

**EXPLORING MECHANISMS FOR SPRING BLOOM EVOLUTION:
CONTRASTING 2008 AND 2012 BLOOMS IN THE SOUTH WEST PACIFIC
OCEAN**

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23 **Abstract**

24 Observations from two research cruises made in 2008 and 2012 to east of New
25 Zealand are put into context with satellite data to contrast and compare surface
26 chlorophyll *a* evolution in the two years in order to explore mechanisms of
27 phytoplankton bloom development in the southwest Pacific Ocean.
28 In 2008, sea surface chlorophyll *a* largely followed the long-term climatological
29 cycle, and 2008 can be considered a canonical year, where the autumn bloom is
30 triggered by increasing vertical mixing at the end of summer, and the spring bloom is
31 triggered by decreasing vertical mixing at the end of winter. In contrast, 2012 was
32 anomalous in that there was no autumn bloom, and in early spring there were several
33 periods of sustained increase in surface chlorophyll *a* that did not become fully
34 developed spring blooms. (In this region, we consider spring blooms to occur when
35 surface chlorophyll *a* exceeds 0.5 mg m^{-3}). These events can be related to alternating
36 episodes of increased or decreased vertical mixing. The eventual spring bloom in
37 October was driven by increased ocean cooling and wind stress and, paradoxically,
38 was driven by mechanisms considered more appropriate for autumn rather than spring
39 blooms.

40

41 **Keywords** Primary production, spring bloom, physical control, wind mixing, heat
42 flux

43

INTRODUCTION

44 Spring blooms of phytoplankton are a near-global phenomenon in subtropical,
45 temperate and subpolar oceans (e.g., Cole *et al.*, 2015, Westberry *et al.*, 2016).
46 Perhaps the most prominent and most studied spring bloom is in the North Atlantic
47 Ocean, (e.g., Henson *et al.*, 2009, and references therein). However, spring blooms
48 have also been observed in the southwest Pacific Ocean, although surface chlorophyll
49 levels there are considerably less than in the North Atlantic Ocean and may only reach
50 1 mg m^{-3} (Chiswell *et al.*, 2013).

51 There are several theories for the cause and timing of spring blooms, and many
52 are one-dimensional (1-d) in the vertical based around some mechanism that retains
53 phytoplankton in the photic zone near the surface in the spring.

54 A commonly cited hypothesis, referred to here as the shoaling mixed layer
55 hypothesis (SMLH), is based on Sverdrup (1953). Under the SMLH, the spring bloom
56 is considered to start when the mixed layer shoals to be less than the critical depth
57 (e.g., Dutkiewicz *et al.*, 2001, Levy, 2015). However, observations of spring blooms
58 occurring before the mixed layer began to shoal led to hypotheses that blooms are
59 initiated by the shutdown of turbulent mixing (Huisman *et al.*, 1999, Taylor & Ferrari,
60 2011) or by the onset of near-surface stratification (Chiswell, 2011).

61 These theories appear to be contradictory, but Chiswell *et al.* (2015b) showed
62 that much of the contradiction disappears when one is careful to distinguish between
63 surface phytoplankton concentrations and depth-integrated phytoplankton stock.
64 Chiswell *et al.* (2015b) proposed a 1-d model, where there is a transition from deep
65 winter mixing to a well-mixed but low turbulence regime in early spring, and then
66 another transition to a (density) stratified regime later in the spring once surface
67 waters begin to warm. In their model, Chiswell *et al.* (2015b) suggested that after an
68 autumn bloom, surface phytoplankton concentrations decrease during deep winter
69 mixing due to dilution (e.g., Evans & Parslow, 1985) and may start to increase once
70 the low-turbulence regime commences (e.g., Huisman *et al.*, 1999, Taylor & Ferrari,
71 2011), but it is only when the ocean begins to stratify that surface production is
72 maximised. Chiswell *et al.* (2015b) note that the depth-integrated phytoplankton stock
73 shows quite different behaviour than surface phytoplankton concentration. Depth-
74 integrated phytoplankton stock can either decrease during winter if winter mixing is
75 deep compared to the photic zone (typically at higher latitudes), or can increase

76 during winter if winter mixing is shallow compared to the photic zone (typically
77 lower latitudes).

78 Many of the arguments supporting the various spring bloom hypotheses and the
79 unified interpretation by Chiswell *et al.* (2015b), are based on observed correlations
80 between various bloom metrics and forcing quantities. For example, between mixed
81 layer depth (MLD) and chlorophyll concentration (Henson *et al.*, 2006), between
82 bloom initiation and the end of convective forcing (Taylor & Ferrari, 2011), between
83 bloom initiation and the net heat flux (NHF) sign change (Cole *et al.*, 2015), or
84 between the seasonal progression of the spring bloom and the seasonal progression of
85 the wind stress (Chiswell *et al.*, 2013).

86 However, there is a danger in inferring a causal connection from the correlation
87 of quantities (i.e., NHF, MLD and wind stress) that are inherently driven by the same
88 solar insolation, and so the relative roles of NHF, MLD and wind stress in the timing
89 of spring blooms are still open to some debate.

90 Here, to further explore the mechanisms of bloom development, we compare the
91 time evolution of blooms in Subtropical Waters east of New Zealand. In both 2008
92 and 2012, research cruises were made to the same region east of the North Island
93 (Figure 1) during the spring with the aim of describing bloom development. During
94 each cruise, measurements of size-fractionated primary production and biomass,
95 nutrients, NHF, MLD and other quantities were made following a floating array
96 deployed near the centre of an anticyclonic mesoscale eddy.

97 Data from the 2008 cruise have been analysed by Chiswell (2011), and were the
98 basis for the onset of stratification hypothesis. Here, we start with a similar analysis of
99 the 2012 data. After this comparison, we use satellite data to put the cruise
100 observations into context of their respective years. In 2008, sea surface chlorophyll
101 concentration largely followed the long-term climatological cycle and 2008 can be
102 considered a canonical year. In contrast, in 2012 was anomalous in that there was no
103 autumn bloom, and in winter and spring there were events that did not become fully
104 developed spring blooms. We consider the departures from climatology in each year
105 to explain these events. We then address the question of how representative the
106 experimental site is of the region in general by considering surface chlorophyll in the

107 region derived from satellite. Finally, we discuss our results and present our
108 conclusions.

109 Before proceeding further, it is worth commenting on the use of the term
110 ‘bloom’. There have been various definitions of a spring bloom. These definitions
111 often include a threshold, for example when surface chlorophyll exceeds 1 mg m^{-3}
112 (e.g., Brody *et al.*, 2013), although as Smayda (1997) notes, what constitutes a bloom
113 may have regional and species-specific aspects. Here we use the term ‘spring bloom’
114 when surface chlorophyll exceeds 0.5 mg m^{-3} to reflect the observations that spring
115 blooms are weaker in the southwest Pacific Ocean than in the Atlantic Ocean. An
116 ‘autumn bloom’ is defined by a threshold level of 0.25 mg m^{-3} .

METHODS

117 *Shipboard measurements*

118 *Hydrography*

119 Cruises were made in both 2008 and 2012 to the same location east of the North
120 Island (Figure 1). These cruises were part of an iron cycling project, and are known as
121 FeCycle II and FeCycle III, respectively. Data from the 2008 cruise (FeCycle II) have
122 been reported elsewhere (Chiswell, 2011, Twining *et al.*, 2014).

123 Each cruise lasted from mid-September until early October. Prior to each
124 cruise, satellite altimeter data were scanned to choose an anti-cyclonic mesoscale
125 eddy close to the nominal study site. Upon arrival at the site, a shipboard ADCP
126 survey was made of the eddy, then a Lagrangian floating array extending to $\sim 120 \text{ m}$
127 was deployed in the eddy centre.

128 During each cruise, daily CTD casts were made at 3 am and noon close to the
129 Lagrangian array. In 2012, the array was lost toward the end of the cruise, after which
130 casts were made at the estimated eddy centre. CTD casts were also made at other
131 times of the day, not necessarily near the Lagrangian array, for a variety of different
132 experiments. To avoid issues associated with non-photochemical quenching (e.g.,
133 Müller *et al.*, 2001) the primary data used here are the 3 am casts.

134 Water samples for chlorophyll, phytoplankton and microzooplankton and
135 nutrient analyses were collected on upcasts using 24 10-L Niskin bottles mounted on
136 the CTD rosette.

137 For each CTD cast, two estimates of the mixed layer depth (MLD_1 and MLD_2)
138 were computed as the depths where the *in situ* density exceeded the surface value by
139 0.125 and 0.025 $kg\ m^{-3}$, respectively (Chiswell, 2011, Chiswell *et al.*, 2013). In this
140 region, MLD_1 can be considered the depth of the seasonal thermocline, whereas
141 MLD_2 reflects weak stratification that would normally be considered to be within the
142 mixed layer (Chiswell, 2011).

143 *Meteorology*

144 Continuous surface measurements of 10-m wind speed, sea surface temperature,
145 sea surface salinity and sea surface transmissivity were also made from the ship's
146 underway sampling system. Surface stress was calculated from 10-m wind speed, W ,
147 as $\tau = \rho_a c_d W^2$, where the air density, ρ_a , was set to 1 $kg\ m^{-3}$, and the drag
148 coefficient, c_d was set to 1.5×10^{-3} (e.g., Kara *et al.*, 2007).

149 In 2012, sensible and latent heat fluxes were calculated from ship-based
150 measurements of wind speed, atmospheric pressure, humidity, irradiance and air and
151 sea surface temperature using the bulk formulae of the NOAA COARE3.1 algorithms
152 (Fairall *et al.*, 2011).

153 *Nutrients*

154 Macronutrients from the upcast water samples were determined using an
155 automated micro-segmented flow analyser with digital detector (Pickmere, 1998).
156 Dissolved iron (dFe) was measured at a set of predetermined depths using standard
157 trace-metal sampling (i.e., a trace-metal clean rosette and Kevlar line), and was
158 determined using flow injection analysis (Floor *et al.*, 2015, Obata *et al.*, 2002).
159 Further analytical details are described in Chandrasekhar *et al.* (2018).

160 *Chlorophyll*

161 The CTD fluorometer was calibrated against chlorophyll obtained from 500 mL
162 samples taken from each water bottle on the CTD casts. Chlorophyll extractions were
163 performed following Parsons *et al.* (1984), using acetone extraction. Chlorophyll in

164 the extracts was determined with a fluorometer calibrated against a pure chlorophyll a
165 standard (Sigma Chemicals).

166 *Size-fractionated primary production*

167 Net primary production was based on radioisotope measurements and 24-hour
168 incubations (e.g., Laws, 1991). Samples were collected pre-dawn from trace-metal
169 clean Niskin bottles deployed on a trace-metal rosette. Water was sampled from three
170 depths: 20, 40, and at one depth within the 60-90 m stratum determined from the
171 previous midday irradiance profiles. Samples were spiked with 20 μCi of Sodium ^{14}C -
172 bicarbonate ($\text{NaH}^{14}\text{CO}_3$; specific activity 1.85 GBq mmol^{-1}) and then incubated for 24
173 hours in neutral-density mesh bags in a deckboard incubator at 6 intensities: 80, 50,
174 30, 15, 3, and 0.5 % of incident irradiance (% I_0) (2008), and 65, 50, 35, 16, 2, and 1
175 % I_0 (2012). These light levels corresponded to *in situ* depths of 2-70 m (2008), and 4-
176 94 m (2012).

177 Upon completion of the 24-hour incubation, samples were analysed by liquid
178 scintillation counting (Beckman LS 5000).

179 *Phytoplankton and microzooplankton identification and enumeration*

180 For the 2012 cruise, phytoplankton $>2 \mu\text{m}$ and microzooplankton were
181 identified and enumerated in 250 mL subsamples preserved with Lugol's Iodine
182 solution (1% final concentration) using a Leica DMI3000B inverted microscopic.
183 Samples were then counted and identified with an inverted microscope at 100x to
184 600x magnification.

185 Phytoplankton were identified where practical to genus or species level but
186 there was no differentiation of plastidic ciliates. Ciliate biomass was estimated from
187 dimensions of 10-20 randomly chosen individuals of each taxon. The volumes were
188 estimated from approximate geometric shapes and were converted to carbon biomass
189 using a factor of 0.19 $\text{pg C } \mu\text{m}^{-3}$ (e.g., Putt & Stoecker, 1989). Separate
190 picophytoplankton ($<2 \mu\text{m}$) samples were frozen in liquid nitrogen (e.g., Lebaron *et*
191 *al.*, 1998) and thawed immediately before counting by flow cytometry following the
192 methods of Hall and Safi (2001).

193 In 2008, the diatom species were analysed by using a combination of light
194 microscopy and the abundance of *Asterionellopsis*16S rDNA sequences as a

195 proportion of diatom sequences, and all photoautotrophic sequences (e.g., Twining *et*
196 *al.*, 2014).

197 *Satellite estimates of sea surface chlorophyll and temperature*

198 The Moderate Resolution Imaging Spectroradiometer (MODIS, Esaias *et al.*,
199 1998), launched in 2002 provides estimates of sea surface chlorophyll concentration.
200 Data used here are 9-km 8-day composites of sea surface chlorophyll downloaded
201 from NASA, <http://oceandata.sci.gsfc.nasa.gov/MODISA/Mapped/8Day/9km/chlor/>.

202 These data were composited for 100 km diameter around the nominal cruise
203 location (180°E, 39°S) to provide time series of surface chlorophyll concentration.
204 The climatological annual cycle of surface chlorophyll concentration at the nominal
205 experimental site was computed using the 8-d composite data from 2003 to 2012, and
206 interpolated to daily values.

207 Sea surface temperature (SST) from the Advanced Very-High-Resolution
208 Radiometer (AVHRR) instruments is available from an objectively-analysed product
209 provided by NOAA (NOAA OI SST V2 High Resolution Dataset, Reynolds *et al.*,
210 2007). Here we use the AVHRR only product (<https://www.ncdc.noaa.gov/oisst>). The
211 climatological annual cycle of SST was computed for the time period 1985 to 2012.

212 *NCEP surface fluxes*

213 Daily values of wind stress, latent and sensible heat, and long- and short-wave
214 radiation daily fluxes at ~2° resolution were downloaded from the National Centers
215 for Environmental Prediction (NCEP) reanalysis products
216 <http://www.esrl.noaa.gov/psd/data/gridded/data.ncep.reanalysis.surfaceflux.html>. To
217 be consistent with the MODIS data, annual cycles of these variables at the nominal
218 experimental site were computed using data from 2003 to 2012.

219 *Argo profiles*

220 The Argo program maintains about 3000 profiling floats around the planet
221 (Gould & Turton, 2006) which provide profiles of temperature and salinity between

222 2000 m and the surface about every 10 d. Argo data are available from the French
223 Research Institute for Exploitation of the Sea (Ifremer) via their website
224 <ftp://ftp.ifremer.fr/ifremer/argo/>.

225 We selected profiles taken within 125 km of the nominal experimental site in
226 each year. This radius was chosen as a compromise between having too few profiles
227 and having profiles that do not reflect the water mass characteristics of the
228 experimental site. There were 42 profiles in 2008, and 23 profiles in 2012 that were
229 within 125 km of the experimental site (Figure 1).

230 Mixed layer depths MLD_1 and MLD_2 were computed from the temperature and
231 salinity profiles using the same criteria as used to compute mixed layer depth from the
232 CTD.

RESULTS

233 *2008 and 2012 cruise observations*

234 The study area is in a region of Subtropical Water (Chiswell *et al.*, 2015a)
235 where the mean surface chlorophyll derived from MODIS is $\sim 0.3 \text{ mg m}^{-3}$ (Figure 1).

236 Locations of all CTD casts made during the two cruises are shown in Figure 2.
237 In 2008, the Lagrangian array remained close to the centre of the eddy until about 4
238 days from the end of the experiment, when ship-board Acoustic Doppler Profiler
239 (ADCP) data indicated that the array spun out of the eddy (Chiswell, 2011). In 2012,
240 the array travelled north west with a mean speed of 0.056 m s^{-1} , but showed a looping
241 structure, which suggests that, as in 2008, it was slipping out from the centre. The 3
242 am and noon CTD casts were made close to the array until 1 October when the array
243 was lost. After this, the eddy centre was estimated from the daily ADCP surveys.

244 Figure 3 summarises the 3 am data for both cruises, showing temperature and
245 chlorophyll derived from the CTD casts, along with wind stress derived from the
246 ship's anemometer, and two estimates of the mixed layer depth, MLD_1 and MLD_2
247 (based on density differences of 0.125 and 0.025 kg m^{-3} , see Methods).

248 The evolution of the MLD and the biological responses during the 2008 cruise
249 (Figure 3, left-hand panels) have been discussed by Chiswell (2011). On arrival at the
250 site, the water column was weakly stratified and near-surface chlorophyll

251 concentration, C_0 , was about 1 mg m^{-3} . Soon after arrival, increasing winds destroyed
 252 the stratification and mixed the phytoplankton down, leading to a decrease in C_0 .
 253 Winds then decreased and an increase in C_0 occurred in the re-emerging
 254 stratification. The depth-integrated chlorophyll stock over the upper 300 m,
 255 $C_{0/300} = \int_0^{300} C(z) dz$, showed little change during the cruise having a mean \pm standard
 256 deviation of $\sim 31.2 \pm 6.7 \text{ mg m}^{-2}$. There was no significant correlation ($r^2 = 0.03$)
 257 between $C_{0/300}$ and C_0 .

258 Chiswell (2011) interpreted the 2008 data to suggest that spring blooms in
 259 surface chlorophyll initiate with the onset of shallow weak stratification that forms
 260 during periods of low winds, and that chlorophyll can be stratified in the mixed layer
 261 defined by MLD_1 . The 2008 spring bloom was dominated by the diatom
 262 *Asterionellopsis glacialis* (Twining *et al.*, 2014), and was likely terminated by iron
 263 limitation, even though diatoms consumed less than 1/3 of the mixed-layer dissolved
 264 iron inventory (Boyd *et al.*, 2012).

265 Conditions during 2012 (Figure 3, right-hand panels), were different, however.
 266 Upon arrival at the site, the water column was $\sim 0.5 \text{ }^\circ\text{C}$ cooler than in 2008, and there
 267 was little evidence of stratification (both MLD_1 and MLD_2 were at about 350 m). The
 268 wind was weaker than in 2008, with 4 relatively calm periods (19 September, 21-24
 269 September, 28-29 September, and 3-5 October) during which the wind stress was less
 270 than 0.1 N m^{-2} (corresponding to a wind speed of $\sim 8 \text{ m s}^{-1}$). These calm periods were
 271 interspersed with periods where the wind stress rose to 0.4 N m^{-2} ($\sim 16 \text{ m s}^{-1}$).

272 During the first calm period (19 September) there was a small ($\sim 0.1 \text{ }^\circ\text{C}$) increase
 273 in surface temperature, with an associated shoaling of MLD_2 . This temperature signal
 274 was mixed down by stronger winds the next day. The second calm period from 21-24
 275 September, lasted considerably longer, but surprisingly, SST did not show any
 276 substantial response, rising by only $0.03 \text{ }^\circ\text{C}$ during this event (in comparison SST rose
 277 $0.35 \text{ }^\circ\text{C}$ during a 2-day calm period in 2008). During this second calm period there
 278 was no apparent increase in stratification - both MLD_1 and MLD_2 remained at about
 279 350 m. Paradoxically, SST started to rise as the wind increased on 25 September, and
 280 continued to increase even as the winds strengthened through 27 September. Also,
 281 counter intuitively, stratification increased during these stronger winds, with MLD_2

282 starting to shoal from about 26 September. The third calm period (28-29 September)
283 was short lived, but substantial surface warming occurred during this calm when SST
284 rose by ~ 0.5 °C. This increase in SST was accompanied by a shoaling in MLD₂ (and
285 temporarily MLD₁).

286 As in 2008, the onset of stratification appeared to trigger a phytoplankton
287 response in the upper 100 m. From about 28 September, there was a general trend for
288 chlorophyll to become more stratified in the water column, with surface chlorophyll
289 concentration rising to ~ 0.8 mg m⁻³ by the end of the cruise.

290 Compared to 2008, there was about 10% less total chlorophyll in the water
291 column, with mean \pm standard deviation of $C_{0/300} = 28.6 \pm 3.8$ mg m⁻² (cf. 31 ± 6.7
292 mg m⁻² in 2008). As in 2008, $C_{0/300}$ changed little during the cruise and was
293 uncorrelated with C_0 ($r^2 = 0.16$).

294 During both cruises, $C_{0/300}$ showed much less variation than C_0 . This suggests
295 that the photic zone was shallower than the depth to which phytoplankton were being
296 mixed. Thus, as the vertical mixing ceased (i.e., as MLD₂ shoaled) phytoplankton
297 below the mixed layer did not survive, and increased biomass at the surface was
298 compensated for by losses at depth (it is probably coincidental that the losses almost
299 exactly balanced the increased production). When MLD₂ deepened (e.g., from 26 Sept
300 2008), mixing distributed the phytoplankton throughout the deepening mixed layer so
301 that the surface concentration decreased even though the total amount of
302 phytoplankton in the water column stayed approximately the same (e.g., Evans &
303 Parslow, 1985).

304 The 2008 and 2012 cruises were different in their nutrient evolution (Figure 4).
305 In 2008, the macronutrients (nitrate, silicate and phosphate) were substantially
306 depleted in the upper 100 m on arrival at the site. The wind event 19-20 September
307 mixed up nutrients from below the nutricline, but these were then consumed by the
308 production starting 23 September (Boyd *et al.*, 2012). Similarly it appears that the
309 stronger winds towards the end of the cruise also mixed nutrients up into to the mixed
310 layer.

311 In contrast, during 2012, nitrate plus nitrite and phosphate were relatively well
312 mixed over the upper 300 m from the beginning of the cruise until they were

313 consumed by phytoplankton production above 100 m from about 28 September.
314 Concentrations of nitrate plus nitrite ($>4 \mu\text{molar}$) and phosphate ($>0.4 \mu\text{molar}$) at the
315 beginning of the cruise were typical of the deeper values seen in 2008.

316 Silicate, on the other hand, showed high levels ($>2.3 \mu\text{molar}$) throughout the
317 water column (except for the very upper few metres) on the first day of the cruise, but
318 after that concentrations ($\sim 1.9 \mu\text{molar}$) dropped to less than half the deep values seen
319 in 2008. Silicate was further depleted (to $\sim 1.5 \mu\text{molar}$) during the increase in
320 phytoplankton biomass starting ~ 28 September. Dissolved iron showed a pattern
321 similar to that of silicate, with high values ($\sim 0.5 \text{ nmolar}$) throughout most of the water
322 column on the first day, but then dropping to $\sim 0.35 \text{ nmolar}$ before being reduced to
323 $\sim 0.1 \text{ nmolar}$ by the production starting ~ 28 September.

324 Even though depth-integrated chlorophyll stocks agreed to within 10% during
325 both cruises (Figure 3D), the phytoplankton community structure and size-
326 fractionated net primary production (NPP) were quite different (Figure 5).

327 During 2008, NPP was initially dominated by cells larger than $20 \mu\text{m}$, and
328 community NPP was 2875 to $4040 \text{ mg C m}^{-2} \text{ d}^{-1}$. During the cruise both the portion of
329 NPP due to cells larger than $20 \mu\text{m}$ and total community NPP decreased by a factor of
330 more than 2, so that NPP was $1446 \text{ mg C m}^{-2} \text{ d}^{-1}$ at the end of the cruise.

331 In 2012, however, cells larger than $20 \mu\text{m}$ accounted for only 8-15% of NPP.
332 NPP was $615 \text{ mg C m}^{-2} \text{ d}^{-1}$ initially and doubled to $1384 \text{ mg C m}^{-2} \text{ d}^{-1}$ at the end of the
333 cruise (one third the maximum rate seen in 2008). The fate of the spring bloom in
334 2008 – as downward export or herbivory – is not known.

335 Early in 2012, picophytoplankton represented around 80% - 90% of NPP in the
336 surface 50 m. This dominance was largely maintained until between 30 September
337 and 5 October, when an increase in diatom abundance occurred (concurrent with the
338 increase in C_0).

339 The $>2 \mu\text{m}$ phytoplankton population consisted of a mix of small flagellates (2-
340 $20 \mu\text{m}$), dinoflagellates and diatoms. The diatom populations included species of
341 *Asterionellopsis*, *Cerataulina*, *Fragilaria*, *Corethron*, *Guinardia*, *Chaetoceros*,
342 *Thalassiosira* and *Ditylum*. The silicoflagellate, *Dictyocha*, was also present. The
343 dinoflagellates which initially outnumbered diatoms were dominated by *Ceratium* (*C.*
344 *lineatum*, *C. furca* and *C. fuscus*), and *Gymnodinium*, but also included some genera

345 which are known to be heterotrophic or mixotrophic (some with endosymbionts)
346 including *Gyrodinium*, *Scrippsiella*, *Dinophysis*, *Protoperidinium* and *Prorocentrum*.
347 On-board deck incubation experiments became diatom dominated primarily by the
348 genus *Asterionellopsis*.

349 The dominance of large cells in the 2008 bloom and the high rates of NPP
350 relative to the 2012 bloom indicate that the fate of this NPP was likely downward
351 export, although we have no sediment trap data to test this.

352 Microzooplankton data from each cruise are shown in Figure 6. In 2008
353 microzooplankton levels were highest on arrival at station, concurrent with the high
354 concentration of chlorophyll seen in the upper water column at that time (Figure 5).
355 There was a general decrease in microzooplankton levels as this initial phytoplankton
356 was mixed down, and then a delayed response of Aloricate ciliates ($>20\ \mu\text{m}$) to the
357 increase in primary biomass seen from 29 September. In 2012, there was a reasonably
358 rapid increase in microzooplankton levels in response to the primary production
359 starting ~28 September.

360 *Heat and wind fluxes during 2012 cruise*

361 A more detailed analysis of the upper water column during the 2012 cruise
362 (Figure 7) explains why the water column did not stratify during the calm period 21-
363 24 September, and why counter-intuitively, SST increased and the mixed layer
364 shoaled when the winds increased from 25 September.

365 Prior to, and during, the 21-24 September calm, the winds were generally from
366 the south, and the air was substantially colder than the ocean with an air-sea
367 difference of $-5\ ^\circ\text{C}$ on 21 September. About 24 September, the wind turned to become
368 from the north, and as the wind speed increased, the air warmed to finally become
369 warmer than the ocean about 27 September. Thus, the cool southerly airflow that
370 dominated the region until ~27 September suppressed almost all ocean heating, with
371 the net result that SST increased only marginally during the 21-24 September calm.

372 It was not until the air became warmer than the ocean on 27 September that SST
373 increased, and the ocean began to stratify. SST peaked during the 28-29 September
374 calm, and this period was characterised by increasing, but weak, stratification and
375 shoaling MLD₂.

376 *Mesoscale variability in 2012*

377 Mesoscale spatial variability in both the physics and biology of the region will
378 be aliased in the Lagrangian sampling, we can use the CTD data collected on the daily
379 surveys to attempt to determine whether the conclusions based on the 3 am casts are
380 likely to be impacted by this aliasing.

381 The horizontal scale of the eddy, and how close the 3 am casts were made to the
382 eddy centre can be estimated from the daily shipboard ADCP surveys (Figure 8). The
383 daily ADCP surveys did not always completely map the eddy (which was also
384 evolving). However, inspection of the maps suggests that at least up until 26
385 September, the 3 am CTD cast was made within 2 to 3 km of the centre of the eddy.
386 By 30 September, however, it appears that the Lagrangian Array was slipping towards
387 the outside of the eddy.

388 Figure 9 shows the sea surface temperature, sea surface chlorophyll, and
389 temperature and chlorophyll sections constructed from all casts. Temperature shows
390 evidence of diurnal heating near the surface, with SST at noon on average 0.14 °C
391 warmer than at 3 am. The diurnal heating was uncorrelated with separation distance
392 between 3 am and noon casts, and with time into the cruise. Early in the cruise this
393 diurnal heating impacted MLD₂, but once the stratification strengthened there was no
394 difference in MLD₂ between the night-time and day-time casts. Apart from the diurnal
395 heating effects, the same progression from well-mixed to stratified conditions would
396 have been observed had the 3 am casts been replaced with any cast taken on the same
397 day, suggesting that spatial variability associated with the eddy was insufficient to
398 alias the observed temporal evolution of the density structure significantly.

399 Surface chlorophyll shows quenching in the upper layers, with surface
400 chlorophyll at noon being 0.19 mg m⁻³ lower on average than the previous 3 am cast.
401 Although quenching was highest late in the cruise, it was also uncorrelated with the
402 separation distance and time into the cruise. This quenching was severe enough that
403 we cannot map chlorophyll across the eddy, but illustrates the importance of using the
404 3 am casts for this analysis.

405 *Comparison of 2008 and 2012 years*

406 The shipboard observations show that in both 2008 and 2012, surface
407 phytoplankton concentration increased in response to the onset of weak stratification
408 (characterised by shoaling of MLD_2 , but not MLD_1), although vertically-integrated
409 chlorophyll stocks remained relatively constant. The main differences are that in 2012
410 there the onset of stratification was delayed by the presence of cool southerly winds.

411 Figure 10 puts the cruise observations into context of the physical forcing
412 during their respective years, showing sea surface chlorophyll, C_0 , from MODIS,
413 temperature from Argo, and NHF and wind stress from NCEP reanalyses. We also
414 show the rate of surface chlorophyll production, $r = \partial \ln(C_0) / \partial t$. The NHF and wind
415 stress have been smoothed in time to approximately match the smoothing inherent in
416 the compositing of the satellite data. We also show the climatological annual cycles
417 for NHF, wind stress, sea surface chlorophyll, and r (see Methods).

418 Although not shown here, of all years between 2002 and 2012, C_0 during 2008
419 was the closest to the climatological annual cycle. Thus 2008 can be regarded as a
420 canonical year, showing both autumn and spring blooms (Figure 10A), although the
421 spring bloom was initially much stronger than climatology.

422 In contrast, 2012 showed little evidence of an autumn bloom, and instead of
423 showing the canonical decrease during winter, C_0 slowly increased from late summer
424 until late spring, but with 1-2 month oscillations (events) superimposed on this rise.
425 The last of these was largest when C_0 peaked at about 60% above the climatological
426 value.

427 The Argo profiles (Figure 10C) were too infrequent to fully resolve the time
428 sequence of temperature, but surface waters were $\sim 20^\circ\text{C}$ in summer and $\sim 13^\circ\text{C}$ in
429 winter in both years. The mixed layer depth, MLD_1 , was typically about 50 m during
430 summer and began to deepen in April, with deepest MLD_1 in late August. In both
431 years, the cruises took place a month to 6 weeks after the time of deepest observed
432 MLD_1 .

433 The NHF in both years (Figure 10D) peaked in June and crossed zero in mid-
434 September, about a month to 6 weeks after the deepest MLD (i.e., the deepest mixed

435 layer occurs a month or so before the ocean stops cooling). In each year, the NHF
 436 showed month to month variability about the climatological annual cycle, with the
 437 longest departure from normal being in 2012 when NHF was consistently lower than
 438 climatology during July and August.

439 The climatological cycle of wind stress has a minimum in summer and peaks in
 440 June (Figure 10E). Both 2008 and 2012 showed large oscillations about this cycle,
 441 this reflects that fact that while winds are generally stronger in winter than in summer,
 442 the wind field in this region is highly variable.

443 Because the sea surface chlorophyll growth rate, r , is the time derivative of
 444 $\ln C_0$, even the climatological value is quite noisy although it shows positive values
 445 from February to April reflecting the autumn bloom, negative values from May to
 446 July and then positive values from August to October. Compared this climatology, r
 447 in both years shows large oscillations, but in 2008 showed peaks in autumn associated
 448 with the autumn bloom and in September associated with the spring bloom (Figure
 449 10F). In 2012, there was a series of oscillations in r from August to October
 450 reflecting the series of blooms seen in sea surface chlorophyll.

451 ***2012 Anomalies***

452 A more detailed analysis of the variability in 2012 can be made by considering
 453 the departures from the climatological mean.

454 Figure 11 shows the surface chlorophyll, C_0 , the growth term, $r = \partial \ln C_0 / \partial t$,
 455 and the NHF anomaly, $\Delta_{NHF} = NHF - \overline{NHF}$, and wind stress anomaly, $\Delta_\tau = \tau - \overline{\tau}$
 456 (where the overbar indicates the climatological value).

457 Vertical lines on all plots indicate 9 local maxima in r , which correspond to
 458 with the leading edges of individual events in C_0 .

459 In 5 out of the 9 instances (March, May, June, early September and October as
 460 indicated by dashed lines) the maxima in r occurred when the wind stress and NHF
 461 anomalies were at or near local positive maxima. This suggests for these 5 instances,
 462 the peaks in surface chlorophyll were driven by higher than normal vertical mixing
 463 and more convective overturn than normal. We refer to these events as mixing events.

464 In 4 of the 9 instances (February, August, late September, and November as indicated
465 by solid vertical lines), the maxima in r occurred when both the heat flux anomaly
466 and the wind stress anomaly were negative. This suggests that the corresponding
467 peaks in surface chlorophyll were driven by increased stability due to reduced
468 turbulence and/or more heat into the ocean than normal. We refer to these events as
469 stability events.

470 Thus Figure 11 suggests that unlike a canonical year, sea surface chlorophyll
471 concentration in 2012 showed a series of winter and spring events modulated by the
472 local wind and heat flux. The event in early October just reached our 0.5 mg m^{-3}
473 spring bloom threshold, but the peak in surface chlorophyll was not until late October.
474 We return to the implications of this findings later, but first investigate whether the
475 results from the nominal site are representative of the region as a whole.

476 *Spatial scales of surface chlorophyll from MODIS*

477 To address the question of how representative the nominal site is of the region
478 in general, Figure 12 shows 8-day composite images of C_0 from MODIS for various
479 dates in 2008 and 2012, along with the climatological values for the same dates.

480 Perhaps the most striking feature of these images is the high degree of
481 patchiness in C_0 , with the obvious implication that had a different experimental site
482 been chosen, a different sequence of events may have been computed for each year.
483 Nevertheless, there are some broad conclusions that are supported by Figure 12.

484 The climatology shows surface chlorophyll concentrations are generally low
485 throughout the region in mid-August. A spring bloom starts in late September and
486 peaks about a month later. By late-November, surface chlorophyll levels decrease to
487 low summer values everywhere except for over the Chatham Rise. The influence of
488 the warm core Wairarapa Eddy (e.g., Roemmich & Sutton, 1998) appears to be strong
489 with reduced surface biomass within the eddy, presumably because of deeper
490 pycnocline (i.e., deeper nutricline) in summer and hence less nutrient availability
491 (e.g., Bradford *et al.*, 1982). Surface chlorophyll concentration is highest along the
492 Subtropical Front along the Chatham Rise in summer. The climatology is consistent

493 with previous work on primary production in the region (e.g., Bradford *et al.*, 1982,
494 Chiswell *et al.*, 2013).

495 Compared to climatology, surface chlorophyll in 2008 shows near-identical
496 sequence, except that values are much higher than expected early in the spring bloom
497 (also seen in Figure 10). The influence of the Wairarapa Eddy is clear, and the spatial
498 structure of surface chlorophyll matches climatology well.

499 In contrast, the 2012 images paint an entirely different picture of surface
500 chlorophyll showing a series of ‘blooms and busts’, some of which are quite limited in
501 areal extent. Surface chlorophyll at the site showed a small event in mid-August (the
502 5th of the 9 anomalies discussed earlier). The composite image for 17 August 2012
503 shows that this bloom was likely limited spatially to a region west of East Cape, and
504 that much of the rest of the region showed chlorophyll levels typical of mid-winter
505 (although the considerable cloud cover means we cannot be sure of this). A little over
506 a month later, the 26 September 2012 image coincides with the mid-point of the
507 cruise, and surface chlorophyll shows levels throughout the region that are
508 substantially lower than climatology. By 4 October a bloom had developed over most
509 of the region (except at the experimental site) that brought surface chlorophyll to near
510 climatology. However, by 20 October (which should be near the peak spring bloom in
511 the climatology) this bloom had disappeared and surface chlorophyll was well below
512 climatology over most of the region. At the experimental site, surface chlorophyll rose
513 rapidly about this time (Figure 10A) and the following 8-day satellite composite (28
514 October) shows an extensive region where surface chlorophyll exceeds 1 mg m^{-3} . On
515 21 November, surface chlorophyll over most of the region was near climatology, but
516 the time series at the site show a small positive anomaly developing (Figure 11),
517 which appears to be a relatively small localised feature.

DISCUSSION

518 The main findings of this work are that in 2008, the timing of the surface
519 chlorophyll concentration at the experimental site followed the climatological annual
520 cycle for this location, although the spring bloom was stronger than climatology. In
521 contrast, in 2012, surface chlorophyll concentration showed little evidence of an
522 autumn bloom and showed a series of winter and spring events modulated by the local
523 wind and heat flux that did not become fully developed blooms until October. The
524 satellite imagery suggests these findings apply to a broad region east of the North

525 Island, although there was substantial spatial patchiness in the surface chlorophyll
526 levels.

527 The 2012 sequence of events in surface chlorophyll illustrates that surface
528 chlorophyll growth can be categorised by what we term either mixing or stability
529 events. Mixing events mix up any deep chlorophyll maximum and/or inject new
530 nutrients into the surface layers allowing increased production (e.g., Findlay *et al.*,
531 2006). Stability events allow phytoplankton to remain in the photic zone and grow
532 (e.g., Chiswell *et al.*, 2015b, Huisman *et al.*, 1999, Taylor & Ferrari, 2011).

533 Autumn blooms are typically mixing events, and the 2008 autumn bloom was a
534 mixing event induced by increased wind stress and the onset of convective overturn at
535 the end of summer.

536 Spring blooms are typically stability events, and there is little doubt that the
537 2008 spring bloom was a mixing event. Surface chlorophyll started to increase at
538 about the time of deepest MLD – almost a month before the NHF changed sign, and
539 the peak of the bloom occurred after the onset of stratification. This timing is
540 consistent with the timeline for spring blooms suggested by Chiswell *et al.* (2015b)
541 who note that in a 1-d system, the mixed layer must start to shoal before the NHF
542 changes sign.

543 The 2008 spring bloom had been underway for some time before the 2008
544 cruise, hence the partial drawdown of nitrate and dissolved iron, and high zooplankton
545 levels seen at the start of the cruise. This conclusion is also supported by Ellwood *et al.*
546 (2015) who found dissolved iron within the surface mixed layer was isotopically
547 heavy. (Isotopically heavy iron occurs when the lighter iron isotopes are selectively
548 removed from the water column due to the uptake by phytoplankton.) Strong winds
549 about 19 September mixed down this early bloom, and resupplied the mixed layer
550 with nutrients to allow the second bloom seen near 25 September. It appears that even
551 in canonical years there are episodic interruptions to the bloom dynamics.

552 The first indication that 2012 was anomalous was the lack of an autumn bloom.
553 At the beginning of March, there was a period of stronger than normal winds and
554 more cooling than normal (event 2), which would normally be expected to drive an
555 autumn bloom. However, these conditions were replaced by a period of negative NHF
556 anomaly which lasted throughout April. This suggests that during late March and

557 April there was less cooling than normal, and that this was sufficient to prevent an
558 autumn bloom from occurring.

559 The progression of events over the rest of 2012 was also different from
560 canonical. The series of mixing events seen in May, June and early September 2012,
561 suggest that even in winter, increased surface chlorophyll can be initiated by increased
562 mixing. Since deep chlorophyll maxima are generally not seen in winter (Chiswell,
563 2011) these winter mixing events were likely driven by entrainment of nutrients
564 leading to increased production in the mixed layer.

565 Three winter/spring stability events occurred in August, late September and
566 November 2012 (events 5, 7 and 9). The late September event was observed during
567 the cruise when surface chlorophyll rose in response to increased stratification (Figure
568 3). It is likely the November bloom was triggered in a similar fashion, but the August
569 event took place while the NHF was still positive (although anomalously weak). It
570 seems unlikely that water column stratification could occur when there was still
571 cooling, and so without *in situ* data for this event, we can only speculate that this was
572 an event triggered by reduced turbulence (e.g., Huisman *et al.*, 1999).

573 Perhaps the most interesting observation of 2012 is that the largest peak in
574 surface chlorophyll, in late October 2012, was likely driven by increased mixing and
575 paradoxically was therefore propelled by mechanisms more appropriate for an autumn
576 bloom rather than a spring bloom.

577 Thus, it seems that in 2012, the spring bloom started with an increase in
578 stratification leading to a conventional bloom in early October, but increasing winds
579 and decreased surface heating led to this bloom initially being mixed out, and then
580 replaced with a mixing bloom in late October.

581 It is not clear from our observations why 2012 should have been such an
582 anomalous year. SST at the site was cooler than climatology throughout most of 2012
583 (Figure 10), and 2012 was the third coolest year between 1985 and 2017 (Figure 13).
584 This is despite the fact that, according to NOAA
585 (www.ncdc.noaa.gov/sotc/global/201213), the global average SST for 2012 was
586 0.45°C above the 20th century mean (and at that time, 2012 was the 10th warmest
587 year on record). At the experimental site there is no clear relationship between El
588 Nino and SST anomaly – for example, SST anomaly was negative during the during

589 the 1992/93 El Nino, but positive during the 1997/1998 El Nino years. There was
590 nothing particularly anomalous about either the annual wind stress or net heat flux
591 during 2012, and there was no clear relationship between either of these quantities and
592 SST (Figure 13). These observations suggest that in 2012, while SST east of New
593 Zealand did not follow the global trends, it was also not driven solely by local forcing
594 and thus was a response to a complex set of forcing that is beyond the scope of this
595 article to determine.

596 It likely that the cooler than normal conditions during 2012 played a role in
597 the mixing spring bloom in that year, because these imply a weaker than normal
598 thermocline. However, how common mixing spring blooms are, and whether they
599 have a significant impact on the annual net primary production is uncertain, and these
600 questions remain topics for future research.

CONCLUSION

601 The temporal evolution of stability during bloom development is critical.
602 Surface chlorophyll blooms can be triggered by loss of stability when increased wind
603 stress and convective overturn lead to mixing up of the deep chlorophyll maximum
604 and or increase nutrients into the mixed layer, or they can also be triggered by
605 increased stability when decreased wind stress and decreased convective overturn lead
606 to conditions when phytoplankton remain in the photic zone. Traditionally, autumn
607 blooms are considered to be triggered by decreasing stability, and spring blooms are
608 considered to be triggered by increasing stability. This research suggests that this
609 paradigm does not always hold, and that there is at least one case where the spring
610 bloom is triggered by loss of stability. We can for now only speculate how common
611 such blooms are, whether this mechanism drives more productive spring blooms than
612 those driven by increased stability.

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628 are available via the New Zealand Ocean Data Network (<https://nzodn.nz>), but all data
629 will be provided on request.

630

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748

FIGURES

749 Figure 1. Study region east of the North Island of New Zealand. Locations of 3 am
 750 casts made during spring bloom cruises in 2008 (red squares) and 2012 (blue
 751 squares) are superimposed on mean sea surface chlorophyll, C_0 , derived from
 752 MODIS aqua ocean colour satellites. The 1000 m isobath is shown as a dashed
 753 line and the centre of the Wairarapa Eddy is labelled WE. Also shown are the
 754 locations of 42 Argo profiles in 2008 (solid red circles) and 23 profiles in 2012
 755 (blue circles) made within 125 km of the nominal experimental site.

756 Figure 2. Locations of CTD casts made during the 2008 and 2012 spring bloom
 757 cruises. Blue squares show casts made at 3 am, red squares show casts made at
 758 noon (no noon casts were made in 2008) and green circles show other casts. The
 759 path of the Lagrangian array in 2012 is shown as a blue line.

760 Figure 3. Shipboard data from 2008 and 2012 cruises. (A) Wind stress, τ , numbers 1
 761 to 4 in 2012 refer to the calm periods discussed in the text; (B) Sea surface
 762 temperature, T_0 ; (C) Temperature, T , from 3 am CTD casts (note different
 763 scales for each year); (D) Surface and depth-integrated chlorophyll from the 3
 764 am CTD casts. Surface chlorophyll, C_0 , is taken as the average over the top 5
 765 m, and the depth-integrated chlorophyll, $C_{0/300}$, is integrated over the top 300
 766 m; (E) Chlorophyll, C , section from the 3 am CTD casts. Two estimates of the
 767 mixed layer depth, MLD_1 and MLD_2 , based on density differences of 0.125 and
 768 0.025 kg m^{-3} , respectively (see Methods), are superimposed on the temperature
 769 and chlorophyll. Panels relating to 2008 data have been adapted from Chiswell
 770 (2011).

771 Figure 4. Nutrients during the 2008 and 2012 cruises from upcast water samples taken
 772 on the 3 am CTD casts. Two estimates of the mixed layer depth, MLD_1 and
 773 MLD_2 , based on density differences of 0.125 and 0.025 kg m^{-3} , respectively (see
 774 Methods), are superimposed on the chlorophyll sections. (A) Wind stress, τ (as
 775 in Figure 3); (B) Chlorophyll, C ; (C) Nitrate, NO_3 , for 2008, and Nitrate plus
 776 Nitrite, $NO_3 + NO_2$, for 2012; (D) Silicate, SiO_3 ; (E) Phosphate, PO_4 ; and (F)
 777 Dissolved iron, dFe , taken from trace-metal samples.

778 Figure 5. Metrics of phytoplankton biomass and productivity for the 2008 and 2012
 779 cruises. **(A)** Percentage of Net Primary Production (NPP) by cells larger than 20
 780 μm ; **(B)** Community NPP (cells larger than 0.2 μm); and **(C)** Chlorophyll, C
 781 (also shown in Figure 3, but with expanded depth scale). Dashed lines are mixed
 782 layer depth, MLD_2 , based on density difference 0.025 kg m^{-3} .

783 Figure 6. Microzooplankton from 2008 and 2012 cruises. **(A)** Wind stress, τ (as in
 784 Figure 3); **(B)** Aloricate ciliates $<20 \mu\text{m}$; **(C)** Aloricate ciliates $>20 \mu\text{m}$; **(D)**
 785 Tintinnids; **(E)** Mean Microzooplankton and chlorophyll concentrations over the
 786 top 100 m. For comparison, contours of chlorophyll (as seen in Figure 3) are
 787 shown in panels B to D.

788 Figure 7. Shipboard measurements from the 2012 cruise. **(A)** Wind speed, W ; **(B)**
 789 Wind direction, θ (180° indicates winds from the south); **(C)** Air minus sea
 790 temperature, $T_{air} - T_{sea}$; **(D)** Sea temperature, T_{sea} , from ships underway system,
 791 and sea surface temperature, T_0 , and chlorophyll, C_0 , from 3 am CTD casts.

792 Figure 8. Locations of CTD casts every second day during the 2012 spring bloom
 793 cruise, Blue squares show the 3 am casts, green squares show casts made
 794 between 12 hours before and 12 hours after the 3 am cast, along with the drifter
 795 track (green shows the full track, blue shows the track within 12 hours of the 3
 796 am CTD cast), and surface velocities within 12 hours of the 3 am CTD cast
 797 from the shipboard Acoustic Doppler Current Profiler (ADCP, cyan vectors).
 798 Each panel is centred on the 3 am cast location and the dashed line shows a 10-
 799 km radius circle centred on that location.

800 Figure 9. **(A)** Sea surface temperature, T_0 , from CTD casts made in the 2012 cruise.
 801 The blue line connects T_0 from the 3 am casts, the green line connects T_0 from
 802 all CTD casts, and red squares show T_0 from the noon CTD casts (see Figure 2
 803 for CTD locations); **(B)** Temperature section from all CTD casts made during
 804 the cruise. The dashed and solid lines are mixed layer depths MLD_1 and MLD_2
 805 calculated using the 3 am casts as shown in Figure 3; **(C)** Sea surface
 806 Chlorophyll, C_0 , from CTD casts made in the 2012 cruise. The blue line
 807 connects C_0 from the 3 am casts, the green line connects C_0 from all CTD casts

808 and red squares shows C_0 from the noon CTD casts; **(D)** Chlorophyll, C ,
 809 section from all CTD casts made during the cruise. The dashed and solid lines
 810 are the 0.5 and 0.25 mg m⁻³ contours shown in Figure 3.

811 Figure 10. Satellite and reanalysis data for 2008 and 2012. **(A)** Sea surface
 812 chlorophyll derived from MODIS satellite (blue line). Vertical dashed line
 813 indicates date of deepest mixed layer from Argo data. Horizontal dashed lines
 814 show 0.5 and 0.25 mg m⁻³ threshold criteria for spring and autumn blooms,
 815 respectively; **(B)** Sea surface temperature (SST) derived from AVHRR satellite
 816 (blue line); **(C)** Temperature derived from Argo profiles made within 125 km of
 817 the nominal site. Red and black dot-dashed lines indicate two estimates of the
 818 mixed layer depth, MLD_1 and MLD_2 , based on density differences 0.125 and
 819 0.025 kg m⁻³ (see Methods); **(C)** Net heat flux, NHF , from NCEP reanalysis
 820 (green); **(D)** Wind stress, τ , from NCEP reanalysis (blue); **(E)** Rate of change
 821 of surface chlorophyll, $r = \partial \ln C_0 / \partial t$. Vertical solid lines in all panels indicate
 822 beginning and ending of spring bloom cruises in 2008 and 2012. Grey lines in
 823 panels A, B, D and E show the climatological annual cycles of the respective
 824 quantities.

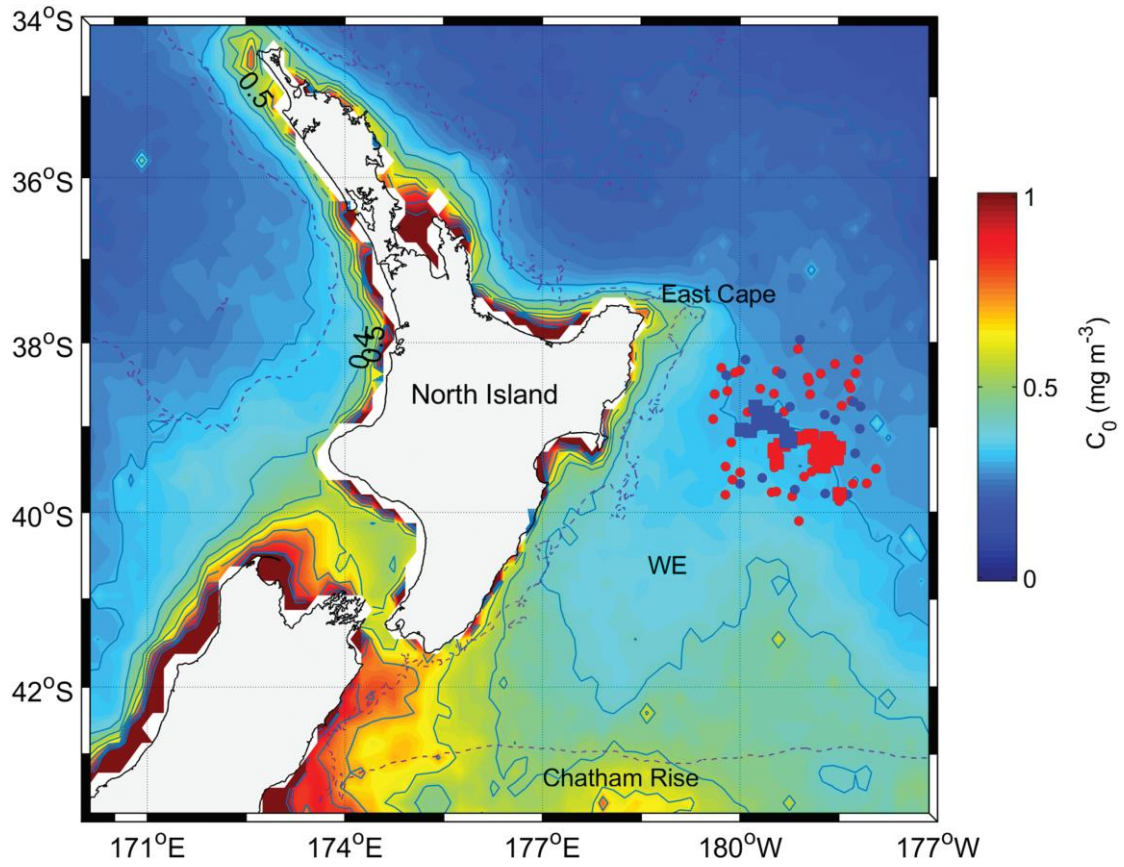
825 Figure 11. Satellite and reanalysis data for 2012. **(A)** Sea surface chlorophyll, C_0 ,
 826 derived from MODIS satellite data for the experimental site shown in Figure 1;
 827 **(B)** Rate of change of surface chlorophyll $r = \partial \ln C_0 / \partial t$; **(C)** Net Heat Flux
 828 anomaly, Δ_{NHF} , calculated as the difference between NHF during 2012 and the
 829 climatological value of NHF ; **(D)** Wind stress annual anomaly, Δ_τ , calculated
 830 as the difference between τ during 2012 and the climatological value of τ .
 831 Vertical lines indicate periods of sustained surface chlorophyll increase as
 832 determined by local maxima in r . Solid lines indicate events driven by more
 833 heat entering the ocean than normal and less winds than normal and are referred
 834 to as ‘stability’ events. Dashed lines indicate events driven by less heat entering
 835 the ocean than normal and/or higher wind stress than normal, and are referred to
 836 as ‘mixing’ events.

837 Figure 12. Sea surface chlorophyll derived from MODIS aqua satellite for selected
838 days. Left-hand panels show the climatological values for the day of year.
839 Centre and right-hand panels show 8-day composite sea surface chlorophyll for
840 dates in 2008 and 2012. Discontinuities along 180° reflect the date-line change,
841 and its impact on compositing data.

842 Figure 13. Annual anomalies for various quantities at the experimental site. For each
843 year, the anomaly is calculated as the mean value of the quantity minus its
844 climatology. **(A)** Sea surface temperature anomaly derived from AVHRR
845 estimates of SST; **(B)** Wind stress anomaly derived from NCEP reanalysis; **(C)**
846 Net heat flux (NHF) anomaly derived from NCEP reanalysis.

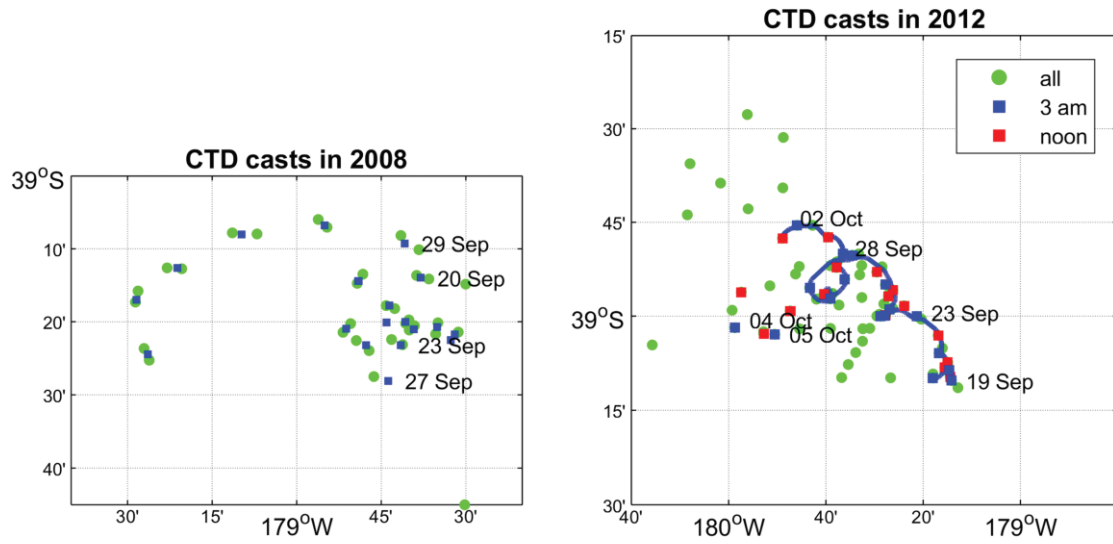
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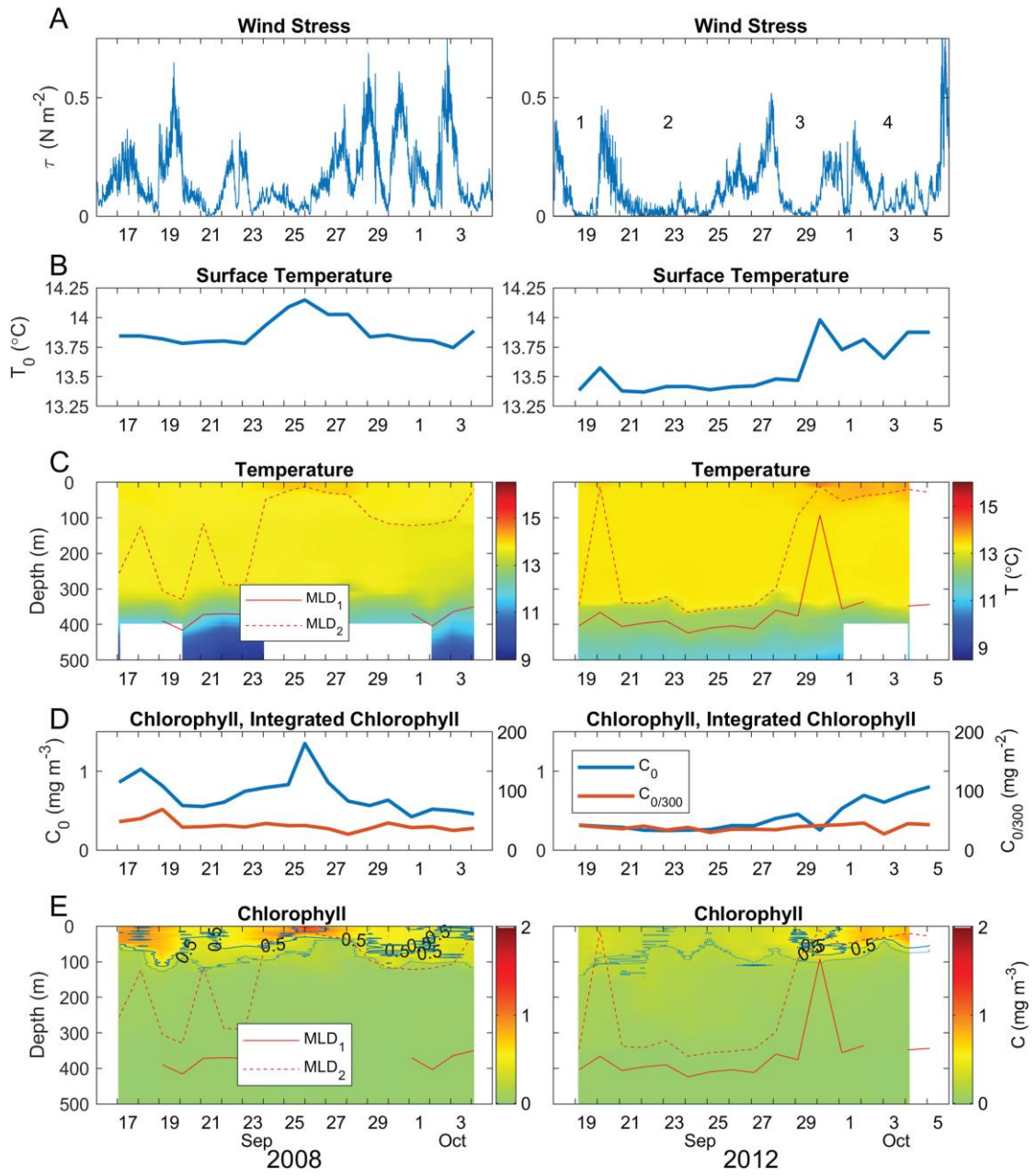


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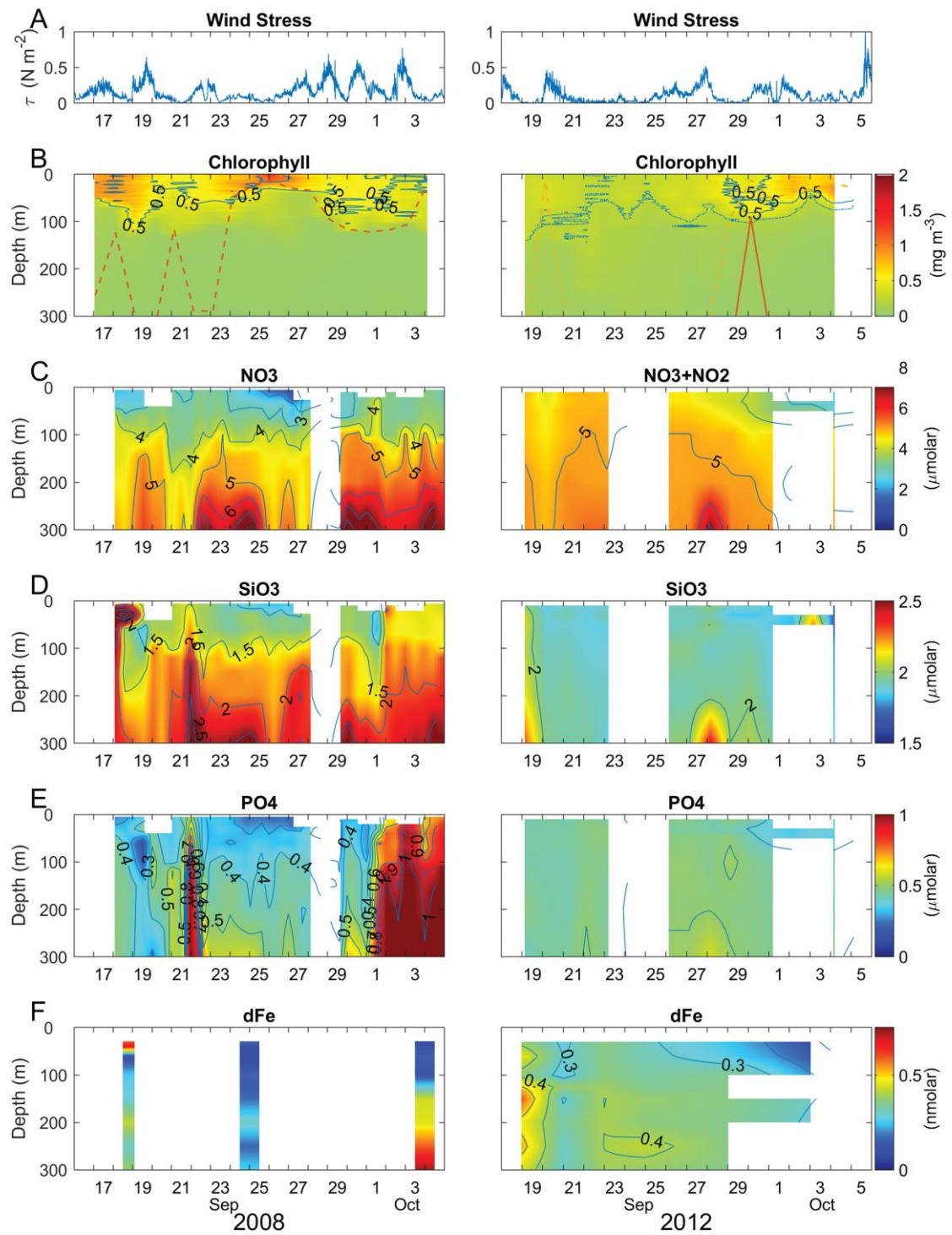
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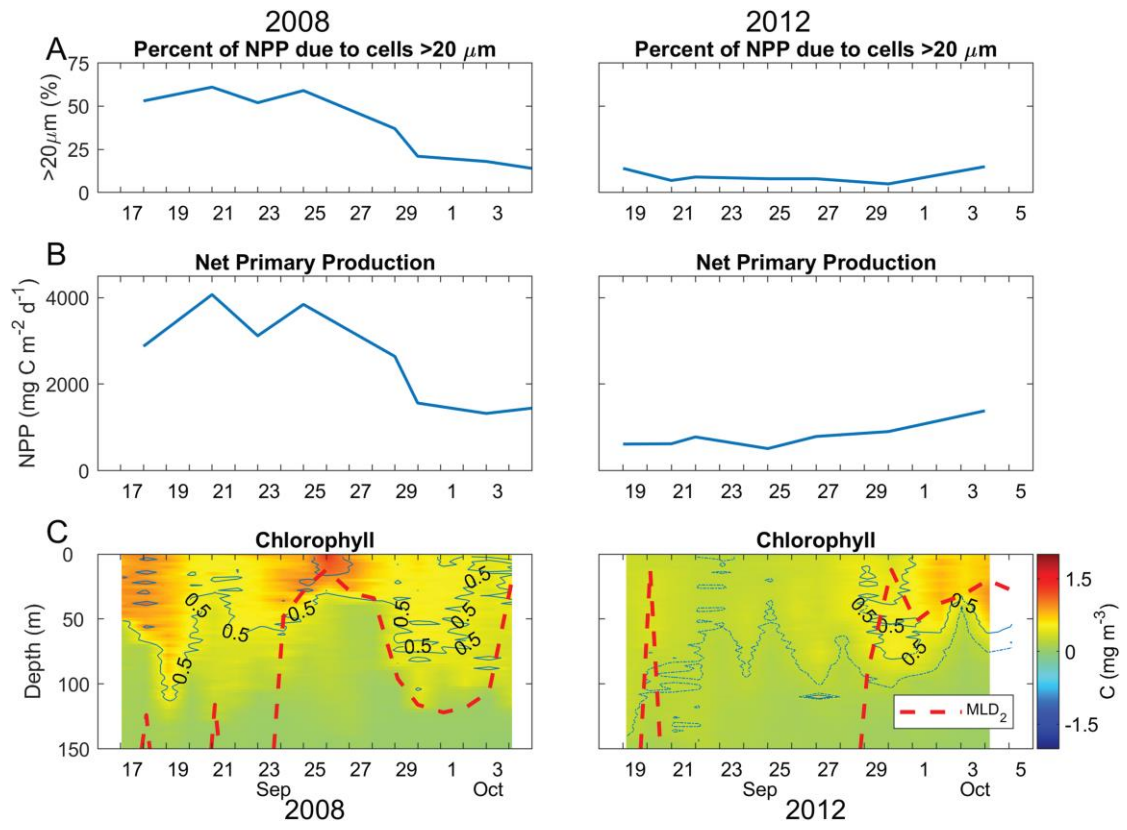


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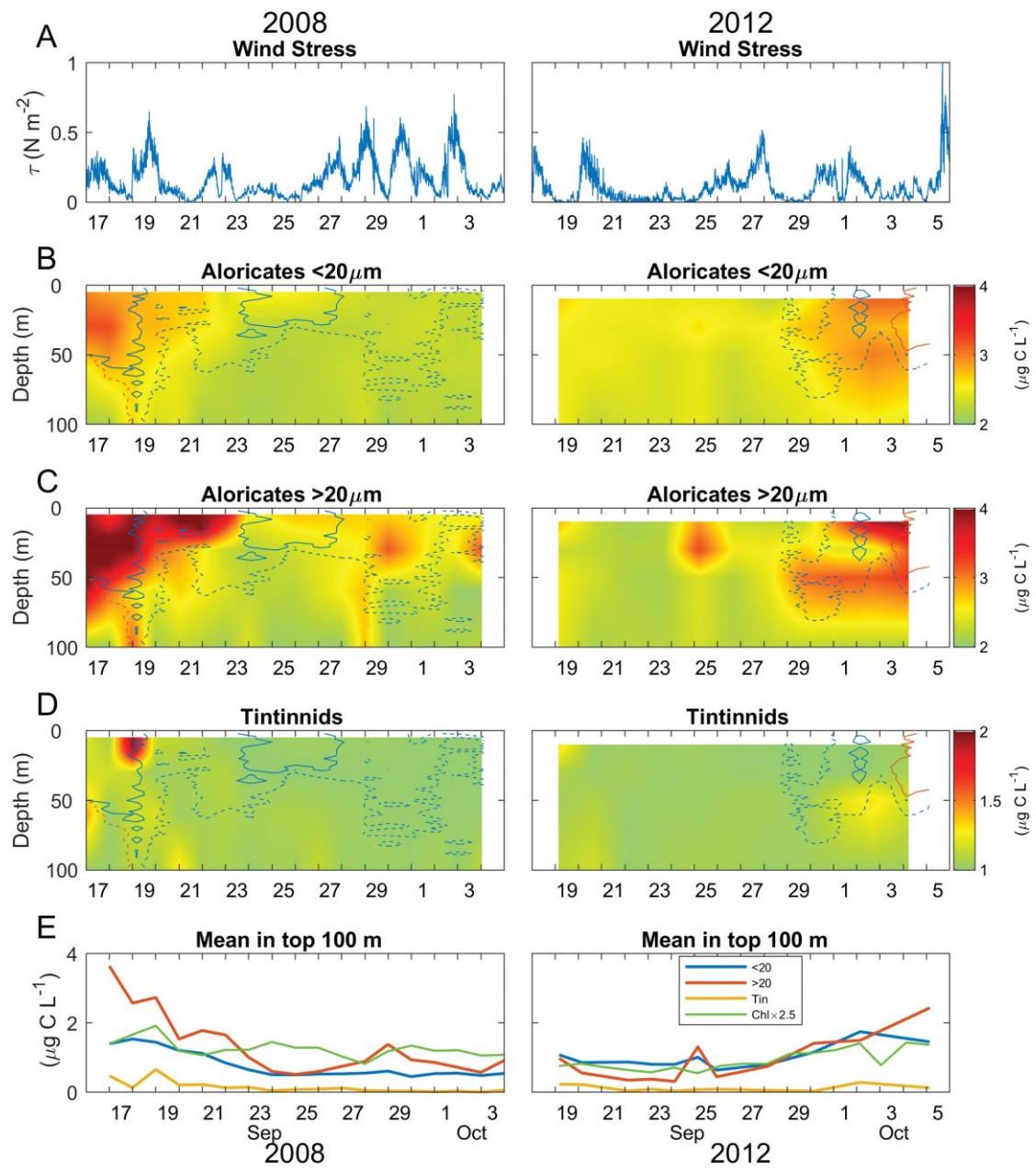


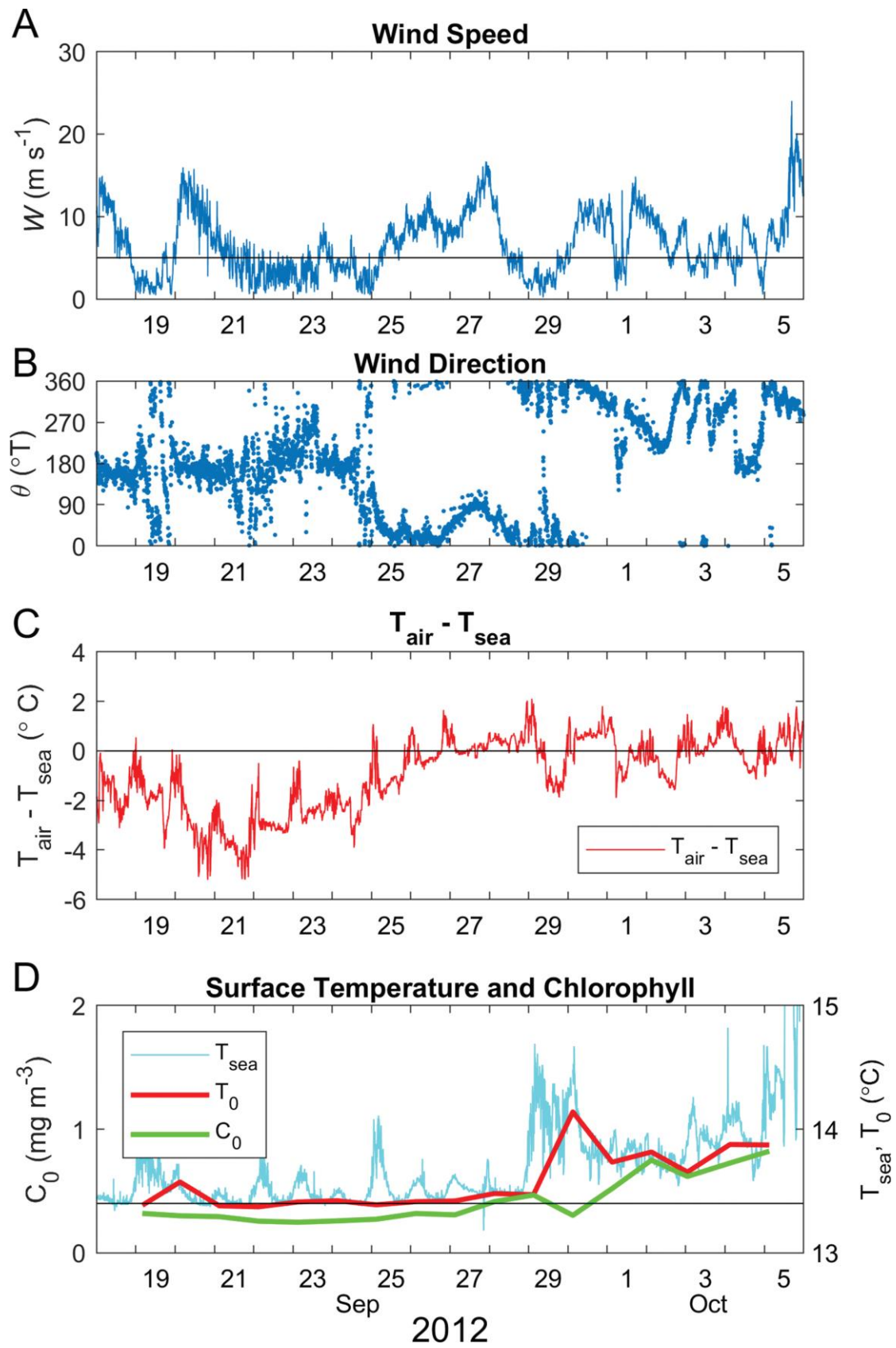
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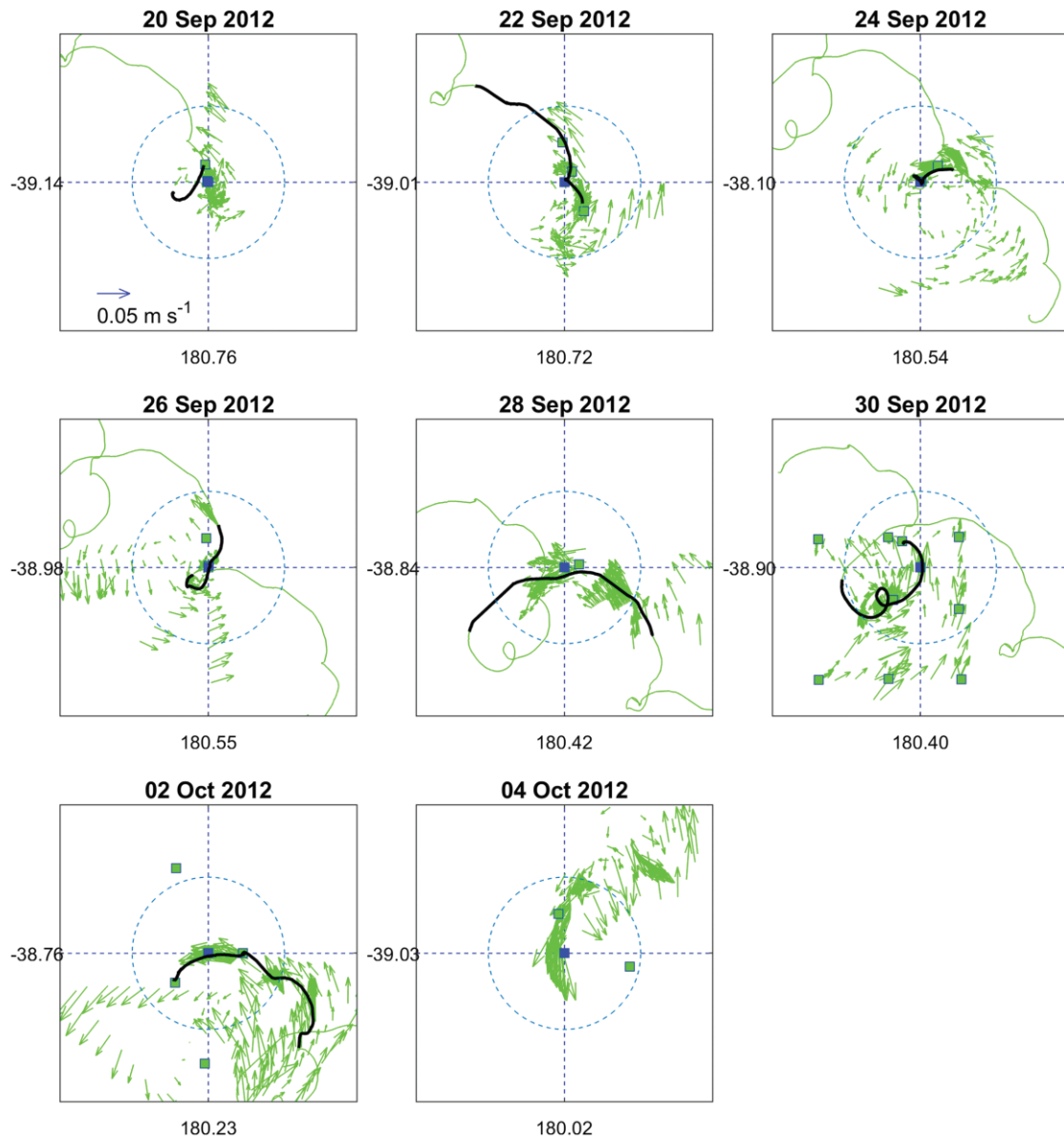




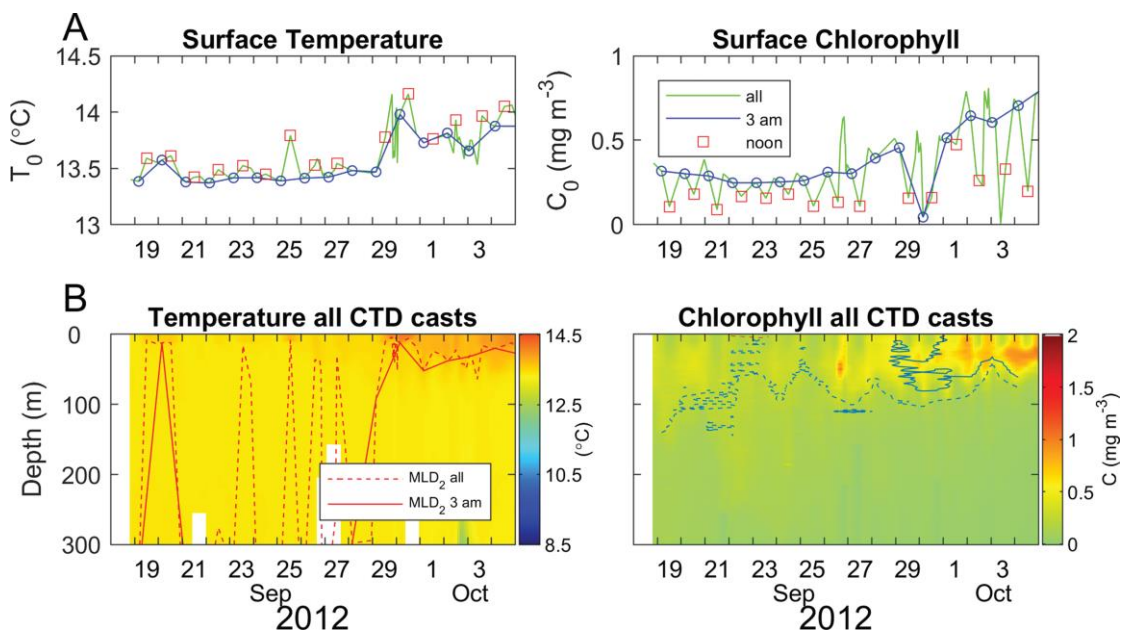
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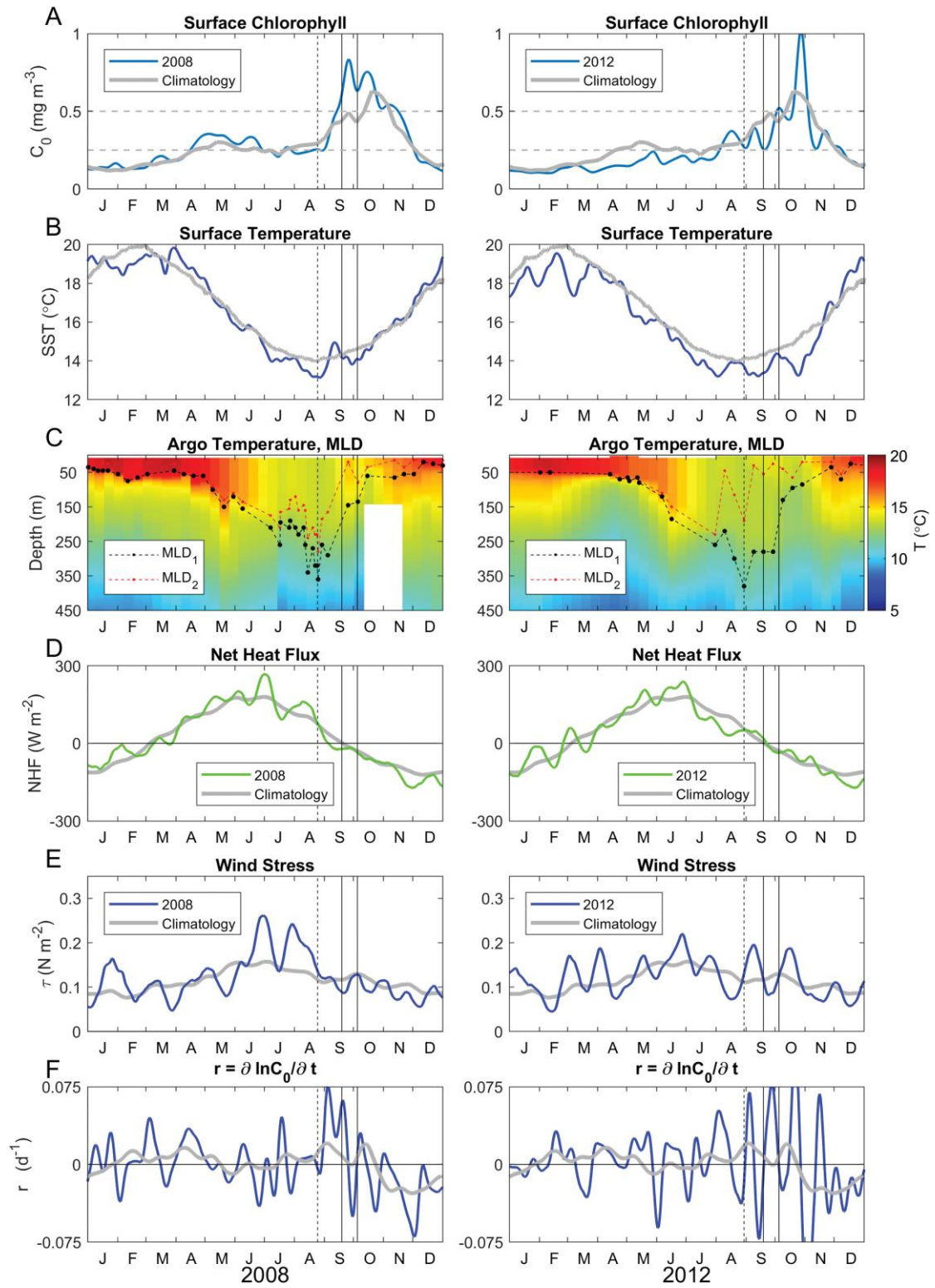




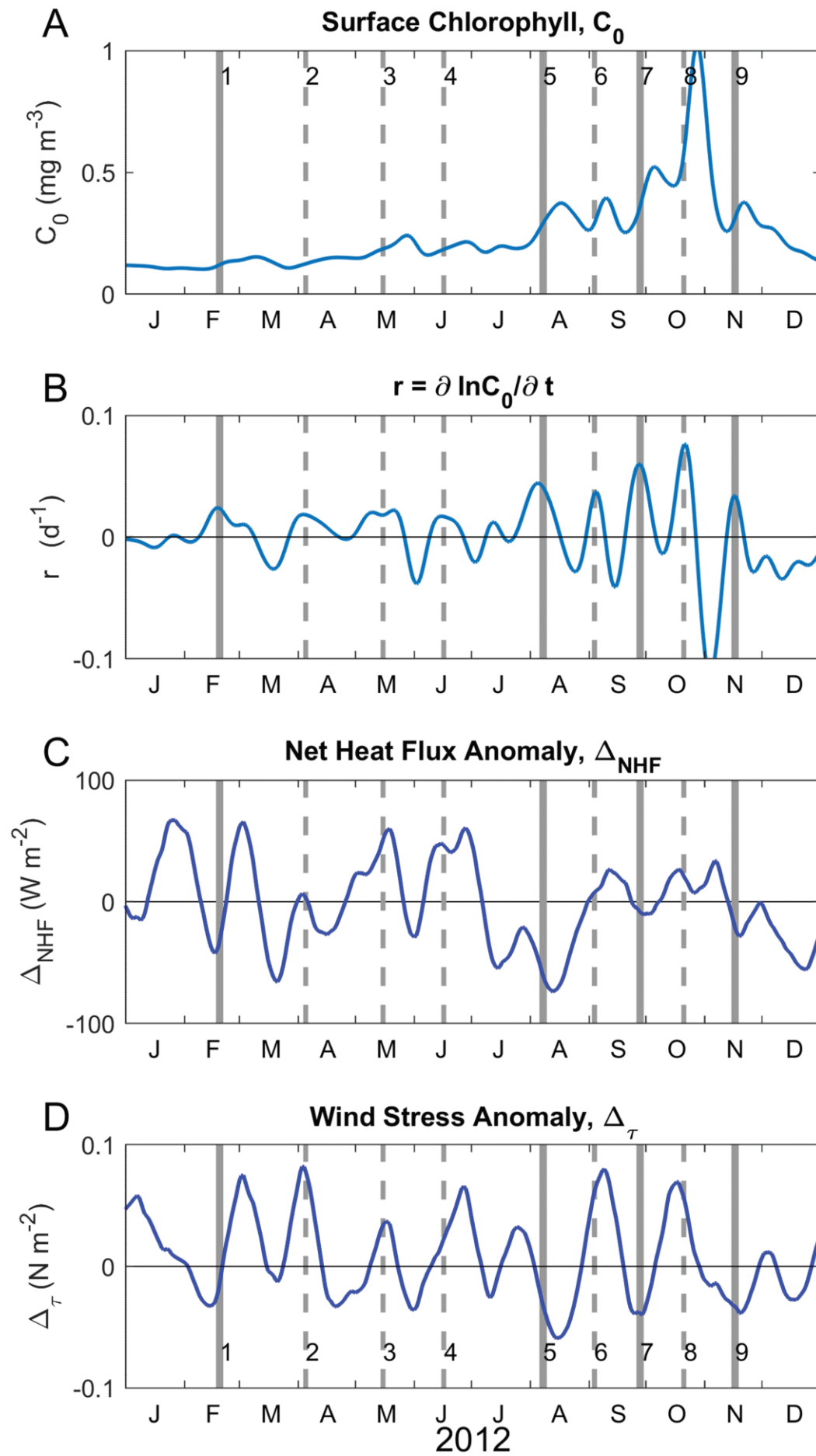
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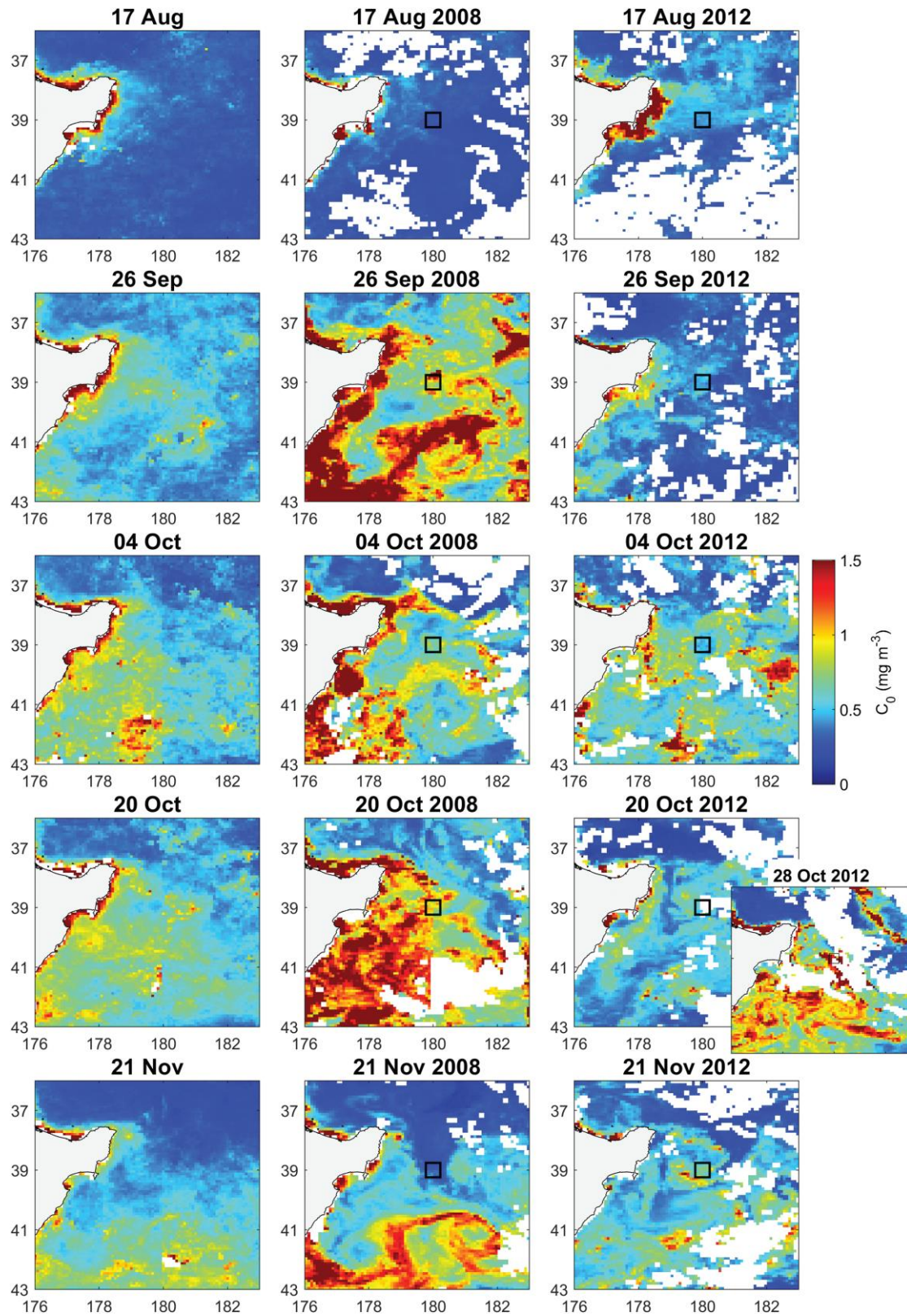


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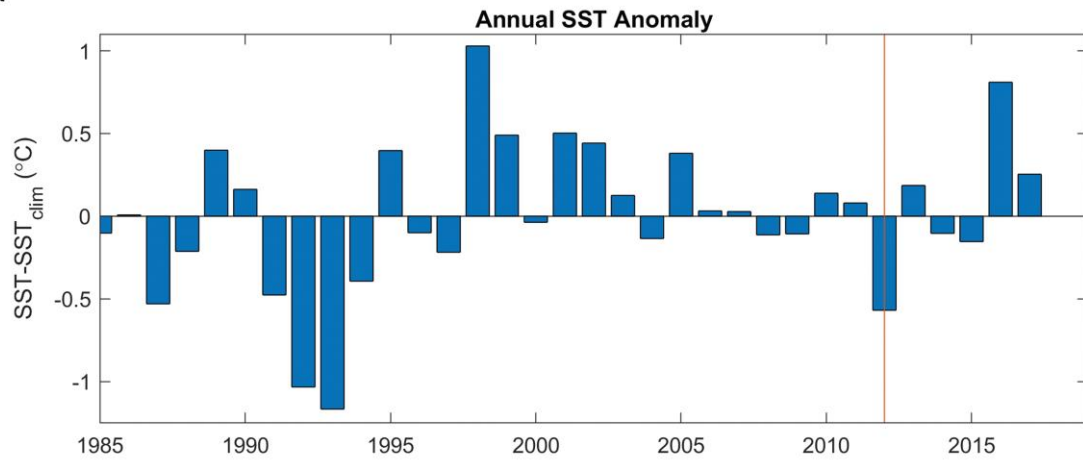


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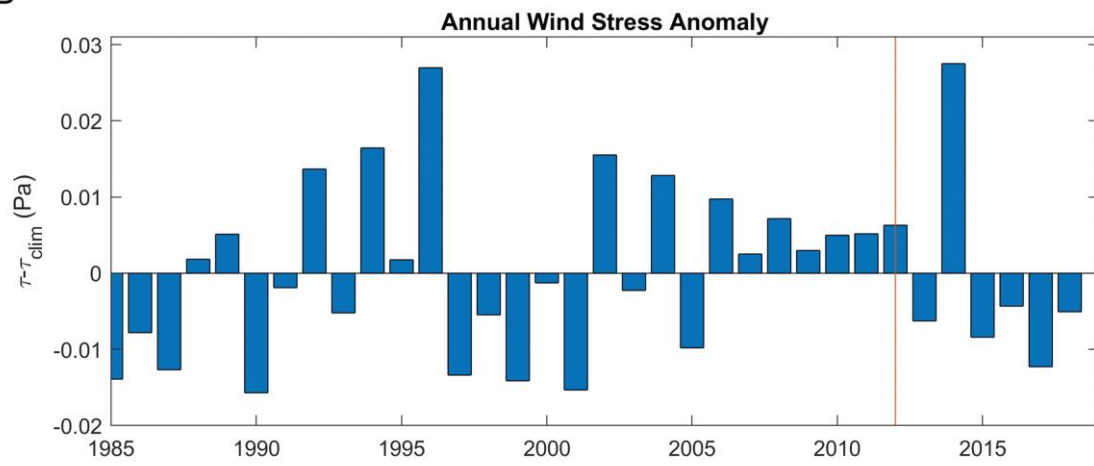




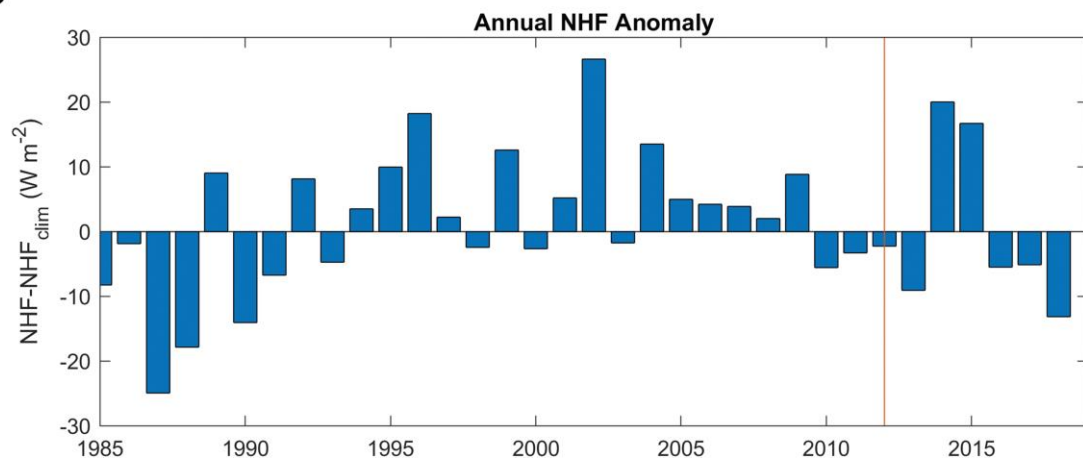
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