Polar Biol (1990) 10: 571-579

Polar Biology

Seasonal and Spatial Variations in the Zooplankton Community of an Eastern Antarctic Coastal Location

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Received 21 June 1989; accepted 4 April 1990

Summary. The zooplankton community of a shallow coastal area in Eastern Antarctica was found to be one of low species diversity dominated by Copepoda. It was comprised of the more common Antarctic oceanic copepod species, medusae, molluscs, euphausiids, several copepod species associated with the ice-water interface and, in summer, benthic fauna larvae. Most species of copepods displayed a marked seasonality in abundance with peak numbers between March and May. It is proposed that several factors, including phytoplankton seasonality contribute to the zooplankton species composition, zooplankton seasonality, and to the temporal differences in the period of maximum abundance between copepod species. Annual vertical migratory behaviour in conjunction with the circulation of Prydz Bay are important determining factors for those species which can be considered as oceanic; *Calanoides acutus*, *Calanus propinquus*, *Ctenocalanus citer*, *Metridia gerlachei*, *Oithona similis* and *Oncaea curvata*. However, for copepod species which can be classified as inshore residents, such as *Stephos longipes*, *Paralabidocera antarctica* and *Drepanopus bispinosus*, it is their association with the ice water interface that determines their seasonal appearance and abundance. Some differences were established between the zooplankton community of the Vestfold Hills and that of other Antarctic coastal regions. This may be attributed, in part, to the extensive shallow areas of the Vestfold Hills coastal region. Spatial distribution of the zooplankton with depth and between sites was investigated and found to be essentially homogenous. When differences were established, in the majority of cases all species present, all age classes and both sexes contributed to the differences.

Introduction

The systematics and distribution of the Antarctic oceanic zooplankton have been well investigated (Hardy and Gunther 1935; Mackintosh 1934, 1937; Ottestad 1936; Foxton 1956; Vervoort 1965; Andrews 1966; Seno et al. 1966; Voronina 1966a, b). More recently the Australian Antarctic Division has been investigating the summer oceanic zooplankton composition in the Prydz Bay region (Ikeda et al. 1984, 1986; Williams et al. 1983, 1986). Hosie et al. (1987) and Hosie and Stolp (1988) determined the zooplankton composition during the post-winter period of maximum northern ice extension off Enderby Land. Bunt (1960), Zvereva (1972), Hicks (1974), Fukuchi and Tanimura (1981), Hopkins (1985), Fukuchi et al. (1985), Tanimura et al. (1986), and Foster (1987) have examined the zooplankton communities beneath sea ice in coastal areas.

The coastal studies have established the existence of a relatively sparse coastal zooplankton community of varying species diversity dominated by Copepoda, and have suggested, as with Antarctic oceanic zooplankton, a marked seasonal variation in abundance. However, apart from Tanimura et al. (1986), quantitative data over a complete year in a coastal Antarctic location has been lacking.

In the present study, three coastal sites adjacent to Davis Station, Eastern Antarctica were sampled over a 12 month period in 1982. The study examined zooplankton species composition, abundance, seasonality, vertical differences in abundance at each site and differences in abundance between sites.

Materials and Methods

Study Area

Three study sites (A, B and C), each with a different substrate, were examined in a shallow bay enclosed by a series of islands directly off Davis Station (68°35'S, 77°58'E) (Fig. 1). Site A had a water depth 9 m below Mean Sea Level with a flat, sandy bottom and scattered rocks to which macrophytes were attached. Site B was 20 m deep

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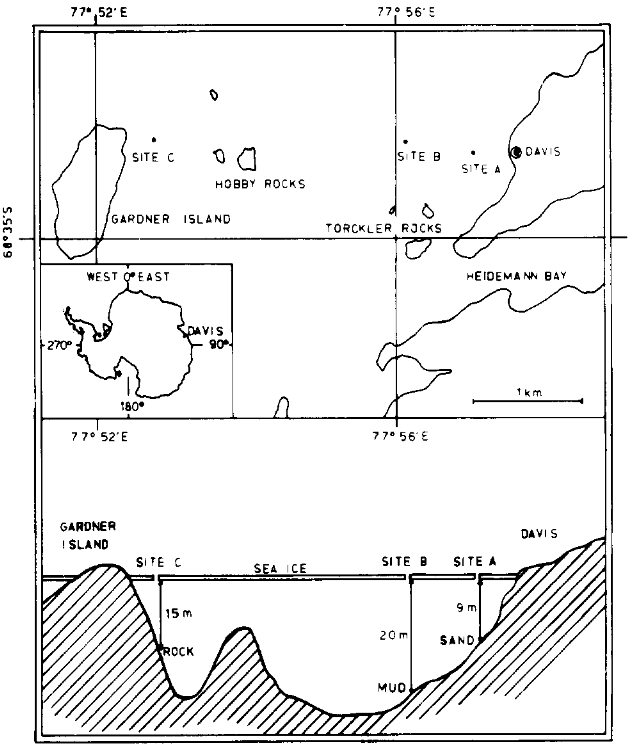

Fig. 1. Location and longitudinal section of study area showing sample sites *A*, *B* and *C*

with a flat mud bottom and no macrophyte cover. Site C was 15 m deep with a sloping, smooth rock substrate and small scattered pockets of sand and shell fragments. For most of the year, this site had approximately 20% macrophyte cover but in the summer months macrophytes covered almost the entire substrate.

Fast ice cleared from the bay in December, 1981. It reformed at the beginning of March, 1982 but was broken up by winds during that month and did not become stable until April. The ice again cleared in January, 1983.

Field and Laboratory Techniques

Zooplankton was sampled monthly for the entire year, except for April, using three methods:

a) a plankton pump with 210 μm mesh net
b) vertically hauling a 28 cm diameter, 210 μm mesh collapsible plankton net
c) vertically hauling a 34 cm diameter, 200 μm mesh fixed frame plankton net.

The plankton pump was adapted from Coughlan and Fleming (1978) and is fully described by Bayly (1986). The volume of water filtered on each sampling occasion was determined by pumping for a standard period of 10 min into a calibrated container. Average flow rate was 42 l/min. By slowly raising and lowering the intake nozzle through a selected depth interval, the water column was segregated into discrete 5 m strata viz. 0–5 m, 5–10 m etc. Prior to ice formation sampling was conducted from boats or amphibious vehicle. After ice formation, all sampling, except for the fixed frame net, was through a 10 cm diameter SIPRE core hole. Fixed frame net hauls were made through a large hole near each site used by divers for examination of the benthos.

A heated shelter was used for plankton pump sampling when ambient air temperatures were below zero. Deep snow prevented the shelter from being transported to site C. Consequently the collapsible and fixed frame nets only, were used at this site for most of the year and the water column partitioned into the same 5 m intervals as at sites A and B.

Three replicate samples were taken of all intervals at all sites when using either the pump or nets. A filtering efficiency of 90% (Tranter and Smith 1968, Tables 4 and 5) was assumed in quantifying all net catches. All counts were transformed to numbers per cubic metre. Samples were preserved in a buffered 4% formaldehyde and sea water solution.

On each sampling occasion, water samples were taken with a 2 l Kemmerer bottle directly beneath the under-ice surface and at every 2.5 m depth interval for salinity, chlorophyll-*a* and phytoplankton cell count analysis. Salinity determinations were later made in the laboratory, with an Anton Parr DMA 55 density meter. A thermometer (±0.1°C) inside the Kemmerer bottle measured water temperature. Methods and results of phytoplankton analyses can be found in Perrin et al. (1987). Ice and snow depths were measured through the SIPRE core-hole at each site on each sampling occasion.

Results

Environmental Parameters

Water temperatures at each site were below 0°C for most of the year (Fig. 2), ranging from +0.4° to −2°C. Temperature stratifications within the water column and between sites, apart from the month of January, were small (a maximum of +0.4°C) or absent.

Little variation in salinity was found between sites and between depth intervals (mean monthly salinities for all depths and sites combined are illustrated in Fig. 3). After the summer thaw, mean salinity at each site in January was 32.9/33.0 ppt. Salt exclusion from developing sea ice (Lake and Lewis 1970) increased salinity to a maximum of 34.5/34.6 ppt in September, October and November. With the summer ice melt, salinity decreased after this period. A distinct halocline was not observed throughout the study except in late December when a layer of 'fresher' water was observed directly beneath the sea ice.

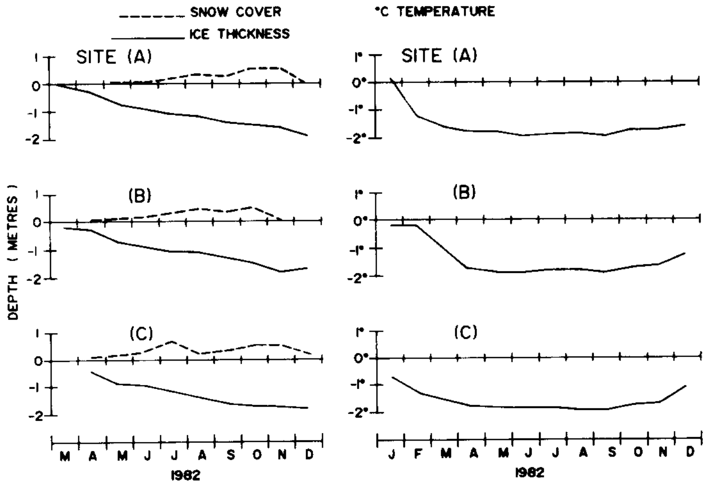

Fig. 2. Monthly measurements of ice thickness, snow cover and water temperature (averaged throughout water column) at sites *A*, *B* and *C*

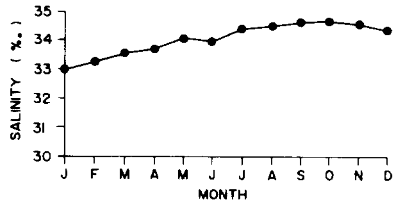

Fig. 3. Mean monthly salinities averaged over all depths and sites

Once stable sea ice had formed in the bay, ice depth at each site increased linearly throughout the year reaching a maximum thickness of 187 cm and 194 cm at sites A and C respectively in December and 194 cm at site B in November (Fig. 2).

Depth of snow covering the sea ice (Fig. 2) was dependent upon prevailing weather conditions and varied considerably between sites and sampling dates. Maximum depths of 60 cm and 53 cm were recorded at sites A and B respectively in October. A snow depth of 57 cm was recorded at site C in this month but the maximum snow cover of 75 cm had been recorded previously in July. Snow cover had virtually disappeared from sites A and B by December and was dramatically reduced at site C.

A small but observable drift of the plankton net when sampling beneath the sea ice showed that the coastal waters were rarely static. The flow was generally in a southerly direction parallel to the coastline and concurred with the general surface circulation of the Prydz Bay cyclonic gyre (Grigoryev 1968; Smith et al. 1984).

Species Composition and Seasonality

The occurrence of the relatively few taxa represented in the inshore zooplankton is summarised in Table 1. Copepoda (12 species) were numerically dominant and were the only group to yield adequate numbers for enumeration and analyses. *Stephos longipes*, *Oithona similis* and *Oncaea curvata* were found in every sampling month and were the most abundant species collected throughout the study. Only juvenile specimens of *Calanoides acutus*, *Calanus propinquus*, *Ctenocalanus citer*, *Metridia gerlachei* and *Stephos* sp. were captured, whereas both adults and copepodites of *S. longipes*, *O. similis*, *O. curvata*, *Paralabidocera antarctica* and *Drepanopus bispinosus* were collected. However, the latter two species were taken only on a few occasions and only in small numbers.

Graphical representations of the monthly counts of the planktonic copepod species, except for *P. antarctica*, *D. bispinosus*, *Stephos* sp. and *Microstella* sp. (which occurred in numbers too low for analysis) are given in Figs. 4 and 5 (results of total copepod abundance are given in Tucker and Burton 1988). The planktonic copepods of all samples from each of the discrete sampling intervals at each site were enumerated. But as differences between sites and depth intervals were minimal (see below) only data for a representative set, site A, 0–5 m, are presented in this paper.

Site and Depth Comparisons

Using the three replicate samples for each depth interval, one way analysis of variance (ANOVA) tests (Sokal and Rohlf 1969) were applied to establish if statistical differences existed for each copepod species and for total copepod abundance between depth intervals and between sites on all sampling dates. All data were transformed by $\sqrt{X+1}$.

Once significant differences were established (5% significance level), Student Newmann Keuls tests (Sokal and Rohlf 1969) were applied to determine which particular depths and sites were significantly different.

On most occasions, no significant differences between depth intervals were established. Of the 26 occasions (out of 201 tested) when abundance for a copepod species did vary significantly with depth, 16 had greater numbers in the bottom strata (ie bottom 5 m). The middle and top strata contained the greater number of individuals on 7 and 3 occasions respectively.

Once it was established that the copepoda had, on most occasions, an essentially homogenous vertical distribution in this shallow water area, mean values of the complete water column at each site were used to examine differences in abundance for each copepod species between sites. Of the 59 ANOVAs performed, 25 were significantly different at the 5% level. In summer, differences between sites A, B and C were established on 6 occasions but no clear pattern was evident. During the remainder of the year when pump samples were taken at sites A and B only, the 19 significant differences established between the two sites included 15 when site A had a significantly larger population for several copepod species and for total copepods.

Although not directly comparable with the other two sites, because of differing sampling methods, the density of copepods at site C was similar to the other sites during the year except in November when it appeared to be two orders of magnitude greater than at sites A and B in the same month.

Discussion

The monitored environmental parameters, temperature, salinity and ice and snow depth indicate that this shallow coastal region, bordering a large, relatively ice free area of Antarctica, does not differ significantly in these physical variables from other inshore Antarctic areas (Bunt 1960). Not surprisingly therefore, the coastal zooplankton species assemblage off Davis is similar to those determined in previous inshore Antarctic studies (Bunt 1960; Zvereva 1972; Hicks 1974; Fukuchi and Tanimura 1981; Hopkins 1985; Fukuchi et al. 1985; Tanimura et al. 1986; Foster 1987). It comprises the copepod species *C. acutus*, *C. propinquus*, *C. citer*, *M. gerlachei*, *O. similis* and *O. curvata* which are recognised also as typical and numerically important members of the Antarctic oceanic zooplankton (Foxton 1956; Hardy and Gunther 1935; Mackintosh 1934, 1937; Ottestad 1936; Seno et al. 1966; Vervoort 1965)

Table 1. Zooplankton species recorded from study area

Taxa	Date of collection	Method of collection
Hydromedusa		
Solmundella bitentaculata Quoy and Gaimard	Apr.	Net
Halitiara spp	Nov.	Net
siphonophore sp.	Nov.	Net
Chromatonema rubrum Fewkes	Nov.	Net
Scyphomedusa		
Desmonema gaudichaudi Lesson	Nov.	Diver
Ctenophora		
ctenophore sp.	Apr., May	Net
Polychaeta		
polychaete spp	Mar., May, July, Aug., Oct., Dec.	Pump and net
polychaete larvae	Jan., Feb., July, Sept., Dec.	Pump and net
Mollusca		
Clione limacina antarctica Smith	Nov., Dec.	Net
Spongiobranchaea australis d'Orbigny	Nov., Dec.	Net
Copepoda: Calanoida		
Calanoides acutus (Giesbrecht)	Jan., Aug.	Pump and net
Calanus propinquus Brady	Jan., Sept., Nov.	Pump and net
Ctenocalanus citer Heron and Bowman	Jan., Nov.	Pump and net
Metridia gerlachei Giesbrecht	Mar., July, Sept., Oct.	Pump and net
Stephos longipes Giesbrecht	All year	Pump and net
Stephos sp.	Jan., May., Aug.	Pump and net
Paralabidocera antarctica (J.C. Thompson)	Jan., Oct., Dec.	Pump and net
Drepanopus bispinosus Bayly	Jan., Aug., Sept.	Pump and net
Cyclopoida		
Oithona similis Claus	All year	Pump and net
Oncaea curvata Giesbrecht	All year	Pump and net
Harpacticoida		
Microstella sp.	Aug., Nov.	Pump and net
harpacticoid spp	All year	Pump and net
Euphausiacea		
Euphausia crystallorophias (juvs) Hold and Tattersal	Apr.	Net
Thysanoessa macrura (juvs) G.O. Sars	Apr.	Net
Amphipoda		
Paramoera walkeri Stebbing	Apr., Aug., Oct., Dec.	Pump and net
Orchomene of *plebs* (Hurley)	July, Oct.	Pump and net
Echinodermata		
echinoderm larvae	Jan., Nov., Dec.	Pump and net
Ascidacea		
ascidian larvae	Jan., Oct., Nov.	Pump and net
Larvacea		
Oikopleura sp.	Feb., Apr., May, Nov., Dec.	Pump and net

and as the dominant surface dwelling summer species (Bradford 1971). However, as in previous studies, the coastal zooplankton community is distinguished from that of Antarctic oceanic waters by the presence of characteristically coastal species, in this case the amphipods, *P. walkeri* and *Orchomene* cf. *plebs*; copepods, *S. longipes*, *P. antarctica* and *D. bispinosus* and larvae of benthic animals.

The zooplankton species assemblage found in the present study, although similar to that in other inshore Antarctic areas, does differ in the presence of *D. bispinosus*, dominance of the calanoid copepod fauna by *S. longipes* and the absence of other typical Antarctic oceanic copepod species, such as *Rhincalanus gigas* and *Euchaeta* spp. *D. bispinosus* was previously recorded only from the fjords and lakes of the Vestfold Hills (Bayly 1982). As many of the previous inshore studies have been conducted in areas of considerable water depth, the extensive shallow areas and adjacent fjords of the Vestfold Hills' coastal region could contribute to these differences.

Abundance estimates for zooplankton during winter off Davis Station are similar to those of Hopkins (1985) and Fukuchi et al. (1985), but considerably lower than those found by Tanimura et al. (1986). The peak concentration of total zooplankton (7,600 individuals m^{-3}) is far

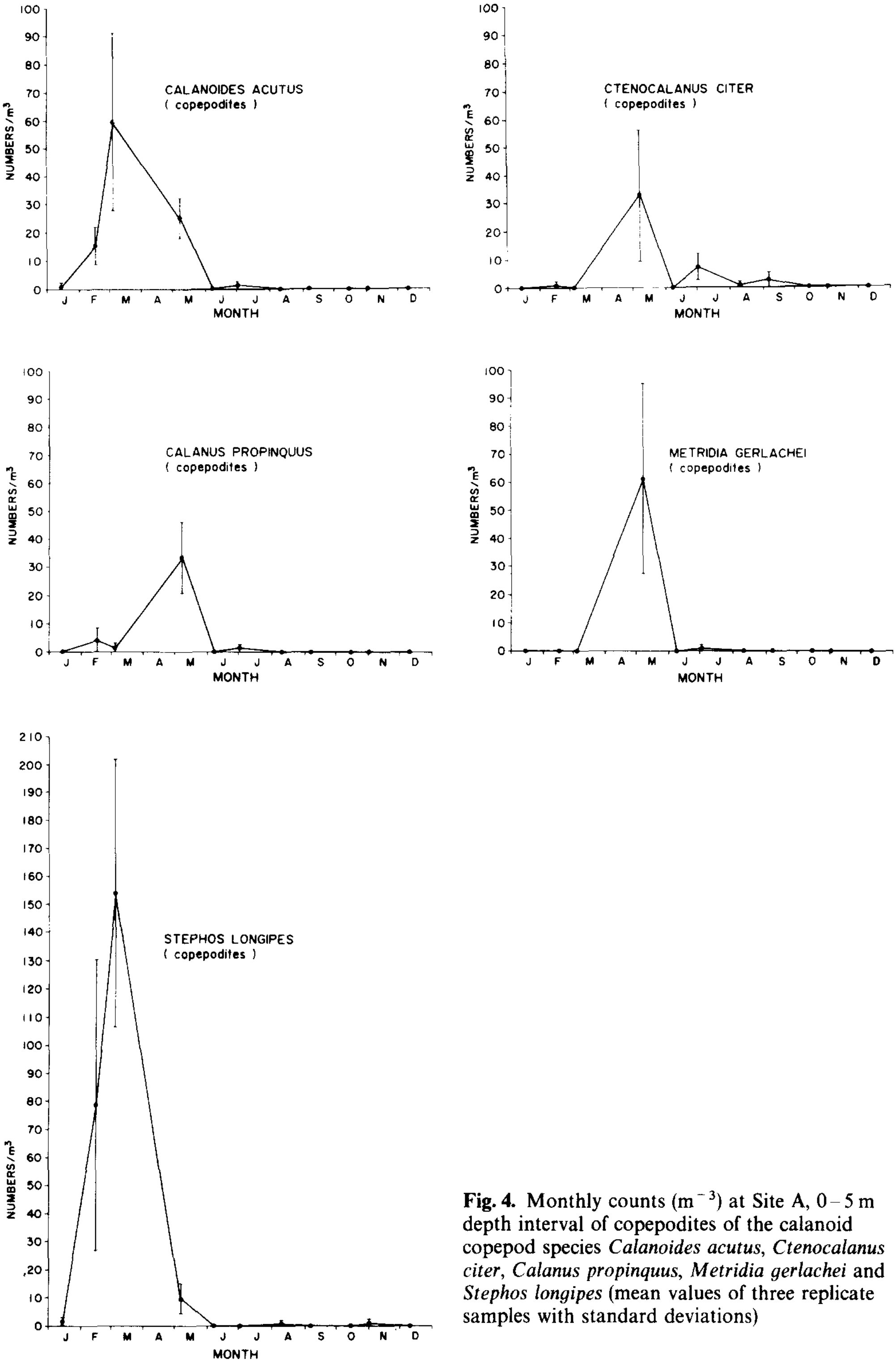

Fig. 4. Monthly counts (m^{-3}) at Site A, 0–5 m depth interval of copepodites of the calanoid copepod species *Calanoides acutus*, *Ctenocalanus citer*, *Calanus propinquus*, *Metridia gerlachei* and *Stephos longipes* (mean values of three replicate samples with standard deviations)

greater than that established by Hopkins (1985) and Fukuchi et al. (1985), but direct comparisons are not possible as these studies collected no data from the early months of the year when zooplankton concentrations off Davis Station were attaining their maximum. However, maximum numbers of copepods established in the present study are comparable to those found by Tanimura et al. (1986) at Syowa Station.

Each of the copepod species enumerated, exhibited a pronounced seasonal cycle of abundance typical of high latitude plankton populations (Mackintosh 1934, 1937; Foxton 1956; Voronina 1970; Grainger 1959, 1962). The

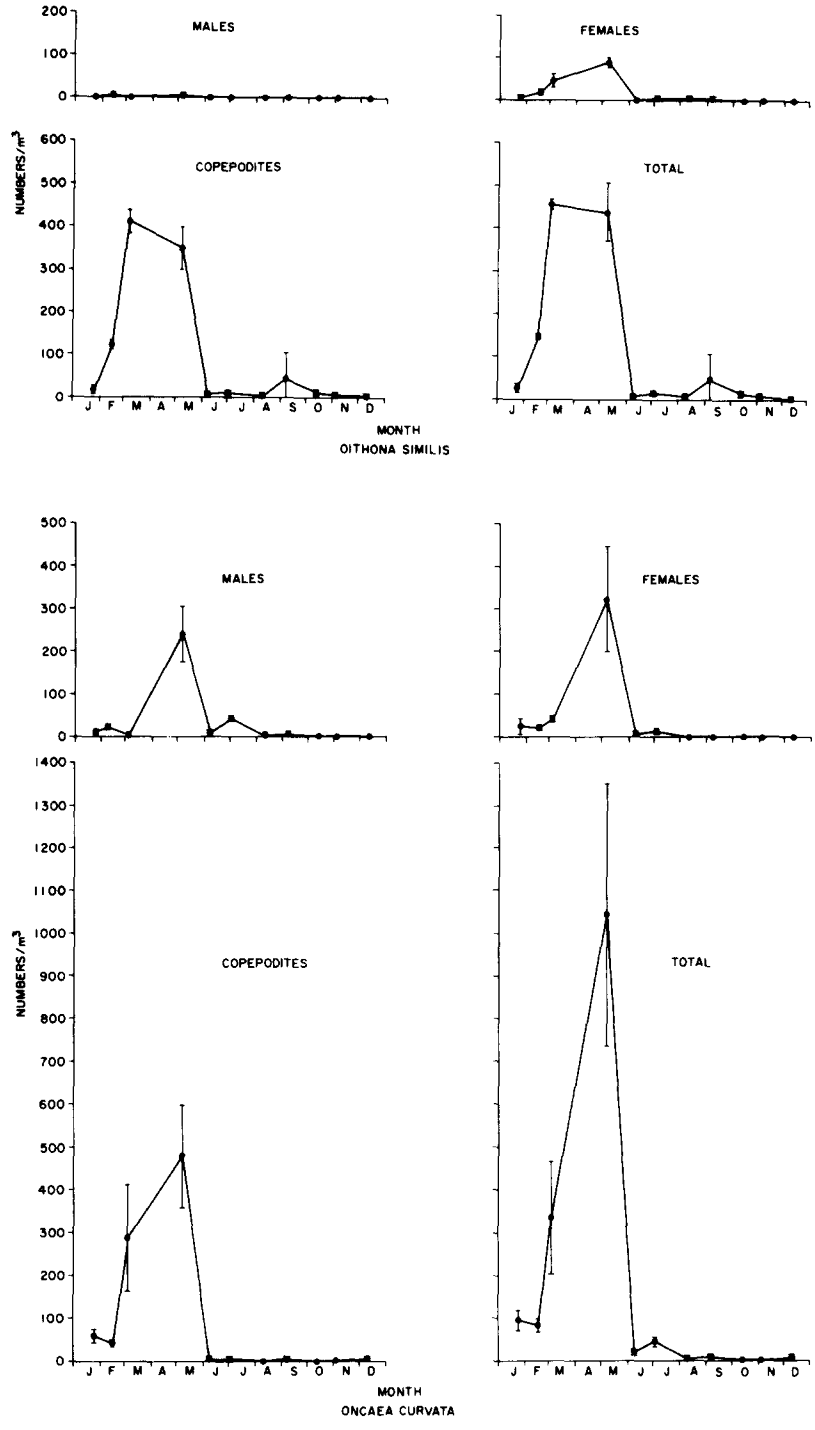

Fig. 5. Monthly counts (m^{-3}) at site A, 0–5 m depth interval of copepodites, males, females and total individuals of the cyclopoid copepod species *Oithona similis* and *Oncaea curvata* (mean values of three replicate samples with standard deviations)

general seasonal pattern was one of increasing numbers from January and February to the period of greatest abundance between March and May but decreasing to relatively low numbers for the remainder of the year. This period of greatest abundance is approximately one month earlier than that established by Fukuchi et al. (1985) and Tanimura et al. (1986) for the coastal zooplankton off Syowa Station.

In contrast to the study of Tanimura et al. (1986) where all copepod species, apart from the copepod nauplii, reached maximum abundance in the same month, the period of maximum abundance for each copepod species in the present study differed within the general seasonal pattern and to a certain extent were separated in time.

Several factors are likely to contribute to the zooplankton species composition of this coastal area, the observed marked seasonality in abundance for each species, and the difference in the period of maximum abundance between copepod species. These are:

a) phytoplankton seasonality and zooplankton diet,
b) annual vertical migration of Antarctic oceanic species,
c) Prydz Bay circulation and
d) association of the inshore species with the ice-water interface.

The annual phytoplankton growth cycle is important in determining the seasonality of this predominantly herbivorous zooplankton population (Voronina 1970) and in particular the most common copepod species which are all small-particle grazers (Hopkins 1987). A lag of several months between phytoplankton build up and that of the zooplankton in high latitudes is a generally recognised phenomenon (Cushing 1959; Heinrich 1962) and was clearly shown in the present study when compared with phytoplankton data collected during the same period (Perrin et al. 1987).

The appearance and seasonality exhibited by several of the copepod species can be associated with their annual vertical migration and life history. Annual vertical migration of the Antarctic oceanic copepods *C. acutus*, *C. propinquus*, *C. citer* and *M. gerlachei* is well documented (Ottestad 1936; Mackintosh 1937; Andrews 1966; Voronina 1966 a,b, 1970; Nakamura et al. 1982) and can be summarised as follows:

From October to December, some components of the zooplankton ascend to the surface waters to take advantage of the quickly developing phytoplankton before reproducing, and descend to deeper waters as phytoplankton production decreases. Depending on species and latitude (populations in higher latitudes have later surface aggregations), accumulation in surface waters takes place in the summer and autumn months. However, each species does not migrate simultaneously and congregation in the surface waters for some species is separated in both space and time (Voronina 1966 a,b, 1970; Nakamura et al. 1982).

It is during this period of surface aggregation that the circulation of Prydz Bay would most likely bring these primarily oceanic, summer/autumn surface dwelling species into the shallow coastal waters off Davis. Further evidence of the Prydz Bay cyclonic gyre (Grigoryev 1968; Smith et al. 1984) seeding the inshore coastal waters of the Vestfold Hills with oceanic species is suggested by the presence of oceanic diatoms in the area during winter (Everitt and Thomas 1986).

Although *O. similis* and *O. curvata* are regarded as deep water oceanic inhabitants (Hardy and Gunther 1935; Seno et al. 1966), their appearance in this coastal region and similar seasonal pattern to the other copepod species of the area, would suggest that they also undergo a similar annual vertical migration and subsequently influx into the area studied.

Whereas the oceanic component of this coastal zooplankton population is brought into the bay, those copepod species that can be regarded as inshore residents are associated primarily with the ice-water interface (Tucker and Burton 1988). *P. antarctica* is closely associated with the development of ice algae in the coastal area (Tucker and Burton 1988), fjords (J. Kirkwood, personal communication) and lakes (Bayly and Burton 1987) of the Vestfold Hills.

S. longipes was the most abundant calanoid copepod captured with peak numbers in February and March confirming the coastal, upper stratum distribution found by Boysen-Ennen and Piatkowski (1988) for this species. *S. longipes* is also an important component of the region's ice-water interface fauna (Tucker and Burton 1988).

Some indication of the seasonality of species other than the Copepoda can be seen from their months of capture listed in Table 1. Carnivorous species such as the medusae, ctenophores and some pteropods occurred during the period of peak copepod numbers i.e. April, May and in densely populated samples from site C in November and December. Larval stages of polychaetes, echinoderms and ascidians had an essentially summer distribution, although some polychaete larvae were found in spring. Polychaete adults occurred occasionally in the plankton, except for late summer; but were probably chance captures of benthic species. Harpacticoid copepods were never a dominant group numerically but were present throughout the entire year. *Oikopleura* sp. was collected mainly in the summer and autumn months. Dates of collection for the amphipods corresponded to their seasonal association with the ice-water interface (Tucker and Burton 1988).

Depth and Site Related Differences

Due to the close association of some copepod species with the ice-water interface, it was expected that at certain times of the year the top stratum of the water column (0–5 m) would contain a significantly greater number of zooplankters. Statistical comparisons showed this not to be the case and illustrates that the copepods found from samples of the interface (Tucker and Burton 1988) form an intimate, localised association with the under ice surface rather than just occupying the uppermost layer of the water column.

On most occasions, the enumerated copepod species were homogenously (both vertically and horizontally) distributed. When differences did occur, they fitted one of the following three patterns:

1. concentration in the bottom 5 m
2. concentration at site A
3. concentration at site C.

The measured parameters (salinity, temperature, ice and snow depth) did not greatly differ between sites and depths, and differences in the distribution of copepods could not be directly correlated with any of these factors. Of the 16 occasions when copepod numbers were greater in the lowest stratum, 5 occurred in January and the other

11 were generally distributed throughout the remainder of the year. In January, the significant differences were largely due to the greater concentrations of *O. curvata* adults in the bottom 5 m but no particular species, age class or sex consistently showed depth related differences.

Between sites, the significantly larger copepod populations established at site A were contributed to, at some stage, by all species but no particular species, age class or sex consistently contributed to the total. Concentration of copepods at site C occurred only on one occasion in November. The sample was dominated by *O. similis* copepodites but all copepod species found within the study area at that time of year contributed to the increase. This increased density of all zooplankters may have been produced by the strong current, from a seaward direction, observed at the time of sampling.

The planktonic fauna of this shallow coastal area of Antarctica has a general paucity of species and marked seasonal variations in abundance with low concentrations of zooplankton for much of the year. Most species were present in large numbers only during the months of and immediately following, the period of high primary productivity. The coastal zooplankton species assemblage of the Vestfold Hills is composed of Antarctic oceanic species, the larvae of benthic animals and those species that are associated with the ice-water interface, which are dependent on the formation and breakup of sea ice and seasonal development of ice algae.

Acknowledgements. We thank the members of the 1982 Australian National Antarctic Research Expedition to Davis for their essential help throughout the year and in particular our biological colleagues at Davis, Mr. R. Perrin and Mr. P. Lu. We also thank Dr. I. Bayly for his field advice and criticism of this manuscript. Mr. G. Hosie also criticised this manuscript.

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