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Wyatt, N

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1 **Phytoplankton responses to dust addition in the FeMn co-limited**
2 **eastern Pacific sub-Antarctic differ by source region**

3 Neil J. Wyatt^{1,2*}, Antony Birchill^{2,3}, Simon Ussher², Angela Milne², Heather A. Bouman⁴, Elizabeth
4 Shoenfelt Troein^{5,6}, Katsiaryna Pabortsava⁷, Alan Wright¹, Oliver Flanagan¹, Thomas S. Bibby¹,
5 Adrian Martin⁷, C. Mark Moore¹.

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7 ¹School of Ocean and Earth Science, National Oceanography Centre Southampton, University of
8 Southampton, Southampton, SO14 3ZH, UK.

9 ²School of Geography, Earth and Environmental Sciences, University of Plymouth, Plymouth, PL4 8AA, UK.

10 ³Current address: Chief Scientist's Group, Environment Agency, Romsey, SO51 7LP, UK.

11 ⁴Department of Earth Sciences, University of Oxford, Oxford, OX1 2JD, UK.

12 ⁵Department of Earth, Atmospheric and Planetary Sciences, Massachusetts Institute of Technology,
13 Cambridge, MA, 02139, USA.

14 ⁶Current address: Isometric, 27 New Dover Road, Canterbury Kent, CT1 3DN, UK.

15 ⁷National Oceanography Centre, Southampton, SO14 3ZH, UK.

16

17 *Corresponding author: Neil J. Wyatt, B528 Portland Square, Drake Circus, Plymouth, PL4 8AA, UK.
18 neil.j.wyatt@plymouth.ac.uk.

19

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36 **Abstract.**

37 The seasonal availability of light and micronutrients strongly regulates productivity in the Southern
38 Ocean, restricting biological utilization of macronutrients and CO₂ drawdown. Mineral dust flux is a
39 key conduit for micronutrients to the Southern Ocean and a critical mediator of multi-millennial-scale
40 atmospheric CO₂ oscillations. Whilst the role of dust-borne iron (Fe) in Southern Ocean
41 biogeochemistry has been examined in detail, manganese (Mn) availability is also emerging as a
42 potential driver of past, present, and future Southern Ocean biogeochemistry. Here we present results
43 from fifteen bioassay experiments along a north-south transect in the under-sampled eastern Pacific
44 sub-Antarctic Zone. In addition to widespread Fe limitation of phytoplankton photochemical
45 efficiency, we found further responses following the addition of Mn at our southerly stations,
46 supporting the importance of Fe-Mn co-limitation in the Southern Ocean. Moreover, addition of
47 different Patagonian dusts resulted in enhanced photochemical efficiency with differential responses
48 linked to source region dust characteristics in terms of relative Fe/Mn solubility. Changes in both the
49 relative magnitude of dust deposition, combined with source region mineralogy, could hence
50 determine whether Fe or Mn limitation control Southern Ocean productivity under future as well as
51 past climate states.

52

53 **Significance statement.**

54 Atmospheric dust supply of micronutrients to the Southern Ocean is an important regulator of
55 phytoplankton productivity, impacting the global carbon cycle. Understanding how phytoplankton
56 respond to changes in dust supply has become increasingly important, with supply predicted to alter
57 with future climate change. We show that Patagonian dusts, which differ in characteristics by source
58 region, can supply different amounts of the essential micronutrients iron and manganese to the
59 Southern Ocean and subsequently drive different responses in the resident phytoplankton. Changes in
60 dust supply, including shifts in source regions, could therefore be an important factor controlling
61 phytoplankton productivity in the past and future Southern Ocean.

62

63 **Introduction.**

64 Productivity in the modern Southern Ocean is restricted by low iron (Fe) and potentially manganese
65 (Mn) availability (1-4) owing to upwelling of macronutrient-rich deep waters depleted in these
66 scavenged trace metals (5, 6), combined with low atmospheric supply (1, 7).

67 Both Fe and Mn are essential requirements in oxygenic photosynthesis, with multiple Fe binding
68 components required to enable photosynthetic electron flow, while the oxygen-evolving complex of
69 photosystem II requires 4 bound Mn atoms (8). Surface uptake by phytoplankton leads to a scarcity of
70 both Fe and Mn in Southern Ocean surface waters, which can subsequently limit productivity, leading
71 to underutilization of macronutrients and net release of deep-ocean carbon (4, 7, 9). Enhanced
72 micronutrient supply, including through increased atmospheric dust fluxes, thus has the potential to
73 drive increased macronutrient utilization, export production and atmospheric CO₂ drawdown (1, 7).
74 Indeed, the higher supply of lithogenic Fe to Southern Ocean phytoplankton during glacial climate
75 periods correlates with increased nitrate removal and productivity and is a critical mediator of
76 millennial-scale atmospheric CO₂ oscillations (7, 10-12). Dust fluxes to the Sub-Antarctic Zone (SAZ)
77 in particular have been associated with a significant fraction of atmospheric CO₂ drawdown during the
78 last glacial cycle (9, 13), with isolation of the deep Southern Ocean by enhanced stratification the other
79 major contributor (13-15).

80 Although there is still uncertainty as to whether global dust deposition rates will increase or decrease
81 due to anthropogenic climate change (16, 17), the expansion of deserts could result in a three-fold
82 greater atmospheric dust loading by the end of the 21st century (18). Regionally, this expansion,
83 coupled with climate related increased storminess, could result in a ten-fold increase in dust loading
84 over the Southern Hemisphere compared with a minimal increase over much of the Northern
85 Hemisphere (18). Any future increase in dust flux may enhance the delivery of Fe and other co-limiting
86 nutrients such as Mn (4, 19), which could be particularly important should warming and freshening of
87 Southern Ocean surface waters increase stratification, and hence reduce supply from subsurface
88 reservoirs (5, 20). The delivery of dust-borne nutrients may be further supported by an increased
89 contribution from wildfire aerosols (21-24), which can relieve nutrient limitation and significantly
90 increase Southern Ocean productivity following exceptional individual events (25).

91 Despite the potential importance of Southern Ocean dust inputs for modern productivity and glacial-
92 interglacial cycles, relatively few studies have investigated the ecophysiological response of natural
93 Southern Ocean phytoplankton communities to direct dust addition. In situ and shipboard bottle
94 experiments of Fe fertilization have typically assessed responses to the addition of inorganic Fe (e.g.,
95 dissolved chloride salts or ferrous sulphate) (26-30). Such addition of Fe may fail to mimic the
96 responses from complex natural substrates, where the (bio-)availability of multiple micronutrients may
97 vary. For example, naturally Fe-limited Southern Ocean phytoplankton have been shown to respond
98 differently to dust addition compared with inorganic Fe (31). Moreover, the increasing evidence that
99 Mn may be co-limiting with Fe in certain settings and regions of the Southern Ocean (4, 19, 32) needs

100 consideration in the context of multiple-micronutrient supply from natural particulates. This is
101 particularly interesting due to the high abundance of both elements in crustal material (sediments,
102 airborne dusts) and similar short oceanic residence times. Indeed, the supply of volcanic ash to
103 Southern Ocean phytoplankton communities has been shown to produce a stronger response than
104 addition of Fe alone, potentially due to relief of Mn (co-)limitation (33). Understanding biological
105 responses to complex natural sources of trace-metal-nutrients may thus be essential for realistic
106 projections of the Southern Ocean biological carbon pump under past and future climates (4).

107 The composition of dust will vary with source provenance (34, 35) and processing both at source and
108 during atmospheric transport (36, 37). In particular, Fe within glaciogenic versus non-glaciogenic dust
109 sources appears to be both more labile and bioavailable due to a higher Fe²⁺ content (35, 38). This
110 higher Fe²⁺ content of glaciogenic dust has been shown to significantly increase growth and
111 photosynthetic efficiency compared with non-glaciogenic dust in a cultured diatom (35). Similarly, the
112 relative abundance, solubility and bioavailability of the multiple trace metals in dust deposition may
113 be key in determining the overall ecosystem response (4).

114 South America is the largest source of dust to the modern Southern Ocean contributing ~60 % of the
115 flux, with Australia the other key source, particularly for the Pacific sector (39, 40). However,
116 increased circumpolar transport of South American dust sources potentially dominated the >3-fold
117 higher dust fluxes and >15-fold higher Fe²⁺ fluxes to the Pacific SAZ during glacial periods (34, 41).
118 Understanding the fertilization potential of this increased glacial bioavailable Fe²⁺ flux, alongside other
119 potentially co-limiting trace-metals for natural phytoplankton communities in the Pacific SAZ, may
120 thus be crucial for determining the likely response of the glacial-interglacial system and more broadly
121 understanding the role of variable dust fluxes and source regions in Southern Ocean biogeochemistry.

122 We thus combined in situ observations with a series of shipboard bottle experiments in the under-
123 sampled eastern Pacific SAZ (3), the region of the modern sub-Antarctic with the lowest annual mean
124 dust flux (Fig. 1A). Experiments were conducted to assess the potential role of natural sources of Fe
125 and Mn in regulating phytoplankton ecophysiology in the region and the broader Southern Ocean.

126

127 **Results and discussion.**

128 **Phytoplankton responses to Fe and Mn amendment.**

129 Eight smaller volume (2-6 day, denoted Ex-S1-S8) and seven larger volume (6 day, denoted Ex-L1-
130 L7) nutrient addition experiments were conducted using various factorial combinations of inorganic

131 Fe and Mn (alongside silicate (Si) and zinc (Zn)), in addition to three different Patagonian dust sources
132 (35) (see Methods). Phytoplankton responses to amendment with Fe and/or Mn showed clear spatio-
133 temporal patterns coincident with in situ variability in the concentration of these metals and prevailing
134 phytoplankton bloom conditions, as influenced by physical setting (Fig. 1B) and indicated by
135 macronutrient drawdown and chlorophyll-*a* concentrations (Fig. 1C-E). Surface chlorophyll-*a*
136 concentrations (Fig. 1C, D) indicated a substantial bloom peaking shortly after the start of the cruise
137 in the southern half of the study region. Correspondingly, surface dissolved silicate (dSi) and Mn
138 (dMn) concentrations (Fig. 1E, F) decreased over time as the bloom progressed, particularly to the
139 south of the region. In contrast, dissolved Fe (dFe) concentrations (Fig. 1G) were more uniformly low
140 ($<0.1 \text{ nmol L}^{-1}$) in surface waters over the observation period.

141 The supply of Fe to incubation experiments significantly increased values of the fluorescence derived
142 parameter F_v/F_m in all experiments (Fig. 2 and Figs. S1, S4, S6), indicating widespread Fe limitation
143 of the efficiency with which extant phytoplankton were converting absorbed light energy to chemical
144 energy during photosynthesis (42). No serial responses (i.e., greater secondary or tertiary effects
145 following the addition of a second or third nutrient in combination, see Methods (43)) were observed
146 at the lower biomass northern OOI station, where dMn remained relatively high (dMn $>0.1 \text{ nmol L}^{-1}$)
147 (Figs. 1, 2 and Figs. S1-S6). In contrast, at stations TN and TS, toward the south of the SAZ, which
148 were characterized by elevated chlorophyll-*a* and rapidly depleting dMn and dSi concentrations (Fig.
149 1 E, F), phytoplankton experimental responses indicated Mn serial/co-stress within all experiments,
150 i.e., F_v/F_m was significantly increased following combined Fe and Mn addition compared with Fe alone
151 (irrespective of further addition of Si (i.e., $\pm\text{Si}$)). Importantly, the observed significant differences in
152 F_v/F_m between Fe($\pm\text{Si}$) and FeMn($\pm\text{Si}$) treatments were characterized by a drop in F_v/F_m within Fe($\pm\text{Si}$)
153 treatments from day 2 to day 6 (e.g., Fig. 2E). Moreover, a small but statistically significant increase
154 in F_v/F_m following sole addition of Mn($\pm\text{Si}$) was observable after 6 days at TS in Ex-L4 and in TN Ex-
155 L7 (Fig. 2F and S1).

156 Chlorophyll-*a* concentrations (Fig. 2 and Figs. S2, S5) and DIN drawdown (Fig. S3) increased
157 alongside F_v/F_m following Fe addition to all experiments. Serial responses to the further addition of
158 Mn and/or Si were always observed to the south of the study region at TN and TS, with the highest
159 chlorophyll-*a* increases and DIN drawdown occurring following the combined FeMnSi addition to
160 these experiments, despite no evidence of primary Si limitation. Our experiments thus indicated Fe-
161 Mn-Si serial limitation of the phytoplankton community in the south of our study region. In contrast
162 to Fe and Mn, that have an absolute requirement in photosynthesis (8, 19) no change in F_v/F_m or
163 biomass was observed following the addition of Zn within the two experiments where this was tested

164 (Fig. 3 and Figs. S4, S5). The absence of a Zn response may be potentially due to elevated in situ dZn
165 concentrations (Table S2) or the potential for metabolic substitution of some of the Zn requirement
166 with Co or Cd in carbonic anhydrase (44, 45).

167 Overall, our experimental data were consistent with serial Fe-Mn-Si limitation developing as both the
168 natural in situ bloom (Fig. 1) and artificially induced blooms within the experiments (Fig. 2) depleted
169 ambient Mn, expanding the growing evidence of an important role for Mn availability in Southern
170 Ocean productivity (4, 19, 32). Moreover, the spatial-temporal patterns observed in the experimental
171 responses were broadly predictable on the basis of the relative availability of dMn and dFe compared
172 with phytoplankton cellular requirements, as calculated using Mn_{Fe}^* ($= dMn - dFe/R_{FeMn}$, where R_{FeMn} ,
173 the assumed cellular molar stoichiometry of Fe:Mn, was taken as 2.67) (3, 4). Specifically, serial Fe-
174 Mn responses were only observed in the low (negative) Mn_{Fe}^* (signifying Mn deficiency) waters to
175 the south (Fig. 1), particularly following the peak of the bloom.

176

177 **Phytoplankton responses to Patagonian dust addition.**

178 Response to Patagonian dust addition revealed insights into the potential role of dust supply in
179 Southern Ocean phytoplankton ecophysiology across naturally occurring biogeochemical gradients.
180 For this study, dust samples included a subset of previously investigated glaciogenic (SMD13-3 and
181 PMG) and non-glaciogenic (CAR19) sources from Patagonia (35). After both 2 and 6 days incubation,
182 the addition of dust resulted in pronounced but varying responses in both F_v/F_m , biomass accumulation
183 and nutrient drawdown, with the glaciogenic SMD13-3 generally providing a stronger response than
184 either the other glaciogenic PMG or non-glaciogenic CAR19 sources (Figs. 2, 3, S4 and S5).

185 Addition of all the dust sources significantly increased F_v/F_m and chlorophyll-*a* after 2 days in all
186 except one experiment (Station OOI Ex-S8) (Figs. S4, S5). Of the three dusts, SMD13-3 promoted the
187 strongest responses, which were frequently comparable to the 2 nmol L⁻¹ inorganic Fe addition from
188 the same experiments (Figs. 2, 3). The stronger response to SMD13-3 addition corresponded with this
189 dust having the highest Fe content by mass (10% compared with 1.3 and 3.7% for PMG and CAR19,
190 respectively, Table S3), a significant fraction of which is comprised of Fe²⁺ silicates (35). Hence, Fe
191 mineralogy and solubility likely contributed to the stronger short-term (2-day) experimental responses,
192 as serial Mn responses were less apparent over these timescales (Fig. 2).

193 After 6 days, the addition of SMD13-3 to station OOI Ex-L5 increased F_v/F_m (Fig. 2) to values
194 comparable to the Fe additions, with no apparent serial Mn response. In contrast, the response to

195 SMD13-3 addition in station TN Ex-L7 was elevated above that of Fe(\pm Si) treatments and equal in
196 magnitude to the combined FeMn(\pm Si) additions. Moreover, unlike in the Fe(\pm Si) treatments, no drop
197 in F_v/F_m from 2 to 6 days was observed in the SMD13-3 dust treatment for TN Ex-L7. These
198 experimental biotic responses thus indicated that Mn released from SMD13-3 particles could alleviate
199 the observed serial Fe-Mn limitation of photochemical energy conversion. Similarly, and in contrast
200 with previous responses of a cultured diatom grown under Fe-deplete, Mn replete conditions (35), the
201 photophysiological response to the glaciogenic PMG dust source in station TN Ex-L7 was lower
202 relative to the non-glaciogenic CAR19 source. Dust addition also stimulated chlorophyll-*a*
203 accumulation (Fig. 2) and DIN drawdown after 6 days in a similar fashion to that observed for F_v/F_m ,
204 with differences in response again related to dust source. Specifically, the SMD13-3 dust provided the
205 largest change in biomass with lower responses to CAR19 and PMG additions. The change in biomass
206 was either comparable or less than that from Fe addition in all experiments. Decreasing biotic
207 responses to dust additions (SMD13-3 \gg CAR19 $>$ PMG), in particular within the serial Fe-Mn
208 limited Ex-L7 experiment (Fig. 2E, F), thus indicated variable amounts and/or kinetics of release of
209 both Fe and Mn.

210

211 **Differential phytoplankton responses linked to source region dust characteristics.**

212 To assess how Fe and Mn were released into seawater and how this may have driven the observed
213 biotic responses, we determined total element contents of the different dust sources and conducted
214 controlled abiotic leaching experiments designed to simulate the shipboard bottle experiments as
215 closely as possible. Measurable dissolved Fe and Mn was leached from each dust source by the 2-day
216 time point (Fig. 4). No further significant increase in measurable dFe or dMn occurred between days
217 2 and 6 (Fig. 4), consistent with the majority of labile Fe and Mn mobilizing rapidly following contact
218 with seawater (46-48). Typical crustal Mn/Fe ratios of less than 0.02 mol mol⁻¹ are expected to be
219 partially offset by fractional Mn solubility in atmospheric aerosols being around one order of
220 magnitude greater than for Fe (47, 49-51), due to much of the Fe in mineral particles being located
221 within refractory phases (52), combined with leached Fe²⁺ rapidly oxidizing to Fe³⁺ under oxygenic
222 conditions. Consistent with this, fractional solubilities within our experimental setup for Fe and Mn
223 were around 0.23 and 1.79 %, respectively, for the glaciogenic PMG source (Table S3), but were even
224 more extreme for the other two sources, with values of 0.05 % (Fe) and 7.29 % (Mn) for the glaciogenic
225 SMD13-3 source and 0.05 % (Fe) and 8.82 % (Mn) for the non-glaciogenic CAR19 source. The
226 SMD13-3 and PMG glaciogenic dust sources used in this study were more highly reduced (35), which

227 in addition to providing soluble Fe^{2+} , could also provide highly soluble reduced Mn^{2+} species.
228 However, the reason for the higher apparent Mn solubility for non-glaciogenic CAR19 is less clear.

229 Consistent with the SMD13-3 dust driving the strongest biotic experimental responses (Fig. 2), it was
230 the strongest source of both leachable dissolved Fe and Mn, releasing 0.84 and 4.64 $\mu\text{mol g}^{-1}$,
231 respectively (Fig. 4), equating to dissolved additions of 0.21 and 0.42 nmol L^{-1} dFe and 1.16 and 2.32
232 nmol L^{-1} dMn to our large and small volume experiments, respectively. Addition of dFe from SMD13-
233 3 to Ex-L7 at station TN was thus one order of magnitude lower than that of the inorganic Fe addition,
234 providing further support for the elevated F_v/F_m compared with that of Fe after 6 days incubation being
235 due to simultaneous Mn release (Fig. 2E, F). Indeed, the dissolved Mn/Fe leach ratio of 5.52 mol mol^{-1}
236 ¹ for SMD13-3 would have provided an excess of Mn relative to Fe and biotic requirements (3, 4, 53),
237 with an estimated Mn_{Fe^*} increase of 1.03 ± 0.09 (1SD) nmol L^{-1} .

238 A similar dissolved Mn/Fe leach ratio of 3.86 mol mol^{-1} was observed for the non-glaciogenic CAR19,
239 however the lower concentrations of both Fe and Mn released would have produced an Mn_{Fe^*} of
240 0.31 ± 0.02 nmol L^{-1} . In contrast, glaciogenic PMG released more Fe than Mn with a Mn/Fe leach ratio
241 of 0.32 mol mol^{-1} corresponding to a Mn_{Fe^*} of 0.00 ± 0.03 nmol L^{-1} . The relative release of Fe and Mn
242 from these natural dust sources was thus decoupled from the total mass content, due to highly variable
243 solubilities (Table S3), with the relative strengths of the biotic responses, particularly after 6 days
244 (Figs. 2, 3) SMD13-3 >> CAR19 > PMG, being relatable to the same sequence of higher absolute Fe
245 and Mn additions and higher Mn_{Fe^*} (Fig. 4).

246 Previous laboratory experiments that observed stronger responses to SMD13-3 and PMG than CAR19
247 under Mn replete, Fe deficient conditions were largely driven by the higher Fe^{2+} content of the
248 physically weathered glaciogenic sources (35, 38). However, within the Mn deficient ($\text{Mn}_{\text{Fe}^*} < \approx 0$)
249 waters of the southeast Pacific SAZ (Fig. 1H), the enhanced Mn supply from the glaciogenic SMD13-
250 3 and non-glaciogenic CAR19 drove the stronger response, highlighting the importance of both in situ
251 nutritional status of the community and the multi-trace-metal characteristics of any inputs in
252 determining system responses.

253

254 **Extrapolating experimental responses to wider scales.**

255 Care must clearly be taken in extrapolating experimental responses such as those presented here to
256 natural system responses to similar drivers (i.e., dust inputs) over different time and space scales (3, 4,
257 54-56). Our experimental dust additions were of comparable magnitude to modern total annual inputs

258 to the South Atlantic sector of the Southern Ocean, which are around two orders of magnitude higher
259 than deposition to the study region (Fig. 1A). Moreover, these experiments were monitored over a 6-
260 day time period in a closed system, which is very different to an in situ open system (54). Indeed,
261 differences in the extent to which the strongest combined Fe and Mn dust source (SMD13-3) could
262 fully reproduce the physiological (e.g., F_v/F_m) and biomass (e.g., chlorophyll) related biotic responses
263 to direct FeMn(\pm Si) addition from 2 to 6 days, were likely due to the order of magnitude lower Fe
264 input from the dust, combined with progressive responses, as artificial blooms proceeded in the bottles.
265 However, combined with other recent observations (4, 32), the progressive in situ development of Mn
266 (co-)deficiency (Fig. 1H) and serial limitation (Fig. 1J, K) during the bloom to the south of our study
267 region and clear biotic responses to dust related Mn inputs (Figs. 2, 3), clearly argue for consideration
268 of larger scale biogeochemical consequences.

269

270 **Biogeochemical implications.**

271 The flux of mineral dust into Southern Ocean waters is among the lowest found on Earth (50). Present
272 day dust inputs to the Southern Ocean from South America, South Africa and Australia follow the
273 circumpolar flow of the westerly winds, predominantly fertilizing surface waters of the Atlantic,
274 Indian, and Pacific sectors, respectively (40, 50, 57). The peak of dust deposition occurs during austral
275 spring and summer (24, 39), contributing to the SAZ mixed layer Fe and Mn inventories that already
276 hold the potential for FeMn (co-)limitation due to Mn deficiency relative to Fe, i.e., $Mn_{Fe^*} \leq 0$ (4, 6).

277 For the Southeast Pacific sector of the SAZ, we observed near zero or negative post-bloom Mn_{Fe^*}
278 values (Fig. 1H) similar to the Mn (co)-limited central Drake Passage (4). The source of dust, and by
279 association mineralogy, is therefore likely to be an important influence on productivity in the SAZ.
280 Specifically, the deposition of dust with high Mn/Fe leach ratios (e.g., SMD13-3, CAR19) would be
281 expected to strengthen regional Fe limitation and/or prevent development of Mn (co-)limitation, whilst
282 deposition of sources with lower Mn/Fe leach ratios (e.g., PMG) could strengthen Mn (co-)limitation,
283 particularly towards the end of seasonal growth.

284 Dust-derived Fe to the SAZ has been associated with atmospheric CO₂ drawdown during the last
285 glacial cycle (9, 13). In contrast to modern/Holocene dust transport, South America was the dominant
286 source of dust to the Pacific Southern Ocean during glacial periods (34). Such changes in source
287 provenance could directly affect the relative magnitude of Fe and Mn delivery, with cascading effects
288 on macronutrient utilization and CO₂ drawdown. Indeed, reconstructions estimate a ~15-fold increase
289 in Fe²⁺ supply to regions of the glacial Southern Ocean in comparison with interglacial periods,

290 suggesting a role for glacier-derived Fe fertilization in the observed declines in atmospheric CO₂ (41).
291 However, our data suggest that dust may be significant in providing both Fe and Mn as biologically
292 essential and potentially co-limiting micronutrients. The efficiency of dust-induced increases in glacial
293 macronutrient utilization and hence ultimately atmospheric CO₂ drawdown may thus have depended
294 on source region influences on both Fe and Mn supply (4, 19).

295 Despite uncertainty as to how anthropogenic climate change will modify global dust deposition rates
296 (16, 17), it has been proposed that the expansion of deserts and strengthening of winds could increase
297 Southern Hemisphere atmospheric dust loading by the end of the 21st century (18). Ocean
298 biogeochemical models also predict strengthening and poleward displacement of westerly winds over
299 the 21st century (58-60), further influencing dust mobilization and source regions. Given the proximity
300 to Southern Hemisphere dust source regions, any increase in deposition rates would likely be greatest
301 between 40 and 60° S.

302 The net effect of altered dust flux on Southern Ocean biogeochemistry further depends on additional
303 climate related changes. The balance between intensification and poleward displacement of westerly
304 winds acting to increase upwelling and subsurface nutrient supply versus warming and freshening of
305 surface waters that can act to increase stratification (58, 61) should determine whether mixed layer
306 productivity increases or decreases (20, 62). The relative importance of dust-borne supply of Fe and
307 Mn to the SAZ can thus be influenced by circulation related changes in the sub-surface entrainment
308 flux of both macro- and micronutrients. For example, the deficiency of both Fe and Mn in upwelling
309 circumpolar deep-waters (6) means that any regionally reduced sub-surface supply of these scavenged
310 micronutrients, potentially coupled with any increased atmospheric dust deposition, might be expected
311 to result in a higher biological pump efficiency, as defined by macronutrient utilization (3, 15, 63).
312 Changes in the magnitude of dust deposition, variations in source regions, and altered circulation
313 patterns could hence all combine to determine whether Fe or Mn limitation control productivity and
314 biological CO₂ uptake potential of the Southern Ocean under future as well as past climate states.
315 However, ocean biogeochemical models currently typically only consider dust deposition from the
316 perspective of Fe supply (9, 19, 64). Our results suggest that dust-borne Mn can have a significant
317 influence on Southern Ocean phytoplankton ecophysiology, emphasizing the need for the
318 incorporation of multi-element dust-driven fluxes in both past and future climate predictions.

319

320 **Materials and methods.**

321 **Voyage and seawater collection.** Experiments and sample collection were carried out on the *R.R.S.*
322 *Discovery* DY111 cruise (December 2nd 2019 – January 9th 2020), a component of the UK Carbon
323 Uptake and Seasonal Traits in Antarctic Remineralisation Depth (CUSTARD) project (Fig. 1). A total
324 of fifteen nutrient and dust addition experiments (Fig. 1 and S6) were conducted along the 89°W
325 meridian at 54°S (Station OOI), 57°S (Station TN) and 60°S (Station TS).

326 **Nutrient amendment experiments.** Eight smaller volume (2-6 day, denoted Ex-S1-S8) and seven
327 larger volume (6-day, denoted Ex-L1-L7) factorial nutrient amendment experiments were conducted
328 (Fig. S6), using similar methods to those employed previously in the HNLC Southern Ocean and
329 elsewhere (28-30, 43). Surface seawater (2-3 m) for experiments was pumped directly into a class-
330 1000 clean air laboratory container using a Teflon diaphragm pump (A-15, Almatec) connected by
331 acid-washed PVC tubing to a towed “Fish” sampler. For each experiment, seawater from the towed
332 fish was collected into either 2 L (Ex-S) or 4 L (Ex-L) acid-washed polycarbonate bottles. Bottles were
333 first filled in random order up to ~50% of total volume, before then being topped up, again in random
334 order. Samples for initial measurements (photophysiology, chlorophyll-*a* and macronutrients) were
335 collected at the beginning, middle (i.e., after all experimental bottles were ~50% full) and end of the
336 filling process. Separate replicate bottles were amended with single or combination additions of Fe,
337 Mn, Zn, and Si to final concentrations of 2 nmol L⁻¹ for each trace metal and 10 μmol L⁻¹ for Si. Control
338 bottles, with no added nutrients, were collected in parallel. Fe, Mn, and Zn were added as FeCl₃, MnCl₂
339 and ZnCl₂, respectively, prepared from ≥99% purity salts (Sigma-Aldrich) and stabilized in 0.024 M
340 HCl (SpA, Romil). The Si solution was prepared from Na₂SiF₆ salt (Sigma-Aldrich) and passed
341 through a column of cation exchange resin (Chelex-100, BioRad) to remove trace metal impurities.

342 Three small volume and two large volume experiments were chosen to investigate the physiological
343 response of resident phytoplankton communities to Patagonian dust amendment. Sediment samples
344 were prepared and sterilized per the methods described in Shoenfelt et al. (2017) (35) with the current
345 study also adopting the same sample names. Glaciogenic (SMD13-3 and PMG) and non-glaciogenic
346 (CAR19) sediment was added to separate incubation bottles by triple rinsing (using filtered surface
347 seawater) of the material from sterile 0.5 mL micro-centrifuge vials and was accompanied by replicate
348 controls whereby identical empty vials were rinsed into separate incubation bottles. No significant
349 differences were observed between controls and these separate dust treatment controls (Fig. 2 and Figs.
350 S4, S5). The addition of a fixed 1 mg mass of each dust source resulted in final additions of 0.5 and
351 0.25 mg L⁻¹ for small and large volume experiments, respectively. All experimental incubations were
352 conducted as biological triplicates, apart from Ex-S6 (all duplicates) and the dust additions to Ex-S8,
353 Ex-L5, and Ex-L7 that were also duplicates. Following nutrient amendment, the bottles were externally

354 sealed with film (Parafilm™) and incubated in a temperature-controlled container set to local sea
355 surface temperature (5.5 – 7.0 °C during the study) and surrounded by daylight simulation LED light
356 banks with ~200 $\mu\text{mol photons m}^{-2} \text{ s}^{-1}$ flux and set to an approximate local day/night cycle of 16 and
357 8 h, respectively.

358 **Sub-sampling.** All experimental bottles in every experiment were sub-sampled for the same set of
359 variables measured for initial conditions (photophysiology, chlorophyll-*a* and macronutrients) after 48
360 hours (2 days) in the clean air laboratory, at which point six of the eight small volume experiments
361 (Ex-S1-S3 and S6-S8) were terminated. To allow for any potentially slower photophysiological and
362 growth response to Zn addition, Ex-S4 and Ex-S5 were allowed to incubate for a further 4 days at
363 which point (i.e., day 6) they were sampled for a second and final time. All the larger volume
364 experiments (Ex-L1-L7) were sub-sampled at 2 days and terminated after 6 days following a second
365 and final sampling.

366 **Phytoplankton photosynthetic physiology.** Variable chlorophyll fluorescence was measured using a
367 Chelsea Scientific Instruments Fastracka™ Mk II Fast Repetition Rate fluorimeter (FRRf) integrated
368 with a FastAct™ laboratory system. Samples (~125 mL) were dark-acclimated for 30 minutes in
369 opaque bottles (Nalgene) and FRRf measurements were blank corrected using carefully prepared 0.2
370 μm filtrates and 18.2 M Ω -cm ultrapure water for each experiment (28). Blanks contributed 2 ± 1 %
371 ($n=15$) of the maximum fluorescence signal during this study. Protocols for FRRf measurements and
372 data processing were similar to those detailed elsewhere (28). Data from the FRRf was analyzed to
373 derive values of the minimum and maximum fluorescence (F_o and F_m , respectively) and the apparent
374 photochemical efficiency of photosystem II (PSII), F_v/F_m (where $F_v = F_m - F_o$) (65). A phytoplankton
375 response from the nutrient or dust amendment experiments was represented by a significant increase
376 in F_v/F_m over that of the control bottles.

377 **Chlorophyll.** Samples for Chlorophyll-*a* analysis (~100 mL) were filtered onto 0.7 μm nominal
378 porosity GF/F filters and extracted into 90% acetone for 24 hours in the dark at 4 °C prior to
379 measurement. Chlorophyll-*a* concentration was determined on a pre-calibrated Turner Designs Trilogy
380 fluorometer (66) whilst at sea within 48 hours of collection.

381 **Macronutrients.** The dissolved concentrations of macronutrients phosphate (PO_4^{3-}), silicate (SiO_2 ; as
382 Si hereafter), and nitrate (determined as nitrate + nitrite) were measured onboard ship within 24 h of
383 sample collection using a SEAL QuAAtro 39 segmented flow auto-analyser following colorimetric
384 procedures provided by SEAL Analytical (Q-064-05, Q-066-05, Q-068-05). Certified Reference

385 Materials (CRM Lots CJ and CB, KANSO, Japan) were used to check for accuracy of the method with
386 excellent agreement.

387 **Trace metals.** Seawater samples for ambient dissolved trace metal determination were collected from
388 the towed “Fish” sampler during the “filling” stage of each experiment, alongside experimental initial
389 samples. Seawater was filtered through 0.2 µm porosity membrane cartridge filters (Sartobran,
390 Sartorius) into trace metal-clean 125 mL low density polyethylene bottles and acidified to pH 1.7
391 (0.024 M) by addition of 12 M ultrapure HCl (UpA, Romil) under a class-100 laminar flow hood in
392 the clean air container. Samples were double bagged in polyethylene bags and stored for analysis.
393 Dissolved trace metal concentration was determined using a standard addition method (67, 68) with
394 off-line pre-concentration and subsequent high resolution ICP-MS (69, 70) at the National
395 Oceanographic Centre, Southampton, UK. Certified values for SAFe (S and D2) reference material
396 compared well with our measured values (Table S1).

397 **Dissolution experiments.** Dust leaching experiments were designed to replicate dust addition to the
398 bioassay experiments as closely as possible. Leaching experiments were performed after the cruise
399 inside a class-1000 clean air laboratory at the National Oceanographic Centre, Southampton, UK,
400 under controlled physico-chemical conditions (12 h light/dark cycles, ~ 25° C) using filtered Southern
401 Ocean surface seawater collected from the “Fish” sampler during DY111 (-56.9° S, -88.7° E).
402 Glaciogenic (SMD13-3 and PMG) and non-glaciogenic (CAR19) sediment was added to 1.5 L of
403 seawater in 2 L acid-washed and well rinsed polycarbonate bottles according to the methods outlined
404 for the nutrient amendment experiments. Sub-samples for dissolved trace metal analysis were taken
405 after 2 and 6 days by filtration through acid-washed 0.2 µm pore size, 25 mm polycarbonate track-
406 etched membrane filters (Nuclepore, Whatman) before acidification (0.024 M) by addition of 12 M
407 ultrapure HCl (UpA, Romil). The filtration manifold consisted of acid-cleaned PTFE manifold tubing
408 and PVC peristaltic pump tubing. A new filter was used for each sub-sample. Dissolved trace metals
409 in sub-samples from the dissolution experiment were analyzed at the same time as for the DY111
410 ambient samples. Whilst metal adsorption to bottle walls may occur over a 2-day period (71), this
411 effect would have been minimized through the large surface area to volume ratio of our experiment
412 bottles, whilst reasonably rapid establishment of equilibrium occurred, as we measured no significant
413 change in either Fe or Mn between two and 6-day time points.

414 **Dust particle digestion.** Dust samples were fully digested after the cruise following recommended
415 GEOTRACES protocols (72). Briefly, the samples were transferred into trace metal-clean
416 perfluoroalkoxy vials (Savillex) under a laminar flow fume hood in a class-100 clean laboratory, into

417 which 1 mL of digest solution (50% HNO₃ + 10% HF, v/v, Optima Grade, Romil) was pipetted. Vials
418 were refluxed at 135 °C for 4 hours and then evaporated to near dryness. Once cooled, 100 µL of
419 concentrated HNO₃ was added to each vial and the samples dried down again. Samples were re-
420 dissolved in 3 mL of 5% HNO₃ solution (spiked with 1 ppb indium as a drift monitor) and refluxed at
421 135 °C for 1 hour. A 0.5 mL aliquot of each sample was diluted to 3 mL with the same 5% HNO₃
422 solution in trace metal-clean, polyethylene Omni-vials (DWK WheatonTM), for analysis by HR-ICP-
423 MS (Element XR – Thermo ScientificTM) at the National Oceanography Centre, Southampton, UK.

424 **Statistical analysis of experimental results and interpretation of ‘(co-)limitation’.** Differences
425 between the various response variables within the experiments were assessed using ANOVA followed
426 by a Bonferroni means comparison test ($p < 0.05$). We adopt a similar definition framework for different
427 ‘types’ of ‘(co-)limitation’ as previously (3, 43, 73), noting that evidence of both serial and independent
428 responses frequently occurred, sometimes within the same experiment (e.g., Fig. 2 and Figs. S1-S3).
429 Moreover, we differentiate at points in the text between stress (a physiological response to
430 environmental change, e.g., F_v/F_m increasing following amendment with a nutrient indicating lower
431 nutrient stress) and ‘limitation’ (e.g., biomass or equivalently net growth rate increases following
432 amendment with a nutrient indicating lowered nutrient limitation) (43). We note that although the
433 former (i.e., a physiological response) is clearly a necessary precursor for the latter, they are not
434 synonymous and are timescale dependent (3). However, all provide evidence for multi-nutrient
435 influence on phytoplankton ecophysiology.

436

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597

598

599 **Figure 1. Biogeochemical setting and spatiotemporal development of Fe and Mn (co-)limitation.**

600 (A) Annual mean dust deposition ($\text{g m}^{-2} \text{y}^{-1}$) in and around the Southern Ocean (24) alongside (B)
601 December 2019 mean sea surface temperature and (C) chlorophyll-*a* concentration (Modis AQUA at
602 4 km resolution) for the study region (red trapezoid in 1A). (D-I) Hovmöller diagrams (time against
603 latitude) showing in situ biogeochemical progression during the DY111 cruise for sea surface
604 chlorophyll-*a* (D), silicate (E), dMn (F), dFe (G), Mn_{Fe}* (H), *F_v/F_m* (I). (J-K) Summarized
605 experimental responses (larger volume experiments after 6-days) to nutrient addition as indicated by

606 changes in F_v/F_m (J) and chlorophyll-*a* (K). Symbol colors indicate the identity and type of limitation,
607 see Figs. S1-S3 (43). Locations of the larger type experiments are labelled in J, see Fig. S6 for all
608 experimental times / locations.

609

610 **Figure 2. Example responses of phytoplankton ecophysiology to nutrient and dust additions.** (A-
611 B, E-F) Apparent photochemical efficiency of PSII (F_v/F_m) and (C-D, G-H) chlorophyll-*a* response
612 to nutrient and dust amendment in Ex-L5 at OOI (A-D) and Ex-L7 at TN (E-H), respectively. For
613 clarity only a subset of the nutrient and dust additions are shown in the time series A, C, E, G, with the
614 day 6 data for all treatments included in B, D, F, H. Symbols for all panels are indicated in C. Large
615 open circles in A, C, E, G indicate initial values. Means (± 1 standard deviation) are indicated in all
616 panels, with individual data points also provided (small symbols) for B, D, F, H. Statistically
617 indistinguishable means evaluated across all treatments in full factorial manner are labelled with the
618 same letter (analysis of variance (ANOVA) followed by Bonferroni post-hoc means comparison test
619 $P \leq 0.05$).

620

621 **Figure 3. Change in apparent photochemical efficiency of PSII ($\Delta F_v/F_m$) and net growth rates**
622 **(μ) in response to nutrient and dust amendment across all experiments.** Delta notation (Δ)
623 indicates change relative to the values in control bottles. Data shown here correspond to the mean
624 responses ($n=2-3$) from all treatments across all bioassay experiments.

625

626 **Figure 4. Patagonian dust dissolution.** Mean (± 1 standard deviation) of dissolved (0.2 μm) trace
627 metal concentrations per unit mass added resulting from leaching of glaciogenic (SMD13-3, PMG)
628 and non-glaciogenic (CAR19) Patagonian dusts into ambient Southern Ocean seawater. Colored
629 circles represent experimental duplicates.

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