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# Seasonal Oceanography from Physics to Micronekton in the South-West Pacific.

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34

Accepted manuscript

35 **Abstract**

36 Tuna catches represent a major economic and food source in the Pacific Ocean, yet are  
37 highly variable. This variability in tuna catches remains poorly explained. The relationships  
38 between the distributions of tuna and their forage (micronekton) have been mostly derived  
39 from model estimates. Observations of micronekton and other mid-trophic level organisms,  
40 and their link to regional oceanography, however are scarce and constitute an important  
41 gap in our knowledge and understanding of the dynamics of pelagic ecosystems. To fill this  
42 gap, we conducted two multidisciplinary cruises (Nectalis1 and Nectalis2) in the New  
43 Caledonian Exclusive Economic Zone (EEZ) at the southeastern edge the Coral Sea, in 2011  
44 to characterize the oceanography of the region during the cool (August) and the hot  
45 (December) seasons. The physical and biological environments were described by  
46 hydrology, nutrients and phytoplankton size structure and biomass. Zooplankton biomass  
47 was estimated from net sampling and acoustics and micronekton was estimated from net  
48 sampling, the SEAPODYM ecosystem model, a dedicated echosounder and non-dedicated  
49 acoustics. Results demonstrated that New Caledonia is located in an oligotrophic area  
50 characterized by low nutrient and low primary production which is dominated by a high  
51 percentage of picoplankton cyanobacteria *Prochlorococcus* (>90%). The area is  
52 characterized by a large-scale north-south temperature and salinity gradient. The northern  
53 area is influenced by the equatorial Warm Pool and the South Pacific Convergence Zone and  
54 is characterized by higher temperature, lower salinity, lower primary production and  
55 micronekton biomass. The southern area is influenced by the Tasman Sea and is  
56 characterized by cooler temperature, higher salinity, higher primary production and  
57 micronekton biomass. Interactions between the dynamic oceanography and the complex  
58 topography creates a myriad of mesoscale eddies, inducing patchy structures in the frontal  
59 area. During the cool season, a tight coupling existed between the ocean dynamics and  
60 primary production, while there was a stronger decoupling during the hot season. There  
61 was little difference in the composition of mid-trophic level organisms (zooplankton and  
62 micronekton) between the two seasons. This may be due to different turn-over times and  
63 delays in the transmission of primary production to upper trophic levels. Examination of  
64 various sampling gears for zooplankton and micronekton showed that net biomass

65 estimates and acoustic-derived estimates compared reasonably well. Estimates of  
66 micronekton from net observations and the SEAPODYM model were in the same range. The  
67 non-dedicated acoustics adequately reproduced trends observed in zooplankton from nets,  
68 but the acoustics could not differentiate between zooplankton and micronekton and  
69 absolute biomasses could not be calculated. Understanding the impact of mesoscale  
70 features on higher trophic levels will require further investigation and patchiness induced by  
71 eddies raises the question of how to best sample highly dynamic areas via sea experiments.

72

73 **Keywords**

74 Zooplankton, nekton, acoustic data, oceanographic surveys, mesoscale eddies, oligotrophic,  
75 primary production

76

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## 77 **1 Introduction**

78 In the South Pacific Ocean fishing of apex predators, such as tuna and billfishes, represents a  
79 major economic and food resource (Bell et al., 2013). Considerable variability in tuna catch  
80 rates is observed in fisheries (Rouyer et al., 2008). Although much of this variability remains  
81 unexplained, tuna abundance in space and time has been correlated with factors including  
82 oceanographic conditions, physiological constraints (*e.g.* temperature, depth, oxygen  
83 requirements), forage availability, and reproductive behavior (Farley et al., 2013; Senina et  
84 al., 2008; Young et al., 2011).

85 Tuna forage predominantly comprises micronekton (Young et al., 2010; this issue).  
86 Micronekton are defined as organisms in the 2-20 cm size range and are predominantly  
87 distributed in the upper 1000 m of the water column. Micronekton play a key role as  
88 intermediaries between plankton production, their prey, and top predators. Since  
89 micronekton biomass is dependent on the availability of plankton prey, it is expected that  
90 plankton production, its oceanographic drivers, and micronekton biomass would be tightly  
91 coupled, and therefore act in concert in determining top predator distributions.

92 The New Caledonian Exclusive Economic Zone (EEZ), a region of more than  $1.4 \times 10^6$  km<sup>2</sup>, is  
93 located in the Coral Sea, at the southeastern edge of the South Pacific (Figure 1). The  
94 dominant feature of circulation across 0-150 m is the westward-flowing South Equatorial  
95 Current (SEC) from  $\sim 25^\circ\text{S}$  to the equator. The SEC flow bifurcates at the Australian  
96 continental margin (Ridgway and Dunn, 2003) at  $\sim 15^\circ\text{S}$ , with one branch connecting with  
97 the southward flowing East Australian Current (EAC) (Qu and Lindstrom, 2002) and the  
98 other forming the Gulf of Papua Current which flows northward along the coast of  
99 Queensland. Within the Coral Sea, the SEC comprises narrow filaments and jets created by  
100 the complex island, reef, seamounts and ridge topography (Gourdeau et al., 2008) namely  
101 the North Vanuatu Jet at around  $13-15^\circ\text{S}$ , and the North Caledonian Jet at around  $17-18^\circ\text{S}$   
102 (Couvelard et al., 2008; Marchesiello et al., 2010). To the south of New Caledonia, the  
103 surface flow returns from the EAC back into the central south Pacific (Figure 1) as the South  
104 Tropical Counter Current (STCC) (Marchesiello et al., 2010). In this region, the structures of  
105 the ocean currents are prone to shear instabilities and high eddy kinetic energy is observed

106 (Qiu et al., 2009). Excluding the very coastal areas, the New Caledonian EEZ is regarded as  
107 oligotrophic (Dandonneau and Gohin, 1984) with a mean nitracline depth of ~110 m (Figure  
108 1). South of 22°S, the region experiences higher productivity (Ceccarelli et al., 2013;  
109 Dandonneau and Gohin, 1984).

110 Within this oceanographic context, the longline fishery for tuna represents approximately  
111 30% of the total fisheries harvest in New Caledonia (Gillett, 2009). Catches are dominated  
112 by albacore tuna (*Thunnus alalunga*) and exhibit two seasonal peaks in July - August and  
113 December, and the highest catch rates occur in the north-western part of the EEZ (Briand et  
114 al., 2011). The influence of temperature, primary production and micronekton density on  
115 tuna catch rates has been demonstrated in New Caledonia (Briand et al., 2011), in American  
116 Samoa (Domokos, 2009) and at the ocean basin scale in the Pacific Ocean (Lehodey et al.,  
117 1998).

118 Large-scale observations of temperature, surface currents and surface primary production  
119 derived from satellite data have allowed validation of the existing oceanographic models,  
120 giving confidence in the use of modeled oceanographic parameters for such analyses.  
121 However there are few observations of biological parameters, including micronekton, to  
122 validate the model biological outputs.

123 At the scale of the South Pacific, nutrient and *in situ* phytoplankton data are sparse, as are  
124 data on zooplankton (Carassou et al., 2010; Le Borgne et al., 2011; McKinnon, 2005; Young  
125 et al., 2011). Knowledge of the micronektonic communities and their distributions is  
126 somewhat more comprehensive, but is based primarily on top predator diet studies (Allain  
127 et al., 2012; Olson et al., 2014; Young et al., 2011, 2010). Few data are available from *in situ*  
128 sampling with nets in the South Pacific (Flynn and Paxton, 2012; McPherson, 1991) and in  
129 general, none of the available micronekton data are coupled with information on  
130 oceanographic conditions. These constitute important gaps in our knowledge and  
131 understanding of the dynamics of the pelagic ecosystem.

132 Prior to this study, *in situ* data on micronekton in the New Caledonian region were derived  
133 from a handful of studies conducted in the eastern part of the EEZ (Grandperrin, 1975,

134 1969; Legand et al., 1970; Roger, 1986, 1974). Overall, data from the New Caledonia region  
135 are limited in both space and time, prohibiting a comprehensive description of the pelagic  
136 ecosystem, including the main seasonal patterns of zooplankton and micronekton and their  
137 relationships with the oceanography.

138 In 2011, we conducted two dedicated multi-disciplinary bio-oceanographic cruises  
139 (Nectalis1 and Nectalis2) in an effort to fill some knowledge gaps highlighted above for the  
140 New Caledonian and greater South Pacific region. Oceanography, nutrient and food web  
141 components were sampled in areas of high (north-west) and low (north-east) albacore tuna  
142 catch rates in the New Caledonia EEZ, during the austral cool and hot seasons when  
143 oceanography is contrasted and tuna catches high. The primary aim of these cruises was to  
144 provide insights into how phytoplankton, zooplankton and micronekton are coupled with  
145 ocean dynamics in the upper water column (0-1000 m). Here we describe the overall  
146 structure of the food web using *in situ* measurements of hydrodynamic parameters,  
147 nutrients, phytoplankton distribution, primary production, and the biomass of zooplankton  
148 and micronekton. We pay particular attention to the inter-comparability of the zooplankton  
149 and micronekton sampling techniques (nets and acoustics) used, and the application of  
150 acoustic techniques to improve estimates of micronekton in the future. We also use the  
151 collected data to assess measures of micronekton estimated using the ecosystem model  
152 SEAPODYM (Lehodey et al., 2010). Finally we interpret our findings in the context of the  
153 broader southwest Pacific.

154

## 155 **2 Methods and data**

156 Two scientific cruises, Nectalis 1 and 2 were conducted onboard the R/V Alis from 29 July to  
157 16 August 2011 (austral cool season - 18 sampling stations) and 26 November to 14  
158 December 2011 (austral hot season - 23 sampling stations) within the New Caledonian EEZ  
159 (Figure 2 and 3). The two cruises were conducted on approximately the same track, with  
160 some differences due to weather conditions. The potential spatial variability introduced by  
161 variability in station positions between cruises was considered minimal in view of the



162 variability of this highly dynamic pelagic system. Details of station sampling and continuous  
163 measurements are summarized in Table 1 and detailed below. Comparisons of ensuing data  
164 made between cruises included all stations.

## 165 **2.1 Data collected during the cruises**

### 166 2.1.1 S-ADCP currents

167 Five minute averaged ocean currents were acquired from 8 m bins across 16 to 200 m depth  
168 using a ship-borne 153 kHz Acoustic Doppler Current Profiler (ADCP – Teledyne RD  
169 Instrument, Seattle, USA). These velocity profiles were edited and processed using the  
170 CODAS software,  
171 ([http://currents.soest.hawaii.edu/docs/adcp\\_doc/codas\\_setup/index.html](http://currents.soest.hawaii.edu/docs/adcp_doc/codas_setup/index.html)) following the  
172 procedure of Hummon and Firing (2003). Data presented are averages over the top 150 m.

### 173 2.1.2 Temperature and salinity

174 An on-board thermosalinograph continuously measured sea surface temperature (SST) and  
175 salinity (SSS). At each station, Conductivity Temperature Depth (CTD) casts down to 500 m  
176 recorded continuous vertical profiles of temperature and salinity. CTD data were checked  
177 for spurious values using the Seasoftware (Sea-Bird electronics, Washington, USA),  
178 binned at 1m intervals and presented for the top 200 m.

### 179 2.1.3 Water sampling

180 Water was sampled during the CTD casts using 8 L Niskin bottles to measure nutrients,  
181 chlorophyll, phytoplankton cell counts, photosynthetic pigments and primary production.  
182 Depth and frequency of sampling varied according to variables measured and associated  
183 analyses (Table 1).

### 184 2.1.4 Nutrients

185 Nitrate, phosphate (Soluble Reactive Phosphorus: SRP) levels were measured in HgCl<sub>2</sub>-  
186 poisoned samples and analyzed in the laboratory within two months of the end of the  
187 cruises using an Auto-analyzer AA3 (Bran+Luebbe, Norderstedt, Germany), as described in  
188 Aminot and K rouel (2007). Nitrate and nitrite (reported as NO<sub>3</sub>) concentrations were  
189 determined at nanomolar precision (Raimbault et al., 1990). SRP concentrations (reported

190 as PO<sub>4</sub>) were analyzed according to Murphy and Riley (1962). Data were interpolated to plot  
191 the 0-180 m vertical profiles using Dr Masson's SAXO package  
192 (<http://forge.ipsl.jussieu.fr/saxo/download/xml/doc/whatissaxo.html>) based on IDL  
193 (Interactive Data Language, Exelisvis, Boulder, USA).

#### 194 2.1.5 **Phytoplankton: biomass and community structure**

195 Phytoplankton composition and community structure were identified from water samples  
196 collected (Table 1) and results were averaged across the depths: 0-50 m and 50-130 m.

##### 197 2.1.5.1 *Chlorophyll*

198 *In situ* chlorophyll a (Chl-a) values were determined after methanol extraction (Le Bouteiller  
199 et al., 1992), using a Turner Design fluorometer (Turner Designs, Sunnyvale, California, USA,  
200 module # 7200-040, Chl-a extracted-acidification) calibrated with pure Chl-a standard  
201 (Sigma). Total Chl-a concentrations were determined from 0.5 L water samples filtered onto  
202 GF/F Whatman filters. Size-fractionated Chl-a across the size classes <3 µm, 3-10 µm and  
203 >10 µm was determined from 2 L water samples collected onto 10 µm, 3 µm nucleopore  
204 and GF/F filters by in-line serial filtrations, and represented proxies of pico-, nano and  
205 microphytoplankton biomasses respectively. The mean and standard deviation of size-  
206 fractionated Chl-a percentages were calculated for each cruise. Total Chl-a data were  
207 interpolated to plot the 0-150 m vertical sections of each cruise using the SAXO package.

##### 208 2.1.5.2 *Cell counts by flow cytometry (FCM)*

209 Water samples of 1.1 mL were fixed by adding paraformaldehyde solution (2% final  
210 concentration) and then frozen in liquid nitrogen on board. Cell counts for pico and  
211 nanophytoplankton (<3 µm, 3-10 µm respectively) were performed with a FACSCalibur flow  
212 cytometer (BD Biosciences, San Jose, California, USA) at the Regional Flow Cytometry  
213 Platform for Microbiology (PRECYM) (<http://precym.com.univ-mrs.fr>). Data were  
214 normalized using both Fluoresbrite® Fluorescent Microspheres (Polysciences Inc. Europe)  
215 and TruCount™ beads (BD) and the mean and standard deviation of cell count percentages  
216 were calculated for each cruise.

### 217 2.1.5.3 *Phycoerythrin*

218 Water samples (4.5 L) were filtered onto 0.4  $\mu\text{m}$  Nucleopore polycarbonate membrane  
219 filters (47 mm diameter) and immediately frozen in liquid nitrogen until analysis. Using  
220 methods described in Neveux et al. (2009), phycoerythrin (PE) was extracted in a 4 mL  
221 glycerol-phosphate mixture (50/50) after vigorous shaking for resuspension of particles  
222 (Wyman, 1992). Using a Perkin Elmer LS55 spectrofluorometer (PerkinElmer, Inc., Waltham,  
223 Massachusetts, USA) and emission and excitation slit widths adjusted to 5 and 10 nm,  
224 respectively, the PE fluorescence excitation spectra were recorded between 450 and  
225 580 nm (emission fixed at 605 nm). Quantitative estimates of phycoerythrin were obtained  
226 from the area below the fluorescence excitation curve, after filter blank subtraction and the  
227 mean and standard deviation calculated for each cruise.

### 228 2.1.6 **Primary production**

229 Net primary production (NPP,  $\text{mgC m}^{-3} \text{d}^{-1}$ , Table 1) was measured using the  $^{14}\text{C}$  tracer  
230 technique (RochelleNewall et al., 2008). Water samples (76 mL) were inoculated with  
231 0.40 MBq of a sodium  $^{14}\text{C}$  bicarbonate solution (Perkin Elmer, initial concentration  
232 37 MBq  $\text{mL}^{-1}$ ) and immediately placed in a thermoregulated (22-24°C) photosynthetron to  
233 incubate samples at varying light levels (11%, 28%, 48%, 68%, 100%). After 1.5 h incubation,  
234 samples were filtered onto 0.4  $\mu\text{m}$  polycarbonate filters (25 mm Whatman Cyclopore) which  
235 were then placed into clean glass liquid scintillation counting vials and stored at -20 °C. In  
236 the laboratory, 100  $\mu\text{L}$  of 0.5N HCl was added to each sample, and the vial left open for 12 h  
237 under a fume hood to remove unfixed  $^{14}\text{C}$ . After acidification and drying, 5 mL of  
238 scintillation cocktail (Ultima Gold MV, Parkard instruments) was added to each sample, and  
239 the samples analyzed in a Packard Tri-Carb (1600TR) Liquid Scintillation Counter  
240 (PerkinElmer, Inc., Waltham, Massachusetts, USA). The mean and standard deviation were  
241 calculated for each cruise.

### 242 2.1.7 **Zooplankton**

243 Three methods were used to estimate zooplankton (organisms 2  $\mu\text{m}$  – 20 mm) biomass: a  
244 Tracor Acoustic Profiling System (TAPS), net sampling and Ship-Borne Acoustic Doppler  
245 Current Profilers (S-ADCP).

246 *2.1.7.1 Tracor Acoustic Profiling System (TAPS)*

247 The TAPS-6™ (BAE systems, San Diego, CA, USA) is a six frequency (265, 420, 710, 1100,  
248 1850, 3000 kHz) profiler (Holliday and Pieper, 1980) used to acoustically detect the micro-  
249 (20-200 µm) and meso- (200-2000 µm) zooplankton from the surface down to 200 m. The  
250 TAPS-6 was used in “cast mode”, profiling the water column in horizontal position with a  
251 descent speed of 0.5 m s<sup>-1</sup>, sampling a volume of about 5 L of water at each ping (ping rate:  
252 2.63 pings s<sup>-1</sup>). The TAPS-6 focused on small and abundant organisms such as copepods,  
253 with larger and less abundant organisms such as euphausiids having less chance to pass  
254 through this small volume (Pieper et al., 2001).

255 The Scattering Volume (Sv) signal (in dB) was transformed into biovolume estimates using  
256 an inversion algorithm following the method applied by Lebourges-Dhaussy et al. (2014) and  
257 successfully applied to small zooplankton (e.g. Holliday et al., 1989; Lebourges-Dhaussy et  
258 al., 2009; Napp et al., 1993; Pieper et al., 1990). The algorithm provided vectors of  
259 abundances per size range for each station, from which biovolumes were estimated in  
260 mm<sup>3</sup> m<sup>-3</sup> and converted into mg m<sup>-3</sup> using a density factor of ~1 kg L<sup>-1</sup> (Simmonds and  
261 MacLennan, 2005). The size range of organisms explored in the inversion process was 0.05-  
262 3 mm (micro- and meso-zooplankton).

263 *2.1.7.2 Zooplankton net sampling*

264 Five layers of the water column were sampled from the surface down to 600 m depth (0-  
265 100, 100-200, 200-400, 400-500, 500-600 m) using an Hydrobios MultiNet (Hydrobios, Kiel,  
266 Germany). Each of the nets used were comprised of 200 µm nylon mesh and equipped with  
267 a mechanical Hydrobios flowmeter. The volume filtered by each net was calculated using  
268 the following equation:

269  $V=d*k*A$

270 where d is the number of revolutions of the flowmeter, k=0.3 m/revolution is the pitch of  
271 the impeller of the flowmeter provided by the manufacturer (Hydro-Bios Apparatebau  
272 GmbH, 2009) and A is the size of the net mouth area (0.25 m<sup>2</sup>).

273 Samples collected by the nets were immediately preserved in a 5 % buffered formalin-  
 274 seawater solution and processed for wet and dry weight analysis later in the laboratory. Dry  
 275 weights (DW) and wet weights (WW) were determined for the 0-200 m and the 0-600 m  
 276 layers respectively.

### 277 2.1.7.3 Ship-Borne Acoustic Doppler Current Profilers (S-ADCP) backscatter

278 The S-ADCP (see section 2.1.1), was also used to provide relative measures of acoustic  
 279 density, as a proxy for zooplankton to micronekton biomass (Flagg and Smith, 1989;  
 280 Heywood et al., 1991; Menkes et al., 2002; Radenac et al., 2010). At 153 kHz, this instrument  
 281 roughly detects organisms across the size ranges of a few millimeters to a few centimeters  
 282 (Sutor et al., 2005). The ADCP echo intensity ( $E_a$ ) was converted into  $S_v$  (in dB) using the  
 283 equation from Deines (1999) modified by Gostiaux and van Haren (2010):

$$284 S_v = C + 10 \log_{10} [(T_x + 273.16) R^2] - L_{DBM} - P_{DBW} + 2\alpha R + 10 \log_{10} [10^{K_c E_a / 10} - 10^{K_c E_{noise} / 10}]$$

285 where  $T_x$  is the temperature of the transducer ( $^{\circ}C$ ),  $L_{DBM}$  is  $10 \log_{10}$ (transmit pulse, in  
 286 meters),  $P_{DBW}$  is  $10 \log_{10}$ (transmit power, in Watts),  $R$  is depth along the beam (m),  $\alpha$  is the  
 287 sound absorption coefficient (dB/m) in water,  $K_c$  is a conversion factor for echo intensity  
 288 (dB/counts),  $E_a$  is the ADCP raw echo intensity (counts) and  $E_{noise}$  is the noise (counts). We  
 289 used the default parameters given in Deines (1999) for the constants  $C$  and  $P_{DBW}$ . During the  
 290 time that the ship was stationary at each station, when ship noise is reduced, we selected  
 291 the minimum value of the echo intensities  $E_a$  in the vertical profiles and the minima were  
 292 then averaged over the entire cruise to obtain  $E_{noise}$ .

### 293 2.1.8 Micronekton

294 Three methods were used to estimate micronekton (organisms 2 - 20 cm) biomass and  
 295 species composition: using an EK60 echosounder, net sampling and the S-ADCP (see section  
 296 2.1.7.3).

#### 297 2.1.8.1 EK 60 echosounder

298 Acoustic data were collected continuously during the cruise using a EK60 echosounder  
 299 (SIMRAD Kongsberg Maritime AS, Horten, Norway) with four hull-mounted split-beam  
 300 transducers (38, 70, 120 and 200 kHz). Echosounder calibration was performed according to

301 Foote et al. (1987) at the beginning of each cruise. Due to the presence of noise in  
302 echograms, linked to the specificities of the installation of the sounder on the R/V Alis and  
303 to rough seas during the cruises, the water column was only sampled down to depths of  
304 100, 200, 250 and 600 m for the 200, 120, 70 and 38 kHz channels respectively. A data  
305 cleaning step was performed with Matlab® (MathWorks, Natick, Massachusetts, USA)  
306 filtering tools provided with the Movies3D software (IFREMER). The EK60 signal was  
307 analyzed in terms of scattering volume (Sv) (MacLennan et al., 2002). It was not possible to  
308 calculate micronekton biomass from echograms produced as the Sv to biomass conversion  
309 requires knowledge of the acoustic properties of the detected organisms added to a  
310 complex inversion of the signal and has not yet been performed for our dataset. The 38 kHz  
311 frequency is commonly used as a proxy for micronekton (Bertrand et al., 1999; Kloser et al.,  
312 2009; McClatchie and Dunford, 2003) and was used to represent micronekton over 0-600 m.

313 To describe the spatial structure of the micronekton biomass derived from the 38 kHz EK60,  
314 we removed the day/night signal from the data as the strong diurnal vertical migration of  
315 micronekton might mask spatial patterns. The data were assigned to either day or night and  
316 average values were calculated for each period for each cruise. The daytime (resp.  
317 nighttime) mean was subtracted from the daytime (resp. nighttime) values to produce  
318 anomalies for each period.

#### 319 2.1.8.2 *Micronekton net sampling*

320 Micronekton were sampled at each station with a mid-water trawl with a 10 mm codend  
321 mesh size. Vertical and horizontal mouth opening of ~10 m each were monitored with trawl  
322 opening sensors (Scanmar, Åsgårdstrand, Norway). Horizontal tows were conducted to  
323 target aggregations visually detected with the EK60 echosounder. Once the trawl net was  
324 stabilised at the chosen depth, it was towed for 30 minutes at 3-4 knots. One or two tows  
325 were conducted at each sampling station between 14 and 130 m at night and between 21  
326 and 540 m during the day. Organisms were sorted on-board into groups and frozen. In the  
327 laboratory, samples were identified at the lowest taxonomic level possible, counted,  
328 measured and weighed. Gelatinous organisms (e.g. siphonophores, salps, pyrosomes) were

329 weighed frozen as a group. Biomass was expressed as mg of wet weight per m<sup>3</sup> filtered. The  
 330 volume of water filtered by the net was calculated as:

$$331 \quad V=S*D,$$

332 with  $S=h*v$  and  $D= R*c$ ,

$$333 \quad c = 2 * \arctan(\sqrt{a / (1-a)})$$

$$334 \quad \text{and } a = [\sin((\text{lat}_2 - \text{lat}_1)/2)]^2 + \cos(\text{lat}_1) * \cos(\text{lat}_2) * [\sin((\text{lon}_2 - \text{lon}_1)/2)]^2$$

335 where V is the volume filtered (m<sup>3</sup>), S is the net mouth opening (m<sup>2</sup>), h and v are the net  
 336 horizontal and vertical mouth opening (m), D is the distance covered by the trawl (m),  
 337  $R=6371.e^{+3}$  m is the earth radius,  $\text{lat}_1$ ,  $\text{lat}_2$ ,  $\text{lon}_1$ ,  $\text{lon}_2$  are the latitude and longitude of the  
 338 start and the end of the set (radian).

339

## 340 **2.2 Other in situ, satellite and model derived datasets**

341 Estimated oceanographic and biological parameters derived from remote sensing and  
 342 physical and biological models were used to undertake direct comparisons between *in situ*  
 343 data and satellite and model derived parameter estimates and investigate relationships of *in*  
 344 *situ* data collected during each cruise with broader scale regional ocean dynamics .

### 345 2.2.1 Ocean Currents

346 We used two datasets, the Kessler and Cravatte (2013) *in situ* dataset and the Ocean  
 347 Surface Current Analysis (OSCAR, <http://www.oscar.noaa.gov/>) satellite-derived dataset.  
 348 The first describes the time-averaged total geostrophic circulation of the top 1000 m. The  
 349 second provides surface currents estimated from a combination of data derived from  
 350 drifting buoys and altimetry at a 5-day and 1/3° resolution.

### 351 2.2.2 Eddies: Okubo-Weiß parameter

352 Surface ocean dynamics were examined using an eddy detection algorithm. The Okubo-  
 353 Weiß (OKW) parameter was calculated from the OSCAR surface currents. It describes the

354 deformation (shear and strain) and rotation (vorticity) of surface currents (Chelton et al.,  
355 2011b; d' Ovidio et al., 2013; Dutrieux et al., 2008). This parameter allows discrimination of  
356 regions where fluids circulate in a closed loop ( $OKW < 0$ , e.g. in the interior of eddies where  
357 vorticity is high) from regions where shear and strain are high ( $OKW > 0$ , e.g. on the edges of  
358 eddies where strain is high). The OKW parameter is always negative within vortices whether  
359 they are cyclonic or anticyclonic (Chelton et al., 2011b).

### 360 2.2.3 Sea Level Anomaly (SLA)

361 Sea level anomalies (relative to the long term mean across the period 1993-2010) were  
362 extracted from [http://www.aviso.oceanobs.com/en/data/products/sea-surface-height-](http://www.aviso.oceanobs.com/en/data/products/sea-surface-height-products/global/msla.html#c5122)  
363 [products/global/msla.html#c5122](http://www.aviso.oceanobs.com/en/data/products/sea-surface-height-products/global/msla.html#c5122) at a resolution of  $1/3^\circ$  and 7 days. SLA was used to  
364 identify downwelling (high values or ridges in SLA) versus upwelling eddies (low values or  
365 troughs in SLA).

### 366 2.2.4 Sea Surface Temperature (SST)

367 Daily SSTs from the Group for High Resolution SST (GHRSSST) were downloaded from the  
368 website <https://www.ghrsst.org/> and used to examine spatial patterns in SSTs in the New  
369 Caledonian EEZ. This freely available product combines several satellite data sources and is  
370 provided at  $1/12^\circ$  grid resolution.

### 371 2.2.5 Primary production

372 Depth-integrated primary production was estimated from satellite-derived chlorophyll,  
373 Photosynthetically Available Radiation (PAR) fields and SST fields using the Vertically  
374 Generalized Production Model (VGPM) (Behrenfeld and Falkowski, 1997). Primary  
375 production was integrated across the euphotic layer, which was statistically derived from  
376 satellite imagery (<http://www.science.oregonstate.edu/ocean.productivity/>). Satellite-  
377 derived chlorophyll is calculated from ocean color data, which, for the period 2002-2009,  
378 were derived from the Sea-viewing Wide Field Of View Sensor (SeaWiFS) satellite after  
379 which data were computed at CLS ([www.cls.fr](http://www.cls.fr)) using the VGPM model and Moderate  
380 Resolution Imaging Spectroradiometer (MODIS) and Medium Resolution Imaging  
381 Spectrometer (MERIS) satellite data. PAR data were derived from the European Center for  
382 Medium Range Forecast (ECMWF) analyses.



### 383 2.2.6 Micronekton from the SEAPODYM model

384 The end-to end spatial ecosystem model SEAPODYM (Lehodey et al., 2008) describes the  
385 interactions of tuna species with the environment and incorporates external forcings  
386 associated with fishing and the environment. It includes environmental parameters such as  
387 temperature, currents, oxygen and primary production as well as a micronekton sub-model  
388 describing the transfer of energy from primary production to tuna species through mid-  
389 trophic levels. The sub-model comprises six functional groups of micronekton occupying  
390 different water layers according to day and night (diel migration model). Modelled  
391 micronekton is advected by currents and assimilates carbon from primary production  
392 produced three months earlier (Lehodey et al., 2010).

393 The micronekton sub-model is driven by satellite-derived primary production (see section  
394 2.2.5) and by the outputs of the GLObal Ocean Reanalysis and Simulations (GLORYS2.V1) of  
395 currents and temperature produced by the French Groupe Mission Mercator Coriolis  
396 (Barnier et al., 2006; Ferry et al., 2012) across two reanalysis periods 2002 – 2008 and 2009 -  
397 2012. The 2002 – 2008 reanalysis was conducted at a daily and 1/4° resolution and was  
398 performed by the MERCATOR-OCEAN operational oceanography center. It is forced by daily  
399 surface meteorological data from the European Centre for Medium-Range Weather  
400 Forecasts (ECMWF). By assimilating satellite-derived sea level anomalies, sea surface  
401 temperatures and *in situ* measurements of vertical temperature and salinity profiles, the  
402 model estimates realistic mesoscale activity with eddy field variability in good agreement  
403 with altimetric data. Reanalysis across 2009-2012 included temperature and currents  
404 provided by the same numerical ocean model, while altimetry, SST and temperature/salinity  
405 profiles were also assimilated in their operational configuration ([http://www.mercator-](http://www.mercator-ocean.fr/)  
406 [ocean.fr/](http://www.mercator-ocean.fr/))(Abecassis et al., 2013).

407 The biomass distribution of micronekton functional groups along the cruise track and in the  
408 south-west Pacific at the time of the cruises was estimated with the SEAPODYM ecosystem  
409 model using a revised definition of vertical biological layer boundaries, at a spatial  
410 resolution of 1/4° averaged over 7 days. Vertical biological layers comprised the epipelagic  
411 layer, which lies between the surface and the euphotic depth (derived from ocean color

412 satellite data and the VGPM model), the mesopelagic layer located at 1-3 times the euphotic  
413 depth, and the bathypelagic layer located at 3-7 times the euphotic depth. The model  
414 simulates a diel behavior of micronekton by considering that during the night, daily  
415 migratory species can move from one layer to another, thus adding to the residing biomass  
416 of non-migratory species of the layer. Because we used 7-day outputs to compare with the  
417 continuous Nectalis data, we reconstructed a SEAPODYM time series with a day/night signal  
418 that mimicked the Nectalis data. We interpolated the Nectalis tracks into the SEAPODYM  
419 model. This interpolation was temporally referenced so that day and night estimates from  
420 SEAPODYM could be extracted.

421 To describe the spatial structure of the micronekton biomass derived from SEAPODYM, we  
422 removed the day/night signal from the data by calculating anomalies following the same  
423 procedure than for 38 kHz EK60 (see section 2.1.8.1).

424

## 425 **2.3 Statistics and comparison of methods**

### 426 **2.3.1 Primary production**

427 The non-parametric rank-sum Wilcoxon-Mann-Whitney test at  $\alpha=5\%$  was used to test the  
428 seasonal difference in *in situ* primary production values and in VGPM satellite-derived  
429 primary production along the cruise track. Spatial auto-correlation was eliminated from the  
430 VGPM dataset by building a new dataset of independent points before conducting the  
431 seasonal comparison.

432 To build this new dataset of independent points, we determined the distance (“d” in km) at  
433 which two points are independent. The initial auto-correlated dataset was then resampled  
434 selecting a point every “d” kilometers creating a dataset of independent points. Shifting the  
435 start position of this subsampling by 1 km, another dataset of independent points was then  
436 created. This procedure was repeated until the number of resampled datasets of  
437 independent points was equal to “d”, and contained a number “n” of independent points  
438 which was the length of the cruise track divided by “d”. In the statistical tests the “d”  
439 resampled datasets of independent points were all tested and the result of the test

440 (difference or no difference) comes with the percentage of the number of “d” tests  
441 producing this result.

442 To estimate the distance “d” between two independent points, empirical spatial variograms  
443 with 10km bins were used. The variogram of the VGPM dataset was compared to the noise  
444 constructed from a series of variograms of 100 randomly re-ordered VGPM datasets by a  
445 Monte Carlo procedure. The distance “d” at which the dataset points become uncorrelated  
446 was estimated when the variogram of the dataset reached the noise.

447 For the VGPM dataset “d” was estimated at ~50 km during Nectalis1 and 100 km during  
448 Nectalis2. Overall a conservative value of 100 km between two successive data points was  
449 considered, prompting ~ 100 possible VGPM datasets of 30 independent points (or,  
450 equivalently degrees of freedom) for Nectalis1 and 35 independent points for Nectalis2.  
451 These 100-ensemble datasets were used for seasonal comparisons.

452 We estimated that *in situ* primary production points were independent (no spatial auto-  
453 correlation) on the basis that the minimum distance between two sampling stations where  
454 *in situ* primary production was measured (144 km) is greater than the estimate at which 2  
455 points were determined to be independent using the VGPM dataset (100 km).

456 The Wilcoxon-Mann-Whitney test at  $\alpha=5\%$  was also used to compare *in situ* primary  
457 production to VGPM data at the location of the *in situ* measures (12 data points). For small  
458 sample sizes, values for significance were read in classical tables, while where sample sizes  
459 were  $n>20$  degree of freedom, the test was calculated using IDL’s routines  
460 (imsl\_wilcoxon.pro).

### 461 2.3.2 Zooplankton

462 A Wilcoxon-Mann-Whitney test at  $\alpha=5\%$  was used to test for seasonal difference in  
463 zooplankton biomasses estimated from the zooplankton net (in DW and WW), the TAPS and  
464 the S-ADCP backscatter. We accounted for the spatial auto-correlation of the S-ADCP by  
465 following the procedure described in section 2.3.1. For the S-ADCP dataset, the distance “d”  
466 at which two points were considered independent was 30 km for both cruises.

467 Consequently, 30 datasets of 100 and 116 independent points were built for Nectalis1 and

468 Nectalis2 respectively for statistical analyses. We estimated that *in situ* zooplankton  
469 biomass estimates (zooplankton net and TAPS) points were independent (no spatial auto-  
470 correlation) on the basis that the minimum distance between two sampling stations (67 km)  
471 is greater than "d" (30 km).

472 The potential for the S-ADCP to provide a proxy of zooplankton biomass was evaluated  
473 against the log-transformed biomass measurements of zooplankton derived from the TAPS  
474 and net sampling using a Spearman's correlation.

475 For this general overview, no detailed examination of zooplankton spatial distribution and  
476 composition were conducted, but will be conducted in a separate study (Smeti pers.  
477 comm.).

### 478 2.3.3 Micronekton

479 A Wilcoxon-Mann-Whitney test at  $\alpha=5\%$  was used to test for seasonal differences in  
480 micronekton biomass estimated by the EK60 and by the SEAPODYM ecosystem model. No  
481 seasonal comparison was conducted on net sampling because of differences in sampling  
482 strategies between the two cruises (non-comparable depth or day-night tows). We  
483 accounted for the spatial auto-correlation of the 38 kHz EK60 Sv and SEAPODYM  
484 micronekton biomass estimates by following the procedure described in section 2.3.1. For  
485 the 38 kHz EK60 Sv dataset the distance "d" at which two points were considered  
486 independent was 30 km for both cruises. Consequently, 30 datasets of 100 and 116  
487 independent points were built for Nectalis1 and Nectalis2 respectively for statistical  
488 analyses. For the SEAPODYM dataset, "d" was estimated at 100 km for Nectalis1 and 50 km  
489 for Nectalis2. A conservative value of "d"=100 km was used for both cruises to build 100  
490 datasets of 30 and 35 independent points for Nectalis1 and Nectalis2 respectively.

491 The potential for the S-ADCP to provide a proxy of micronekton biomass was evaluated  
492 against the Sv values of the four frequencies of the EK60 echosounder. To do this, the EK60  
493 high-resolution time and vertical profiles were averaged to the ADCP time/vertical  
494 resolution. The Sv was calculated for a 5-minute Elementary Sampling Unit (ESU) and 8 m  
495 height layers. Correlations between data provided by the S-ADCP and the four frequencies

496 of the EK60 were investigated using a Spearman's correlation. We accounted for the spatial  
497 auto-correlation by computing 30 correlation coefficients from the 30 resampled datasets of  
498 independent points distant of 30 km, as explained above. The range of correlation  
499 coefficients from the 30 correlation ensemble was provided as well as the percentage of  
500 these correlations significant at  $\alpha=5\%$  level.

501 Estimates of epi and mesopelagic micronekton biomass ( $\text{mg m}^{-3}$ ) derived from SEAPODYM  
502 were compared to the estimates of micronekton biomass derived from the 38 kHz EK60  
503 echosounder. The high-resolution EK60 data were averaged across  $\frac{1}{4}$  degree grid squares  
504 along the cruise track to correspond with the spatial resolution of the SEAPODYM  
505 ecosystem model. Correlation between the two data series was investigated applying the  
506 same procedure as for EK60 vs. S-ADCP. and accounting for the Spatial auto-correlation was  
507 accounted for by calculating the correlation on 100 resampled datasets of independent  
508 points distant of 100 km from the two biomass series..

509

## 510 **3 Results**

### 511 **3.1 Physical oceanography and biogeochemistry**

#### 512 3.1.1 Surface features

513 During the cool season (Nectalis1) thermosalinograph measurements showed that surface  
514 waters in the southern part of the cruise track (south of  $19^{\circ}\text{S}$ ) had an average temperature  
515 of  $23.6 \pm 1.0^{\circ}\text{C}$  and salinity of  $35.2 \pm 0.2$  while the northern part of the cruise was  
516 characterized by waters of  $25.3 \pm 0.7^{\circ}\text{C}$  and  $35.0 \pm 0.1$  (Figure 2). During the hot season  
517 (Nectalis2), overall SST and SSS patterns were similar, although temperatures were warmer  
518 by  $\sim 3^{\circ}\text{C}$ . Salinity was very similar in the south but lower by  $\sim 0.1$  in the north (Figure 3).  
519 During both cruises, salinity varied across similar gradients to temperature, but in the  
520 opposite direction at both larger-scales and smaller scales. For example, high temperature  
521 and low salinity waters were observed during Nectalis1 at stations 4 and 5 with waters with

522 particularly low temperature and high salinity observed at stations 1 and 2 during both  
523 cruises. This gradient was observed in particular during Nectalis2.

524 During both cruises, ADCP surface layer (0-150 m) currents varied in a similar way across  
525 large and small spatial scales to surface-only currents derived from OSCAR. North of 19°S,  
526 the currents were predominantly directed westward, while in the south they were  
527 predominantly directed eastward. Along the western coast of the main island of New  
528 Caledonia, currents were flowing predominantly south-eastward during Nectalis1 and  
529 southward during Nectalis2. In addition to these broad scale patterns, high current  
530 variability was observed, for example at stations 6-7 during Nectalis1 and stations 7-8-9  
531 during Nectalis2.

532 Satellite-derived SST clearly showed the large-scale north-south gradient in observed during  
533 both cruises. Smaller scale meandering of the SST field centered at ~19-20°S was observed  
534 with strong association between the thermohaline patterns and the currents. Meanders  
535 were noted through intrusions of warmer waters from the north which were advected  
536 south (e.g. Nectalis1 station 8, 17, Nectalis2 station 9) and intrusions of cooler waters from  
537 the south which were advected north (e.g. Nectalis1 stations 6, 7, 16, Nectalis2 stations 17-  
538 18).

539 Values of OKW and SLAs along with current vectors from both OSCAR and S-ADCP described  
540 an important turbulent eddy activity. Cyclonic eddies (“upwelling” type eddy) corresponding  
541 to sea level depression (or equivalently, thermocline uplifting) were observed during the  
542 cool season, for example at ~23°S 161°E (eddy A on Figure 2), at stations 6-7 (eddy B) and at  
543 ~16.5°S 159°E (eddy C) the south-eastern edge of which was sampled at station 10 (Figure  
544 2). During the hot season, strong cyclonic eddies were observed at ~24°S 156°E (eddy D on  
545 Figure 3), ~24°S 164°E (eddy E) and ~25°S 172°E (eddy G) and a series of energetic eddies  
546 were observed between stations 7 and 18 (eddies H, I, J). The edge and the center of an  
547 anticyclonic eddy (“downwelling” type eddy with thermocline deepening and sea-level  
548 ridge) were sampled during the hot season at stations 8 and 9 respectively (eddy K, Figure  
549 3). Overall, lower eddy activity was observed during the cool season (Figure 2) than during  
550 the hot season (Figure 3).

## 551 3.1.2 Vertical structures

552 During the cool season, stations 8 - 18 in the north and east were characterized by relatively  
553 warm, low salinity waters with a mixed layer depth of ~60m and low values of nitrate  
554 ( $0.05 \pm 0.07 \mu\text{M}$ ) to a depth of ~90 m (Figure 4). The Deep Chlorophyll Maxima (DCM)  
555 ( $\sim 0.25\text{-}0.3 \text{ mg m}^{-3}$ ) and the nutricline were located at ~90 m depth (Figure 4). By contrast,  
556 stations 1 - 7 in the south and west were comparatively cooler with higher surface salinity.  
557 At these stations, higher concentrations of nitrate ( $0.13 \pm 0.12 \mu\text{M}$ ) and chlorophyll content  
558 occurred with more frequent maxima at the surface. Phosphate concentrations varied with  
559 an average of  $0.067 \pm 0.038 \mu\text{M}$  from the surface to 100 m depth and were occasionally  
560 lower than  $0.05 \mu\text{M}$  in the surface layer. Within this general pattern, a number of stations  
561 demonstrated unique characteristics. Cool, highly saline waters which were homogeneous  
562 down to 100 m with a shallow nutricline and enhanced chlorophyll were recorded at  
563 stations 1 and 2 (Figure 4). Waters with a deep mixed layer, elevated chlorophyll from the  
564 surface down to 100 m were also recorded at stations 6 and 7, contrasting with the  
565 surrounding waters (Figure 4). High surface (0-20 m) chlorophyll levels ( $0.23 \mu\text{g l}^{-1}$ ) were  
566 recorded at station 10 (Figure 4).

567 The north-south gradient in temperature and salinity observed during the cool season was  
568 also evident at depth during the hot season, with warmer and fresher waters north of  $\sim 20^\circ\text{S}$   
569 observed at stations 8 - 19 (Figures 3 and 4) and cooler and saltier waters south of  $\sim 20^\circ\text{S}$   
570 observed at stations 1 - 7 and 20 to 23. The mixed layer across all stations was shallower  
571 during the hot season, located at  $\sim 25$  m, denoting stronger surface stratification in the  
572 water column than during the cool season. Surface waters were low in nitrate  
573 ( $0.03 \pm 0.02 \mu\text{M}$ ) across almost the entire cruise track (Figure 4) and the DCM was often  
574 centered at around 100 m with mean values of  $\sim 0.41 \pm 0.16 \text{ mg m}^{-3}$ . In general, above the  
575 DCM in the top  $\sim 50$  m, chlorophyll concentrations were slightly lower than during the cool  
576 season (Figure 4), particularly in the southern part of the survey area. Phosphate tended to  
577 be low ( $0.05 \pm 0.03 \mu\text{M}$ ) for stations 1 - 7 and 20 - 23 in the southern part of the cruise track  
578 in comparison to stations in the northern part of the cruise ( $0.09 \pm 0.03 \mu\text{M}$ ). A few stations  
579 had unusual characteristics: high temperatures and low salinities down to 100 m were

580 observed at station 9 and surface nitrate was slightly enhanced at stations 7 and 8  
581 ( $0.09 \pm 0.01 \mu\text{M}$ ) compared to other stations ( $0.02 \pm 0.02 \mu\text{M}$ ).

582

### 583 **3.2 Primary production**

584 Depth- integrated measurements of *in situ* primary production in the photic layer and  
585 similar satellite-derived net primary production (NPP) from VGPM along the cruise track  
586 were significantly higher during the cool season ( $352 \pm 160 \text{ mgC m}^{-2} \text{ d}^{-1}$  and  
587  $301 \pm 62 \text{ mgC m}^{-2} \text{ d}^{-1}$  on average respectively) than during the hot season  
588 ( $231 \pm 133 \text{ mgC m}^{-2} \text{ d}^{-1}$  and  $199 \pm 55 \text{ mgC m}^{-2} \text{ d}^{-1}$ ) (Figure 5 and Table 2)

589 The NPP pattern (Figure 2) demonstrated a strong gradient during the cool season with  
590 values of  $\sim 350 \text{ mgC m}^{-2} \text{ d}^{-1}$  in the southern part of the survey area (south of  $20^\circ\text{S}$  and west  
591 of the main island) and values lower than  $200 \text{ mgC m}^{-2} \text{ d}^{-1}$  in the northern part of the survey  
592 area (north of  $20^\circ\text{S}$  and east of the main island). During the hot season the entire region was  
593 more oligotrophic, with a weaker north-south gradient, and average values of  
594  $\sim 200 \text{ mgC m}^{-2} \text{ d}^{-1}$  in the survey area (Figure 3). Within this large-scale gradient, specific  
595 patterns linked to mesoscale structures were observed. For example, the center of some  
596 eddies were characterized by enhanced primary production (e.g. Nectalis1 eddy A; Nectalis2  
597 eddy D; Nectalis2 eddy G), while primary production was enhanced at the edge of others  
598 (e.g. Nectalis1 station10 eddy C; Nectalis2 series of eddies H, I, J).

599 No significant differences were found between *in situ* production estimates and VGPM  
600 satellite values at the *in situ* sample locations (Figure 5).

601

### 602 **3.3 Phytoplankton**

603 During the cool season, size fractionated chlorophyll was dominated by picophytoplankton  
604 ( $< 3 \mu\text{m}$ ) across all stations (mean= $75.9\% \pm \text{SD}=17.2\%$  in biomass); nano and micro-  
605 phytoplankton represented  $12.8\% \pm 9.6\%$  and  $11.3\% \pm 12.6\%$  respectively of chlorophyll  
606 biomass. The cyanobacteria *Prochlorococcus* were the dominant species of the



607 picophytoplankton group ( $91.9\% \pm 6.3\%$  in abundance; Figure 4) with cell abundances of up  
608 to  $250 \times 10^3 \text{ mL}^{-1}$ . Remaining abundances of picophytoplankton across stations were  
609 comprised of *Synechococcus* ( $6.3\% \pm 6.2\%$ ) and picoeukaryotes ( $1.8\% \pm 0.8\%$ ). Overall  
610 phytoplankton composition did not vary latitudinally or longitudinally, with the exception of  
611 particular features observed at stations 2 and 10 (eddy C). In comparison to other stations,  
612 higher proportions of large cells were observed at station 2 from the surface to 150 m  
613 ( $\sim 30\%$  nano- and  $\sim 28\%$  microphytoplankton in abundance) and at station 10 from the  
614 surface to 50 m ( $\sim 17\%$  nano- and  $\sim 31\%$  microphytoplankton in abundance).

615 The fractionated chlorophyll and community structure during the hot season was similar to  
616 that observed in the cool season with picophytoplankton and *Prochlorococcus* dominating  
617 the communities ( $83.4\% \pm 10.4\%$  in biomass and  $92.3\% \pm 7.8\%$  in abundance respectively;  
618 Figure 4). Nano and micro-phytoplankton represented  $8.6\% \pm 5.4\%$  and  $7.9\% \pm 7.1\%$   
619 respectively. However, cell abundance was much lower during the hot season, with  
620 maximum cell counts of *Prochlorococcus* of  $160 \times 10^3 \text{ mL}^{-1}$ . Remaining cell abundances were  
621 comprised of *Synechococcus* ( $5.0\% \pm 6.8\%$ ) and picoeukaryotes ( $2.7\% \pm 1.7\%$ ). Again, the  
622 phytoplankton structure was relatively homogeneous along the cruise track with the  
623 exception of station 9 (eddy K) which had a higher proportion of larger cells from the  
624 surface to 50 m ( $\sim 7\%$  nano- and  $\sim 39\%$  microphytoplankton in abundance) than the rest of  
625 the stations ( $\sim 13\% \pm 3.1\%$  nano- and  $\sim 11\% \pm 5.0\%$  microphytoplankton in abundance; Figure  
626 4). Phycoerythrin (PE) concentration was also much higher at this station (1836 fluorescence  
627 unit vs.  $389 \pm 359$  fluorescence unit for the other stations).

### 628 **3.4 Zooplankton**

629 Diurnal variability in zooplankton biomass was observed with all methods, with enhanced  
630 biomass at night in the top 200 m during both cruises (Figure 6 and 7). Zooplankton WWs  
631 during the hot season however were relatively similar during the day and at night, which is  
632 at odds with dry weight (DW) estimates where diurnal variability is evident (Figure 6 and 7).  
633 Zooplankton wet weight (WW) (Figure 6) vertical profiles showed that the majority of the  
634 biomass concentrated in the top 100 m, deeper biomass rapidly decreased.

635 Mean biomass estimates from the TAPS ( $\sim 100 \text{ mg m}^{-3}$ ) were more than one order of  
636 magnitude higher than WW estimates from net samples ( $< 6.5 \text{ mg m}^{-3}$ ) and DW estimates  
637 from net samples ( $< 6 \text{ mg m}^{-3}$ ) (Table 2). Zooplankton biomasses derived from TAPS and  
638 WW estimates across all sampling stations were not significantly different between the two  
639 cruises, while significant differences were observed in DW (Nectalis1<Nectalis2) and S-ADCP  
640 (Nectalis1>Nectalis2) estimates (Table 2).

641 Correlations between acoustic biomass proxies and net biomass measures for zooplankton  
642 were all significant, with the TAPS and S-ADCP having the highest correlation overall (Table  
643 3). Estimates derived from net samples demonstrated similar correlations with those  
644 derived from the S-ADCP and those derived from the TAPS (Table 3). Correlation values  
645 between zooplankton measurements were roughly similar across the two depth ranges  
646 explored: 0-100 m and 0-200 m.

647

### 648 **3.5 Micronekton**

649 Preliminary examination of the micronekton composition indicated that micronekton net  
650 catch was dominated by gelatinous organisms (e.g. siphonophores, salps, pyrosomes),  
651 which represented 53.8% of the overall wet weight biomass. Fish, molluscs and crustaceans  
652 represented 36.5%, 7.6% and 2.1% of the biomass, respectively. In total, approximately 480  
653 taxa were identified, including  $\sim 240$  fish taxa,  $\sim 95$  crustacean taxa,  $\sim 85$  mollusc taxa and  $\sim 60$   
654 gelatinous organism taxa. Of those species able to be identified, those species with the  
655 highest biomasses in each taxa group were the lanternfish *Ceratoscopelus warmingii*,  
656 *Hygophum hygomii* and *Diaphus perspicillatus*; the molluscs *Sthenoteuthis oualaniensis*,  
657 *Abraliopsis sp.* and *Abralia omiaie*; and the crustaceans *Thysanopoda tricuspoidata*,  
658 *Thysanopoda cristata* and *Euphausia mucronata*. Of the gelatinous organisms the most  
659 abundant were Pyrosomatidae, Abylidae and *Pyrosoma atlanticum*.

660 Biomass estimates from *in situ* measurements from the micronekton nets for the 0-600 m  
661 and from SEAPODYM model were in the same range:  $\sim 4 \text{ mg m}^{-3}$  (Table 2).

662 During both seasons, the EK60 and SEAPODYM signal anomalies indicated that the region  
663 north of  $\sim 19^{\circ}\text{S}$ - $20^{\circ}\text{S}$  had lower micronekton biomass than the region south of this latitude  
664 (Figure 8). Smaller scale variability was also apparent in both datasets, most prominently  
665 south of  $19^{\circ}\text{S}$ - $20^{\circ}\text{S}$  where patches of higher biomass were observed; for example along the  
666 west coast of the main island and at  $\sim 20.5^{\circ}\text{S}$   $161^{\circ}\text{E}$  during Nectalis1 and  $\sim 20.5^{\circ}\text{S}$   $158^{\circ}\text{E}$   
667 during Nectalis2.

668 Micronekton abundance estimated from the S-ADCP, the nets, the EK60 and the SEAPODYM  
669 model exhibited a clear maximum at night (Figure 7). Vertical profiles of the micronekton  
670 estimated from the 38 kHz EK60 Sv (Figure 6) demonstrated a bimodal distribution with  
671 higher micronekton biomass estimates occurring at 0-200 m and 400-600 m than at other  
672 depths during both the day and night.

673 Seasonal differences observed in micronekton biomass estimated by the EK60 Sv and  
674 SEAPODYM were not statistically significant (Table 2). Conversely, estimates derived from  
675 the S-ADCP were different with higher values during the cool season (Table 2).

676 Micronekton estimates derived from the EK60 Sv and S-ADCP Sv were highly correlated, and  
677 the highest correlation was observed with the 70 kHz EK60 (correlation range = 0.87-0.96)  
678 (Table 4). Micronekton biomass estimates calculated by the 38 kHz EK60 Sv were highly  
679 correlated with estimates derived from the SEAPODYM model (correlation range = 0.73-  
680 0.79) (Table 4).

681

## 682 **4 Discussion**

### 683 **4.1 *Oligotrophic waters and water masses***

684 The physical, biogeochemical and biological data collected during the two Nectalis cruises,  
685 in two contrasting seasons, have provided new insights into the spatial and temporal  
686 dynamics of the pelagic ecosystem in the waters around New Caledonia. Observations  
687 collected from the two cruises support prior characterization of the region as oligotrophic.  
688 The vertical nutrient profiles, low nitrate and sometimes low phosphate, low primary

689 production and chlorophyll biomass, and a phytoplankton composition dominated by small  
690 size cells (picophytoplankton), were consistent with previous studies in South Pacific region  
691 (Campbell et al., 2005; Jacquet et al., 2006; Young et al., 2011) and are typical of a Low  
692 Nutrient Low Chlorophyll (LNLC) system. Although it is generally thought that nitrate is the  
693 main limiting nutrient in this oligotrophic region (Le Borgne et al., 2011), some  
694 phytoplankton species may be limited by phosphate (Moutin et al., 2005) and this can  
695 induce higher contributions of diazotrophs such as *Trichodesmium sp.* in this area.  
696 *Trichodesmium sp.* was not observed in the samples we collected, but it was seen at the  
697 surface of the water along the track at one occasion. Examination of isotope values  
698 calculated from biological samples collected during the Nectalis cruises (Hunt et al., this  
699 issue) suggests the contribution of diazotrophs to phytoplankton composition as previously  
700 observed in the area (Campbell et al., 2005; Dupouy et al., 2011).

701 Two distinct water masses were encountered in the studied area. North of 19°S-20°S,  
702 waters in the top 200 m were characterized by warm temperature, low salinity, low nitrate,  
703 lower primary production and lower micronekton biomass estimates. These characteristics  
704 are representative of the “Coral Sea” oligotrophic regime (Ceccarelli et al., 2013), and are  
705 largely influenced by the warmer and fresher waters of the south Pacific convergence zone  
706 (SPCZ) where the SEC predominantly flows,.

707 South of 19°S-20°S, waters are characterized by colder temperature, higher salinity, a  
708 shallower nitracline, higher nitrate content in the surface layer, higher primary production  
709 and higher micronekton biomass estimates and are under the influence of the South  
710 Tropical Counter Current branches (Marchesiello et al., 2010).

711 Although water masses were variable latitudinally, phytoplankton compositions were very  
712 similar throughout the whole area.

#### 713 **4.2 Horizontal advection, mesoscale and submesoscale phenomena**

714 Large regional-scale organization of surface currents, SST, SSS and primary production was  
715 observed to be strongly distorted by meanders and smaller scale phenomena under the  
716 influence of horizontal advection from highly variable currents. The similarity of

717 temperature and salinity variations suggested the action of advection processes in  
718 modifying salt and temperature at small scales. Numerous processes such as upwellings,  
719 mesoscale (20-100 km, Lévy, 2008) eddies and submesoscale (2-20 km) fronts were  
720 observed influencing the biological distributions in complex manners.

721 In the south/south-westward flowing the ALIS currents observed during the Nectalis cruises  
722 along the west coast of New Caledonia (Marchesiello et al., 2010), an example of coastal  
723 upwelling was observed at stations 1 and 2 during the two seasons. This coastal upwelling  
724 was characterized by cool temperatures and high salinities observed to be homogeneous  
725 down to 100 m during the cool season and down to 50 m during the hot season. During the  
726 cool season the upwelling was also characterized by a shallow nutricline, enhanced  
727 chlorophyll at the surface and higher proportion of large phytoplankton cells, which were  
728 not observed during the hot season. A coastal upwelling induced by south-east trade winds  
729 particularly during the hot season has been reported in a number of other studies  
730 (Ganachaud et al., 2010; Marchesiello et al., 2010).

731 Observations during each season described quite turbulent ocean circulation with myriads  
732 of small cyclonic and anticyclonic eddies of ~50-100 km in size. Such observations have also  
733 been reported by Chelton et al. (2011b).

734 The region is known for its strong interactions between the SEC, which enters from the east,  
735 the STCC flowing from the west and the tortuous topography of island masses and ocean  
736 floor ridges. These interactions between the large scale currents and topography produce  
737 non-linearities in the ocean currents (Couvelard et al., 2008; Marchesiello et al., 2010) which  
738 can favor eddy developments. Eddies can also be associated with incoming Rossby waves  
739 (Killworth et al., 2004) as well as barotropic instabilities resulting from the sheared  
740 westward and eastward currents in the northern region of the EEZ (Figure 1). South of  
741 ~22°S, Rossby waves and baroclinic instabilities between the surface flowing STCC and the  
742 deeper flowing SEC are also known to generate eddy activity as depicted in strong ocean  
743 eddy kinetic energy which peaks during the hot season (Qiu et al., 2009).

744 Primary production and phytoplankton composition within eddies can differ depending  
745 upon the oceanographic processes and underlying trophic mechanisms operating in time  
746 and space. At the mesoscale, cyclonic eddies (southern hemisphere) induces upwellings  
747 near eddy centers and “eddy pumping” (Martin and Richards, 2001; McGillicuddy et al.,  
748 2007, 1998) of nutrients into the photic layer. Its effects are most commonly observed near  
749 eddy centers where enhanced chlorophyll can be found. Conversely in downwelling eddies  
750 (anticyclonic in the southern hemisphere) poorer waters are expected. Lateral advection of  
751 pre-existing primary production gradients by eddies (Chelton et al., 2011a) or advective  
752 concentration/dispersion of floating materials (Dandonneau et al., 2003) are also common  
753 mechanisms and linked to mesoscale phenomena. Maximum impacts on phytoplankton are  
754 expected at the eddy edge or out of eddies in association with the frontal submesoscale  
755 dynamics. Vertical pumping may also occur within submesoscale structures produced by  
756 eddy-eddy interactions through frontal and ageostrophic mechanisms (e.g. Klein and  
757 Lapeyre, 2009; Lévy, 2008).

758 A number of eddies and frontal oceanographic processes were observed during the Nectalis  
759 cruises. The sampling resolution of both *in situ* and satellite data during the Nectalis cruises  
760 was sufficient to observe mesoscale eddies (20-100 km scale). However the sampling  
761 resolution was insufficient to differentiate between submesoscale fronts (2-20 km scale,  
762 Lévy, 2008) and lateral advection.

763 Enhanced primary production was observed mainly south of  $\sim 20^{\circ}\text{S}$  in the New Caledonia EEZ  
764 at the center of several cyclonic eddies (e.g. Nectalis1 eddy A; Nectalis2 eddy D; Nectalis2  
765 eddy G) suggesting the occurrence of eddy pumping. Lower primary production was  
766 observed in the downwelling (anticyclonic) eddy at station 9 during Nectalis2 (eddy K). In  
767 downwelling areas lateral advection from fluid convergence can concentrate floating  
768 organisms (Dandonneau et al. 2003) such as the diazotrophic cyanobacterium  
769 *Trichodesmium* which can be quite frequent in the region (Dupouy et al., 2011). At station 9  
770 (Nectalis 2) a higher proportion of large phytoplankton cells with higher concentration of  
771 phycoerythrin suggested the presence of *Trichodesmium*, consistent with lateral advection  
772 accumulation.

773 Enhanced primary production and chlorophyll were observed more commonly at the edge  
774 of several eddies to the north of  $\sim 20^{\circ}\text{S}$  in the more oligotrophic regions. Enhanced primary  
775 productivity may have resulted from chlorophyll advected into the area either from the  
776 north via a series of cyclonic eddies (e.g. Nectalis2 series of cyclonic eddies H, I, J; Nectalis1  
777 station 10 eddy C) or from the south (Nectalis1 stations 6-7 eddy B). The increased  
778 proportion of larger phytoplankton cells at Nectalis1 station 10 (eddy C) is consistent with  
779 evolution in composition of eddies with time. The phytoplankton community may have  
780 developed in the north and aged along the eddy streamlines as it was advected to the south  
781 by eddy currents. However this observation was not consistent for all eddies observed with  
782 no specific phytoplankton composition observed at some eddies (e.g. Nectalis1 station 6  
783 eddy B).

784 Overall, the primary production patterns around New Caledonia appeared to be more highly  
785 dominated by horizontal advection rather than by vertical processes (direct eddy pumping).  
786 The patchy and high frequency signal complicated the general understanding of the  
787 ecosystem organization, as is often the case in oligotrophic waters. More generally, how  
788 mesoscale eddies and the submesoscale structures affect primary production is still under  
789 debate (Chelton et al., 2011a; Gruber et al., 2011; Klein and Lapeyre, 2009; Lévy, 2008) and  
790 the Nectalis data suggests that there is not one particular mechanism at work during the  
791 period of the cruises in this region of the South Pacific.

792 The effect of primary production dynamics at these scales on upper trophic levels are also  
793 poorly understood because of the difficulty of accessing datasets spanning a wide range of  
794 trophic levels at the scales relevant to eddies and submesoscale structures. Similarly to  
795 primary production, the few examples of zooplankton organization around eddies (e.g.  
796 Lebourges-Dhaussy et al., 2014; Menkes et al., 2002; Roman et al., 1995) show a variety of  
797 organizations. The S-ADCP backscatter (not shown), EK60 Sv and SEAPODYM micronekton  
798 data showed strong patchiness, especially in the south, indicating the influence of  
799 mesoscale features on the organization of zooplankton and micronekton. Similarly to  
800 zooplankton, the relationship between mesoscale features and micronekton distribution is

801 considered to be complex and not yet well understood (Béhagle et al., 2014; Domokos,  
802 2009; Potier et al., 2014).

### 803 **4.3 Seasonality**

804 Observations collected during the Nectalis cruises reflected strong seasonality in  
805 hydrodynamics and water column characteristics in response to the seasonal migration of  
806 the solar heating and convective system of the SPCZ. The hot season was characterized by  
807 warmer and fresher ocean conditions, increased eddy activity, lower NPP and  
808 phytoplankton biomass, and higher stratification as modelled by Marchesiello et al. (2010),  
809 The cool season was characterized by lower eddy activity, higher NPP and phytoplankton  
810 biomass. The NPP latitudinal gradient during the cool season mimicked the SST gradient,  
811 indicating a tight coupling between ocean dynamics and phytoplankton growth. There was a  
812 stronger decoupling between the surface temperature patterns and primary production  
813 during the hot season, as expected in oligotrophic waters (Le Borgne et al., 2011).

814 Primary production almost doubled during the cool season compared to the hot season.  
815 Contradictory seasonal signals for zooplankton and micronekton biomass, however were  
816 provided by various sampling methods, resulting in an inability to determine seasonality in  
817 mid-level organisms. Two hypotheses, possibly acting in combination, may explain the  
818 observations. Firstly, enhanced net primary production during the cool season may have  
819 been largely due to enhanced recycling, with a small portion of the primary production  
820 transmitted to higher trophic levels. Secondly, different turn-over times between  
821 phytoplankton and zooplankton/micronekton may have induced a time decoupling and a  
822 delay in transmission of primary production to secondary and tertiary levels.

823 It should be noted that, at the time of the cruises in 2011, the South Pacific was considered  
824 to be in a weak La Niña state  
825 (<http://iri.columbia.edu/climate/ENSO/currentinfo/archive/201110/technical.html>). In the  
826 New Caledonia region, the expected response of the ocean to La Niña is a weakening of the  
827 trade winds during the hot season and slightly warmer SST conditions ( $\sim+0.5^{\circ}\text{C}$  in average)



828 with a slightly deeper thermocline (Menkes, 2012). This weak effect of ENSO in the New  
829 Caledonian area however, is unlikely to bias the seasonal view from the two cruises.

#### 830 **4.4 Diel migration**

831 Classical diel behavior of organisms migrating towards the surface at night and to deep  
832 waters during the day was observed in both zooplankton and micronekton using acoustic  
833 methods. Using net sampling however, the day-night difference in zooplankton DW was not  
834 observed in the zooplankton WW for the 0-200 m depth during the hot season. This may be  
835 explained by the increase of gelatinous organisms (mainly salps and doliolids) at the surface  
836 during the hot season (H. Smeti, *pers. com.*) and their representation in WW and DW  
837 estimates. Because gelatinous organisms comprise the largest group in WW estimates, their  
838 diel behavior will dominate any diel signal for zooplankton. As they rarely migrate vertically,  
839 little day-night differences in WW would be expected for zooplankton. The proportion of  
840 DW biomass contributed by gelatinous organisms however is much smaller. The  
841 predominance of diel vertical behavior in the other taxa groups then results in a diel signal  
842 being evident in zooplankton DW.

#### 843 **4.5 Measuring primary production, zooplankton and micronekton**

844 Despite the high variability observed in our primary production *in situ* measurements,  
845 particularly during the cool season, and despite their small number (12 measures out of 41  
846 stations for both cruises), we estimated they were reasonably representative of the entire  
847 cruise. *In situ* measures of primary production during both Nectalis cruises were similar to  
848 previous studies in the region ( $300 - 1000 \text{ mgC m}^{-2} \text{ day}^{-1}$  in September 2004 at  $28^{\circ}\text{S}$  and  
849  $\sim 155^{\circ}\text{E}$ - $162^{\circ}\text{E}$  according to Young et al. (2011). These *in situ* measurements were also in the  
850 range of values estimated by satellite for the season, providing some validation and allowing  
851 confidence in using the satellite VGPM values for a larger scale assessment of primary  
852 production.

853 The biomass estimates of microzooplankton and mesozooplankton ( $\sim 20$ - $2000 \mu\text{m}$ ) provided  
854 by the S-ADCP were significantly correlated to the estimates using acoustics (TAPS) and  
855 nets. Estimates derived from the S-ADCP however, are likely to include other organisms and

856 therefore the S-ADCP provides a proxy which is not only reflective of zooplankton biomass  
857 (e.g. Burd and Thomson, 2012; Chereskin and Tarling, 2007). The strong correlation  
858 between the 153kHz S-ADCP Sv and the EK60 signal, the frequencies of which detect a range  
859 of organisms from zooplankton to micronekton and larger, indicate that estimates provided  
860 by the S-ADCP also include estimates of micronekton biomass. Although the results did not  
861 allow us to define precisely which size-range of organisms was detected by the S-ADCP, and  
862 despite the difficulties in calibrating the S-ADCP onboard vessels (Gostiaux and van Haren,  
863 2010), our results suggest that this instrument may provide a useful proxy of relative  
864 biomass of zooplankton and micronekton confirming its use as a functional tool for this  
865 purpose (Brierley et al., 1998; Flagg and Smith, 1989; Heywood et al., 1991; Lee et al., 2008;  
866 Radenac et al., 2010). Given that the S-ADCP has been used routinely for more than two  
867 decades to sample ocean currents, the data provided by these instruments could potentially  
868 be useful for mapping zooplankton/micronekton biomass distributions.

869 Correlations between net and acoustic (TAPS) estimates of zooplankton biomass observed  
870 in this study have also previously been observed (e.g. Lebourges-Dhaussy et al., 2014;  
871 2009a). Preliminary comparisons between the target micronekton trawls and the EK60  
872 acoustic signal however, were not correlated. These data need to be further explored. Low  
873 but significant correlations between micronekton net sampling and acoustic EK60 Sv have  
874 previously been found for micronekton south of New Caledonia using standardized oblique  
875 tows from 600 m to the surface at night (Young et al., 2011). Net sampling at targeted depth  
876 and selectivity/catchability/avoidance biases are some of the classic issues that may explain  
877 the often low correlation between micronekton net sampling and acoustic estimates (Kloser  
878 et al., 2009; Koslow et al., 1997).

879 Zooplankton biomass estimates provided by the TAPS were observed to be more than one  
880 order of magnitude higher than the biomass estimates provided by net sampling. These  
881 results are at odds with previous comparisons in other regions (e.g. Lebourges-Dhaussy et  
882 al., 2014, 2009) and at present we do not have a clear explanation for this discrepancy.  
883 Several hypotheses can be proposed which might explain such a disagreement. The TAPS  
884 detects organisms in the 50-3000  $\mu\text{m}$  size range, while the nets used during the cruises only

885 collected organisms larger than 200  $\mu\text{m}$ . The smaller sized organisms detected by the TAPS  
886 but not collected by the net may lead to smaller biomass estimates from net samples.  
887 Exploration of the data suggested that differences in the size ranges sampled by each  
888 method cannot explain the large difference in the two estimates. A plausible explanation  
889 could be the inadequacy of the parameterization of the model used in the inversion  
890 algorithm to calculate biomass from the TAPS signal. This would induce an overestimation of  
891 the biovolume by the TAPS if, for example, the density contrast between organisms and the  
892 water is underestimated. Further exploration of both the data and sampling of the water  
893 column by the TAPS is required. Moreover, vertical net sampling of the water column may  
894 be insufficient for representatively sample the oligotrophic waters around New Caledonia as  
895 the quantity of zooplankton collected was very low. Additional cruises are needed in which  
896 alternative sampling methods such as oblique tows which filter larger quantities of water  
897 and collect larger quantities of samples can be trialed and investigated.

898 Biomass estimates of micronekton provided by net sampling and those provided by the  
899 SEAPODYM ecosystem model were observed to be in the same range. Because the net  
900 sampled at specific depths thereby providing estimates which were not representative of  
901 the whole water column, and because of the relative simplicity of the way in which  
902 micronekton are estimated in SEAPODYM (Lehodey et al., 2010) this was not necessarily  
903 expected. Additionally, micronekton biomass estimates provided by SEAPODYM were  
904 significantly correlated to the 38 kHz EK60 acoustic signal. Again this was not expected as  
905 the ocean currents used to force SEAPODYM and determine micronekton spatial  
906 distribution in the sub-model come from a model reanalysis and not observations. Hence  
907 good space/time coherence between observed and modeled mesoscale structures at the  
908 time of the observations would not necessarily be expected. Given that the SEAPODYM  
909 simulation is simply eddy permitting, these results are encouraging and indicate that the  
910 influence of mesoscale features on micronekton biomass is adequately captured by  
911 SEAPODYM in this region.

912

913 **4.6 A broader view of the south-west Pacific**

914 The correlations observed between observations and both VGPM satellite-derived primary  
915 production and SEAPODYM estimates of micronekton biomass provide some confidence in  
916 using these products in describing the ocean dynamics of the broader south-west Pacific  
917 Ocean (~15°S-35°S and 150°E-175°E) encompassing the Coral Sea.

918 Looking more broadly than the region in which the cruises were conducted, horizontal  
919 advections also shaped the horizontal structure of primary production in the. (Figure 9).  
920 Using VGPM satellite-derived primary production data and SEAPODYM micronekton  
921 estimates, higher primary production and micronekton values were observed south of 23°S  
922 during the cool season and south of 31°S during the hot season than areas further north.  
923 Across the overall south west Pacific Ocean region, primary production was much stronger  
924 (by approximately a factor 2 to 3) during the cool season compared to the hot season as the  
925 SPCZ regime weakened and stronger winds promoted replenishment of surface nutrients  
926 (Figure 9). A similar seasonal signal was observed in micronekton biomass as derived from  
927 SEAPODYM however, the contrast between seasons was smaller than that observed in  
928 primary production estimates (micronekton was higher during the cool season by a factor  
929 <2).

930 Micronekton biomass south of 20°S as provided by SEAPODYM was globally organized in  
931 very patchy structures and the primary production maxima provided via remote sensing did  
932 not necessarily match the micronekton maxima. One good example can be found in the  
933 “downwelling” anticyclonic eddy in the EAC at 32°S-155°E, where primary production was  
934 organized in a strong band around the eddy whereas micronekton biomass was organized  
935 along a filament at the edge of the eddy. Estimates of micronekton biomass provided by  
936 SEAPODYM indicated that the southern region was richer in biomass, but was also much  
937 more variable than the northern region (Figure 9).

938 Presence of patchy structures and decoupling between different trophic levels raises  
939 uncertainty associated with using snapshot surveys to understand the coherence of an

940 ecosystem in turbulent regions. Additional observations in the region will be needed to  
941 confirm the nature of the ecosystem organization at (sub) mesoscales.

942

## 943 **5 Conclusions and perspectives**

944 By collecting new data extending from the ocean dynamics to micronekton in the top  
945 600 m, the two Nectalis cruises conducted in the south-west Pacific Ocean in austral cool  
946 and hot season of 2011 have provided a better understanding of the pelagic offshore  
947 ecosystem of this oligotrophic region. Multiple methods were used to measure zooplankton  
948 and micronekton (S-ADCP, TAPS, zooplankton net, SIMRAD EK60, micronekton net).  
949 Correlations were found between methods, however, net biomass estimates and acoustic-  
950 derived estimates did not compare very well. On the other hand, estimates of micronekton  
951 provided from net sampling and SEAPODYM were in the same range. The S-ADCP  
952 reproduced adequately the trends observed in micronekton and zooplankton, but was  
953 unable to distinguish zooplankton from micronekton and absolute biomasses could  
954 therefore not be calculated. Calibration of the different methods used to estimate  
955 zooplankton and micronekton will require additional and more specifically designed studies.  
956 Based on large existing S-ADCP datasets, the demonstrated relation between the S-ADCP  
957 signal and the zooplankton/micronekton biomass estimates provides the opportunity to  
958 estimate relative zooplankton/micronekton biomasses on much larger scales than those  
959 available from dedicated instruments such as EK60 or TAPS. Such effort will be undertaken  
960 in the New Caledonia region using the available S-ADCP database spanning the past 20  
961 years. In line with this work, we believe that the development of on-board calibration  
962 methods for the S-ADCP similar to those for echosounders (e.g. EK60) would be of great  
963 interest, particularly in providing absolute measures of abundance. Models such as  
964 SEAPODYM would benefit from absolute biomasses to better calibrate energy transfer  
965 parameterizations.

966 Based on our limited dataset and the resolution of our data, we could not examine the  
967 systematic effects of submesoscale phenomenon such as eddies and fronts on ocean

968 biochemistry and planktonic/nektonic communities structures during the Nectalis cruises.  
969 Data collected however, did suggest that horizontal advection was dominant over eddy  
970 pumping. Our study highlights the difficulty of understanding the impact of eddies in  
971 oligotrophic conditions without a full three dimensional dataset. We were also unable to  
972 explore the role that spatial variability might have at the submesoscale (frontal) level, a  
973 scale at which ecosystems have been shown to organize in some cases (e.g. Lebourges-  
974 Dhaussy et al., 2014; Lévy et al., 2012; Tew Kai et al., 2009). This remains an open question  
975 of wide scientific interest. Further, two cruises in two seasons are not sufficient to fully  
976 describe the role of seasonality on the ecosystem. Additional *in situ* measurements will be  
977 required to further understand the magnitude of the spatial distribution and seasonal cycle  
978 of zooplankton/micronekton biomass in the region, as planned in the coming years within  
979 the framework of the Nectalis program.

980 The synoptic Nectalis cruises and the SEAPODYM model at the regional scale indicated that  
981 the micronekton structure south of 20°S was remarkably patchy during both seasons in  
982 relation to the mesoscale dynamics of the region. This patchiness raises the question of how  
983 to best sample the region with dedicated cruises. At present, we have chosen to broadly  
984 sample the New Caledonian EEZ. We believe that given the large uncertainty in  
985 understanding of the ecosystem organization and species, it is still useful to pursue this  
986 effort and will be carried out in a series of two additional cruises in the coming years. We  
987 also do note that it is extremely difficult to interpret ecosystem signals at the mesoscale  
988 level using transects organized to cover wide spatial areas. We therefore aim to design  
989 dedicated cruises to follow a number of eddies in the region and understand the time  
990 dynamics of such evolving systems.

991

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1006

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1317 ecology and niche segregation in oceanic top predators off eastern Australia. Mar.  
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1321 Table 1. Summary of the cruise activities.

	Nectalis1	Nectalis2
Number of sampling stations	18	23
<b>Physics:</b>		
Temperature, salinity, fluorescence, oxygen 0-500 m: CTD sensors	All stations	All stations
Currents: 153 kHz ship borne-ADCP (16-200 m)	Along the track	Along the track
Sea surface salinity and temperature: thermosalinograph	Along the track	Along the track
<b>Nutrients:</b>		
Nutrients, NO <sub>x</sub> , SRP, 8 depths: 180 m, 150 m, 130 m, 90 m, 70 m, 40 m, 3 m; CTD water sampling	All stations	All stations
<b>Phytoplankton &amp; pigments:</b>		
Total Chlorophyll, 8 depths, fluorometry	All stations	All stations
Size fractionated chlorophyll (<3 μm, 3-10 μm, >10 μm): 8 depths, fluorometry	Stations 2, 4, 6, 8, 10, 12, 14, 16	Stations 1, 2, 6, 9, 11, 14, 17, 20, 23
Pigments: Phycoerythrin, 4 depths in the euphotic zone depending of the stratification (3m, between 20-40m, DCM, below DCM) spectrofluorometry.	Every other station	Every other station
Cell counts: CTD water sampling and flow cytometry	Stations 1, 3, 5, 7, 9 11, 13, 14, 15, 17, 18	Stations 1, 3, 5, 7, 9, 11, 15, 17, 19, 21, 23
<b>Primary production:</b>		
3 depths (surface, between 20-40m, DCM), <sup>14</sup> C tracer technique	Stations 1, 4, 7, 9, 13, 16, 17	Stations 4,8,12,15, 21
<b>Zooplankton:</b>		
Net sampling: Hydrobios 5 layer (0-600 m) mesh > 200 μm	All stations	All stations
Acoustics: 1 frequency 153 kHz S-ADCP (16-200 m)	Along the track	Along the track
Acoustics: 6 frequency zooplankton profiler TAPS (0- 200 m)	All stations	All stations
<b>Micronekton:</b>		
Net sampling: micronekton net between 14 and 540 m depth (10 mm codend mesh size)	All stations	All stations
Acoustics: 4 frequency EK60 SIMRAD echosounder (0- 600 m)	Along the track	Along the track
Acoustics: 1 frequency 153 kHz S-ADCP (16-200 m)	Along the track	Along the track

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1323



1324 Table 2. Mean and standard deviation (SD) of primary production, biomass estimates and  
 1325 acoustic signal of zooplankton and micronekton during the cool season (Nectalis1) and the  
 1326 hot season (Nectalis2). Results of the Mann-Whitney statistical test (for  $\alpha=5\%$ ) comparing  
 1327 Nectalis 1 (N1) and Nectalis2 (N2) and percentage of the number of tests producing this  
 1328 result for datasets with spatial auto-correlation (see section 2.3.1 for detailed explanation).  
 1329 Seasonal difference between micronekton biomass estimates derived from net sampling  
 1330 was not undertaken because different times and depths were sampled during each survey.  
 1331 DW: dry weight; WW: wet weight.

	Nectalis1		Nectalis2		Seasonal difference (Mann-Whitney) and percentage of tests producing the result
	Mean	SD	Mean	SD	
<i>In situ</i> primary production ( $\text{mgC m}^{-2} \text{d}^{-1}$ )	352	160	231	133	N1>N2
Satellite derived primary production along the cruise track ( $\text{mgC m}^{-2} \text{d}^{-1}$ )	301	62	199	55	100% N1>N2
Sv ADCP (dB)	-82.2	3.5	-83.4	2.8	80% N1>N2; 20% No difference
TAPS biovolume ( $\text{mg m}^{-3}$ )	107.7	37.3	106.7	22.6	No difference
Zooplankton DW. 0-200 m ( $\text{mg m}^{-3}$ )	3.9	2.6	5.8	2.3	N1<N2
Zooplankton WW. 0-600 m ( $\text{mg m}^{-3}$ )	6.3	3.4	5.6	1.8	No difference
Micronekton (net) $\text{mg m}^{-3}$	3.4	3.0	7.1	6.8	
Sv EK60 0-600 m (dB)	-77.8	2.7	-77.7	2.6	No difference at 100%
Micronekton (SEAPODYM 0-600 m $\text{mg m}^{-3}$ )	4.3	1.2	4.3	0.9	No difference at 100%

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1336 Table 3. Correlations between estimates of zooplankton biomass derived from each of the  
 1337 sampling methods deployed during the cruises. Grouped Nectalis1 and 2 Spearman's  
 1338 correlations and p-values between zooplankton dry and wet weight measurements (in  
 1339  $\text{mg m}^{-3}$ ) from net sampling and their acoustic proxies, S-ADCP Sv (in decibels, dB) and TAPS  
 1340 biovolume (in  $\text{mg m}^{-3}$ ) for the averaged top 100 m and top 200 m. Statistics involving S-  
 1341 ADCP Sv is performed by calculating  $\log_{10}$  of TAPS biovolume, zooplankton DW and WW.

Variables	Spearman's correlation coefficient		p-value	
	0-100 m	0-200 m	0-100 m	0-200 m
S-ADCP Sv vs. $\log_{10}$ (TAPS biovolume)	0.58	0.64	7e-5*	7e-6*
S-ADCP Sv vs. $\log_{10}$ (zoopl. dry weight from net)	0.53	0.66	6e-4*	1e-5*
S-ADCP Sv vs. $\log_{10}$ (zoopl. wet weight from net)	0.44	0.36	5e-3*	0.03*
TAPS biovolume vs. zoopl. dry weight from net	0.52	0.61	9e-4*	6e-5*
TAPS biovolume vs. zoopl. wet weight from net	0.46	0.55	3e-3*	4e-4*

1342 \* significant correlation at 5%

1343

1344

1345 Table 4. Correlations between estimates of micronekton biomasses. Grouped Nectalis1 and  
 1346 2 Spearman's correlations and significance between the four frequencies of S-ADCP Sv (dB)  
 1347 and the corresponding EK60 Sv (dB) averaged across 0-200m, and between estimates  
 1348 derived from  $\log_{10}$  (SEAPODYM) and the corresponding 38 kHz EK60 Sv (dB) average across  
 1349 0-350 m. Statistics involving S-ADCP Sv is performed by calculating  $\log_{10}$  of TAPS biovolume,  
 1350 zooplankton DW and WW.

1351

Variables	Range of Spearman's correlation coefficient	Percentage of significant correlations at $\alpha=0.05$
S-ADCP Sv vs. 200 kHz EK60 Sv	0.83-0.90	100%
S-ADCP Sv vs. 120 kHz EK60 Sv	0.85-0.92	100%
S-ADCP Sv vs. 70 kHz EK60 Sv	0.87-0.96	100%
S-ADCP Sv vs. 38 kHz EK60 Sv	0.73-0.79	100%
$\log_{10}$ (SEAPODYM) vs. 38 kHz EK60 Sv	0.66-0.80	100%

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1355 **Figures**

1356 Figure 1: Mean 1998-2007 primary production estimated from satellite (VGPM) in  $\text{mgC m}^{-2}$   
1357  $\text{d}^{-1}$  (shading). Regions of ocean depth shallower than 200 m have been blocked out. Mean  
1358 depth of the  $1 \mu\text{M}$  nitrate isopleth (proxy for the nitracline depth) was extracted from CARS  
1359 climatology (<http://www.marine.csiro.au/~dunn/cars2009/>) (Ridgway et al., 2002) in meters  
1360 (contour lines) and mean 0-150 meter total geostrophic currents sourced from Kessler and  
1361 Cravatte (2013) (vectors). The New Caledonia Exclusive Economic Zone is delineated by the  
1362 white line.

1363 Figure 2: Mean surface *in situ* (left column) and satellite-derived (right column)  
1364 oceanographic conditions in the New Caledonian region during the cool season (Nectalis1 -  
1365 29 July to 16 August 2011): cruise track and station numbers with those sampled at night in  
1366 bold red and those sampled during the day in regular black (top left); thermosalinograph  
1367 sea-surface temperature in  $^{\circ}\text{C}$  (SST) and salinity (SSS) (middle left); 0-150 m averaged  
1368 currents in  $\text{m s}^{-1}$  (vectors) from the S-ADCP with blue and red arrows indicating eastward  
1369 and westward currents respectively (bottom left); surface currents (vectors) from OSCAR  
1370 (right column), scale identical to S-ADCP scale; MODIS-VGPM derived depth-integrated net  
1371 primary production in  $\text{mgC m}^{-2} \text{d}^{-1}$  (top right); GHRSSST satellite sea surface temperature in  
1372  $^{\circ}\text{C}$  (top-middle right); sea level anomalies (SLA) referenced to the mean geoid in cm  
1373 (bottom-middle right), letters indicate eddies identified in the text; eddy depiction index:  
1374 Okubo-Weiß parameter ( $\text{day}^{-2}$ ) (bottom right). The cruise track is plotted in black on the  
1375 right column.

1376 Figure 3: Mean surface *in situ* (left column) and satellite-derived (right column)  
1377 oceanographic conditions in the New Caledonian region during the hot season (Nectalis2 -  
1378 26 November to 14 December 2011). See Figure 2 caption for details.

1379 Figure 4. Biogeochemical parameters across 0-200 m along cruise tracks during the cool  
1380 season (Nectalis1, left panel) and the hot season (Nectalis2, right panel), from CTD sensors  
1381 and bottle water analyses. The x-axis labels denote station numbers. From top to bottom:  
1382 temperature ( $^{\circ}\text{C}$ ), salinity, nitrate ( $\text{NO}_3 \mu\text{M}$ ), phosphate ( $\text{PO}_4 \mu\text{M}$ ), chlorophyll ( $\text{mg m}^{-3}$ ) and

1383 phytoplankton composition. The connected filled circles on the temperature and salinity  
 1384 panels represent the mixed layer depth, calculated as the depth at which the density equals  
 1385 the surface density + 0.03 kg m<sup>-3</sup> (de Boyer Montégut et al., 2004). The connected filled  
 1386 diamonds on the chlorophyll panel represent the depth at which nitrate reaches 1 µM, a  
 1387 proxy for the nitracline depth. Phytoplankton composition is described as a percentage of  
 1388 picoplankton (< 3 µm, black), nanoplankton (3 µm to 10 µm, blue) and microplankton  
 1389 (> 10 µm, red) biomass; orange symbols represent the ratio of *Prochlorococcus* cells to total  
 1390 picoplankton cells (in % abundance); the dots represent the average value of the top 50 m  
 1391 and the crosses represent the average value of the 50-130 m layer.

1392 Figure 5: Box plots of the distribution of *in situ* (In situ) primary production and satellite-  
 1393 derived (VGPM) primary production recorded at the points where *in situ* production  
 1394 measurements were performed (Sat.) and along the cruise track (Sat. full). Estimates are  
 1395 given for the cool (Nectalis1) and the hot season (Nectalis2). The boxplots denote mean  
 1396 values and 25% and 75% interquartiles (IQ25 and IQ75 respectively); the whiskers represent  
 1397 IQ25-1.5x(IQ75-IQ25) and IQ75+1.5x(IQ75-IQ25); dots represent outliers.

1398 Figure 6: Day (plain line) and night (dashed line) 0-600 m mean vertical profiles of  
 1399 zooplankton wet weight (mg m<sup>-3</sup>) and mean vertical profiles of 38kHz EK60 scattering  
 1400 volume (dB) during the cool season (Nectalis1, thick line) and the hot season (Nectalis2, thin  
 1401 line).

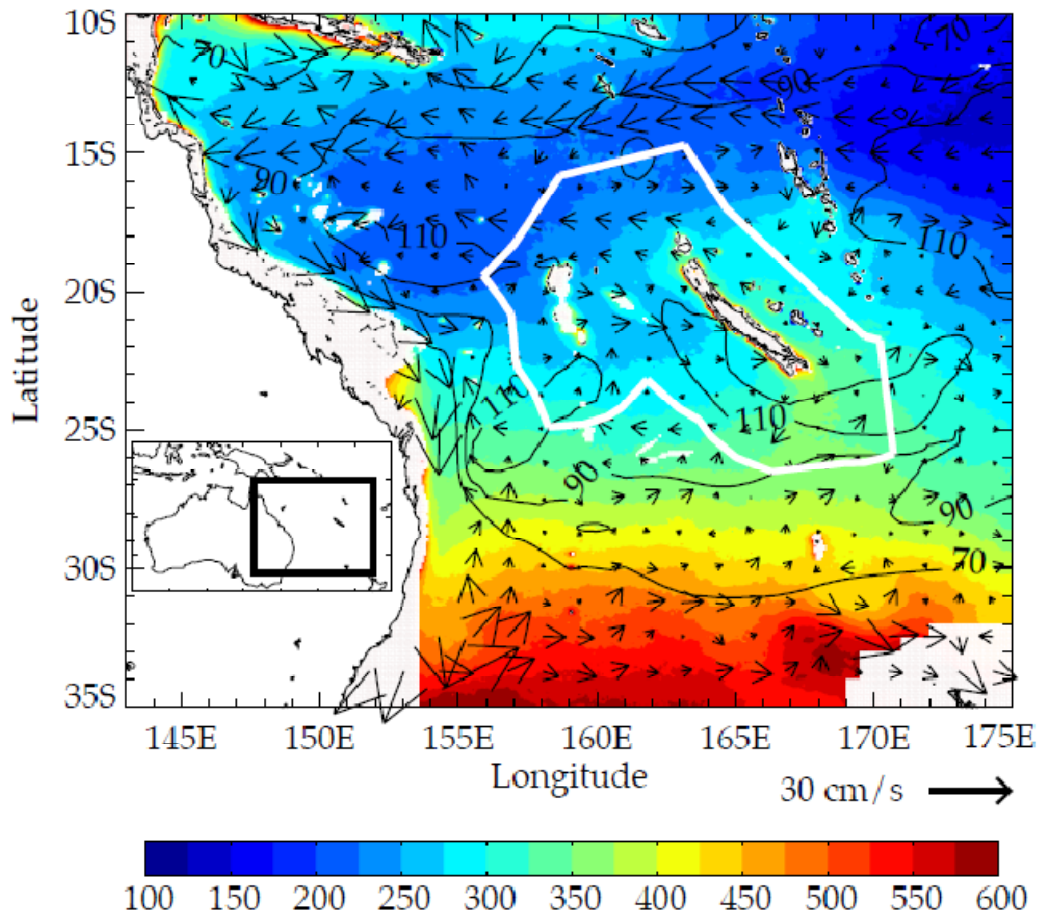
1402 Figure 7: Estimates of zooplankton and micronekton biomass during the day (D) and night  
 1403 (N) during the cool season (Nectalis1, 1) and the hot season (Nectalis2, 2) using the different  
 1404 methods employed during the cruises. From left to right: distributions of mean S-ADCP Sv  
 1405 (dB) across 0-150 m, mean TAPS biovolume (mg m<sup>-3</sup>) across 0-200 m, mean zooplankton dry  
 1406 weight (DW, mg m<sup>-3</sup>) across 0-200 m, mean zooplankton wet weight (WW, mg m<sup>-3</sup>) across 0-  
 1407 200 m, micronekton wet weight (mg m<sup>-3</sup>) from cumulated net samplings at discrete depths  
 1408 between 14 and 540 m, mean 38 kHz EK60 Sv (dB) across 0-350 m, and corresponding  
 1409 depth-averaged mean (epi- and mesopelagic layers) of micronekton biomass estimates from  
 1410 the SEAPODYM model. The boxplots denote mean values and 25% and 75% interquartiles  
 1411 (IQ25 and IQ75 respectively); the whiskers represent IQ25-1.5x(IQ75-IQ25) and

1412  $IQ75+1.5 \times (IQ75-IQ25)$ ; dots represent outliers. Note that biomass estimates from  
1413 SEAPODYM and EK 60, have been identically averaged over three euphotic depths (~350 m)  
1414 and day/time periods (see text for further details).

1415 Figure 8. Spatial distribution of the epi- and mesopelagic micronekton biomass ( $\text{mg m}^{-3}$ )  
1416 estimated from SEAPODYM at the stations and periods of the cruises (top panels) and the  
1417 corresponding observed 38 kHz Sv from the EK60 echosounder (bottom) during the cool  
1418 season (Nectalis1, left panel) and the hot season (Nectalis2, right panel). The day/night  
1419 signal was removed from the data (see text for details). For the sake of clarity the EK 60 Sv  
1420 data were arbitrarily re-transformed into a linear scale by computing  $10^{-Sv/100}$ , but the unit  
1421 by itself has no significance. The EK 60 data have been vertically averaged over the same  
1422 depths as the micronekton model incorporated into SEAPODYM (3 euphotic layers ~350 m)  
1423 and the data was resampled onto the model  $\frac{1}{4}^\circ$  grid resolution.

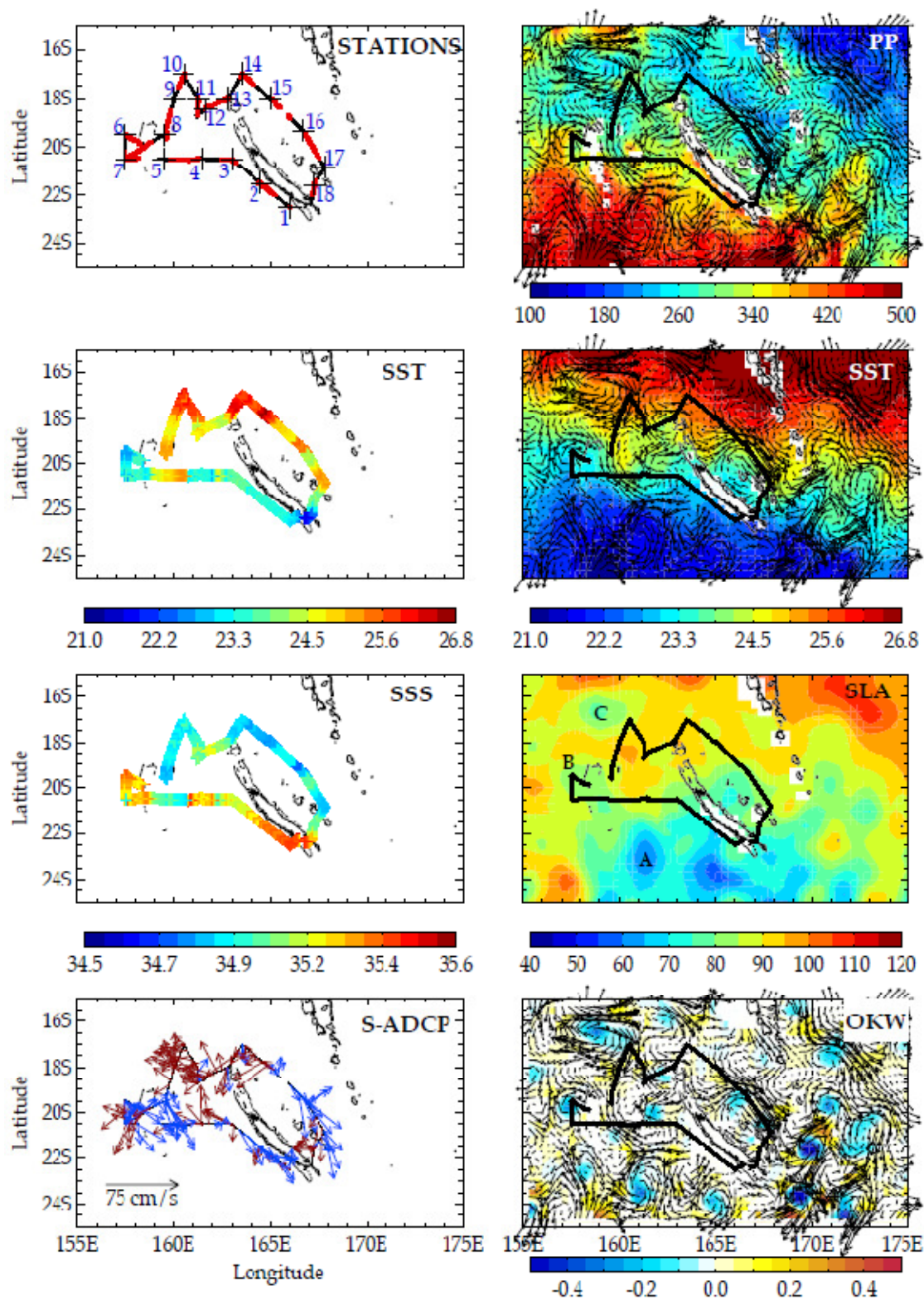
1424 Figure 9: Satellite primary production (VGPM in  $\text{mgC m}^{-2} \text{day}^{-1}$ ) and euphotic layer currents  
1425 from GLORYS (top panel). Averaged micronekton biomass ( $\text{mg m}^{-3}$ ) estimated by SEAPODYM  
1426 and averaged currents from GLORYS across the water column (0 – 1000m) (bottom panel).  
1427 Cool season (Nectalis1, left panel), hot season (Nectalis2, right panel).

1428

1429 **Figure 1**

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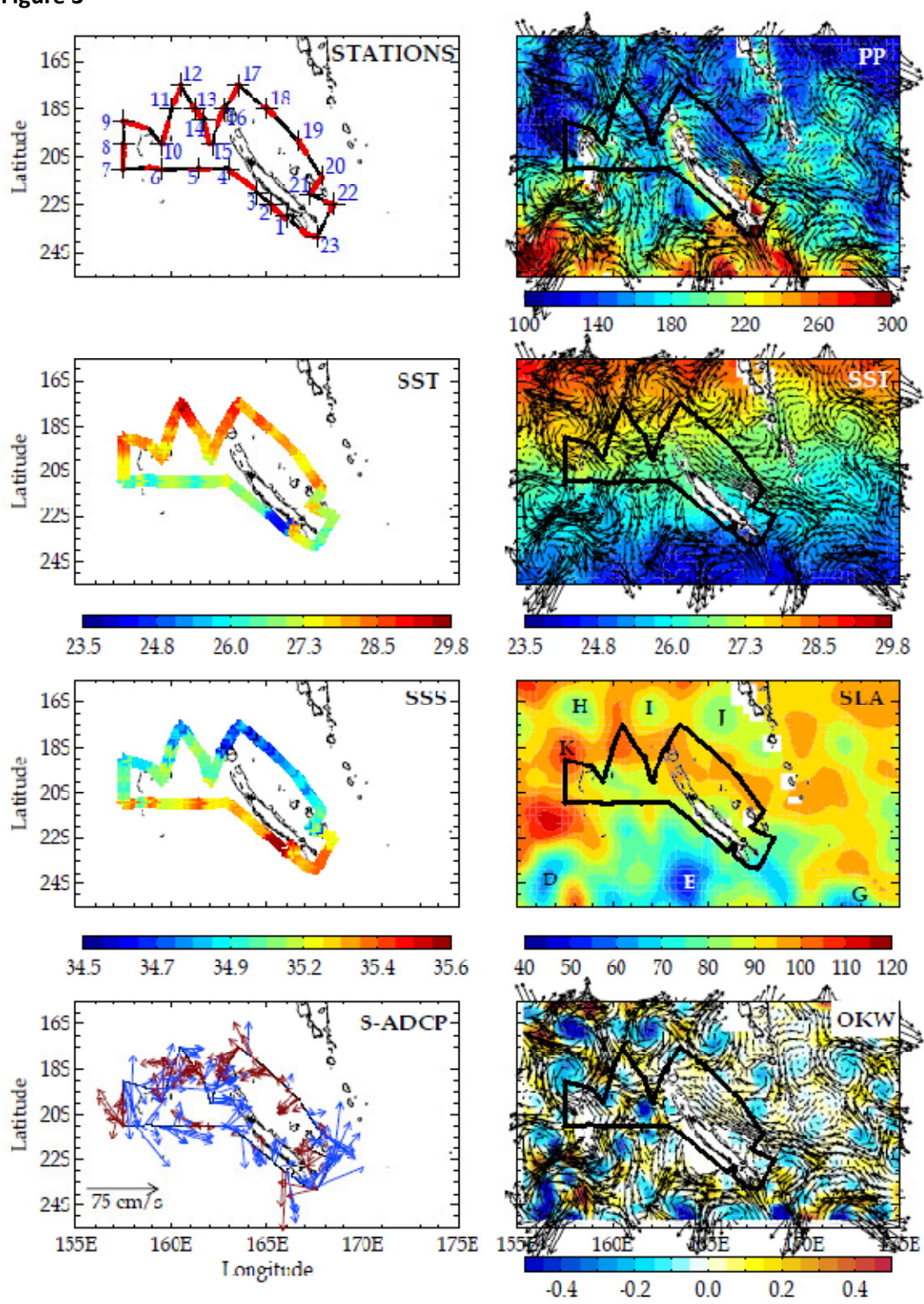
1432 **Figure 2**

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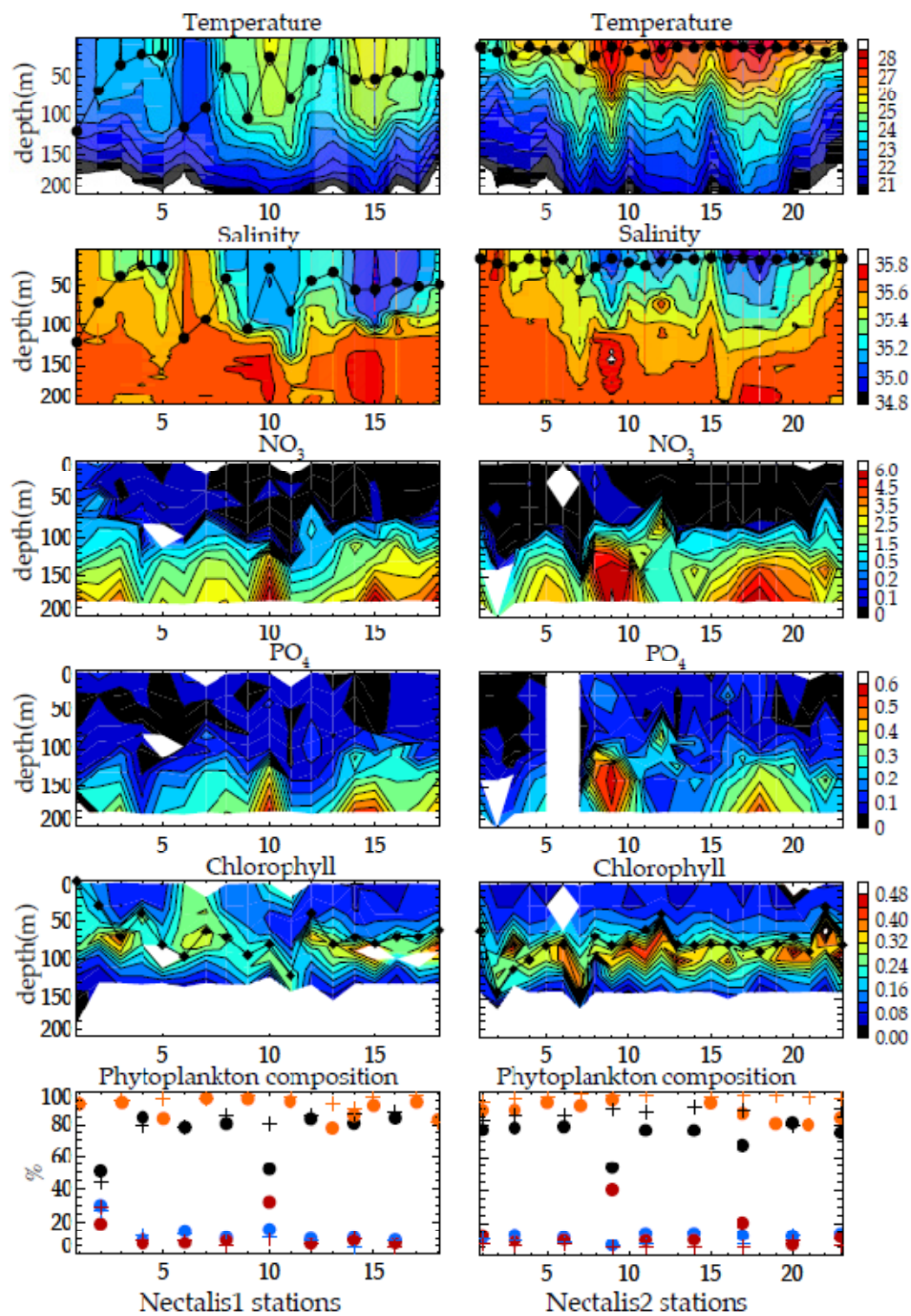
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1435 **Figure 3**

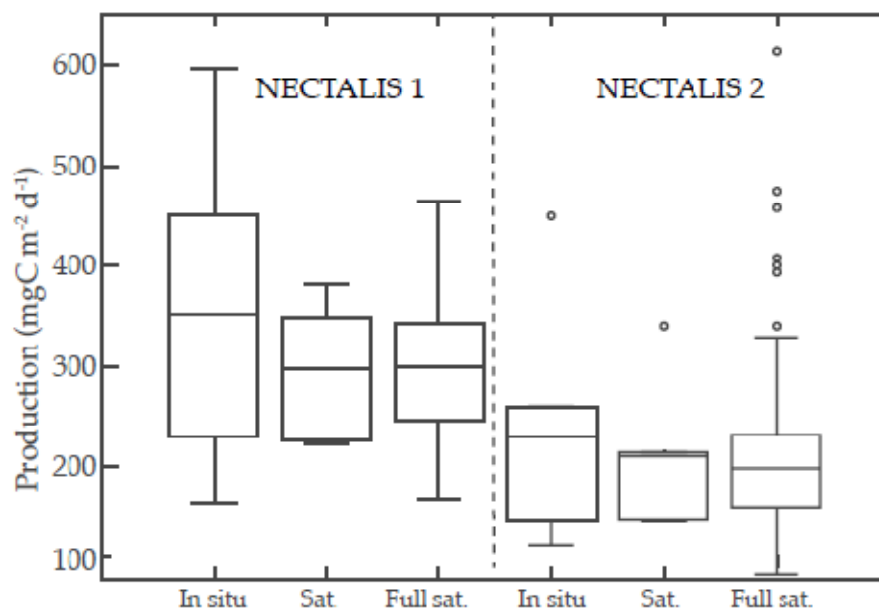
1436

1437 Figure 4



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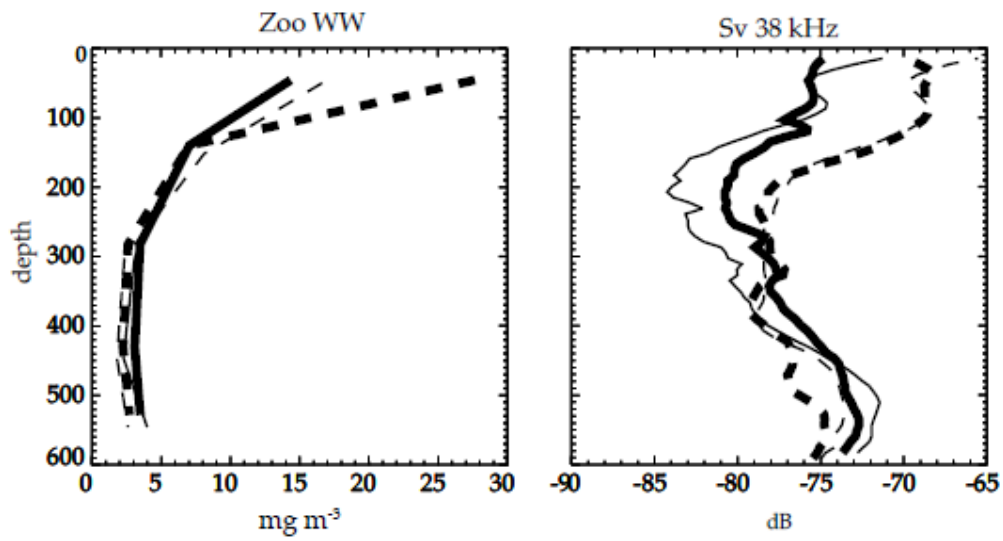
1440 **Figure 5**

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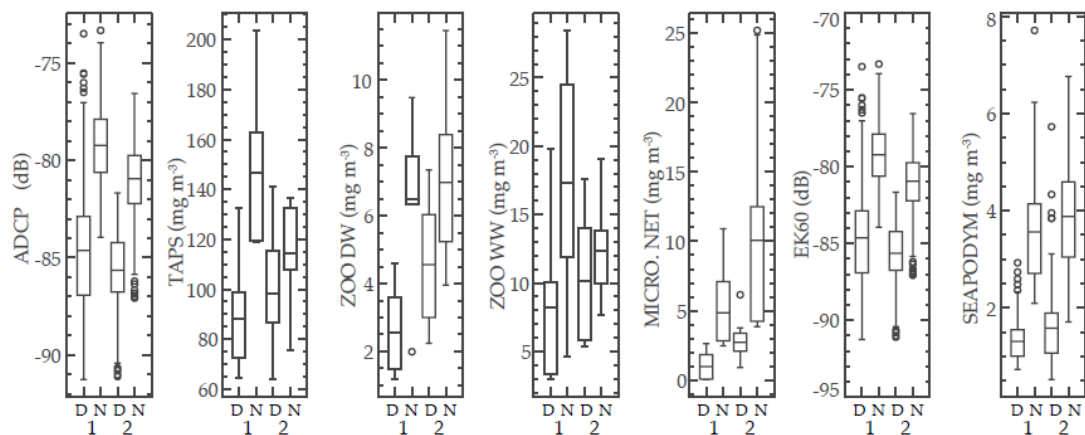
1444 **Figure 6**

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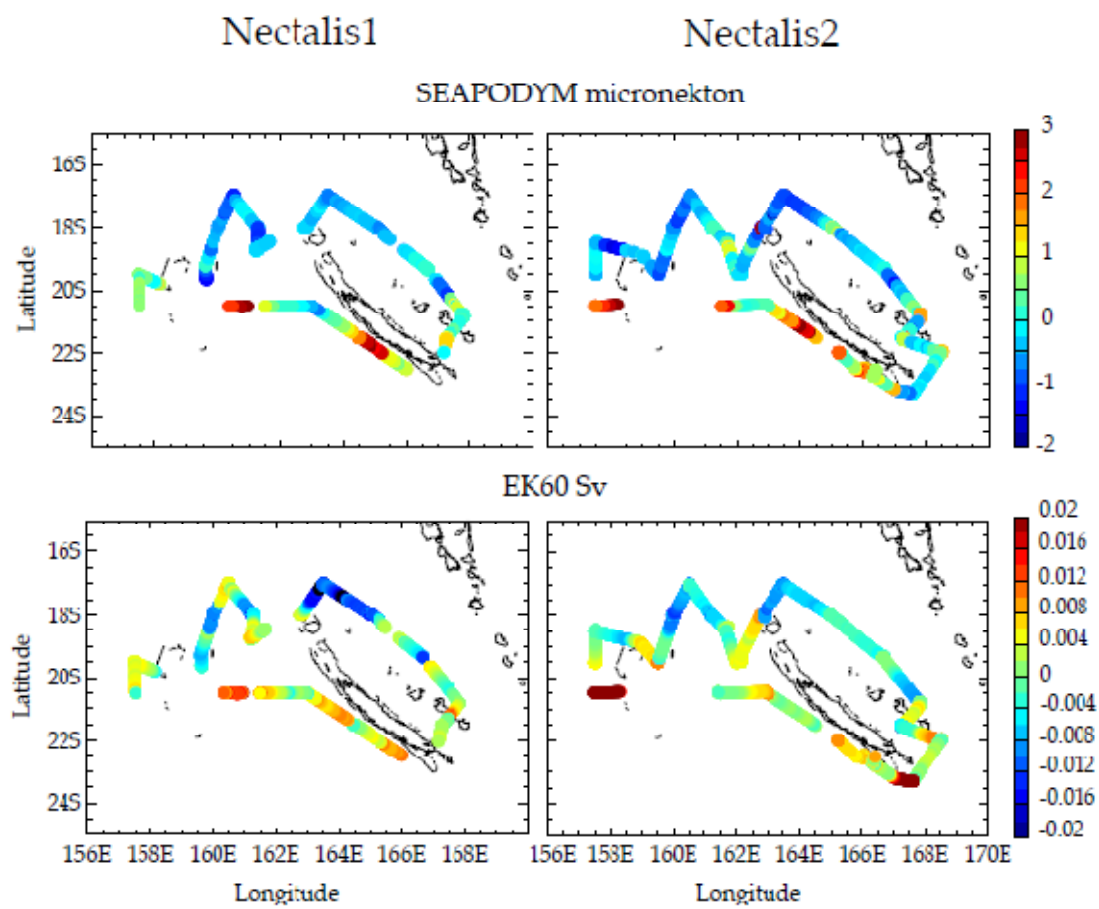
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1448 **Figure 7**

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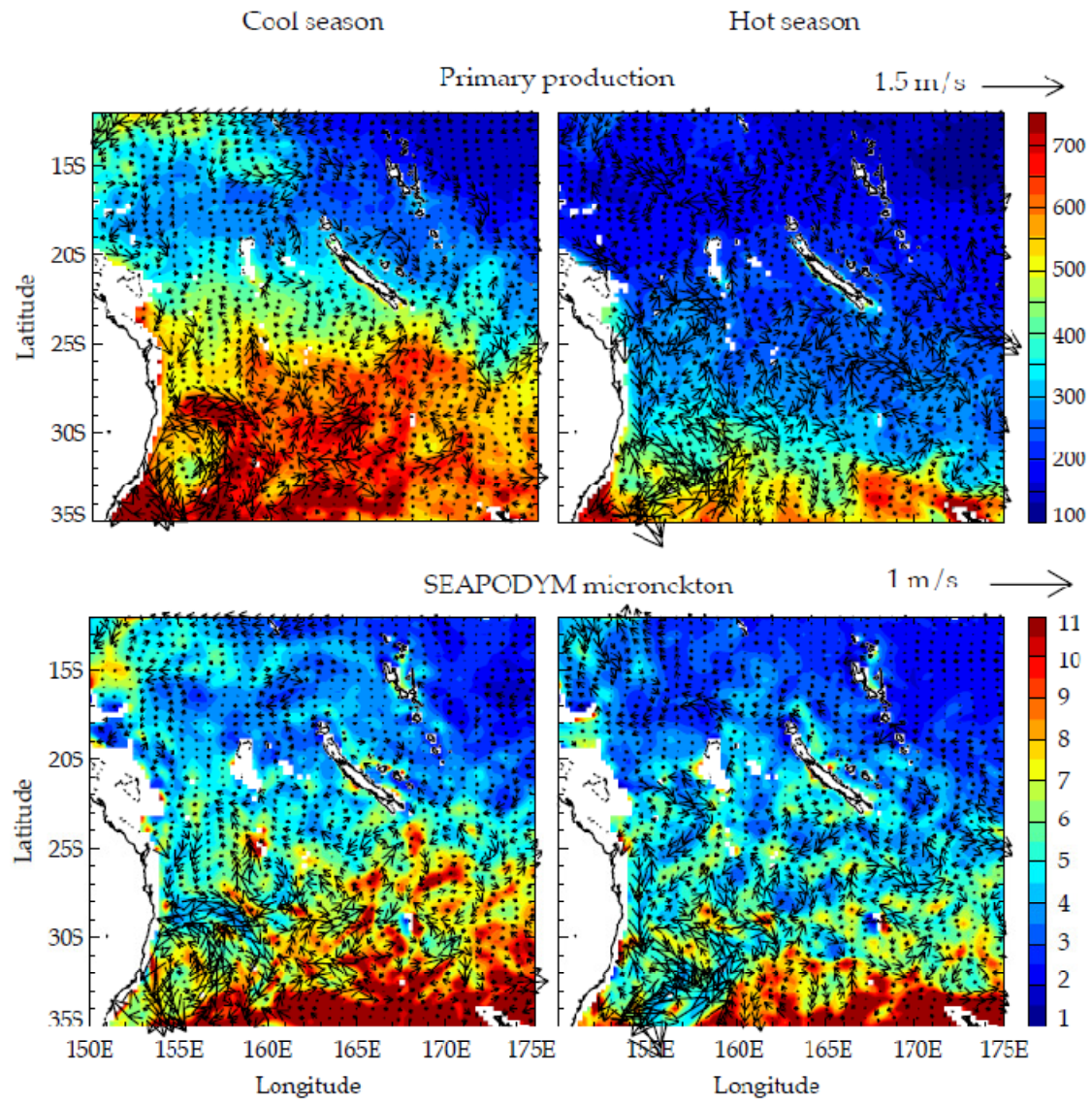
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1451 **Figure 8**

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1454 **Figure 9**

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