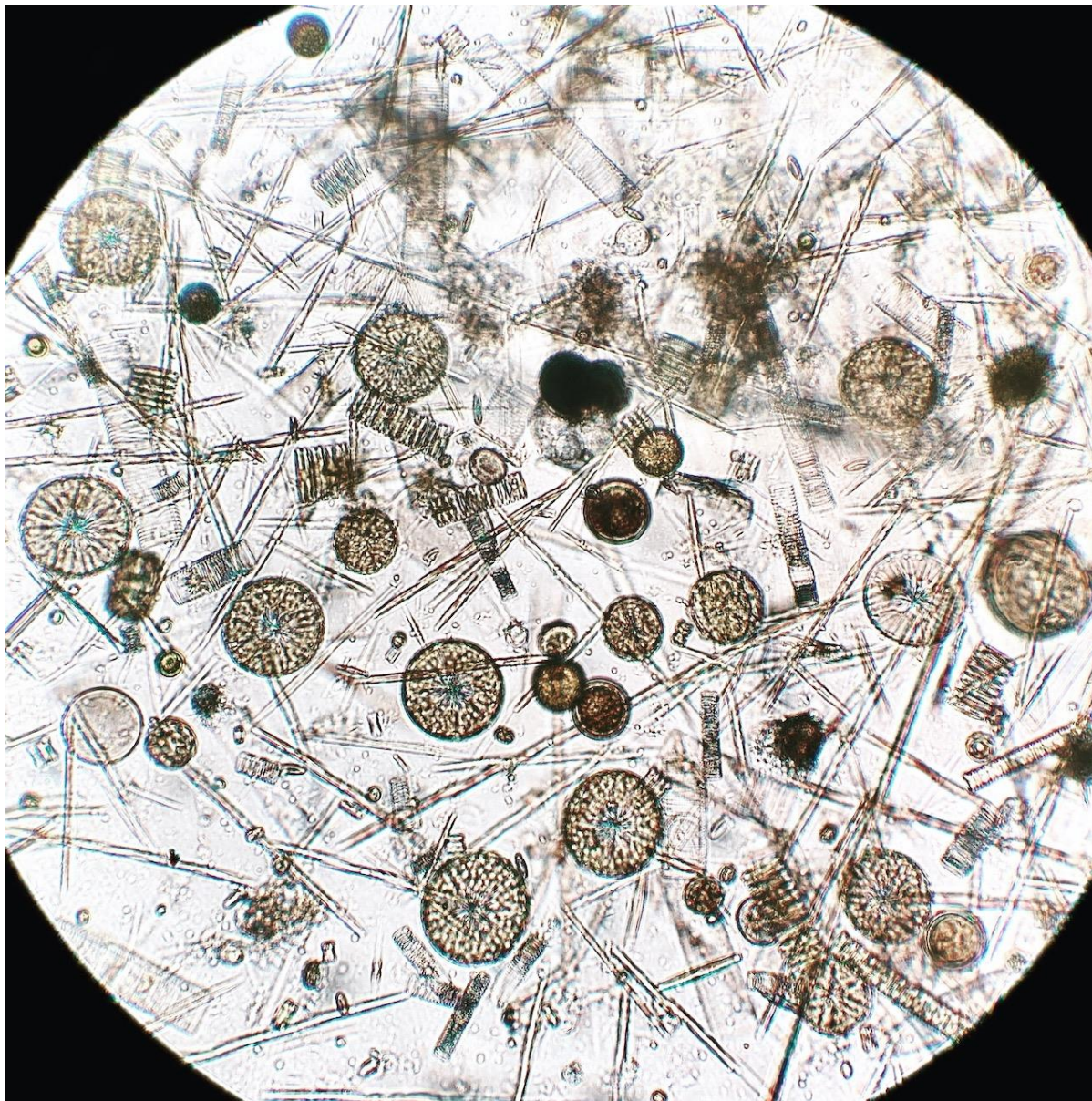
Figure 12



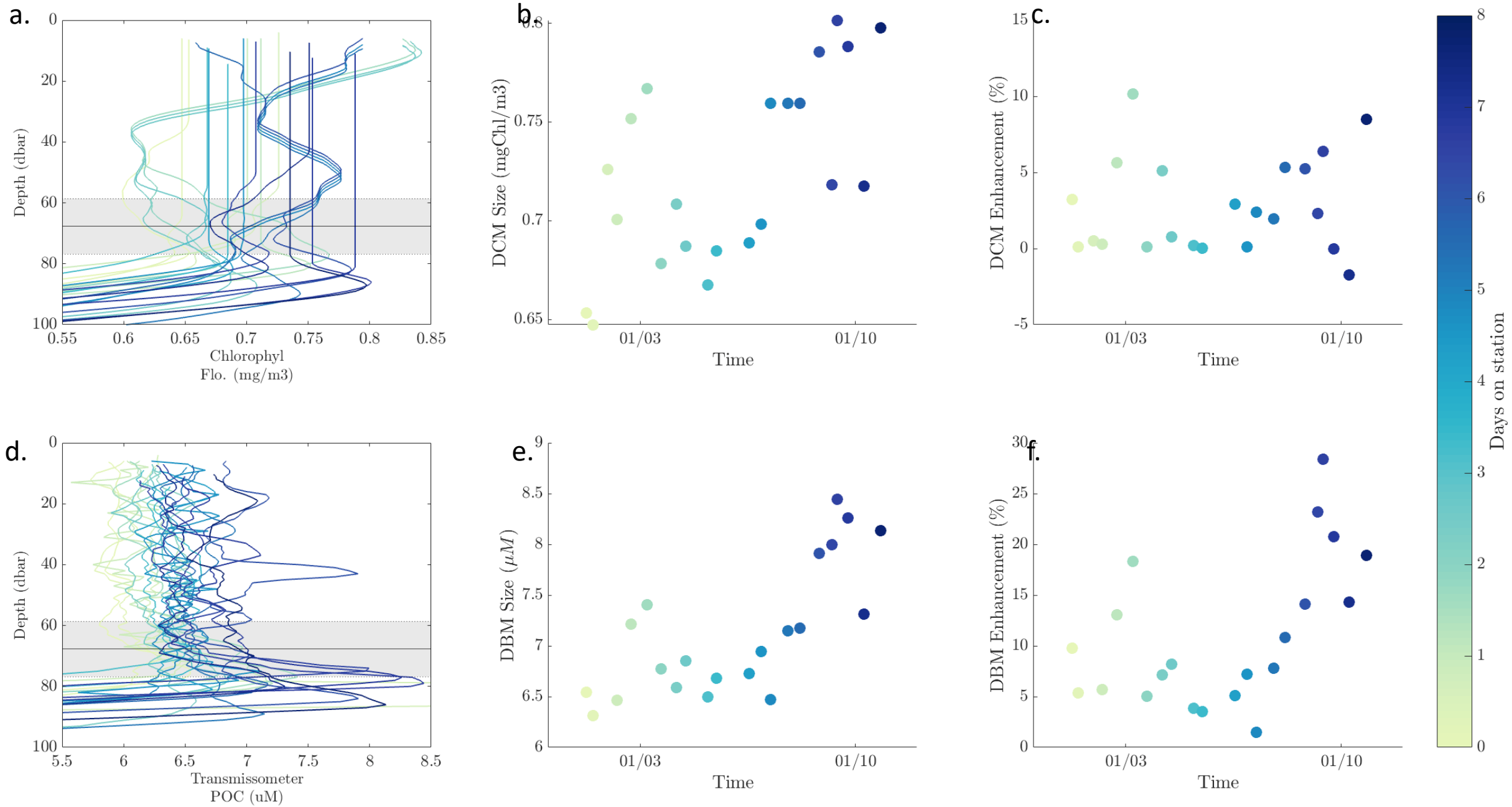
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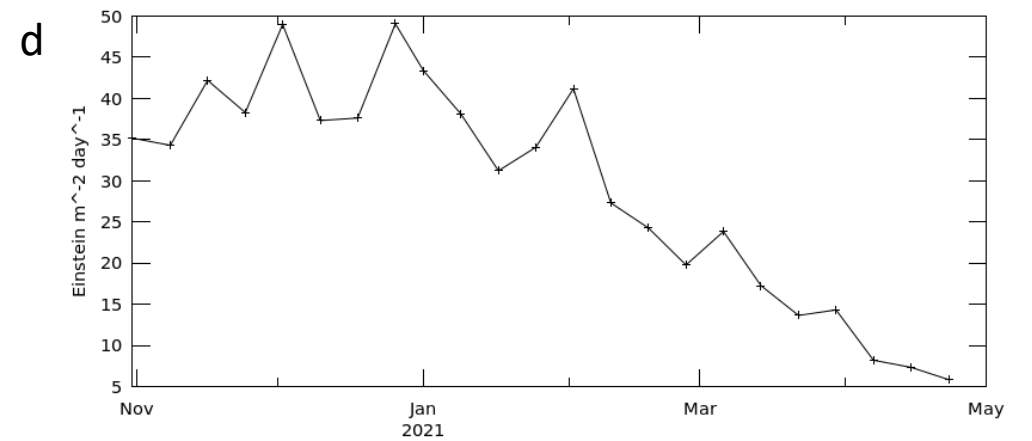
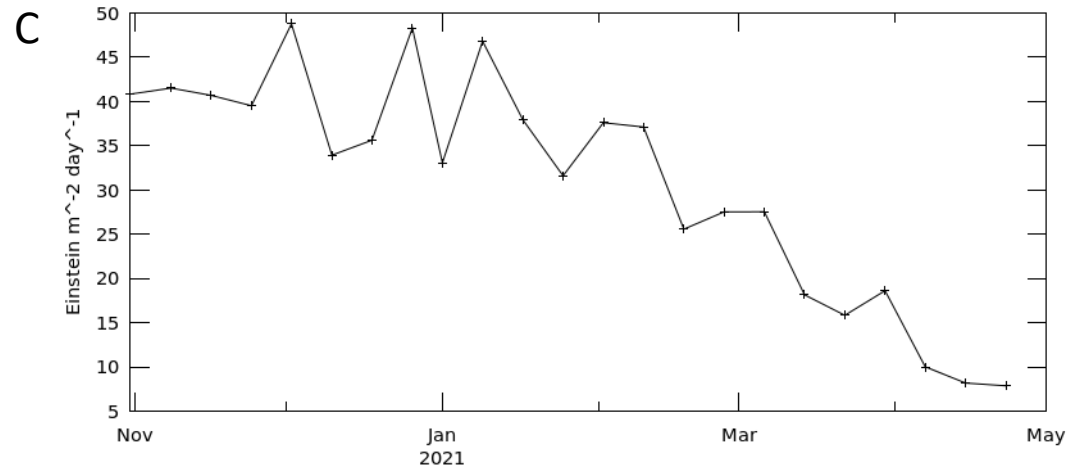
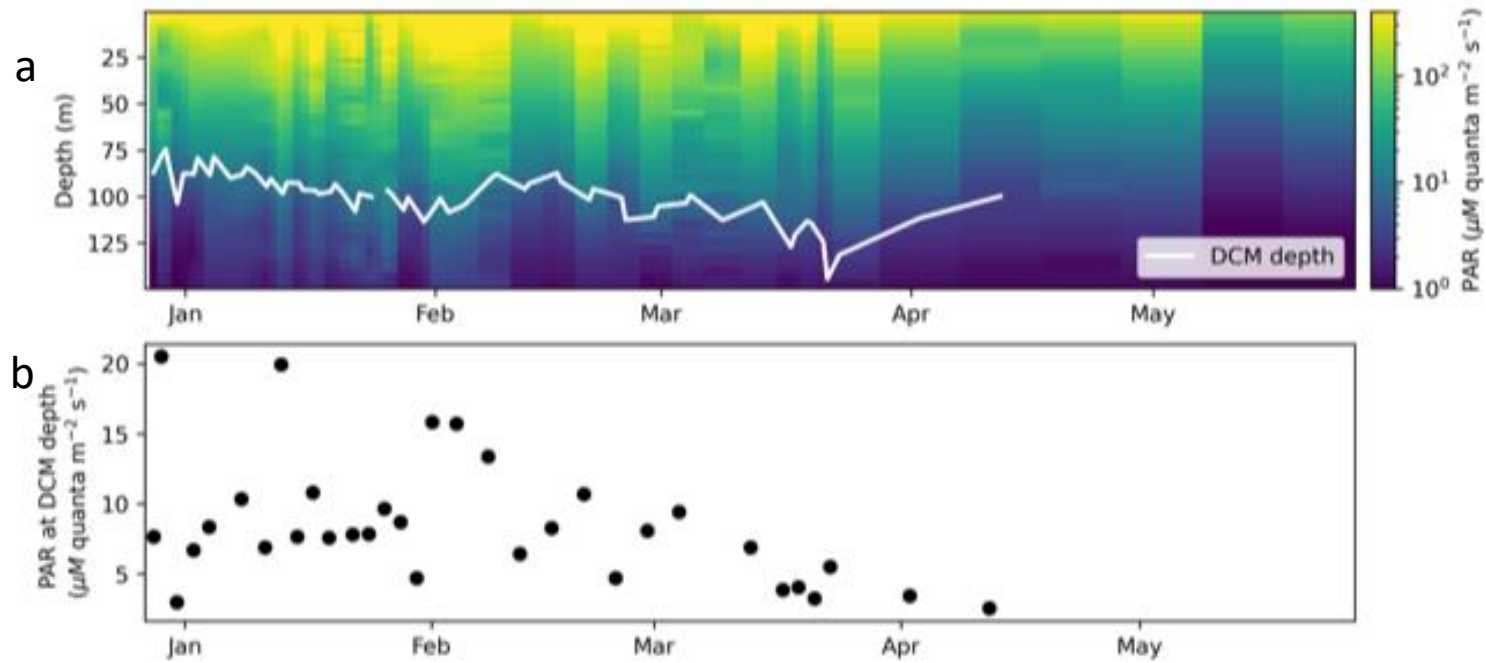
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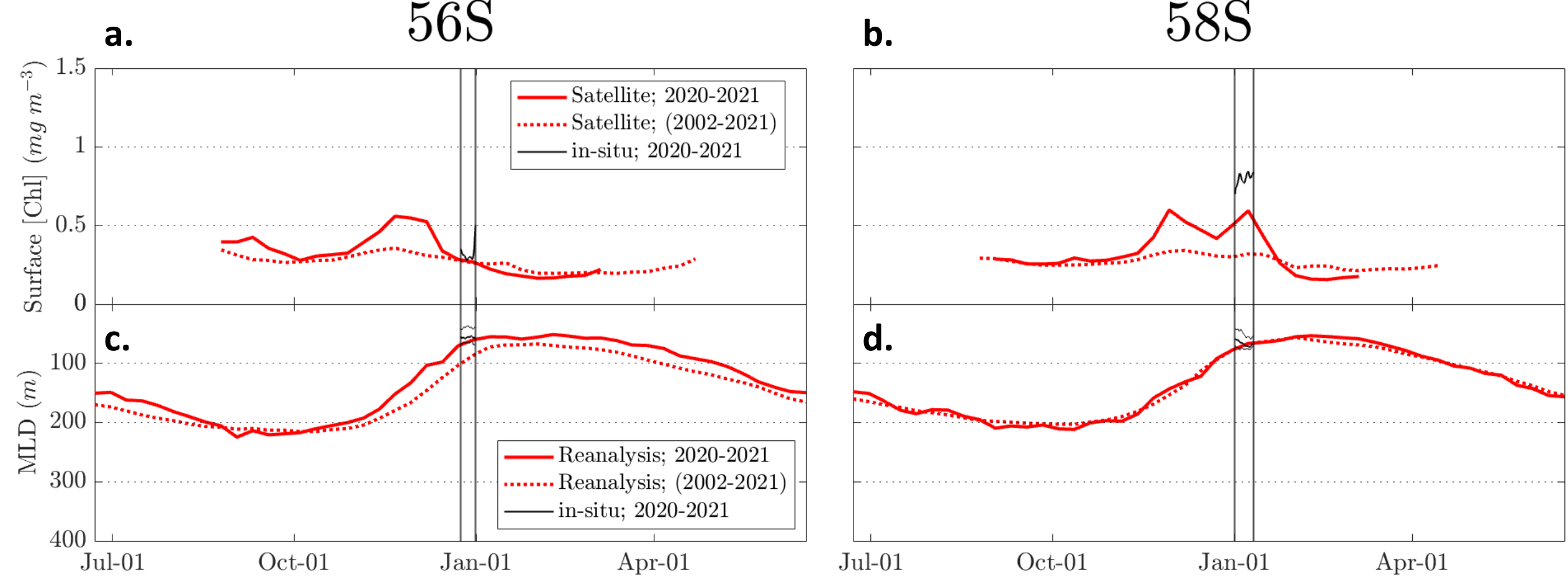
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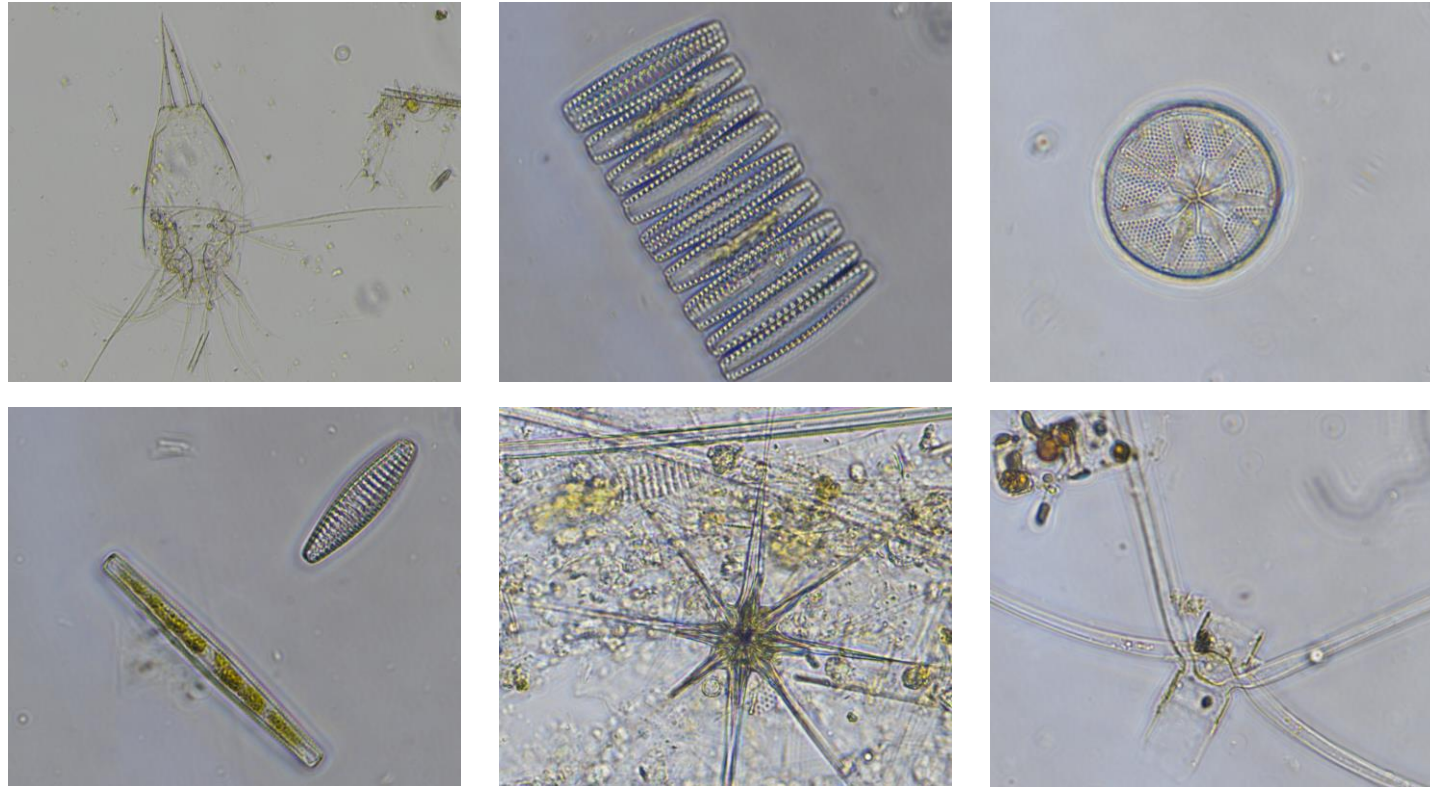
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Location	Feature	Depth Range (m)	NPP (mmol C m ⁻³ d ⁻¹)	Chlorophyll Fluorescence (mg m ⁻³)	Phytoplankton Biomass (mmol m ⁻³)	Cell-specific Division Rate (d ⁻¹)	Phytoplankton Biomass (mmol m ⁻³)	Cell-specific Division Rate (d ⁻¹)
					Without Photoacclimation C:Chl =30 (g:g)		With Photoacclimation C:Chl = 30 g:g below SML C:Chl = 15 g:g below SML	
56 S	SML	14.2 – 57.3	.53	.26	.65	.82	.65	.82
	DBM	71.4 – 86.7	.27	.51	1.28	.21	.64	.44
	DCM	80.4 – 103.3	.23	.48	1.20	.19	.60	.38
58 S	SML	10.6 – 67.7	.98	.59	1.48	.66	1.48	.66
	‘Deep’	67.7 – 82.7	.21	.42	1.05	.20	.53	.40

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