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Mesoscale eddies and the impact of coastal iron supply on primary production in the South Pacific Subtropical Front

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ABSTRACT

24 Subtropical and Subantarctic waters either side of the southern hemisphere 25 Subtropical Front are considered iron-limited, suggesting production within the front 26 is dependent on a supply of iron from atmospheric deposition, zonal advection of 27 coastal water, or upwelling. We present the results from a one-day biogeochemical 28 survey in Subtropical Water east of the North Island, New Zealand, in a region where 29 mesoscale cyclonic and anticyclonic eddies entrain chlorophyll in filaments around 30 the eddies. There was no significant relationship between upper-mixed layer 31 chlorophyll and any physical or macronutrient quantity. However, chlorophyll was 32 significantly positively correlated with dissolved iron. A simple model suggests that 33 while vertical entrainment of iron into the upper mixed layer occurred, most of the 34 dissolved iron in the eddy was due to entrainment of high-iron coastal water into low-35 iron offshore Subtropical Water, and that this iron supports primary production in 36 otherwise iron-deficient water. We suggest that a significant component of the total 37 primary production within the STF may be determined by mesoscale eddy induced 38 lateral advection of iron.

39

40 Keywords: Iron supply; Neritic water; Subtropical water; Primary production; South-

- 41 west Pacific Ocean; New Zealand
- 42

1. Introduction

43 Primary production at subtropical latitudes in the South Pacific Ocean is 44 determined by the nutrient and physical characteristics of two main surface water 45 masses in the region. To the south, Subantarctic Water (SAW) is recognised as high 46 nitrate-low chlorophyll water (HNLC) where surface summer and winter nitrate concentrations are typically 7 and 15 mmol m⁻³, respectively (Johnson et al., 2017), 47 yet mean sea surface chlorophyll (SSC) is typically only 0.3 mg Chl m⁻³ (Banse and 48 49 English, 1997). SAW is considered iron-limited (Abraham et al., 2000; Boyd et al., 50 1999; Boyd et al., 2000), and it is often concluded that overall production in SAW 51 depends on the input of dissolved iron (dFe). To the north, Subtropical Water (STW) 52 is regarded as being at least seasonally, if not year round, oligotrophic, where surface nitrate concentrations are typically <2.5 mmol m⁻³ year round (Chiswell et al., 2022; 53 54 Ellwood et al., 2018). Although STW has not been as well studied as SAW, it is also 55 likely to be seasonally depleted in dFe both in the western (Ellwood et al., 2008) and 56 eastern (Blain et al., 2008) South Pacific Ocean.

57 These two water masses meet at the Subtropical Front (STF), which spans the 58 globe near 40°S, and is a region of high primary production, where the mean SSC can exceed 0.75 mg Chl m⁻³ (Figure 1a). Since both STW and SAW are probably iron-59 limited, primary production in the STF is likely to be supported by an influx of dFe. 60 61 Three commonly discussed candidates for iron enrichment in the ocean are 62 atmospheric deposition (e.g. Jickells and Moore, 2015), zonal advection of high-iron 63 neritic water (e.g. Boyd et al., 2012; Ellwood et al., 2014; Graham et al., 2015), and 64 mesoscale-eddy driven vertical pumping (e.g. Uchida et al., 2020), and it seems that 65 primary production along the STF must be controlled by some combination of these three mechanisms. Since mean SSC tends to show higher values closer to land (Figure 66 67 1a), the two most likely mechanisms would appear to be atmospheric deposition and 68 zonal advection. However, there is no consensus on which mechanism dominates, and 69 there is not yet a complete understanding of the role of iron in STF production.

The mean circulation east of the North Island is dominated by the warm-core anticyclonic Wairarapa Eddy, which recirculates STW from the northern edge of the STF so that there is a region of enhanced SSC extending from East Cape to the Chatham Islands (Figure 1b). Mean SSC is depressed at the centre of the eddy, and this depressed biomass has been related to the deeper mixed layer in the eddy centre limiting primary production (Bradford et al., 1982; Waite et al., 2007). However, this
picture is only true in the mean, and at any given time, the region is dominated by a
complex pattern of anticyclonic and cyclonic mesoscale eddies likely shed near the
East Cape and propagating south (Chiswell, 2005).

During September-October 2012, a two-week cruise was made east of the North Island, New Zealand, to investigate the role of iron in the evolution of the spring bloom in STW. The spring bloom was not spatially heterogeneous, and a satellite image transmitted to the ship showed that SSC in the region was dominated by eddy mixing, with filaments of high SSC entrained around mesoscale eddies. As a result of this image, a one-day survey was designed to investigate an anticyclonic eddy and its impact on production.

86 This article presents the results of this survey, where we found no discernible 87 differences in the water mass properties, mixed-layer depths, or macronutrient 88 concentrations between regions of high and low SSC in and around the eddy. The 89 only measurable differences were that dFe was higher in regions of high SSC and 90 where the upper mixed layer was deeper. A simple model suggests that while vertical 91 entrainment of iron into the upper mixed layer occurred, most of the dissolved iron 92 signal was due to the eddy entraining high-iron coastal water into low-iron offshore 93 Subtropical Water, and that near-surface chlorophyll was a response to this iron. The 94 resulting implication is that a significant component of the total primary production 95 within the STF is determined by mesoscale-eddy induced zonal advection of iron.

2. Data and Methods

The cruise was made to the study site east of the North Island, nominally at
180°E, 39°S (Figure 2) from mid-September until early October 2012 to study the
2012 spring bloom. Details of the cruise and the results, including the bloom
development, are given in Chiswell et al. (2019).

100 The one-day survey track was based on a MODIS image of 30 September 101 (Figure 3) showing an anticyclonic eddy centred near 180°E, 39°S (labelled A₁ in 102 Figure 2). The survey track started near the centre of the eddy as suggested by the 103 surface chlorophyll pattern, and was then made about 50 km to the north/north-west 104 before returning to the eddy centre. Data from a shipboard ADCP were used to determine near-surface ocean velocity and used to guide the survey in locating theeddy centre.

Both vertical profiles from CTD casts, and near-surface underway data from a
towed-fish and the ship's sea chest instrumentation were collected.

- 109 Twelve CTD casts were made, from 03:30 on 2 October until 04:30 on 3
- 110 October (New Zealand Standard Time), 4 casts (2 through 5) were made during
- 111 daylight, one cast (6) was made in twilight while the rest were made during the night.
- 112 The CTD casts were made using a standard SeaBird 911 and carousel water sampler.
- 113 Temperature, salinity, transmissivity, photosynthetic active radiation (PAR), and
- 114 fluorescence profiles were measured to at least 350 m depth. Water samples for
- 115 chlorophyll extractions and nutrient analyses were collected on up-casts using 24 10-L
- 116 Niskin bottles mounted on the CTD rosette.

117 Chlorophyll derived from the CTD fluorometer was compromised by non-118 photochemical quenching (e.g., Carberry et al., 2019) during the daylight casts, so the 119 CTD fluorometer data are not used in the analysis. Instead, following Bishop (1999), 120 particulate organic matter (POM) was taken to be negatively proportional to the beam 121 attenuation coefficient, *c*, derived from the CTD transmissometer as $c = \ln(T_r)/r$, 122 where T_r is the transmissivity, and *r* is the path length. With no local calibration 123 between POM and *c*, POM was normalised to have a maximum value of 1.0. A

124 comparison of POM and CTD-derived chlorophyll (Chl) from night-time casts (to

125 avoid quenching issues) for depths 5> 30 m over the entire 2-week cruise indicated a

- 126 not quite linear relationship ($r^2 = 0.89$, Figure 4g). To the extent that Chl is an
- 127 indicator of biomass, this supports the assumption that POM can be taken as a proxy
- 128 for phytoplankton biomass.

129 The one-percent light level for each daylight cast was computed by fitting an 130 exponential decay with depth function, $I = I_{sfc} \exp(-k \times z)$ to each PAR profile, and 131 computing the one-percent light level as $Z_{100} = \ln(0.01)k$.

Macronutrients from the CTD up-cast samples were determined using an
automated micro-segmented flow analyser with digital detection (Pickmere, 1998).
The standard error in the automated analyses for each nutrient was estimated as the
standard deviation of samples taken over a 6-hour night-time period earlier during the

136 two-week cruise when the ship was on station. These overall standard deviations were 137 0.390, 0.064, 0.23 and 0.093 µmol L⁻¹ for nitrate, phosphate, silicate and ammonium, 138 respectively. All indicators suggested variations seen in nutrient profiles were outside 139 the error for individual measurements.

- Near-surface dFe was measured from sea water pumped from a towed 'tracemetal fish', and was determined using flow injection analysis (Floor et al., 2015;
 Obata et al., 2002). Further analytical details are described in Ellwood et al. (2015).
- Continuous near-surface measurements of temperature, salinity and
 fluorescence were made with a thermosalinograph (Seabird 38 and 21 sensors) and
 fluorometer (Wetlab ECO triplet) in the ship's sea chest. The sea chest also contained
 an inline Fast Repetition Rate Fluorometer (Chelsea Instruments FASTtracka FRRF)
 that provided measurements every 2 minutes of near-surface minimum (F_o) and
 maximum (F_m) fluorescence in the dark-acclimated state.
- 149 There was almost certainly some NPQ in the FRRF fluorescence (F_o and F_m), 150 however, two extracted chlorophyll measurements from water samples during the 151 survey agree well with F_o (see Figure 8), and here, F_o is used as a proxy for near-152 surface phytoplankton biomass (e.g., Ellwood et al., 2015).
- 153 The Moderate Resolution Imaging Spectroradiometer (MODIS, Esaias et al.,
- 154 1998), launched in 2002 provides satellite-derived estimates of sea surface
- 155 chlorophyll. Data used here were downloaded on land in near real time from the
- 156 Ocean Color website (https://oceancolor.gsfc.nasa.gov/) and transmitted to the ship157 once per day.
- Daily estimates of surface currents were obtained from the AVISO (Archiving,
 Validation and Interpretation of Satellite Oceanographic data).
- Least-squares regressions between various quantities were performed using
 Matlab's fitlm.m routine, which provides p-values, assuming that the number of
- 162 degrees of freedom equals the data length minus 2. Linear regression slopes are
- 163 considered significant if p < 0.05.

3. Results



185 **3.2 Physics of Eddy A1**

The MODIS image of 30 September (Figure 3) showed clear evidence of anticyclonic eddy A1 centred near 180°E, 39°S. Unfortunately, the considerable cloud cover (typical for New Zealand) meant the next clear image was not until 2 October, i.e. after the survey had been started. SSC had evolved into a quite different looking feature by 2 October, and little information can be gleaned on how this change evolved – whether, for example, it was due to the eddy fragmenting and disappearing or whether growth in SSC obscured the eddy. 193 All twelve CTD casts made in the survey had a shallow upper mixed layer 194 between 15 and 40 m thick sitting over a near-isopycnal layer that extended to 195 between 250 and 350 m depth (Figure 4). For all casts, except cast 7 (which was the 196 most inshore station) this deep mixed layer had density, $\sigma_t = 26.499 \pm 0.001$ kg m⁻³ 197 (there was a 0.055 °C and 0.01 range in temperature and salinity in this layer).

198 This near-isopycnal deep layer was almost certainly a remnant mixed layer from 199 the previous winter mixing, whereas the upper mixed layer reflects the emergence of 200 new stratification in the spring. Density differences between the upper and remnant mixed layers ranged between 0.07 and 0.17 kg m⁻³ (Figure 4c). Thus using the 201 common 0.125 kg m⁻³ density difference criterion for mixed layer depth (e.g., Kara et 202 al., 2000) would sometimes place the mixed layer as the upper mixed layer and 203 204 sometimes as the remnant mixed layer. Here, the upper mixed layer depth (uMLD) was defined as the depth where the density exceeded the surface value by 0.05 kg m^{-3} , 205 206 and the remnant mixed layer depth (rMLD) was defined as the depth where the 207 density exceeded the 200m value by 0.05 kg m^{-3} .

The upper mixed layer was on average 0.36°C warmer and 0.017 fresher than the remnant mixed layer. Temperature in the upper mixed layer ranged from 13.58 to 13.93°C, and while the warmest temperature was from noon on 2 October, any effects of diurnal heating were aliased by spatial variations in the temperature field since the second-warmest temperature was from 03:30 on 2 October.

213 Gridded upper and remnant mixed layer depths are shown in Figure 5, along 214 with the velocities at 10-m and 100-m derived from the ADCP. The 100-m velocities 215 are from near the top of the remnant mixed layer, but are at the depth limit of the 216 ADCP and are noisier than the 10-m velocities. Velocities from both levels show 217 anticyclonic circulation. The remnant mixed layer was deeper at the centre of the eddy (Figure 5b), consistent with anticyclonic eddies, reflecting the fact that these eddies 218 219 extend to near the sea floor (Chiswell, 2003). The uMLD was negatively but not significantly correlated with rMLD (slope = -0.1, $r^2 = 0.24$, p-value =0.1). 220

221 The ADCP velocities indicate the anticyclonic eddy was at least ~30 km in 222 radius with speeds at 10 m depth being ~0.4 m s⁻¹ at the northern edge of the survey 223 (Figure 5). The vorticity ζ calculated from the 10-m velocities was 1.4×10^{-4} s⁻¹ 224 leading to a Rossby number $R_o = \zeta / f$ of -0.16, which puts this eddy into the mesoscale class (i.e. $|R_o| << 1$), thus, geostrophy approximately holds, the flow is twodimensional and the magnitude of the vertical velocity is several orders of magnitude smaller than the horizontal velocities (Mahadevan, 2016).

A 3-D view (Figure 6) shows the eddy from a different perspective, and shows the relatively thin warm fresher upper mixed layer sitting over the deeper remnant mixed layer that is warmer and more saline near the centre of the eddy. The remnant mixed layer was deepest near Casts 2 and 10 with shallowest values near the edge of the survey (Casts 6 and 8), whereas the upper mixed layer was shallowest near Cast 2 and deepest near Casts 6 and 8.

234 **3.3** Chlorophyll distribution within Eddy A1

235 Chlorophyll profiles from the CTD fluorometer (Figure 4d) show NPQ above 236 about 30 m depth in casts made during the day. However, POM was well-mixed in the 237 upper mixed layer in all casts (Figure 4e), likely due to wind-mixing from strong 238 winds on 1 October (see Chiswell et al., 2019). This suggests that all biological 239 quantities (i.e. phytoplankton, dFe, and nutrients) were well mixed in the upper mixed 240 layer, and that near-surface values (in particular, the towed-fish and sea-chest data) 241 well represent upper mixed layer values.

The mean one-percent light level during the survey was 60 m, indicating that all upper mixed layers were shallower than the euphotic zone. In every cast, POM was elevated in the upper mixed layer and then decayed with depth to reach values 0.05 to 0.09 in the remnant mixed layer. POM in the upper mixed layer (hereafter, POM_u) ranged from 0.57 to 1.0, and visually separates into two groups, which we term highand low-POM groups, having mean POM_u values of 0.88 and 0.63, respectively (Figure 4e).

There is little correlation between POM_u and any physical variable. Inspection of Figure 4 shows there is no immediately obvious relationship between POM group and temperature, salinity, or density. The two warmest, freshest, and lightest upper mixed layers were high-POM, but so too was the coolest, most saline, and densest upper mixed layer. There is also no clear relationship between POM_u and uMLD, for example, two high-POM casts had the shallow uMLD, but other high-POM casts had deep uMLD.

- Least-squares regressions between POM_u and upper mixed layer temperature or salinity return non-significant results with low correlation-squared ($r^2<0.1$, p>.1, not shown). There is also no statistically significant relationship between POM_u and either uMLD or rMLD ($r^2 \sim 0$, p>0.1, not shown).
- Much of the reason for these low correlations is because (as is illustrated in the 3-D view of the eddy, Figure 6d), POM was high both near the centre of the eddy (casts 2 and 3 with high upper layer T and S, and shallow uMLD) as well as on the flanks of the eddy (casts 6 to 8 with low upper layer T and S, and deeper uMLD).

264 Figure 7 shows the macronutrient concentrations (NH₄, NO₃+NO₂, PO₄, SiO₄) 265 as a function of depth, colour-coded by POM group. Unfortunately, the depth levels 266 for the nutrient sampling were pre-determined before the survey, and the 30-m level 267 falls near the base of the upper mixed layer in many casts (see Figure 4), which complicates interpretation (i.e. not all these 30-m nutrient values were unambiguously 268 269 from the upper mixed layer). There is considerable scatter, but most macronutrients 270 increased with depth. At 10 m depth (which is the only level consistently in the upper 271 mixed layer), NO₃+NO₂ and PO₄ showed lower values for the casts that had high 272 POM_u, which would be consistent with the uptake of these nutrients by 273 phytoplankton, but SiO₄ and NH₄ show no evidence of uptake.

274 While Chl and POM_u from the CTD casts, and F_o from the FRRF are all proxies 275 for phytoplankton biomass, Fo is the more useful proxy to compare with dFe because 276 of its more frequent sampling, and it is worth demonstrating that F_o correlates well 277 with the other measures of phytoplankton biomass. Surface chlorophyll from the 278 night-time CTD casts and POM_u from all casts align well with F_0 (r² values of 0.74 279 and 0.38, and p-values of 0.007 and 0.033, respectively, Figure 8a). Similarly, Fo and 280 POM_u both compare well with SSC from the 2 October MODIS image (which was 281 taken about the time cast 4 was made). There are some discrepancies, but except for 282 the last two casts (by which time the satellite image was 12 to 16 hours old), high F_o 283 and POM_u generally overlie regions of high SSC, and low F_o and POM_u overlie 284 regions of low SSC (Figure 8b).

Figure 9a presents F_o along with dFe from the tow fish. The ship passed through a region of elevated phytoplankton biomass during the morning of 2 October, followed by low biomass in the afternoon and then elevated biomass during the night 288 (these are the regions near the centre and on the flanks of the eddy seen in Figure 6).

289 A least-square regression (with F_o values interpolated to the dFe sample times)

suggests that dFe is positively correlated with F_o ($r^2 = 0.27$; p = 0.006, Figure 9d).

291 That dFe is correlated with phytoplankton biomass is also illustrated when dFe is

superimposed on satellite SSC where high values of dFe coincide with high SSC

293 (Figure 8b).

Dissolved iron, dFe, is correlated with uMLD ($r^2 = 0.18$; p = 0.03, Figure 9b, e), although since the operational procedure was to deploy the trace-metal tow fish between the CTD casts, the dFe values were taken in slightly different locations, and there is the possibility that small-scale patchiness confounds this relationship. Because dFe increases with depth (Chiswell et al., 2019, Figure 4), this suggests that part of the dFe signal could be due to entrainment of higher-dFe water as the upper mixed level deepened.

301 The upper mixed layer depth and F_o were uncorrelated ($r^2=0.01$; p=0.175, not 302 shown), so they can be used as independent variables in a linear predictor to estimate 303 dFe,

304
$$dFe_{est} = a \times uMLD + b \times F_0 + c$$

305 A multiple least-squares linear regression using the data shown in Figure 9, returns a $= 0.003 \pm 0.0018$ nmol L⁻¹ m⁻¹ and $b = 0.37 \pm 0.14$ nmol L⁻¹, and $c = -0.18 \pm 0.10$ nmol 306 L^{-1} , with an overall p-value of 0.005. A fit with uMLD and F₀ de-meaned and 307 308 normalised by their respective standard deviations, returns $a = 0.019 \pm 0.01$, b = 0. 025 ± 0.1 , and $c = 0.17\pm0.1$, indicating that the contribution to iron uptake/loss by 309 310 normalised fluorescence variations is about 1.3 times that of normalised mixed layer 311 depth variations. Whether computed dimensionally or non-dimensionally, the fit, dFe_{est}, accounts for 36% of the variance in dFe (Figure 9f). The implications of this 312 fit are discussed in detail later, but for now we simply comment that positive *a* is 313 consistent with entrainment of high-dFe water from depth, whereas positive b is 314 315 unexpected since one might expect uptake of iron to lead to negative b.

4. Discussion

The remnant mixed layer in eleven of the twelve casts had near-identical density $(\sigma_t = 26.499 \pm 0.001 \text{ kg m}^{-3})$, suggesting that the deeper water within Eddy A₁ had a 318 common origin. This eddy was likely formed near East Cape where one to two eddies 319 are shed per year that propagate south-west, but are topographically blocked by the 320 Chatham Rise so that in the mean, the circulation is as shown in Figure 1 (Chiswell, 321 2005). The CTD casts were made only to 500 m at most, so that the full water-column 322 baroclinic structure of eddy A₁ cannot be determined from this survey. However, the 323 mean Wairarapa Eddy extends to at least 1000 m depth (Roemmich and Sutton, 324 1998), and individual mesoscale eddies are as deep (Chiswell, 2003), hence the 325 observation that the remnant mixed layer structure is consistent with anticyclonic 326 rotation (i.e. deeper mixed layer in the centre of the eddy, Figure 5). The shallow 327 upper mixed layer (mean depth = 30 m) had negligible impact on the circulation.

328 The upper mixed layer during the survey was on average 0.37°C warmer and 329 0.019 fresher than the remnant mixed layer. This temperature difference is similar to 330 that seen earlier in the cruise as the ocean became warmer and began to stratify 331 (Chiswell et al., 2019). The decrease in salinity in the upper mixed layer can be 332 accounted for by local precipitation exceeding evaporation (0.01m of rain would lead 333 to about 0.01 salinity decrease if mixed over a 30-m upper mixed layer). Thus, the T-334 S properties of the upper mixed layer were likely to have been heavily modified by 335 recent heating and rainfall, and so cannot be used to determine if regions of high- and 336 low-POM were of coastal vs offshore origin (or vice-versa).

337 In every cast, the upper mixed layer showed more POM than in the remnant 338 mixed layer (Figure 4e), indicating more phytoplankton biomass in the upper mixed 339 layer. A complete analysis of this production is beyond the scope of this article, 340 however, higher phytoplankton biomass in the upper mixed layer is broadly consistent 341 with the Onset of Stratification model for spring blooms (Chiswell, 2011), but the lack of correlation between POM_u or F_o with either depth or temperature of the upper 342 343 mixed layer suggests that the amount of phytoplankton biomass in the upper mixed 344 layer cannot be ascribed to the age (assuming that a cooler upper mixed layer is 345 formed more recently than a warmer upper mixed layer), or depth of the upper mixed 346 layer. In other words, it seems unlikely that regions of low-biomass had stratified 347 more recently or were earlier in the spring bloom cycle than regions of high-biomass.

348 Apart from a suggestion of nitrate and phosphate uptake, there was no349 statistically significant relationship between phytoplankton biomass in the upper

mixed layer and macronutrients, although this lack of relationship may well have beendue more to the lack of vertical nutrient sampling.

352 There was also no statistically significant relationship between upper mixed 353 layer chlorophyll or POM and the remnant mixed layer depth. At first glance, this 354 may not be surprising since it is unlikely that a mixed layer some 200-300 m below 355 the upper mixed layer has a role in determining the upper mixed layer production. 356 However, it has been suggested (Uchida et al., 2020) that vertical velocities associated 357 with mesoscale eddies can bring iron-rich water from depth into the mixed layer 358 where it can be consumed by phytoplankton, and their model simulations show much 359 higher dFe in eddy-rich areas. Crucially, however, within their eddies they found a 360 negative relationship between dFe and phytoplankton biomass, which we did not see, 361 so while we cannot exclude such a mechanism from playing a role, it seems unlikely 362 that it is the dominant mechanism driving the production within the eddy field in our 363 study.

The only significant relationships we could find here were between dFe and chlorophyll or POM, and between dFe and upper mixed layer depth, with a simple linear model accounting for 36% of the variance in dFe.

While dFe was not measured within the remnant mixed layer during this survey, three days earlier in the cruise it was about 0.35 nmol L⁻¹ (see Figure 4 in Chiswell et al., 2019). About 18% of the near-surface dFe variance can be explained by deepening of the upper mixed layer, and to the extent that the uML deepens through vertical mixing, this suggests entrainment of high-dFe water from the remnant mixed layer into the upper mixed layer (Figure 9e).

373 About 27% of the variance in near-surface dFe is explained by increased F_o, 374 (Figure 9d). This positive relationship between dFe and phytoplankton biomass is a 375 little surprising because one would expect uptake during a bloom to lead to a negative 376 relationship. When combined with the satellite images showing apparent lateral 377 entrainment of neritic water, we suggest that the most likely explanation for this result 378 is that the eddies transport high-dFe coastal water offshore. This conclusion is 379 supported by results from the same region in 2008, where Ellwood et al. (2014) found 380 that mixed layer Mn:Fe and Mn:Al ratios were elevated compared to crustal values,

and based on these ratios and particle-backtracking simulations, suggested the mostlikely source of iron was continental water.

Even so, if the coastal water had uniform iron concentration, uptake would lead to a negative relationship between dFe and phytoplankton biomass. There are two potential reasons for a positive relationship. One is that our results are confounded by atmospheric deposition, the other is that coastal water has such a large range in dissolved iron that uptake is obscured by this variability.

388 If phytoplankton are iron-limited, patchy atmospheric deposition of iron could 389 lead to patches of phytoplankton, and thus to a positive relationship between dFe and 390 phytoplankton, although it is by no means certain that deposition leads to increased 391 dFe since lithogenic particles associated with atmospheric deposition can remove 392 soluble iron in the water column via scavenging (Tagliabue et al., 2017).

393 Atmospheric deposition of dust in the New Zealand region has long been 394 ascribed to Australian dust storms (Boyd et al., 2004; Kidson, 1930; Mahowald et al., 395 2009), but there are not sufficient data to determine the temporal and spatial scales of 396 the deposition in the region. Ellwood et al. (2018; their Figure 5) present a map of 397 annual mean Fe deposition based on modelling of global dust distributions (Albani et 398 al., 2014) that shows broad area of deposition extending east of Australia and 399 covering New Zealand. This modelled deposition has little of the spatial structure of 400 surface chlorophyll seen in Figure 1, in particular there is no evidence of high 401 deposition along the STF, and since the STF is considered to be region of high dFe 402 (Banse and English, 1997; Boyd et al., 2004) this argues that deposition is not the 403 major source of iron to the STF. Such featureless deposition might be expected in the 404 annual mean, but various attempts to investigate the role of atmospheric deposition 405 from satellite imagery have not provided more precise information on the temporal 406 and spatial scales of deposition at shorter time scales. Boyd et al. (2004) inferred 407 oceanic supply of dFe from episodic increases in chlorophyll concentrations in SAW 408 seen in ocean colour images between 1997 and 2001, and found no evidence that 409 these events were mediated by atmospheric iron supply, although they also could not 410 explain these events from lateral advection or vertical mixing, and did comment that 411 dust storms during this time sent plumes over both STW and SAW. They concluded 412 that more data are needed, including on rainfall patterns in relation to dust plume 413 trajectories to distinguish wet from dry deposition.

With little to no measurements of atmospheric deposition of iron in the region,the role of deposition in this mesoscale eddy system must remain an open question.

416 This then raises the question of whether our implied finding that dFe is high and 417 variable in coastal water is consistent with previous work. There is surprisingly little 418 information on dFe in coastal North Island water, however, it is reasonable to assume 419 that coastal water, in general is higher in dFe than offshore water. For example, 420 Hutchins et al. (1998) found dFe in California coastal water to vary between <0.1 and >8.0 nmol L⁻¹, and explained this high variability was due to uneven distributions of 421 sources of iron such as rivers and resuspension of shelf sediments. More locally, 422 423 Sander et al. (2015) found dFe on average to be 1.0 ± 0.4 nmol L⁻¹ in neritic water on the Otago shelf, compared to 0.2 ± 0.1 nmol L⁻¹ offshore in SAW. Croot and Hunter 424 425 (1998) reported dFe as high as 6 nmol L^{-1} on the Otago shelf, which they suggested 426 was due to wind-induced upwelling rather than fluvial input. Upwelling occurs around 427 the North Island east coast (Sharples and Greig, 1998) and may also be a significant 428 source of dFe. On balance, it seems that high and variable dFe in coastal water is a 429 reasonable finding.

430 Evidence that dFe is limiting in south-west Pacific Ocean STW is more scarce, 431 perhaps because STW is generally considered oligotrophic in macronutrients and 432 there has been relatively little interest in iron in these waters. However, Ellwood et al. (2008) found winter dFe levels ~0.1 nmol L^{-1} within and across the Subtropical Front 433 434 in the Tasman Sea. Near 30°S, Ellwood et al. (2018) found surface dFe less than 0.2 nmol L⁻¹ in the central Tasman Sea. Furthermore, phytoplankton located north of the 435 436 Tasman Front (i.e. in STW, but to the west of our study region) were considered to be 437 near the threshold for iron limitation (Ellwood et al., 2013).

438 In summary, the main results of this study are that the mesoscale eddies off the 439 east coast of New Zealand are deep, with their circulation driven by the deep 440 baroclinic structure, whereas (at least during the spring bloom) the surface production 441 is largely constrained to a shallow upper mixed layer. From a biological perspective, 442 the main role of the mesoscale circulation is to mix high-dFe neritic water with low-443 dFe offshore STW. Since extensive mixing of the two water masses extends several 444 hundred km offshore, we conclude that a significant component of production within 445 the STF is likely determined by mesoscale eddy induced zonal advection of iron. This 446 conclusion supports those made by Graham et al. (2015), who suggested that

bioavailable iron from the continental shelves is entrained into western boundarycurrents and then advected along the STF.

449

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References

Figures

465	
466	Figure 1. Mean sea surface chlorophyll (SSC) from 2002 - 2016 derived from the
467	Moderate Resolution Imaging Spectroradiometer (MODIS) on NASA's
468	Aqua satellite. a) Mean SSC for the southern hemisphere; and b) Mean
469	SSC for the New Zealand region. Black vectors are mean sea surface
470	velocity derived from AVISO ocean altimeter data. Red lines are 0.5 and
471	0.75 mg Chl m ⁻³ contour levels, dash-dot black line is 1000 m isobath,
472	showing the Chatham Rise extending east of New Zealand. EC, WE, and
473	CI indicate East Cape, Wairarapa Eddy, and Chatham Islands.
474	
475	Figure 2. a) Sea surface chlorophyll (SSC) from 2 October 2012 derived from the
476	Moderate Resolution Imaging Spectroradiometer (MODIS) on NASA's
477	Aqua satellite. Vectors are surface currents derived from AVISO ocean
478	altimeter data. Labels A, and C indicate anti-cyclonic and cyclonic eddies,
479	numbered eddies are referred to in the text. The blue line near eddy A_1
480	indicates the cruise track during the one-day survey; b) Rossby number
481	(vorticity divided by planetary vorticity, $R_0 = \zeta / f$) for 2 October 2012.
482	Dashed contours indicate $R_0 = \pm 0.1$; and c-f) Histograms of Rossby
483	number for regions where SSC exceeds various levels. Dash-dot line in a
484	and \mathbf{b} indicates the 250 m isobath, and data are only shown where the water
485	depth is greater than 250 m to exclude the coastal zone.
486	
487	Figure 3. Moderate Resolution Imaging Spectroradiometer (MODIS) images of sea
488	surface chlorophyll (SSC) from 30 September to 4 October, 2012. a) 30
489	September; b) 2 October; c) 4 October; and d) enlarged view of 2 October,
490	along with upper mixed-layer velocity from the ship's ADCP (red vectors).
491	Numbered circles show the CTD cast locations from the one-day survey
492	made in the anticyclonic eddy A1 shown in Figure 2. Colours of the circles
493	in d) indicate whether the casts were considered high-POM (green) or low-
494	POM (blue, see text). Black vectors are surface currents derived from
495	AVISO satellite altimetry.

496	
497	Figure 4. Profiles from the 12 CTD casts made during the one-day survey. a)
498	Temperature (T); b) Salinity (S); c) Density (σ_t); d) Chlorophyll (Chl); e)
499	Particulate organic matter (POM); f) Temperature vs. salinity (T-S); and g)
500	POM vs Chl for the upper 5 to 30 m from CTD casts made over the entire
501	cruise. Casts have been colour-coded by two groups, high-POM (green) and
502	low-POM (blue). Horizontal blue line shows the mean one-percent light
503	level (Z_{100}) from the daylight casts. Horizontal red dashed lines show the
504	nutrient sample depths. Note the change of depth scale between upper and
505	lower panels. Magenta lines in plots are from cast 7, which was closest
506	inshore and had lowest temperature and salinity in the remnant mixed layer.
507	
508	Figure 5. Gridded mixed-layer depths derived from CTD casts shown in Figure 4.
509	a) Upper mixed layer depth (uMLD); and b) Remnant mixed layer depth
510	(rMLD). Red and blue vectors are ADCP-derived velocities at 10 m and
511	100 depths, respectively, showing anticyclonic circulation.
512	
513	Figure 6. Three-dimensional views of a) Tempearture (T); b) Salinity (S); c)
514	Density (σ_t); and d) Particulate organic matter (POM) from the one-day
515	CTD survey. Red vectors are ADCP-derived velocities at 10 m showing
516	anticyclonic circulation. Vertical lines indicate upper mixed-layer depths
517	and are colour-coded as high POM_u (green) and low POM_u (blue). Black
518	and white dashed lines indicate the depths of the remnant and upper mixed
519	layers, respectively. Numbers in d are the cast number. Note change of
520	vertical (depth) scale between a , b and c , d .
521	
522	Figure 7. Macronutrient profiles, from the CTD survey. a) Ammonium (NH ₄); b)
523	Nitrate plus nitrite (NO ₃ +NO ₂); c) Phosphate (PO ₄); and d) Silicate (SiO ₄).
524	Values have been colour-coded as high-POM (green) and low-POM (blue)
525	profiles (see Figure 4). Errror bars are one standard deviation of analytical
526	errors and do not include CTD sampling errors.

527	
528	Figure 8. a) Time series of fluorescence (Fo) from Fast Repetition Rate
529	Fluorometer (green line, and 1-hour smoothed, dark-green line), surface
530	chlorophyll from night-time CTD casts (dark green squares), extracted
531	chlorophyll from water samples at 10 m (red diamonds), and upper-mixed
532	layer particulate organic matter (POM_u) from CTD casts (circles). POM_u
533	has been colour-coded as high- POM_u (green) and low- POM_u (blue); and
534	b) Scatter plots of F_o , POM _u , and dFe superimposed over sea surface
535	chlorophyll (SSC) derived from Moderate Resolution Imaging
536	Spectroradiometer for 2 October 2012 (see Figure 3). Note the colour scale
537	for SSC is as shown in Figure 3. Numbers in circles indicate CTD cast
538	number. Casts 2 to 5 were made during daylight.
539	
540	Figure 9. Dissolved iron from underway tow fish (dFe), fluorescence from Fast
541	Repetition Rate fluorometer (Fo), upper mixed layer depth from CTD casts
542	(uMLD), and fit of dFe from linear model ($dFe_{est} = a \times uMLD + b \times F_0 + c$).
543	a) dFe and F_0 ; b) dFe and uMLD; c) dFe and dFe_{est} ; and d-f) linear
544	regressions of F_0 , uMLD, and dFe_{est} against dFe, where F_0 and uMLD, has
545	been interpolated to dFe sample times. All slopes are considered significant
546	(p<.05). In a) and b) scales for F_o and uMLD are shown to the right of the
547	axes.

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