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1 **Iron supply pathways between the surface and subsurface waters of the Southern**
2 **Ocean: from winter entrainment to summer storms**

3

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- 13
- 14 • Eddy advection and winter mixing support annual surface iron supplies in equal proportion in an eddy resolving model.
 - 15 • Eddy advection contributes 25% to restocking subsurface iron reservoir in addition to 75%
16 by local recycling.
 - 17 • Storms are the most efficient in increasing iron supplies in early summer and over ocean
18 fronts.
- 19

20 **Abstract**

21 Dissolved iron (DFe) plays an immeasurable role in shaping the biogeochemical processes of the
22 open-ocean Southern Ocean. However, due to observational constraints iron supply pathways
23 remain poorly understood. Using an idealized eddy-resolving physical-biogeochemical model
24 representing a turbulent sector of the Southern Ocean with seasonal buoyancy forcing and zonal
25 winds overlaid by storms, we quantify the importance of a range of subsurface and surface iron
26 supply mechanisms. The main physical supply pathways to the surface layer are via eddy advection
27 and winter convective mixing in equal proportions. The associated subsurface loss of DFe is
28 restocked via net remineralisation (75%) and eddy advection (25%). Summer storms resulted in
29 weak DFe supplies relative to the seasonal supplies (<7.6%). However, in situations of deep
30 summer mixed-layers and when interacting with underlying ocean fronts, summer storms resulted
31 in enhanced diffusive and advective DFe supplies and raised summer primary production by 20%
32 for several days.

33 **Plain Language Summary**

34 The surface of the Southern Ocean is iron depleted, which strongly limits the amount of
35 phytoplankton growth that can occur. Every year, deep mixing in winter moves large quantities of
36 iron from a subsurface under-utilized iron reservoir to the surface alleviating the iron limitation.
37 Once there is sufficient light in spring, phytoplankton consume this iron supply leaving the summer
38 months iron depleted. How exactly phytoplankton are supported through the summer when iron
39 limitations are strong remains under question. This study uses a numerical model to simulate the
40 seasonal and intraseasonal iron supply pathways. We show that physical supplies via advection by
41 eddies and winter mixing drive surface seasonal supplies in equal proportions. During summer,
42 storms supply iron via intermittent mixing and thus increase primary production, particularly over
43 regions of strong ocean fronts.

44 **1 Introduction**

45 Dissolved iron (DFe) limits phytoplankton growth across the surface of the Southern Ocean (SO),
46 particularly in the open-ocean regions far from terrestrial DFe supplies (Boyd and Ellwood, 2010;
47 Moore et al., 2013). Analysis of a compilation of open-ocean DFe data has suggested that the
48 limitation is alleviated on an annual basis by a ‘once-off’ basin-wide supply during winter driven
49 by deep convective mixing, which entrains large volumes of iron-laden subsurface waters to the
50 surface (Tagliabue et al., 2014). During spring, when light availability increases, the winter supply
51 is consumed by the development of widespread phytoplankton blooms, such as occurring in the
52 sub-Antarctic zone (SAZ, Thomalla et al. 2011 and Racault et al. 2012). During summer, physical
53 iron supplies (i.e., via diapycnal mixing and advection) between the subsurface and surface ocean
54 have been estimated to be negligible in comparison to winter entrainment (Tagliabue et al., 2014)
55 and rapid iron biological recycling is thought to extend the spring phytoplankton production
56 through the summer months (Boyd et al., 2005; Tagliabue et al., 2014; Boyd et al., 2017).

57 In addition to the ‘once-off’ seasonal supply, there is increasing observational evidence from
58 satellites (Fauchereau et al., 2011; Thomalla et al., 2011; Carranza and Gille, 2015) and from *in-*
59 *situ* high-resolution gliders (Swart et al., 2015; Mtshali et al., 2019) that storms could be entraining
60 intermittent DFe supplies that could support phytoplankton production, especially in summer when
61 DFe limitations are strongest (Boyd, 2002; Ryan-Keogh et al., 2018; Mtshali et al., 2019).

62 Carranza and Gille (2015) found strong positive correlations between high wind-speeds with
63 enhanced surface chlorophyll in summer and concluded that local storm-driven entrainment was
64 the dominant nutrient supply mechanism over advection by Ekman pumping. Further, Swart et al.
65 (2015) linked sustained summer chlorophyll in the SAZ to wind-driven mixed-layer depth (MLD)
66 variability on synoptic timescales. The role of storm-driven mixing in supporting SAZ summer
67 production was explored in a one-dimensional modelling study by Nicholson et al. (2016), which
68 showed that intermittent mixing events could entrain subsurface DFe, provided there was a
69 subsurface post-storm resupply mechanism.

70 Many theoretical studies have investigated in detail the importance of wind in increasing the
71 supply of nutrients to the subsurface and the surface ocean, particularly when the wind interacts
72 with different meso and submesoscale features (fronts and eddies, e.g., Mahadevan and Tandon,
73 2006; Lévy et al., 2009; Whitt et al., 2017a, 2017b). These studies have focused on particular
74 localized scenarios and their relevance has not yet been contextualized within the broader seasonal
75 mean state. The SO, in particular the SAZ, is a region of strong eddy (Frenger et al., 2015) and
76 small-scale frontal activity (du Plessis et al., 2017, 2019); and strong winds from passing storms
77 (Yuan, 2004; Patoux et al., 2009; Yuan et al., 2009). We hypothesize that storms increase mixing
78 and advection during summer that are enhanced by wind-mesoscale interactions and may result in
79 non-negligible physical iron supplies from the subsurface to the surface ocean to support
80 phytoplankton production beyond what is possible by the once-off winter supply.

81 We aim to address the following, from a seasonal-scale perspective: What are the dominant supply
82 mechanisms of dissolved iron over the seasonal cycle? What maintains the sub-surface iron
83 reservoir? From an intraseasonal-scale perspective: How is iron supplied and utilized in response
84 to summer storms? We address these questions using an idealized eddy-resolving biogeochemical
85 model of the SO, forced by winds and climatological heat fluxes (seasonal forcing) and by a series
86 of passing storms (intraseasonal).

87 **2 Model setup and design**

88 **2.1 Physical Model**

89 The model architecture was provided by the Nucleus for European Modeling of the Ocean
90 (NEMO, Madec, 2008). The domain, zonal and meridional extent of $L_x = 2000$ km and $L_y = 3000$
91 km respectively (representing $40 - 70^\circ\text{S}$) and vertical extent of 4000 m, was setup on a β -plane
92 with $f_0 = -1 \times 10^{-4} \text{ s}^{-1}$ and $\beta = 1 \times 10^{-11} \text{ m}^{-1} \text{ s}^{-1}$ at the center. A linear equation of state dependent on
93 temperature is used with a thermal expansion $\alpha = 2 \times 10^{-10} \text{ K}^{-1}$. The eastern and western boundaries
94 were periodic, while the northern and southern were restricted. The northern boundary temperature
95 was restored to an exponential profile to allow deep residual overturning (Abernathey et al., 2011)
96 and varied seasonally in the upper 150 m to mimic observed seasonal variability at 40°S (Jouanno
97 et al., 2016). Random bathymetry (Figure S1) with linear bottom friction was used to limit the
98 zonal volume transport (Rintoul et al., 2001). In the vertical, 50 levels were used, with 10 levels
99 of 10 m thickness in the upper 100 m, increasing exponentially in thickness to 172 m at the bottom.
100 For vertical mixing we used a Generic Length Scale scheme with a k - ϵ closure (Reffray et al.,
101 2015), and for tracer and momentum advection, a 3rd order upstream biased scheme and no
102 additional explicit diffusion. Refer to Jouanno et al. (2016) for further description of the

103 configuration, including rationale for the choice of bathymetry, restoring, mixing and advection
104 schemes.

105 The configuration was initialized using a hierarchy of increasing horizontal resolution starting
106 from 100 km, initialized from rest and adjusted for 200 years. This initialized a 24 km resolution
107 run, which spun-up for 400 years, from which a 5 km run was initialized (then adjusted for 30
108 years). Our analysis is based on the mesoscale resolving 5 km run. Outputs are saved as two-day
109 means and the last five years of model integration are analyzed. The analysis is restricted to a
110 northern band ($x = 2000 - 2800$ km) of the domain, which is representative of SAZ like conditions
111 (Figure S1) and not influenced by boundary conditions.

112 **2.2 Seasonal and storm surface forcing**

113 The surface boundary was forced mechanically by wind and thermodynamically by heat fluxes.
114 The heat fluxes varied seasonally and zonally and were constructed from OAFflux data between
115 1984 – 2007 (Yu and Weller 2007 and Jouanno et al. 2016). Background wind stress (τ_b) is
116 uniform in time and varies zonally as:

$$117 \quad \tau_b = \tau_0 \sin \frac{\pi y}{L_y}$$

118 where, $\tau_0 = 0.15 \text{ Nm}^{-2}$.

119 SO mid-latitude storms are large cyclonic features (diameter of 900 km, Figure S2), which were
120 represented here as cyclonic anomalies of varying magnitudes in the background wind stress field
121 and were created using a Rankine vortex model (described in Jouanno et al. 2016). The direct
122 effect of storms on heat flux is not accounted for. Storm characteristics (i.e., duration and
123 magnitude) have been designed based on statistics for the SO (Patoux et al., 2009). The simulated
124 storms are unique, they have different magnitudes, locations across the domain, and times in each
125 year. They have periods of approximately 10 days and traverse zonally across the domain in two
126 days, i.e., the time interval during which their associated winds reach maximum intensity (linear
127 intensification and decay occur over periods of 1 day each). A total of 16 summer storms passed
128 over the region analyzed over 4 consecutive summers (Figure S2). Storms are stronger in intensity
129 during winter months than in summer, as observed to occur by Yuan et al. (2009), thus the storm
130 wind stress max (τ_{max}) is modulated by a seasonal cycle where it varies from $\tau_{max} = 1.5 \text{ Nm}^{-2}$
131 in winter to $\frac{\tau_{max}}{2}$ in summer. This seasonal storm intensity, together with background wind and
132 heat flux, resulted in the seasonality of the MLD, which deepened in response to convective
133 cooling and stronger storms in winter to a mean of ~ 175 m and shoaled to a mean of ~ 30 m in
134 summer due to strong buoyancy forcing via surface heating (in agreement with SAZ MLD ranges
135 in du Plessis et al. 2019).

136 **2.3 Biogeochemical Model**

137 The biogeochemical model Pelagic Interaction Scheme for Carbon and Ecosystems (PISCES,
138 Aumont et al. 2015), a well-tested and constrained model, simulates the cycle of DFe,
139 phosphorous, nitrogen, and silicate. PISCES was coupled online to the dynamical configuration
140 described above. DFe has been initialized based on lower ranges for the SO, which is more
141 representative of open-ocean waters (Tagliabue et al., 2012). We set DFe to 0.05 nmol L^{-1} in the

142 surface increasing linearly to 0.5 nmol L^{-1} until 500 m depth (Figure S3), after which DFe is kept
143 constant. For simplicity, we chose to force the model with high (by two factors) nitrate,
144 phosphate and silicate, such that the two limitations on phytoplankton are light and iron. While
145 silicate limitation occurs in the SO (Boyd et al. 2002), these broadly repleted macronutrient are
146 typical of SO surface waters, especially in the SAZ (Giddy et al., 2012), and are therefore not the
147 primary limitation. Nutrient profiles are restored at their northern boundary to the initial profile.
148 The Monotonic Upstream centered Scheme for Conservation Laws (MUSCL) in flux-form is
149 used for the advective transport of biogeochemical tracers (Lévy et al., 2001).

150 **3 Results**

151 Here we first show the model ability to simulate seasonal and intraseasonal responses of surface
152 phytoplankton, then the seasonal and intraseasonal (summer storms) pathways of DFe are
153 investigated.

154 **3.1 Surface chlorophyll**

155 The seasonal surface chlorophyll (chl_{surf}) shows a spring bloom peaking to $\sim 0.5 \text{ mg m}^{-3}$ during
156 September and a constant mean of $\sim 0.2 \text{ mg m}^{-3}$ in summer (Figure 1a). This range is comparable
157 with open-ocean SO chlorophyll (Thomalla et al., 2011). There are raised intraseasonal peaks of
158 chl_{surf} , as the one highlighted by the grey band in Figure 1a. These anomalies are related to
159 increased windspeed anomalies associated with the prescribed storms (Figure 1b). The strongest
160 correlations occurred 0 - 2 days after the storm passage, consistent with Carranza and Gille (2015).
161 For illustration, chl_{surf} patterns are shown in Figure 1c-e before, during and after a passing storm
162 in November. Pre-storm, chl_{surf} was low and spatially heterogeneous, with the highest
163 concentrations occurring within mesoscale fronts while background concentrations were low ($<$
164 0.15 mg m^{-3}). The storm-driven enhancements of chl_{surf} is evident both in the frontal features and
165 in the background concentrations (mean increase of 12%, Figure 1d, S4). However, the strongest
166 increase of chl_{surf} (52%) occurs in frontal features, particularly evident in the post-storm stage.

167 **3.2 The seasonal dissolved iron budget**

168 To investigate the pathways of DFe, the supplies were averaged spatially and separated into
169 contributions driven by physical and biological processes. The physical contributions were
170 separated into vertical diffusion and total advection (the sum of lateral and vertical components,
171 Figure 2a-d). The total biological contribution to the DFe budget includes DFe uptake by
172 phytoplankton and supply by net remineralization. Net remineralization includes disaggregation
173 of small particulate iron; zooplankton excretion and sloppy feeding; coagulation and aggregation
174 of particulate iron; and scavenging.

175 In the euphotic layer (set constant defined by maximum depth of production), the signature of the
176 “once-off” winter DFe supply is seen as a gain of vertical diffusive DFe during winter (July –
177 September) (Figure 2c). This corresponds to diffusive entrainment associated with mixed-layer
178 deepening (Figure 2e). A cumulative supply (averaged spatially and summed temporally) of 4.3
179 $\mu\text{mol DFe m}^2 \text{ yr}^{-1}$ was brought to the surface due to deep winter mixing, which is in the lower
180 range estimated by Tagliabue et al. 2014. In winter the total advective supply of DFe has a lower
181 magnitude with respect to mixing (Figure S5). However, it is larger in spring and early summer

182 (October - December). The total annual cumulative supply of this advective flux was $4.5 \mu\text{mol}$
 183 $\text{DFe m}^2 \text{ yr}^{-1}$, thus has a comparable magnitude to the “once-off” winter supply. Together, advection
 184 and diffusion maintain a positive DFe tendency during winter. The advective flux can be explained
 185 by increased eddy advection (Figure 2a-d), during winter, spring and early summer which
 186 dominates the vertical flux (Figure 2f). This increase in the advective flux is not present in a lower
 187 resolution run (Figure S6), where mesoscale eddies are not resolved.

188 Euphotic layer primary production (PP_{eup}) increases from June (Figure 2c). After winter, when the
 189 MLD shoals (Figure 2e), a spring bloom is present peaking between September and October,
 190 which rapidly decreases DFe. However, even during summer months elevated PP_{eup} is maintained
 191 (Figure 2c). The seasonal range of PP_{eup} (converted to carbon: $200 - 400 \text{ mg C m}^{-2} \text{ d}^{-1}$) falls within
 192 open-ocean estimates (Arrigo et al., 2008). After the spring bloom, when the MLD remains
 193 shallow ($\sim 30 \text{ m}$), most of the summer PP_{eup} is sustained by the net remineralized supply
 194 (cumulative of $33 \mu\text{mol DFe m}^2 \text{ yr}^{-1}$), particularly in the late summer period when PP_{eup} and net
 195 remineralization are tightly coupled (Figure 2c).

196 In the subsurface (Figure 2d), there is a cumulative loss of DFe primarily due to winter entrainment
 197 ($-4 \mu\text{mol DFe m}^2 \text{ yr}^{-1}$), restocked by eddy-driven advection ($1 \mu\text{mol DFe m}^2 \text{ yr}^{-1}$) and
 198 remineralization ($3.4 \mu\text{mol DFe m}^2 \text{ yr}^{-1}$). Note the weak subsurface production in October (-0.4
 199 $\mu\text{mol DFe m}^2 \text{ yr}^{-1}$). Net remineralization, although lower than in the euphotic layer, continuously
 200 supplies the subsurface reservoir, particularly during winter to spring (Figure 2d). While advection
 201 contributes to restocking the subsurface between November to February.

202 3.3 Impact of summer storms

203 Figure 3a and b show the spatially averaged storm-driven change of chl_{surf} , PP_{eup} and MLD for
 204 16 unique summer storms (Figure S2). The change is computed from the time-step at the peak of
 205 the storm and the time-step before the storm (Δ : storm-pre storm). Both $\Delta\text{chl}_{\text{surf}}$ and $\Delta\text{PP}_{\text{eup}}$ are
 206 strongly positively correlated to ΔMLD ($r = 0.808$ and $r = 0.801$ respectively). In other words,
 207 the stronger storm-driven deepening of the MLD the larger the response in $\Delta\text{chl}_{\text{surf}}$ and $\Delta\text{PP}_{\text{eup}}$.
 208 During early summer, storms drive the largest change in ΔMLD ($> 10 \text{ m}$) and thus of $\Delta\text{PP}_{\text{eup}}$,
 209 which increases up to $30 \text{ nmol DFe m}^2 \text{ d}^{-1}$, approximately 15% increase relative to the mean
 210 summer range of PP_{eup} (Figure 3b). In late summer, both mean storm-driven $\Delta\text{PP}_{\text{eup}}$ and ΔMLD
 211 are negligible.

212 Next, we quantify how much of the increase in $\Delta\text{PP}_{\text{eup}}$ in response to storms is in strong fronts
 213 (horizontal gradients in sea surface temperature $> 65^{\text{th}}$ percentile), versus weak/no fronts (Figure
 214 3c). For 14 summer storms, the mean response of $\Delta\text{PP}_{\text{eup}}$ in fronts compared to weak/no fronts is
 215 the same ($r = 0.98$), particularly for late summer storms. However, $\Delta\text{PP}_{\text{eup}}$ is skewed toward larger
 216 values in frontal areas, even for weak $\Delta\text{PP}_{\text{eup}}$ and there are a few cases in early summer where
 217 $\Delta\text{PP}_{\text{eup}}$ is larger in fronts, up to a factor of two. These cases had deeper pre-storm MLD's and
 218 stronger winds.

219 Figure 4 focuses on the storm for which there is a doubling of $\Delta\text{PP}_{\text{eup}}$ at fronts (Figure 3c). The
 220 storm occurred between the 16 - 18th of November marked in Figure 1a and c, d). The response
 221 of PP_{eup} is maximum a few days after the storm ($\sim 22^{\text{nd}}$) and stronger in fronts. During the storm,
 222 diffusive entrainment is the dominant DFe supplier to the top 50 m, coinciding with a deepening
 223 of the MLD and the active mixing extent (Figure 4 c, f). The diffusive supply is stronger (42%)

224 in fronts (e.g., 300 nmol DFe m³ d⁻¹ compared to 172 nmol DFe m³ d⁻¹ in no fronts). Advection
225 resupplies some of the entrained DFe beneath the MLD during the storm (Figure 4 b, c) and is
226 also stronger in fronts (e.g., 105 nmol DFe m² d⁻¹ compared to 51 nmol DFe m² d⁻¹ in weak/no
227 fronts). The enhanced advection in both scenarios is due to Ekman pumping (accounting for 50%
228 increase in mean total vertical advection, Figure S7), while the remainder is due to the rectified
229 effect of mesoscale-wind interactions.

230

231 **4. Discussion and conclusion**

232 This study investigates the dissolved iron budget in the open waters of the SAZ with an idealized
233 eddy-resolving biogeochemical model, intermittently disturbed by storms to investigate seasonal
234 and intraseasonal supply pathways.

235 On the seasonal-scale, in addition to the “once-off” winter DFe supply to the surface by convective
236 mixing (Tagliabue et al., 2014), this study shows that enhanced eddy activity contributes to a DFe
237 supply of similar magnitude over the year (Figure 2c) and is thus an important supply mechanism
238 for SO productivity (supporting 14% annual and 25% spring-summer production). Our estimate
239 of the eddy DFe flux is likely underestimated as the horizontal resolution used (~5 km or 1/24°) is
240 not sufficient to represent submesoscale iron fluxes (Rosso et al., 2016; Takaya et al., 2019).

241 Iron supplies to the euphotic layer can only be maintained if the subsurface iron reservoir is being
242 refilled. In the subsurface, we showed that the dominant seasonal supplies were via net
243 remineralization (July to October), a result of detrainment of euphotic bioavailable iron during
244 winter, and via total advection driven by seasonally increased eddy advection (November to
245 February) (Figure 2d). No previous studies have contrasted the role of these different subsurface
246 pathways. However, individual studies have shown that remineralization (Boyd et al., 2017),
247 upwelling (Rosso et al., 2016) and lateral advection (Bowie et al., 2009) are important. The impact
248 of remote advection was excluded here but has been shown to be important (Graham et al., 2015),
249 as have hydrothermal vents (Tagliabue et al., 2010; Ardyna et al., 2019) and aeolian dust (Jickells
250 et al., 2005).

251 On the intraseasonal-scale, we investigated whether summer storms could supply iron to support
252 summer production above and beyond these seasonal iron supplies. Storm-driven supplies are
253 currently unresolved by temporal coverage of available DFe observations (Mtshali et al., 2019). In
254 agreement with Fauchereau et al. (2011) and Carranza and Gille (2015), we found strong positive
255 correlations between storm-driven anomalies of the MLD with surface chlorophyll, but also with
256 primary production (Figure 3a,b). Moreover, we showed that the magnitude of these anomalies is
257 dependent on the timing of the summer storm. Early summer storms had the largest mean impact
258 (20 m) on the MLD and thus on primary production. During this period, the largest increase in
259 production (40 nmol DFe m² d⁻¹) resulted from storm-front interactions. Fronts amplified the
260 storm-driven iron supplies primarily via enhanced diffusive entrainment associated with deeper
261 mixing and enhanced advection below the MLD. Furthermore, the storm-driven mixing
262 contribution of DFe is larger than the advective contribution, so Ekman pumping, and more
263 generally enhanced advection, is of second order compared to mixing (Figure 4). While these
264 results support a well-established hypothesis that winds interacting with fronts enhance mixing
265 (Lévy et al., 2009; Whitt et al., 2017a) and advection (Franks and Walstaad, 1997; Lévy et al.,

266 2009; Whitt et al., 2017b), when contrasted against the seasonal-scale perspective, it results in at
267 most a 20% increase of PP for several days. Towards late summer, storm-frontal interactions were
268 inhibited by strong heat flux and weaker winds that maintained shallow MLDs, limiting both
269 entrainment of iron and the development of instabilities (Capet et al., 2008; Sasaki et al., 2014;
270 Callies et al., 2015; Lévy et al., 2018; du Plessis et al., 2019).

271 Our approach is based on a simplified model in which some connected and potentially relevant
272 processes have not been accounted for and may result in the underestimation of storm impacts.
273 The first simplification concerns the representation of the storms, which only includes an anomaly
274 in the wind stress. However, surface heat loss has been shown to be important: Carranza and Gille
275 (2015) showed that SO summer MLD variance was explained by windspeed (21.8%) and net
276 surface heat flux (16.7%). This unaccounted thermodynamic effect may further destabilize the
277 MLD during a storm, and potentially increase the storm-driven DFe supply during late summer
278 when buoyancy forcing is strong. The two storms that stand out in Figure 3c are likely most
279 representative of reality because they are associated with mixed-layer anomalies that are
280 comparable to the magnitude observed in the SO (i.e., summer SAZ MLD standard deviations of
281 16 m, Swart et al., 2015). The model horizontal resolution (not submesoscale-resolving) could
282 potentially underestimate the effect of storms. Increasing the horizontal resolution could lead to
283 stronger and deeper responses in vertical advection and diffusion and it might also impact the deep
284 iron reservoir. Since Jouanno et al. 2016 demonstrated full-depth impacts of a storm on dissipation
285 and advection. The quantitative results in our model should be considered the lower range of
286 potential impacts of storms on DFe supply.

287
288 The idealized nature of our simulation has not allowed us to explore the full range of situations
289 that are representative of the SO. For instance, the timing of our bloom is too early compared to
290 some observations (e.g. Swart et al. 2015). These findings give new insight on the response of
291 biophysical processes to storm events. Given the potential susceptibility of SO iron supplies and
292 primary production to future changes in storm seasonality and characteristics, future work should
293 investigate the regional-scale sensitivity of storm-driven iron supplies by testing a wider range of
294 SO mixing seasonal cycles (e.g., Llort et al., 2016; 2019), which could affect the bloom timing,
295 mean seasonal supplies and the significance of storms.

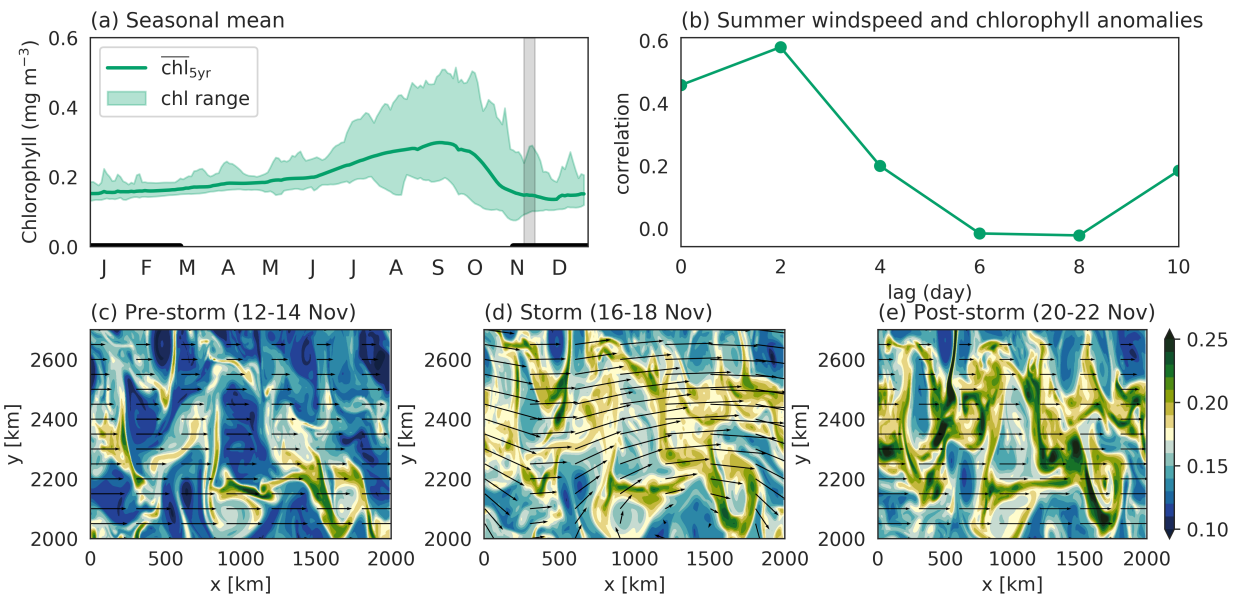
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Figures:



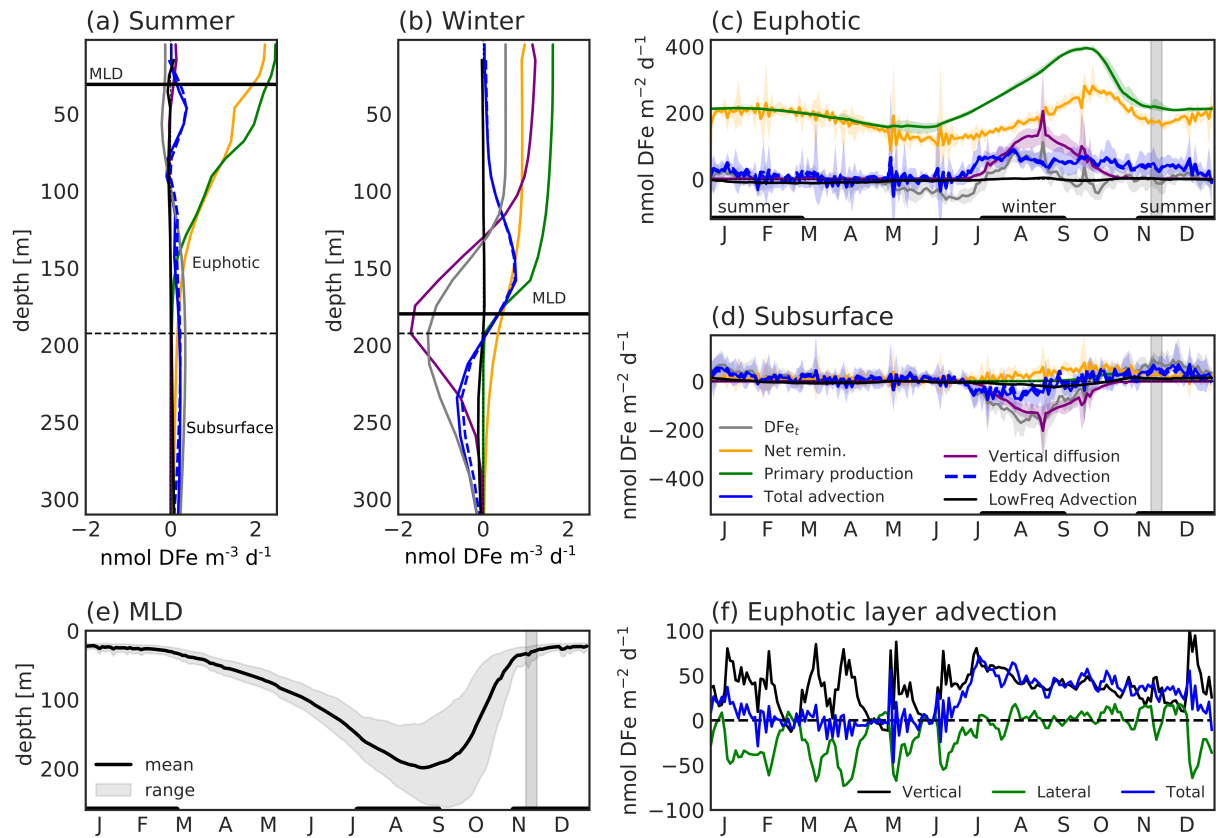
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315 **Figure 1:** a) Seasonal mean of surface chlorophyll (mg m^{-3}), with green shading for the range (min
316 - max), (b) cross-correlation between summer (01 November - 01 March) intraseasonal anomalies
317 in windspeed (16 individual storms) and in surface chlorophyll, and (c-e) the response of two-day
318 mean surface chlorophyll to a single and unique storm occurring in one summer as marked by gray
319 shading in (a). Black vectors in c-e are wind stress.

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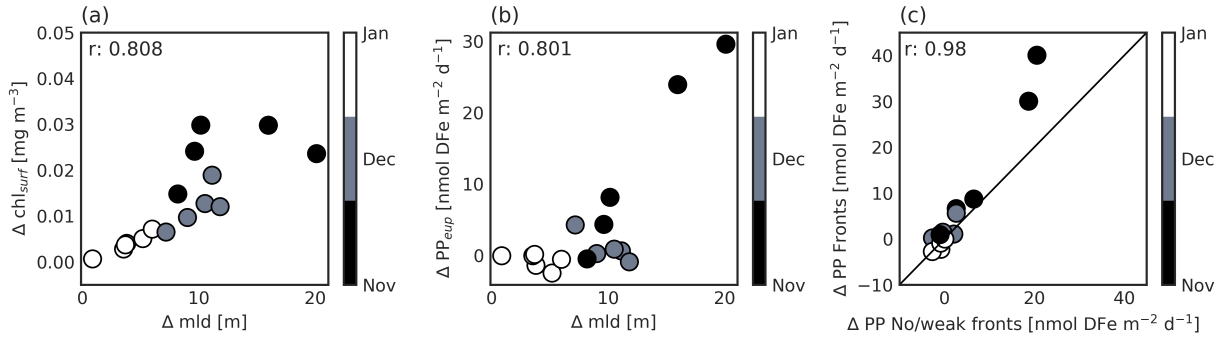


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324 **Figure 2:** The seasonal climatology of the dissolved iron (DFe) budget computed over 5 years and
 325 averaged spatially. The iron budget terms (nmol DFe m³ d⁻¹) include net primary production (i.e.
 326 phytoplankton uptake of DFe shown as positive for comparison), total advection, low frequency
 327 total advection (computed from two-month running average of u , v , w and DFe), eddy advection
 328 (total - low frequency), vertical diffusion, net remineralization and the total DFe tendency (DFe_t).
 329 Vertical profiles for each term averaged in (a) summer (November - February) and (b) winter (July
 330 - August). Iron budget terms are integrated vertically over: (c) the euphotic layer (0 - 190 m) and

331 (d) a subsurface layer (190 - 300 m, the DFe reservoir). Climatologies of (e) mixed-layer depth
 332 and (f) vertical and lateral components of euphotic layer integrated advection.

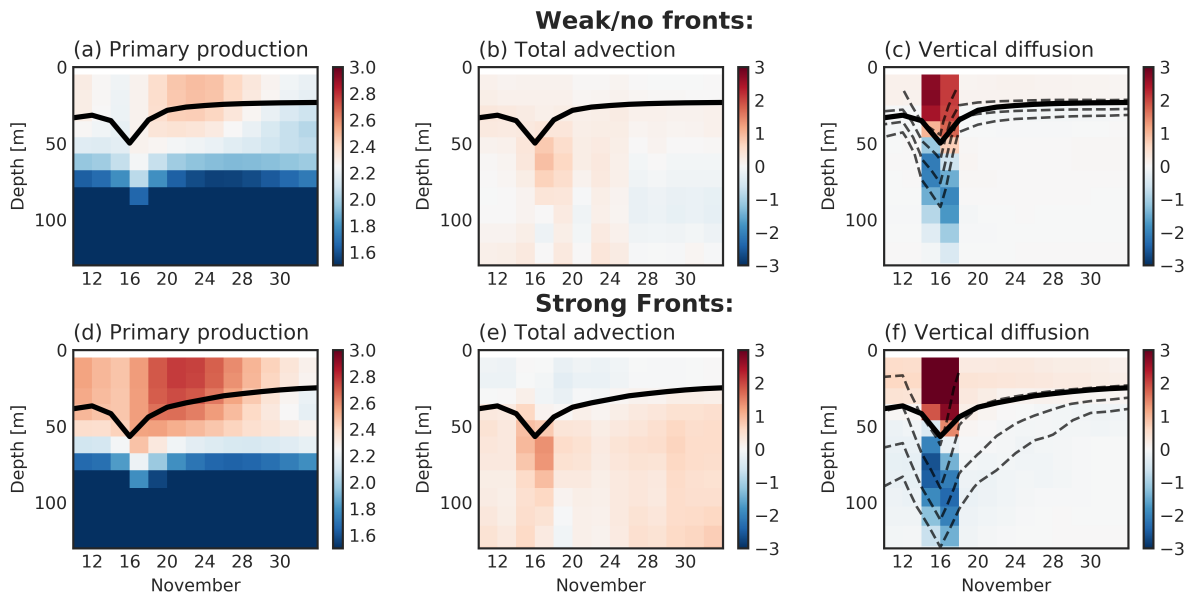
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335 **Figure 3:** (a, b) The relationship between the storm-driven change (Δ : storm – pre-storm) of (a)
 336 surface chlorophyll (chl_{surf} , mg m^3) and (b) euphotic layer integrated primary production ($\Delta \text{PP}_{\text{eup}}$,
 337 $\text{nmol DFe m}^2 \text{d}^{-1}$) against the storm-driven change on the mixed-layer depth (ΔMLD , m), for 16
 338 individual summer storms over 4 consecutive summers. (c) The relationship between $\Delta \text{PP}_{\text{eup}}$
 339 separated spatially into fronts (ΔPP fronts) and weak/no fronts (ΔPP weak/no fronts). The 1:1 line
 340 is marked in black. Fronts are regions with strong ($> 65^{\text{th}}$ percentile) horizontal gradients in sea
 341 surface temperature. In (a) and (b) each point represents the spatially averaged impact of a storm.
 342 Pearson correlation coefficient (r) is on each panel.

343



344

345 **Figure 4:** Depth-time composites separated and averaged in regions of weak/no fronts (top) and
 346 strong fronts (bottom) showing the storm-driven response of (a, d) net primary production and
 347 iron supply for (b, e) total advection and (c, f) vertical diffusion. Units in $\text{nmol DFe m}^3 \text{d}^{-1}$. (c, f)

348 dashed-lines are $\log_{10}(k_z)$ at -7, -6, -5 and -4 $\text{m}^2 \text{s}^{-1}$. The black line is the mean MLD within
349 fronts and no/weak fronts.

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