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Studies of Phytoplankton Species and Photosynthetic Pigments in a Warm Core Eddy of the East Australian Current. I. Summer Populations

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ABSTRACT: Summer phytoplankton populations in a warm core eddy of the East Australian Current were studied by thin-layer chromatography for pigments and by microscopy of living samples for species identification. Small differences in phytoplankton populations at the eddy centre compared to surrounding waters were observed. These included higher subsurface chlorophyll maxima (0.49–0.89 $\mu g\ l^{-1}$ eddy centre; 0.33–0.38 $\mu g\ l^{-1}$ eddy edge; 0.27–0.34 $\mu g\ l^{-1}$ midway positions) due to increased diatom abundance, a lower proportion of nanoplankton chlorophyll (52 % eddy centre; 73 % eddy edge), a dominance change from *Rhizosolenia alata* (eddy edge) to *Nitzschia seriata* (eddy centre), and a decreased number of dinoflagellate species.

INTRODUCTION

Warm core eddies, 200–300 km in diameter, are a general feature of the southerly-flowing East Australian Current (Hamon, 1965). They originate by a 'pinching off' process from warm subtropical waters of the Coral Sea (Nilsson et al., 1977), and migrate slowly southwards as far as the eastern end of Bass Strait (Cresswell and Golding, 1979). Their main structural features are strong surface currents (3.5–4 knots) in the form of a ring, with deep isothermal layers (up to 300 m) in the eddy centre (Andrews and Scully-Power, 1976). They occur in the deep waters seaward from the edge of the continental shelf, and can have a lifetime of 6–12 months (Hamon and Golding, 1979). The surface waters of an eddy may be 2 C° warmer than the outside water in late winter (Hamon, 1968), but in summer may be overlain by a warm surface layer from outside, thus causing temperature discontinuities at the surface to disappear.

An opportunity to study the phytoplankton populations of a warm core eddy in offshore waters south of Sydney occurred in November–December 1978, during the R.V. 'Sprightly' cruise SP16/78. This eddy (Eddy F, centred at 36°36'S, 151°45'E) had separated from the East Australian Current about three months earlier; a complete description of its physical properties is reported (Boland and Church, submitted). The cruise track (Fig. 1) enabled us to sample phytoplankton species and photosynthetic pigments at the edge of the eddy, at midway positions and at its centre, as well as the Port Hacking 300 m shelf station (Stn. 289) close to Sydney. The methodology we used (light microscopy of living samples for phytoplankton species identification, and thin-layer chromatography for photosynthetic pigments) was previously used successfully for studies at the inshore Port Hacking 100-m station near Sydney (Jeffrey, 1974; Jeffrey and Carpenter, 1974; Hallegraeff, in press) and in the Central Pacific Gyre (Jeffrey, 1976).

We present here chlorophyll profiles, chromatographic pigment analyses and species compositions of phytoplankton populations at eddy centre, edge and midway stations. A greater species diversity was observed at the eddy edge, an increased phytoplankton biomass at the eddy centre. In addition, many important characteristics of the phytoplankton flora of the East Australian Current were recorded.

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MATERIALS AND METHODS

Collection of Samples

Cruise track and station positions of R.V. 'Sprightly' Cruise SP 16/78 (30 November–8 December 1978) are shown in Figure 1. Samples for phytoplankton species and pigment analysis were taken at Stations 289, 290, 293, 295, 298, 301 and 305 on 30 November, 1, 2, 3, 4, 5 and 7 December, respectively. Water samples were

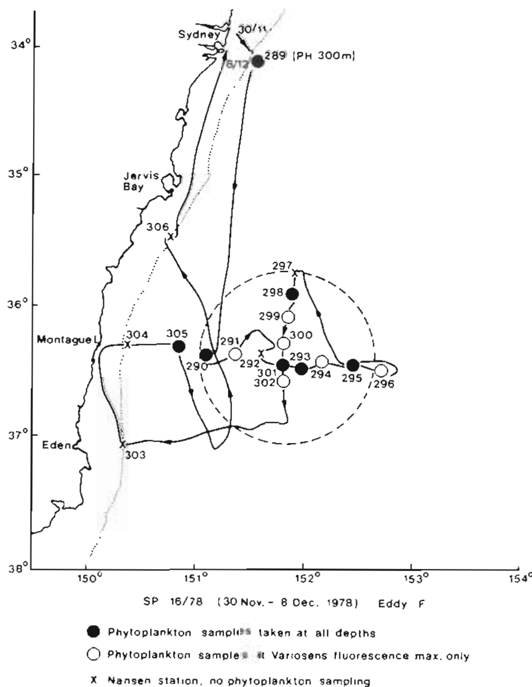

Fig. 1. 'Sprightly' cruise track (SP16/78), 30 November to 8 December 1978; sampling stations and approximate position of Eddy F, based on XBT data

collected with 30 l Niskin bottles (General Oceanics, Inc.) at depths of 0, 25, 50, 75, 100, 150 and 200 m. A few samples were also collected at 300, 500 and 1000 m depth. Additional depths were chosen from *in situ* depth profiles of chlorophyll *a* fluorescence (*in vivo*), obtained by lowering a Variosens II fluorometer (Früngel and Koch, 1976) through the water column prior to the collection of the discrete water samples. A further set of 10 l samples were taken at Stations 291, 294, 299, (midway between eddy centre and eddy edge) and 300 and 302 (eddy centre) at the Variosens maximum only.

Preparation of Water Samples for Pigment Analysis

Immediately after collection, 10 l of the sample was filtered under slight negative pressure (10 cm Hg) on to a 47 mm Whatman GF/C filter (median retention size 0.70 μm). About 5 ml of a 1 % $MgCO_3$ suspension was added to the last 200 to 300 ml seawater to act as a buffering agent during subsequent storage. After filtration, the filters were folded, placed in 10 ml graduated glass centrifuge tubes, and immediately frozen in liquid nitrogen. The tubes were stored frozen (– 20 °C) in the dark until extraction and chromatographic analyses were performed some 2–6 weeks later. (Control tests with cultured species showed a 5–10 % loss of chlorophyll *a* after 6 weeks storage and only 2–3 % formation of pheophytin *a*.) These samples constituted the unfractionated or total phytoplankton.

To determine the proportion of 'nanoplankton' present, another 5 l of seawater from the same 30 l Niskin bottle was gently poured through a piece of 10 μm mesh nylon gauze (Henry Simon and Co., Sydney) mounted on top of the receiver flask of the filter holder. The resulting filtrate (containing predominantly small flagellates with diameters $\lesssim$ 15 μm together with a few small diatoms; tests described by Hallegraeff, in press) was filtered through Whatman GF/C filters and stored frozen as described above. This fraction is referred to below as < 15 μm fraction.

Preparation of Water Samples for Species Identification

For microscopic examination, the phytoplankton from a second 5 l sample taken from the same Niskin bottle was concentrated to about 10 ml in a continuous plankton centrifuge (Davis, 1957) at 15 000 *g* using a flow rate of approximately 1 l per 6 min. The harvested algae were examined immediately (on board ship) in the living state with an inverted microscope, and the proportions of all species, especially the fragile flagellates, were noted. Line drawings and photographic records were made. The samples were subsequently fixed in 3 % glutaraldehyde buffered with 0.01 M phosphate, pH 7.8, and stored at 5 °C for 3–5 weeks until analyses were completed. This gentle membrane fixative was used in an attempt to preserve delicate species usually destroyed by harsher techniques (e.g. Lugol's iodine mixture and Steedman's formaldehyde fixative; UNESCO, 1976).

Pigment Extraction

All operations involving pigment extractions and chromatography were done in darkened fume cupboards to prevent photo-oxidative pigment damage. The frozen filters were extracted by adding 5 ml 100 % acetone to each filter in its centrifuge tube, and leaving

overnight at 5 °C. 100 % (not 90 %) acetone was always used in the initial extractions to inactivate the chlorophyllase found in some unicellular algae, particularly diatoms (Barrett and Jeffrey, 1964, 1971). Next morning, each filter was removed from its tube, cut into small pieces, placed in a Potter-Elvehjem ground glass homogenizer, and mechanically ground for several minutes with two lots of 2 ml portions of 100 % acetone. The combined acetone extracts were then adjusted to 90 % with distilled water, and centrifuged at 2500 *g* for 5 min. Absorption spectra of the clarified extracts were read in 1 cm cells in a Cary 17 spectrophotometer using the 0.1 or 0.2 absorption scale for increased sensitivity. Chlorophylls were determined using the trichromatic spectrophotometric equations of Jeffrey and Humphrey (1975), which recent tests have shown to be the most accurate available for the three chlorophylls *a*, *b* and *c* (Lorenzen and Jeffrey, in press). The sensitivity of our methodology allowed 0.01 mg phytoplankton chlorophyll *a* from 1 l seawater to be determined accurately (± 5 %).

Thin-Layer Chromatography

Pigment extracts were prepared for chromatography by transferring the pigments from acetone to diethyl ether (Mallinckrodt, peroxide-free), by adding an equal volume of diethyl ether to the acetone extract and gently mixing with 10 volumes of cold (5 °C) 10 % NaCl solution, as previously described (Jeffrey 1968a, 1974, 1976). The pale yellow-green ether layer was collected, evaporated to about 0.5 ml under a stream of nitrogen, and stored at – 20 °C in the dark. Chromatographic analysis was completed within 1–4 h of this step.

Pigments were chromatographed on thin layers of cellulose powder (Macherey-Nagel, MN 300) which had been extensively washed to remove impurities which interfered with the chromatography (Jeffrey, in press). The chromatographic solvents were: first dimension, *n*-propanol in light petroleum (60°–80 °C fraction) in the proportions 2.5:97.5 (v/v); and second dimension, light petroleum, chloroform and acetone in the proportions 75:25:0.5 (v/v/v).

Chromatograms (10 × 8 cm) were developed in small tanks (15 × 12 × 15 cm) lined with filter paper and pre-equilibrated for a few minutes with the appropriate solvents. Development of the first dimension took about 4 min (longer direction first), after which the plates were removed, air dried for 5 min in absolute darkness, and then run in the second dimension (2–3 min). The plates were then examined under UV light, and a tracing of the chromatogram taken.

Species Counts

For quantitative species counts 2.5 ml subsamples of the glutaraldehyde-fixed phytoplankton were settled overnight in counting chambers (Utermöhl, 1958), and examined in an inverted microscope under phase contrast. The whole bottom area of the chamber was counted at low magnification (× 200) for rare and large species (such as large dinoflagellates), and a 'random' portion (10–30 fields) was counted at low magnification (× 200) for diatoms, and at higher magnification (× 700) for flagellates. A counting error of 10–15 % was accepted for the small flagellates, and an error of 15–25 % for the diatoms and dinoflagellates. For estimates of cell volume, average cell dimensions were determined for each species, by approximating cell shape to the closest solid geometric configuration (Smayda, 1978). Such techniques gave volume estimates for small green flagellates of 15 μm^3; small coccolithophorids, 90 μm^3; small naked dinoflagellates, 270 μm^3; *Nitzschia seriata*, 850 μm^3; *Thalassiothrix longissima*, 1800 μm^3; *Rhizosolenia alata*, 20 000 μm^3 and *Ceratium fusus*, 55 000 μm^3.

RESULTS

Chlorophyll Depth Profiles

Table 1 lists the chlorophyll concentrations of selected eddy centre, eddy edge and midway stations.

Table 1. Concentration of chlorophyll *a* at selected stations determined by trichromatic spectrophotometry

Station	Chlorophyll *a* concentration: Water column maximum ($\mu g\ l^{-1}$)	Water column (0–200 m) ($mg\ m^{-2}$): Total	Water column (0–200 m) ($mg\ m^{-2}$): < 15 μm fraction	< 15 μm fraction (% of total chlorophyll)
Eddy centre				
293	0.89	54.7	24.5	45
300	0.67			
301	0.49	32.9	19.5	59
302	0.72			
Eddy edge				
290	0.38	33.4	24.0	72
295	0.38	22.7	17.3	76
296	0.33			
298	0.34	29.8	21.5	72
305	0.36	26.9	19.2	72
Midway positions				
291	0.27			
294	0.31			
299	0.34			

Table 2. Phytoplankton species list of all stations (289, 290, 293, 295, 298, 301) studied. + species found at eddy centre; O species found at eddy edge

Species	Group	Species	Group	Species	Group
Dominant species (1–100 % of total phytoplankton biomass)					
+O *Nitzschia seriata*	DIAT	+O *Gephyrocapsa oceanica*	PRYM	+O *Gymnodinium simplex*	DIN
+O *Nitzschia longissima*	DIAT	+O Green flagellate (1–3 μm)	PRAS	+O *Gymnodinium* spp. (2)	DIN
+O *Rhizosolenia alata*	DIAT	+O *Gymnodinium* cf. *bogoriense*	DIN	+O *Amphidinium acutissimum*	DIN
+O *Thalassiothrix longissima*	DIAT	+O *Gymnodinium cinctum*	DIN	+O *Oxytoxum variabile*	DIN
+O *Emiliania huxleyi*	PRYM	+O *Gymnodinium nanum*	DIN	+O *Oxytoxum globosum*	DIN
Subdominant species (0.01–1 % of total phytoplankton biomass)					
+O *Ceratium carriense*	DIN	O *Chaetoceros didymus*	DIAT	+O *Oxytoxum elongatum*	DIN
O *Ceratium falcatum*	DIN	+O *Chaetoceros* spp. (4)	DIAT	+O *Oxytoxum scolopax*	DIN
+O *Ceratium furca*	DIN	O *Cochlodinium virescens*	DIN	O *Oxytoxum* sp.	DIN
+O *Ceratium fusus*	DIN	O *Dinophysis caudata*	DIN	O *Peridinium crassipes*	DIN
+O *Ceratium horridum*	DIN	+O *Dinophysis hastata*	DIN	O *Peridinium minusculum*	DIN
+O *Ceratium pentagonum*	DIN	O *Dinophysis* cf. *ovum*	DIN	+O *Peridinium* spp. (2)	DIN
+O *Ceratium teres*	DIN	+O *Dinophysis* sp.	DIN	+O *Podolampas elegans*	DIN
+O *Ceratium tripos*	DIN	O *Gonyaulax kofoidii*	DIN	+O *Pronoctiluca spinifera*	DIN
O *Ceratium* spp. (2)	DIN	O *Gonyaulax* sp.	DIN	+O *Prorocentrum dentatum* (= *Prorocentrum obtusidens*)	DIN
O *Chaetoceros affinis*	DIAT	O *Gyrodinium* spp. (2)	DIN	+O *Rhizosolenia stoltherfothii*	DIAT
O *Chaetoceros danicus*	DIAT	O *Leptocylindrus danicus*	DIAT		
		+O *Oxytoxum elegans*	DIN		
Rare species (0.001–0.01 % of total phytoplankton biomass)					
O *Amphisolenia laticincta*	DIN	O *Dactyliosolen mediterraneus*	DIAT	+O prymnesiophytes, unidentified (5)	PRYM
O *Anthosphaera robusta*	PRYM	+O *Dictyocha fibula*	SIL	O *Pyrocystis robusta*	DIN
O *Asterionella glacialis*	DIAT	O *Distephanus octonarius*	SIL	O *Rhizosolenia alata* f. *indica*	DIAT
+O *Asteromphalus flabellatus*	DIAT	O *Ditylum brightwellii*	DIAT	O *Rhizosolenia hebetata*	DIAT
O *Bacteriastrum delicatulum*	DIAT	O *Eucampia zoodiacus*	DIAT	+O *Rhizosolenia setigera*	DIAT
O *Biddulphia mobiliensis*	DIAT	O *Eutreptiella* sp.	EUGL	O *Schroederella delicatula*	DIAT
O *Calciosolenia* sp.	PRYM	+O *Fragilaria* sp.	DIAT	O *Skeletonema costatum*	DIAT
O *Climacodium frauenfeldianum*	DIAT	O *Guinardia flaccida*	DIAT	O *Stauroneis membranacea*	DIAT
+O coccolithophorids, unidentified (4)	PRYM	+O *Navicula* sp.	DIAT	O *Streptotheca thamensis*	DIAT
O *Corethron criophilum*	DIAT	+O *Planktoniella sol.*	DIAT	+O unidentified flagellates (3)	?
+O *Coscinodiscus lineatus*	DIAT	O *Pleurosigma* sp.	DIAT	O *Thalassionema nitzschioides*	DIAT
O *Coscinodiscus* sp.	DIAT	O *Prorocentrum lima* (= *Exuviella marina*)	DIN	+O *Thalassiosira* spp. (2)	DIAT
+O *Cryptomonas* spp. (2)	CRYP			O *Tropidoneis* sp.	DIAT

CRYP cryptomonad, DIAT diatom, DIN dinoflagellate, EUGL euglenophyte, PRAS prasinophyte, PRYM prymnesiophyte, SIL silicoflagellate

The chlorophyll concentrations at the subsurface maxima were in general higher at eddy centre stations than at midway or edge positions. Differences in the total water column values were less pronounced. The < 15 μm fraction was a large component of the total phytoplankton. At the eddy edge it was 72–76 % of the total chlorophyll, whereas at the eddy centre it was 45 and 59 %. The depth of the subsurface chlorophyll maxima varied from 50 to 100 m at both eddy edge and eddy centre stations.

Phytoplankton Species

Phytoplankton cell numbers for five dominant species categories were counted for all the stations analysed for chlorophyll. These species categories were: two large diatom fractions (*Nitzschia seriata* plus *N. longissima*, and *Rhizosolenia alata*), and three small flagellate categories (coccolithophorids, non thecate dinoflagellates and small green flagellates). These dominant phytoplankton species ranged in abundance from 10 to 140 $\times 10^3$ cells l^{-1} for *Nitzschia* species, from 0.5 to 15 $\times 10^3$ cells l^{-1} for *Rhizosolenia alata*, from 10 to 30 $\times 10^3$ cells l^{-1} for small non-thecate dinoflagellates (mainly *Gymnodinium*), up to 90 $\times 10^3$ cells l^{-1} for small coccolithophorids (*Emiliania huxleyi*) and *Gephyrocapsa oceanica*) and up to 400 $\times 10^3$ cells l^{-1} for small green flagellates.

Complete phytoplankton species lists at all stations studied are given in Table 2. Dominant species (1–100 % of the total phytoplankton biomass) included *Nitzschia seriata* and *N. longissima*, *Rhizosolenia alata*, *Thalassiothrix longissima*, small dinoflagellates (9 species), coccolithophorids (*Emiliania huxleyi* and *Gephyrocapsa oceanica*) and a small green flagellate (a *Micromonas*-like prasinophyte). Subdominant species (0.01–1 % of the total phytoplankton biomass) included the dinoflagellates *Ceratium* spp. (10), *Dinophysis* spp. (4), *Gonyaulax* spp. (2), *Oxytoxum* spp. (4), *Peridinium* spp. (4) and the diatoms *Chaetoceros* spp. (7), *Leptocylindrus danicus* and *Rhizosolenia stoltherfothii*. Rare species (0.001–0.01 % of the total phytoplankton biomass) included representatives of seven algal classes – diatoms, dinoflagellates, prasinophytes, prymnesiophytes, cryptomonads, silicoflagellates and euglenophytes. Thus, in the dominant category, 16 species were recognised; in the subdominant category, 39 species (mostly dinoflagellates); and in the rare category, 49 species including many delicate phytoflagellates from 7 classes.

Small but significant differences in species composition were found between eddy edge and eddy centre stations using dominance diversity curves (Fig. 2). Species abundances (expressed as relative contribution to total phytoplankton cell volume) were plotted on a log scale on the ordinate, against the rank of the species on a linear scale on the abscissa, arranged in order from most numerous to least numerous (Hallegraeff and Ringelberg, 1978). Phytoplankton numbers were integrated over the entire water column for these plots.

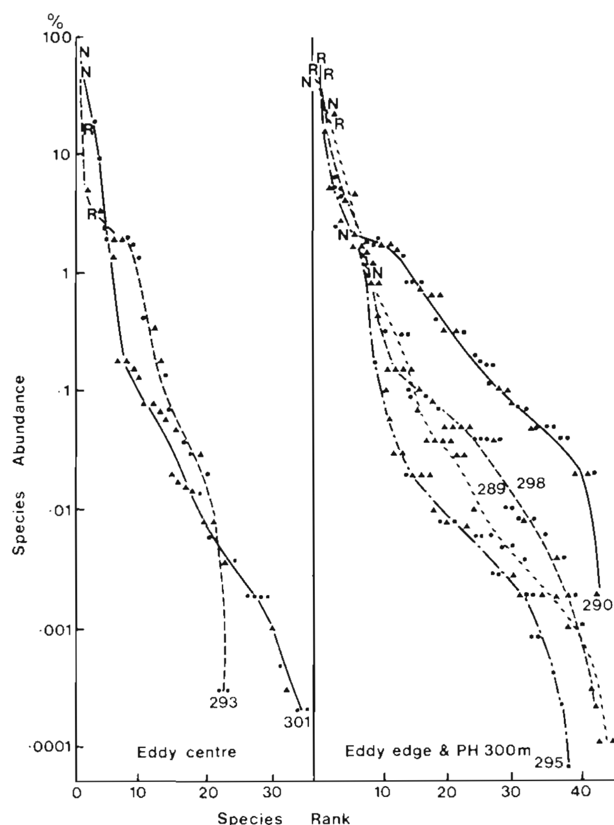

Fig. 2. Dominance-diversity curves of phytoplankton at eddy edge (290, 295, 298), eddy centre (293, 301) and the Port Hacking 300 m (289) stations. Ordinate represents relative species abundance by volume; abscissa, species ranked in order from most abundant (Rank No. 1) to least abundant (Rank No. 44). N: *Nitzschia* and R: *Rhizosolenia*, the two dominant organisms. ▲ dinoflagellate species; ● others

Nitzschia and *Rhizosolenia* were the two most abundant genera (by volume) at both eddy centre and eddy edge stations. However, *Nitzschia* was more abundant (47–75 %) than *Rhizosolenia* (4–20 %) at the eddy centre stations, whereas *Rhizosolenia* was more abundant (45–69 %) than *Nitzschia* (1–21 %) at the eddy edge stations. A total of 23–35 phytoplankton species were recognised per station for the eddy centre, whereas at the eddy edge 38–44 species were recognised. This difference in species number between the two locations was due to the larger number of dinoflagellate species at the eddy edge stations (Table 2, Fig. 2). Thus more steeply oblique curves resulted for the eddy centre stations (293, 301), whereas flatter sigmoid curves, indicating a more even distribution of

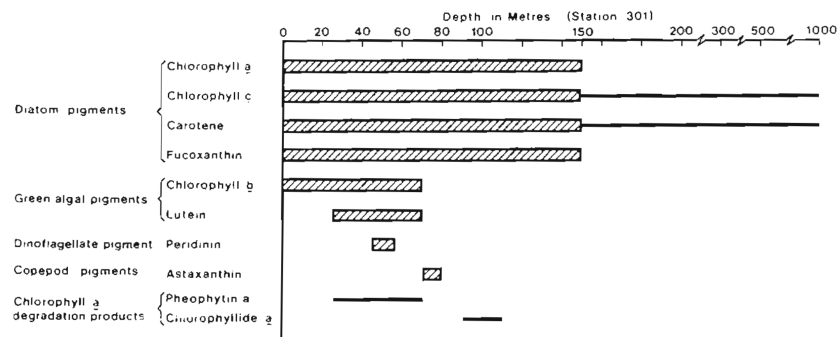

Fig. 3. Profiles of pigments with depth at eddy centre, Station 301. Hatched bands: pigments associated with living cells; black bars: pigments associated with detrital material

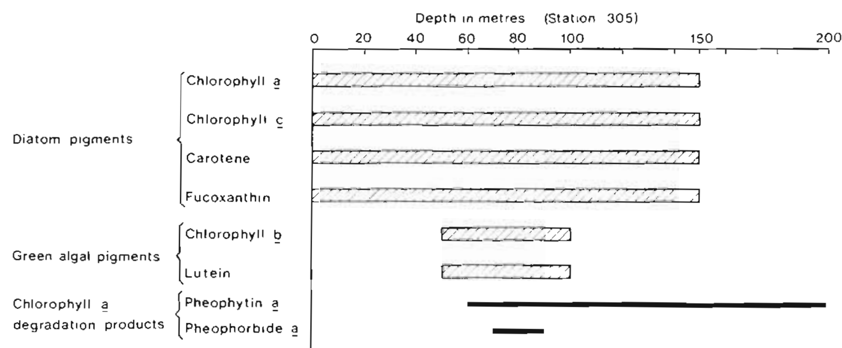

Fig. 4. Profiles of pigments with depth at eddy edge, Station 305. For further information see legend to Figure 3

species abundances, occurred at the eddy edge stations (290, 295, 298). The anomalous dominance diversity curve of the edge station 290, located towards the coastal side of the eddy, may be the result of admixture of phytoplankton of different origins.

Chromatographic Pigment Analyses

Chromatographic pigment analyses for one eddy centre station (from surface waters down to 1000 m) and one eddy edge station (from the surface down to 200 m) are plotted in Figures 3 and 4 to show associations of pigments with living algae (cross hatched bands) and pigments from detrital material (solid bars). In Figure 3 (Station 301) chlorophylls *a* and *c*, carotene and fucoxanthin (diatom and coccolithophorid pigments) occurred at all depths down to 150 m; chlorophyll *b* and lutein (green algae), down to 75 m; the dinoflagellate carotenoid, peridinin, at 50 m; and astaxanthin (a copepod carotenoid) at 75 m. At depths below 150 m, the only pigments detected were carotene, chlorophyll *c* and brownish material from the 'origin' of the chromatograms. Since no chlorophyll *a* was present, these pigments must have been detrital in origin.

At the eddy edge station (Figure 4, Station 305) living diatoms were also dominant down to 150 m depth, with green algae located between 50 and 100 m. The chlorophyll degradation products pheophytin *a*, chlorophyllide *a* and pheophorbide *a* were found in the water column at these stations. Chromatographic analysis for all other stations (60 samples) showed similar results. No significant differences in pigment distribution in the water column of edge or centre stations were observed.

DISCUSSION

Chlorophyll Concentrations

Previous studies of phytoplankton chlorophyll in offshore waters of the East Australian Current (Humphrey, 1970) showed a relatively low level of surface chlorophyll (0.5 $\mu g\ l^{-1}$) with an euphotic zone total of about 20–30 mg m^{-2}. The present work and other more general studies in the same area (e. g. Tranter et al., 1979) confirm these values. Chlorophyll *a* concentrations at the water column maxima ranged from 0.27 to 0.89 $\mu g\ l^{-1}$ for all stations studied, with an euphotic zone (200 m) total of 22.7 to 54.7 mg m^{-2} Higher con-

centrations of chlorophyll *a* occurred at the subsurface maxima of the eddy centre compared to eddy edge or midway positions (Table 1). Whether these localised increases were due to nutrients made available by convective overturn inside the eddy (Tranter et al., 1980), or to some 'phytoplankton-concentrating' mechanism (due to hydrodynamic forces at the centre of the rotating eddy), is unknown.

Phytoplankton Species

The species composition of the phytoplankton populations at eddy edge and eddy centre stations showed some distinct differences. At both locations the two diatoms *Rhizosolenia alata* and *Nitzschia seriata* were co-dominant, but *Rhizosolenia* was more abundant at the eddy edge, whereas *Nitzschia* dominated the eddy centre (Fig. 2). Differences in species diversity at the two locations were revealed by the dominance diversity curve analyses (Fig. 2), which showed a greater diversity of dinoflagellates at the eddy edge. In a study of phytoplankton assemblages of cold core Gulf Stream rings (Ortner et al., 1979), the communities of the rings were quite distinct from both the slope water populations where the rings originated, and the north Sargasso Sea populations in which the ring systems were embedded. Such distinct differences as these were not found in the warm core eddies of the present study. Eddies in the East Australian Current cannot be treated as isolated 'incubators', since they may be subject to sudden influxes of new water from the north (Boland and Church, submitted). This might be one reason for the relatively small differences in the phytoplankton populations observed at the eddy centre and eddy edge locations in this study.

The nanoplankton fraction was an important part of all the phytoplankton populations examined, accounting for 45–59 % of the total phytoplankton chlorophyll at the eddy centre and 72–76 % at the eddy edge. This was due to differences in diatom abundance at eddy edge and eddy centre (Table 1). The $< 15\ \mu m$ fraction comprised small non-thecate dinoflagellates, prymnesiophytes (e. g. coccolithophorids) and green flagellates (Table 2). The significance of the nanoplankton in the world's ocean is becoming increasingly evident whenever size fractionations of phytoplankton chlorophyll, productivity and cell biomass are made (Malone, 1971; Reynolds, 1973; Beers et al., 1975; Durbin et al., 1975; Skjoldal and Lännergren, 1978; Takahashi et al., 1978; Eppley and Weiler, 1979). In addition to the species found in the East Australian Current, cryptomonads, small pennate diatoms (Moestrup, pers. comm.) and minute blue-green algae (Waterbury et al., 1979) may be common in other waters. The importance of diatom-dominated or flagellate-dominated floras in food chain dynamics has recently been recognised by Parsons et al. (1978). Factors such as light gradients, specific nutrient fluxes, inherent differences in algal growth rates and grazing pressure determine whether diatoms or flagellates dominate. These groups are said to support distinctly different food chains (Parsons, 1979). More experimental work needs to be done to substantiate these interesting suggestions.

Green Flagellates

At all stations green flagellates were particularly important, as judged by species counts, chlorophyll *a* : *b* ratios (Jeffrey and Hallegraeff, 1980) and the presence of chlorophyll *b* on the chromatograms (Figs 3, 4). The dominant green microflagellate (1–3 μm) resembled the small prasinophyte *Micromonas* under light microscopy, but electron microscopy is required for positive identification. *Micromonas* is known to have a wide distribution in the world ocean (Throndsen, 1976) and has now been identified in New Zealand waters (Moestrup, 1979). Fragile prasinophytes and chlorophytes have been recognised in many areas by the use of enrichment cultures (Throndsen, 1969, 1970, 1976), examination of living samples (present work), electron microscopy of wild collections (see review by Jeffrey and Vesk, in press), and identification of chlorophyll *b* (green algae) on pigment chromatograms of natural phytoplankton (Jeffrey, 1974, 1976).

In the present work the maximum concentration of green flagellates was found at depths of 60–75 m, where the light field would be predominantly low intensity blue-green radiation (Water type IA, B, Jerlov, 1976). This raises the question of which pigment(s) are harvesting the light for photosynthesis. If the light field was in the region of 400–500 nm or extended to 550 nm would the energy harvested by the blue absorption band of chlorophyll *b* be sufficient? The carotenoids fucoxanthin and peridinin supplement the light-harvesting capacities of chlorophylls *a* and *c* in diatoms and dinoflagellates (Haxo, 1960), but no such evidence has yet been presented for the carotenoids lutein, violaxanthin or neoxanthin supplementing the light-harvesting capacities of chlorophylls *a* and *b* in green algae. Siphonaxanthin, which absorbs at 540 nm *in vivo* and is found in some siphonous green seaweeds (Jeffrey, 1968b; Kleinig, 1969), and unicellular prasinophytes (Ricketts, 1970), does have a light-harvesting function (Kageyama et al., 1977). However, we found no siphonaxanthin on any of the chromatograms in this study. Instead, large amounts of a lutein-like

pigment (absorption maxima: ethanol, 424, 447, 175 nm; diethyl ether, 422, 445 and 457 nm) were found on the chlorophyll *b*-containing chromatograms. It is interesting that the chorophyll *a* : *b* ratio of several marine prasinophytes is lower than that of other chlorophytes (Wood, 1979), perhaps indicating an increased importance for chlorophyll *b* as a light-harvesting pigment in marine species. Experimental studies of the light-harvesting capacities of planktonic algae grown under low intensity blue-green light (Jeffrey and Vesk, 1977; Vesk and Jeffrey, 1977) have shown that the pigment content per cell of the green flagellate *Dunaliella tertiolecta* increases by about 40 % under blue-green irradiance, although no change in the relative proportions of the pigments occurs (Hallegraeff, unpublished data). Knowledge of the precise spectrum of underwater radiation at depths where the green flagellates are dominant, would help to decide whether chlorophyll *b* alone, or some other light-harvesting carotenoid, should be implicated.

Other Surveys of Eddy Systems in the East Australian Current

Routine monitoring of phytoplankton abundance in this eddy (Eddy F), and a subsequent Eddy J, by *in vivo* surface fluorescence measurements (Tranter et al., 1980; Brandt et al., in press) has confirmed our findings that only small differences in phytoplankton populations of these eddies and the surrounding waters occur. Exceptions are occasional increased phytoplankton concentrations at frontal boundaries at the southern sector of these eddies (Tranter et al., 1979; 1980), which may be enriched by subantarctic waters (Rochford, 1979). The factors controlling these concentrations are being studied.

The presence of warm-core eddies may more markedly affect the distribution of biota higher up the food chain. Brandt and Wadley (in press) observed a recognizably distinct species composition of mesopelagic fishes inside Eddy F compared to the edge, and species diversity was higher outside than inside Eddy J (Brandt et al., in press). It is not yet known whether these fish populations are responding directly to a physical gradient such as temperature, or to a correlated biological gradient, such as food abundance.

CONCLUSIONS

This single 'snapshot' of the early summer phytoplankton populations of a warm core eddy in the East Australian Current showed only small differences between stations at the eddy centre and eddy edge.

Increased phytoplankton chlorophyll due to localized diatom concentrations (up to 10^5 cells l^{-1}) occurred at the eddy centre (Table 1, Fig. 2). Small (< 15 μm) coccolithophorids, non-thecate dinoflagellates and green flagellates were relatively more important at the eddy edge (72–76 % of the total phytoplankton chlorophyll) than eddy centre stations (45–59 %; Tables, 1, 2). Differences in species diversity were revealed by dominance-diversity curves (Fig. 2). These showed a dominance change from the diatom *Rhizosolenia alata* (eddy edge) to *Nitzschia seriata* (eddy centre), and a decreased number of dinoflagellate species in the eddy centre.

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