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Continuous Plankton Recorder sampling between New Zealand and the Ross Sea, 2006–2013

New Zealand Aquatic Environment and Biodiversity Report No. 128

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This project was established in 2008 to sample plankton annually for five years as the first part of a longer term 15 year time series to monitor primary and secondary productivity along a transect in New Zealand waters and the Southern Ocean, as part of the SCAR Southern Ocean Continuous Plankton Recorder Survey. Data from three other transits to the Ross Sea by RV *Tangaroa* in 2006, 2008 and 2010 have also been incorporated into this study as they occurred within the Ross Sea region.

Through collaboration with Sanford Limited, the FV *San Aotea II* was used to deploy the Continuous Plankton Recorder (CPR) on transits between New Zealand and the Ross Sea toothfish fishing grounds. The overall objective of the project was to map quantitative changes in the distribution of epipelagic plankton, including phytoplankton, zooplankton and euphausiid (krill) life stages, in New Zealand's EEZ and transit to the Ross Sea, Antarctica.

Forty-two individual tows of the CPR from the FV *San Aotea II* were carried out on five return-transits. More than 2300 segments of silk were collected from more than 22 000 km of towed distance, between 44.5°S and 77.2°S. In the laboratory 856 000 individual zooplankton specimens were counted and identified. For analysis, data were split into five latitudinal zones; the Sub-Tropical Zone (STZ), the Sub-Antarctic Zone (SAZ), the Polar Frontal Zone (PFZ), the Permanent Open-Ocean Zone (POOZ) and the Sea Ice Zone (SIZ). The STZ had the lowest zooplankton abundance of all the zones but the second highest diversity of zooplankton (number of taxa). The SAZ had a higher diversity of zooplankton species than the STZ, while the PFZ and the POOZ had high levels of zooplankton abundance with less diversity. Copepods, and especially the small (approximately 1 mm) cyclopoid copepod *Oithona similis,* made up the majority of zooplankton individuals identified in this study.

Zooplankton abundances and communities were compared between the Ross Sea region (RS[1]) and the East Antarctic region (EA[2]), using the NZ-CPR data, and Australian and Japanese CPR data respectively. Latitudinal patterns in species composition were similar between the Ross Sea and East Antarctic regions and with those reported from previous studies. However, CPR data from the present study and three transits to the Ross Sea by RV *Tangaroa* in 2006, 2008 and 2010 showed that zooplankton abundance in the Ross Sea region was substantially higher than in the East Antarctic region, and higher than predicted from models built from previously-collected CPR data.

Chlorophyll-*a* concentrations were also higher in the Ross Sea region compared with the East Antarctic region during the study period, as shown in both CPR Phytoplankton Colour Index scores and ocean colour satellite data. There is an indication that yearly variability in zooplankton abundance in the Ross Sea region is higher than in the East Antarctic region. Particularly high zooplankton abundances in the Ross Sea region occurred in December 2009 as a result of more than a 10-fold increase of *Fritillaria* sp. (a solitary, free-swimming tunicate). This high abundance in December 2009 corresponded to unusually high chl-*a* throughout the Ross Sea region. There has been a statistically significant trend of increasing zooplankton abundance in all zones of the East Antarctic region since 1991, but no increasing trend in zooplankton abundance in the Ross Sea region was

[1] The Ross Sea (RS) region for the purposes of this report is defined as the area between New Zealand and the Ross Sea lying between 160°E and 150°W. This encompasses the FAO/CCAMLR statistical area 88.
[2] The East Antarctic (EA) region is defined as the area between 60°E and 160° E, and south of the South Antarctic Front where there has been a high level of CPR sampling since 1991. The EA incorporates the FAO/CCAMLR statistical areas 58 south of 55° S.

discernible over the sampling period 2006–2013. There was no significant trend in the average size of the copepods in the Ross Sea region during the sampling period, but the East Antarctic showed a trend towards larger copepod species from 1991.

1 INTRODUCTION

Zooplankton are a component of marine ecosystems, linking primary production with higher level consumers, including fish, seabirds and marine mammals. The sensitivity of plankton to oceanic discontinuities (e.g. fronts) and to changes in the environment makes them useful indicators of water mass types and of ecosystem health (Bathmann et al. 2000; Mackas & Beaugrand 2010). Changes in plankton abundance over time may also act as early warning indicators of critical shifts in ecosystem function (Beaugrand 2005). While satellite data provide year-round sea surface temperature, sea height and ocean colour data, satellites cannot be used to distinguish between different phytoplankton types, nor do they provide information on zooplankton, which requires in situ sampling. The cost of undertaking ship-based marine research coupled with the high spatial and temporal variability in zooplankton distributions limits the feasibility of monitoring or mapping zooplankton using research vessels. The Continuous Plankton Recorder (CPR) method of sampling provides a cost-effective, scientifically-rigorous way of measuring zooplankton community composition (biodiversity), abundance and distribution over large ocean areas (thousands of kilometres) and over extended time periods (decades). There is increasing appreciation of the need to map and monitor key components of marine ecosystems both within New Zealand (New Zealand Biodiversity Strategy 2000, Theme 9) and internationally (e.g. IndiSeas Project, www.indiseas.org).

The CPR is a high-speed plankton sampler originally designed to be towed behind merchant ships as they steam at cruising speed along regular shipping routes (Warner & Hays 1994). CPRs have been deployed from merchant ships along repeated shipping routes in the North Sea and Northeast Atlantic for over 75 years. Data from as far back as 1948 (zooplankton) and 1958 (phytoplankton) can be directly compared with present day samples, representing a multi-decadal planktonic data set (Warner & Hays 1994). Such long-term marine environmental datasets are extremely rare, and the CPR time series is globally one of the longest running monitoring programmes in the world (Hays et al. 1993). Long-term time series data are extremely valuable in the characterisation of interannual variation and long-term change in plankton populations, and for developing a predictive understanding of the response of marine ecosystems to environmental variability and human activities. Variations in plankton abundance in the Atlantic have been linked to climatic variability, including the North Atlantic Oscillation, Gulf Stream Index, and changing sea surface temperatures (Reid et al. 1998; Beare & McKenzie 1999).

With increasing pressure to determine how ocean ecosystems are responding to climate change, as well as placing global warming in the context of other climatic cycles, the use of the CPR is expanding throughout the globe. The SCAR Southern Ocean CPR survey (SO-CPR) began in 1991 to monitor variability in zooplankton abundance in Antarctic waters, with special emphasis on annual variation in krill larvae, over a number of spatial and temporal scales (Hosie et al. 2003). Through a collaboration between the Australian Antarctic Division, Tasmania, and the Japanese National Institute of Polar Research, the area south of Australia between 60°E and 160°E has been extensively sampled, supported by detailed data analysis and modelling by NIWA (Pinkerton et al. 2010b). Between 1991 and 2011, over 400 tows[3] were made, providing over 36 000 nautical miles of records. One of the most interesting findings of SO-CPR thus far is that despite the Open-Ocean Zone being considered oligotrophic (Banse 1996; Atkinson 1998) this area supports a large diversity and higher than expected abundance of zooplankton (Hosie et al. 2003). Emerging data also suggest that the CPR provides enough taxonomic resolution to distinguish zooplankton assemblages related to frontal zones

[3] A "tow" is a single deployment of the CPR. After about 450 nautical miles of towing, the CPR unit must be recovered, the cassette (which collects the zooplankton sample) replaced and the CPR can then be redeployed. CPR tows will be shorter than this if the ship stops for other operations.

in the Southern Ocean (Hunt & Hosie 2003; 2005). SO-CPR is directly involved with monitoring programmes such as those conducted by CCAMLR (the Convention on the Conservation of Antarctic Marine Living Resources), SOOS (Southern Ocean Observing System), and contributes to the Global Alliance of CPR Surveys (GACS).

In New Zealand there have been local investigations into zooplankton distribution and biomass within the EEZ (Bradford-Grieve et al. 1996, 1998; Bradford 1985) and in the Ross Sea (Pane et al. 2004 and references therein). Prior to our study, zooplankton biomass and biodiversity in the Ross Sea region had been sampled opportunistically and not as part of a regular time-series. The CPR enables plankton sampling to be carried out across broad temporal and spatial scales, and the establishment of the NZ-CPR Survey has extended the range of knowledge of plankton biodiversity in the Ross Sea Region adding data to the SO-CPR database and the Global Alliance of CPR Surveys (GACS). Plankton dynamics are central to marine ecosystem function, and as such should be measured as part of all long-term oceanic field programmes focussed on long-term change resulting from the combined effects of climate change and harvesting (Delegations of New Zealand and USA to CCAMLR 2013).

OVERALL OBJECTIVE:

To map changes in the quantitative distribution of epipelagic plankton, including phytoplankton, zooplankton and euphausiid (krill) life stages, in New Zealand's EEZ and transit to the Ross Sea, Antarctica.

SPECIFIC OBJECTIVES:

1. *To set up a time series of annual CPR data collection by deployment from a toothfish vessel on the annual summer transit between New Zealand and the Ross Sea.*

2. *To identify phytoplankton and zooplankton according to strict observation protocols determined by the SAHFOS[4] CPR Survey and SO-CPR[5]*

3. *To enter species data, frequency and location along the transect into a spreadsheet that will allow spatial mapping of the plankton density and distribution.*

4. *To analyse the full dataset after 5 years of data collection to: (a) determine trends in the dataset and (b) compare results with Australian datasets available through SO-CPR.*

5. *To evaluate the continuation of the programme.*

Summary of Objectives

In order to carry out the sampling, a collaboration was set up with a commercial fishing company, Sanford Limited, who regularly send vessels to the Ross Sea for the Antarctic toothfish harvest. The FV *San Aotea II* was used to tow the CPR to and from the Ross Sea annually in the Austral summer, leaving in November/December and returning in January/February the following year. Training was provided each year to the dedicated CPR handler in how to operate the equipment. Extensive training and support were also provided to the NZ-CPR plankton analyst by the SCAR Southern Ocean CPR Survey (SO-CPR), and the Sir Alister Hardy Foundation for Ocean Science (SAHFOS). This included training in the use of the SO-CPR sampling protocols, the identification of zooplankton, and the use

[4] Sir Alister Hardy Foundation for Ocean Science which runs a CPR Survey in the North Atlantic.
[5] Southern Ocean Continuous Plankton Recorder Survey run from Australian Antarctic Division, Tasmania, Australia.

of the Phytoplankton Colour Index. The NZ-CPR analyst attended international plankton identification workshops and took part in quality control checks as part of this training. After analysis, the CPR data collected by the NZ-CPR Survey were collated and stored in the SCAR Southern Ocean CPR database. This database is supported and managed by the Australian Antarctic Division's Data Centre. The data are freely available and can be provided to MPI electronically as required.

This report presents CPR zooplankton and phytoplankton data collected during the annual transits to the Ross Sea from 2008–2013 by FV *San Aotea II*, combined with similar data collected during RV *Tangaroa* voyages in 2006, 2008 and 2010. The Ross Sea data is then compared with the CPR dataset from the SO-CPR region of the East Antarctic.

2 METHODS

2.1 CPR Methodology

The Continuous Plankton Recorder is a robust plankton sampler that is towed approximately 100 m astern of the ship as it travels at cruising speed. During a tow, water enters a small aperture at the front of the CPR body where it passes through a 270 µm filtering collecting silk (Figure 1). As the CPR moves through the water, an external propeller advances the silk at a rate of about 1 cm per 1 nautical mile irrespective of the speed of the ship. The filtering silk then gets covered by a 'covering' silk, with the plankton sandwiched between the two layers. Both silks are then rolled into a storage tank where a supply of buffered 40% formaldehyde preserves the sample. Silks are about 6 m long, resulting in a maximum towing distance of 450 nautical miles. In practice however, the length of individual tows may vary due to operational requirements of the vessel, or to the sea state. For example; greater vertical undulation results in shorter horizontal towed distance, while a following sea can lead to longer distances.

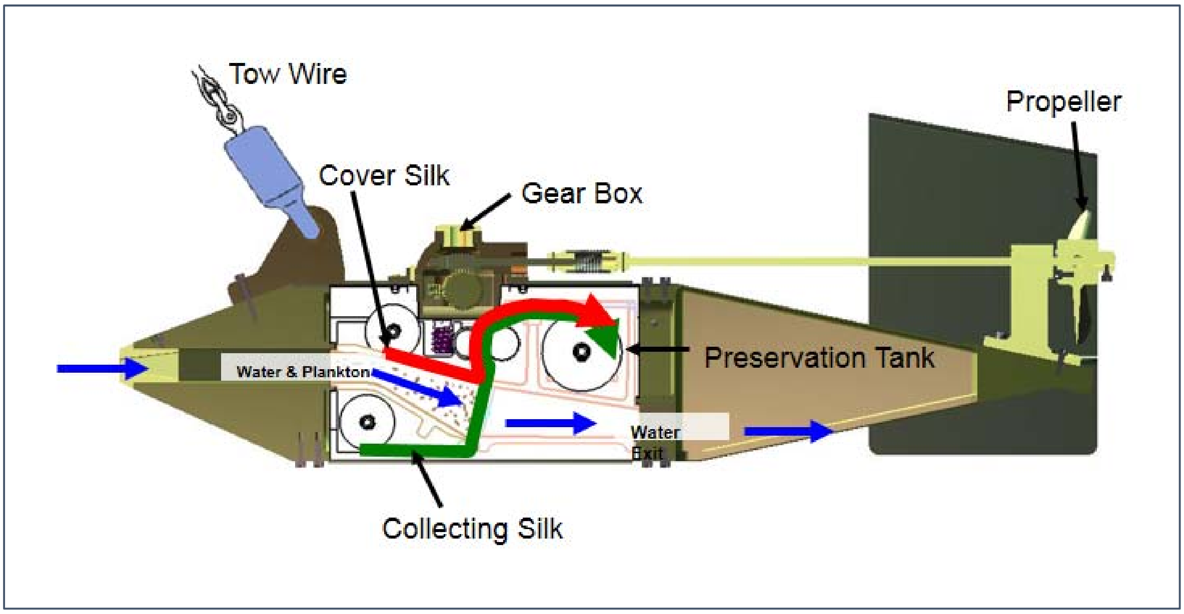


Figure 1: The internal workings of the Continuous Plankton Recorder (CPR).

The CPR is towed horizontally at a depth of approximately 10 metres. Diurnal vertical migration of plankton can have an effect on the abundances and species caught by the instrument. Typically, higher abundances of zooplankton are recorded at night when they tend to move up in the water column. These diel variations can be informative, as migrations in zooplankton can be ecologically important. For example, juvenile animals may move up into the surface waters at night to avoid predators, and to feed. The vertical transport of nutrients produced by the migrating animals could also play an important role in supporting microbial communities at lower depths. (Kerfoot 1985; Steinberg et al. 2002). Comparative studies have shown that the CPR results are comparable with plankton net systems fitted with the same mesh, and the horizontal CPR tows are indicative of plankton diversity deeper in the water column (Hunt & Hosie 2003).

The small aperture of the CPR (12.7 × 12.7 mm) is most effective for capturing mesozooplankton (0.2 – 2 mm size). Larger organisms are unlikely to be sampled well by the CPR, particularly those such as Antarctic krill that form swarms and have strong predator evasion responses. This results in under-estimates of their abundance compared with large net systems such as the Rectangular Mid-water Trawl, or when compared with biological hydro-acoustic estimates. Nonetheless, krill of all species are collected by the CPR and their smaller developmental stages (larvae) are sometimes abundant in samples.

Gelatinous zooplankton e.g., salps and jellyfish, are often poorly sampled by the CPR because of their large size, and the soft bodies of those that are caught can be damaged when trapped between the silks, making identification difficult. These species were identified to genus or species level where possible. Larvaceans are very abundant in CPR samples, and while the body of the larvacean is often damaged or missing, they can be counted relatively easily and the tails readily identified to genus level. Crustaceans and other harder-bodied zooplankton such as Foraminifera can usually be identified to a standard taxonomic level and counted, while damaged individuals can only be identified to a coarser taxonomic resolution compared to intact specimens.

2.2 CPR Deployments in Ross Sea region

As part of this project, the CPR was deployed by the fishing vessel FV *San Aotea II* on 10 transits (5 southwards and 5 northwards) between New Zealand and the Ross Sea. Each transit consisted of multiple individual CPR deployments (tows) between December and February for the five years between 2008 and 2013 (Table 1). The commercial fishing company, Sanford Limited provided the opportunity for the CPR to be towed behind the FV *San Aotea II* as it travelled to and from the Ross Sea region for the fishing season for Antarctic toothfish (*Dissostichus mawsoni*). The advantage of using this vessel was that it travelled a similar route every year, with long periods of uninterrupted steaming. The FV *San Aotea II* crew became adept at deploying and retrieving the CPR at regular intervals, with a dedicated person trained in the operation of the unit. Training included (1) loading internal cassettes with new silks (2) adding buffered formaldehyde to the cassette storage tank, (3) loading the cassettes into the main body of the CPR and making sure the gears were meshed, (4) deploying and towing the CPR, (5) retrieving the sampled silks, labelling, preserving them, and recording appropriate data. Crew were trained in the safe use of formaldehyde, made aware of contingencies, and supplied with all appropriate tools, chemicals, and safety equipment. GPS time and position data were recorded hourly (where possible) in a logbook and later matched with the plankton data. The sampling silks were preserved in individually labelled jars and returned to the laboratory when the ship returned to port.

Table 1: Summary of FV *San Aotea II* CPR data collection as part of this project between 2008–2013. Transit: S=southward (New Zealand to Ross Sea); N=northward (Ross Sea to New Zealand).

Season	Transit	Start date	End date	Start latitude (°S)	Start longitude (°E)	End latitude (°S)	End longitude (°E)	Number of tows	Distance towed (nmi)
2008–09	S	19-Dec-08	26-Dec-08	44.80	171.38	66.20	178.23	5	897
2008–09	N	23-Jan-09	2-Feb-09	71.15	-179.57	53.87	174.59	6	1 413
2009–10	S	13-Dec-09	17-Dec-09	52.73	173.48	65.06	-175.69	2	809
2009–10	N	9-Feb-10	17-Feb-10	70.70	179.36	46.29	171.13	4	1 527
2010–11	S	23-Nov-10	27-Nov-10	44.68	171.39	59.98	177.41	3	963
2010–11	N	15-Jan-11	23-Jan-11	71.72	-179.40	45.24	171.24	7	1 740
2011–12	S	28-Nov-11	4-Dec-11	44.54	171.35	62.64	172.00	4	1 133
2011–12	N	22-Feb-12	26-Feb-12	75.68	169.11	61.55	176.31	2	884
2012–13	S	3-Dec-12	27-Jan-13	46.29	170.81	77.17	166.47	4	899
2012–13	N	14-Feb-13	24-Feb-13	75.87	-178.74	46.35	171.69	5	1 614
Total								42	11 879

The CPR was also deployed during three RV *Tangaroa* voyages in 2006, 2008 and 2010 under separate funding (Appendix 2). These data add to and extend the data series for the Ross Sea region as a whole and were used in conjunction with the FV *San Aotea II* data. The locations of CPR sampling from the RV *Tangaroa* varied significantly among the voyages and were often distant from the transit routes of the FV *San Aotea II*, but still within the Ross Sea region as defined in Section 2.3. Consequently the CPR data from the RV *Tangaroa* voyages are not as useful for assessing variability in zooplankton over time as those from the FV *San Aotea II* voyages, and were not used as part of the analyses outlined in Section 2.5.4.

2.3 Description of the Sampling Area

The Ross Sea region is defined in this report as the area between New Zealand and the Ross Sea, lying between 160°E and 150°W and south of 40°S. The Ross Sea region is wholly contained within FAO/CCAMLR statistical area 88. This region was visited annually during the austral summer by the FV *San Aotea II* from 2008–2013 and by RV *Tangaroa* in 2006, 2008 and 2010. The sampling area of the FV *San Aotea II* extended from just south of the port of Timaru in the South Island of New Zealand, to the Ross Sea, Antarctica. The exact route, especially in the south of the region, varied among years as this depended on the fishing locations chosen by the master of the fishing vessel. The route in higher latitudes was also affected by the distribution and concentration of sea-ice. The RV *Tangaroa* voyages departed and returned from Wellington in the North Island and provided samples from more northerly latitudes down to the Ross Sea.

CPR data from the Ross Sea region in this study were compared to the East Antarctic region. The East Antarctic region is defined between 60°E and 160°E, and south of the Sub-Tropical Front. The East Antarctic region is the area of the Southern Ocean where there has been the highest level of CPR sampling since 1991 and is used as a reference area for comparison with the Ross Sea region CPR data. The East Antarctic region as defined here is largely contained within FAO/CCAMLR statistical areas 58 (between longitudes 80° and 150°E) as shown in Figure 2.

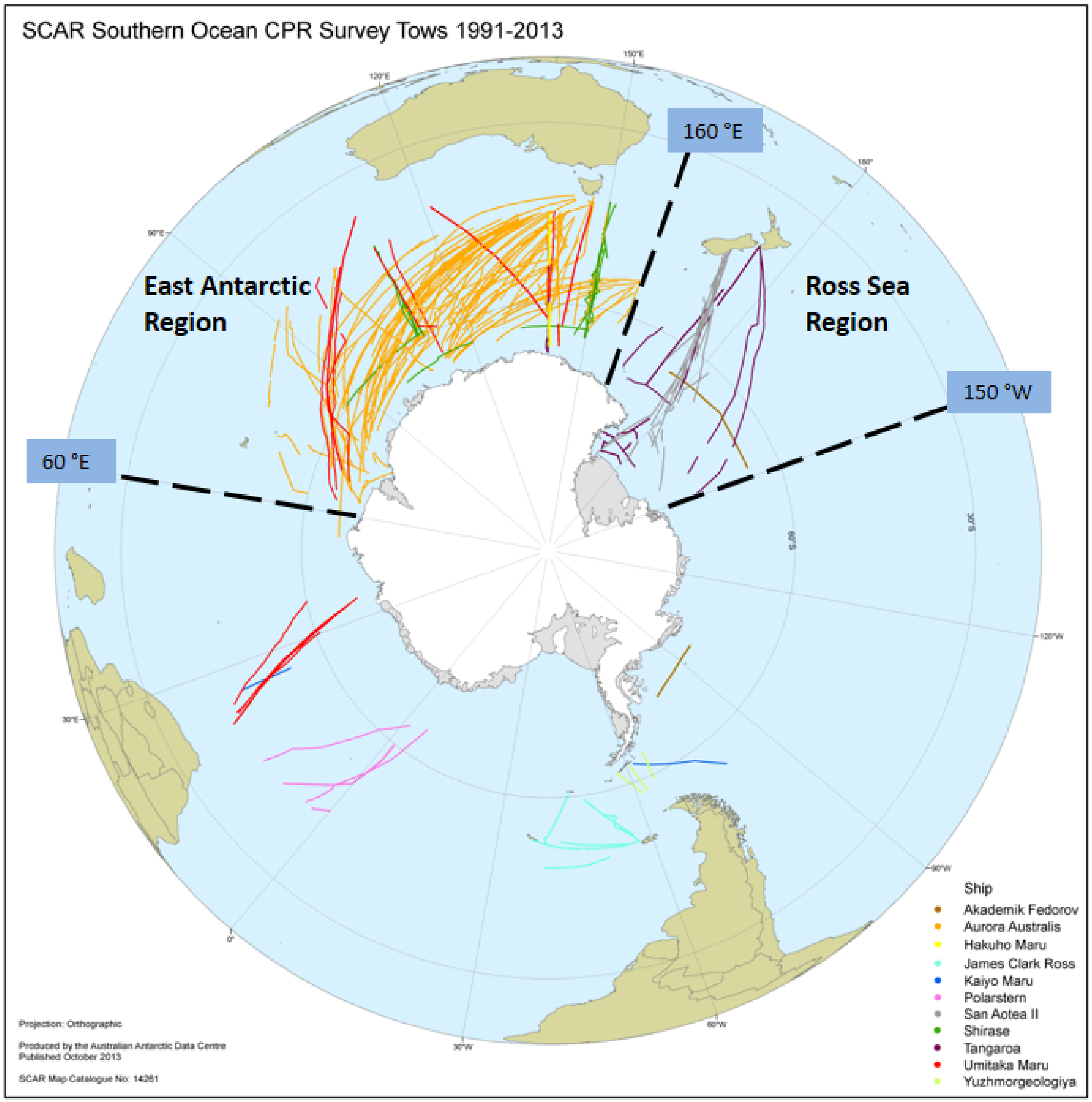


Figure 2: The geographic regions of the SCAR Southern Ocean CPR Surveys. Within the Ross Sea region the FV *San Aotea II* tows are shown in light grey and the RV *Tangaroa* tows are in purple. The orange, red, and green tows in the East Antarctic region are those of the Australian Antarctic Division and NIPR from Japan. Voyages from other ships from various countries are also shown as in the legend. Map courtesy of the Australian Antarctic Data Centre © Commonwealth of Australia 2013.

2.4 Post-voyage sample processing

In the laboratory, each pair of silks from the Ross Sea CPR tows was unrolled and cut into segments representing approximately 5 nautical miles of towed distance. The last segment at the end of a tow was sometimes shorter than 5 nautical miles and was either included with the penultimate segment if less than 2.5 nautical miles or retained as a short segment if more than 2.5 nautical miles. A Phytoplankton Colour Index (PCI) score was assigned to each 5 nautical mile segment based on Pantone colour charts (www.pantone.com) with scores of 0 = no colour, 1 = very pale green, 2 = pale green and 3 = green. Pantone colour codes corresponding to these indices depend on the dominant phytoplankton group and other coloured material in the water. The PCI is indicative of the chlorophyll-*a* concentration based on the Sir Alister Hardy Foundation for Ocean Science (SAHFOS) method (Reid et al. 1998). Training in the use of the PCI was provided by staff at the Australian Antarctic Division (AAD), Tasmania as well as senior analysts at the SAHFOS laboratory in the UK.

All zooplankton were rinsed off each 5 nautical mile silk segment and counted and identified under a dissecting microscope using the SO-CPR Survey method (Hosie et al. 2003). This method was developed from the SAHFOS method to be a more conservative and thorough approach, and to eliminate the need for highly specialised equipment. When zooplankton abundances were very high, subsampling using a Motoda plankton splitter was carried out (Motoda 1959). The efficiency of the plankton splitter was tested to ensure that each subsample was an accurate representative of the whole sample. Zooplankton were identified to the lowest taxonomic level possible, ideally to species. As mentioned above, some zooplankton are easily damaged, notably gelatinous and soft bodied species, and were identified to a coarser taxonomic resolution only. Antarctic krill (*Euphausia superba*) and other euphausiids were identified to developmental stage where possible, as were copepods (adults and copepodite stages) (McLeod et al. 2010).

2.5 Data analysis

2.5.1 Oceanographic Zones

CPR data from the Ross Sea and East Antarctic regions were split into five latitudinal zones based on the mean latitudinal positions of the oceanographic fronts within the Antarctic Circumpolar Current. These are associated with particular water mass features, which determine the location of the fronts. The frontal positions used in this report are taken from Orsi et al. (1995) and Sokolov & Rintoul, (2009), and are generally recognised as the international standards.

- The Sub-Tropical Zone (STZ) lies north of the Sub-Tropical Front (STF) as defined by Orsi et al. (1995). For the New Zealand CPR transects this coincides approximately with the continental shelf waters of New Zealand.
- The Sub-Antarctic Zone (SAZ) between the STF and the Sub-Antarctic Front (SAF) to the south, lies between approximately 53° and 58°S (Sokolov & Rintoul, 2009).
- The Polar Frontal Zone (PFZ) is between the SAF and the Polar Front (PF), and lies between about 58° and 62°S.
- The Permanent Open-Ocean Zone (POOZ) for this report is defined as south of the Polar Front and north of the Sea Ice Zone (SIZ). It is a very narrow band at the point where the CPR transects cross.
- The northern limit of the SIZ is defined as the maximum winter sea ice extent (mean position for 1979 to 2008) based on the 15% ice cover threshold and was approximately 61.5° to 63.5°S.

These zones are illustrated in Figures 3 and 4.

2.5.2 CPR zooplankton data grouping

Prior to higher statistical analysis, all zooplankton taxa identified from the CPR samples were aggregated into thirteen groups across a range of taxonomic levels. Groups were determined based on relative abundance, role in the food web, potential as indicators of acidification, and the statistical robustness of measures derived from them (Table 2). (See Appendix 3 for the complete species list). In addition to the thirteen taxonomic groupings, total abundance across all taxa was used as a response variable in analyses.

Table 2: Thirteen groupings of zooplankton taxa from the CPR used in this study.

Group No.	Group name	Description
1	*Oithona similis*	Small (1 mm) cyclopoid copepod which is generally the most numerically abundant copepod in SO-CPR samples.
2	Calanoid copepods	Diverse and abundant order of copepods in higher latitudes and important food source for predators.
3	Copepod (other and unidentified)	Cyclopoida, Harpacticoida and unidentified copepods (due to damage). (Note that counts of unidentified copepods were much less than those of calanoid copepods.)
4	Amphipoda	Order of crustaceans with no carapace and generally with laterally compressed bodies - mostly detritivores or scavengers.
5	Chaetognatha	Commonly known as arrow worms, a phylum of predatory marine worms that are a major component of plankton worldwide.
6	Euphausiidae	All adult and developmental stages of krill (generally unidentified to species or genus).
7	Foraminifera	Very abundant calcareous (calcite) zooplankton that could be affected by ocean acidification.
8 9	*Fritillaria* sp. *Oikopleura* sp.	Two abundant larvacean genera. These are both solitary, free-swimming filter feeding tunicates (sea-squirts).
10	Ostracoda	Class of crustacea also known as “seed shrimp” - typically around 1 mm in size, with flattened bodies and bivalve-like, chitinous or calcareous “shell”.
11	Pteropoda	Calcareous (aragonite) pelagic gastropod predicted to be affected by ocean acidification.
12	Salpa	Filtering soft-bodied zooplankton.
13	Other	Includes remaining organisms which are rarely identified including cephalopods, fish, fish eggs, isopods, “jellies” (ctenophores, siphonophores), mysids, polychaetes, protozoa and shrimps.

2.5.3 Average Copepod Community Size (ACCS)

The Average Copepod Community Size (ACCS) metric was used to compare numerical dominance in copepod species between zones (Beaugrand et al. 2003). The ACCS metric did not use the groupings in Table 2. Instead, the ACCS metric is the mean adult length of all copepods in the sample, based on representative individual adult lengths (see Appendix 4). Copepods which could not be taxonomically identified to at least order level were excluded from the ACCS analysis (9% of total zooplankton abundance).

2.5.4 Multivariate PRIMER analysis of zooplankton communities

Patterns in zooplankton abundance and community composition measured by the CPR on the FV *San Aotea II* deployments were investigated using the PRIMER v 6.1.13 statistical package (PRIMER-E, Plymouth: Clarke & Warwick 2001; Clarke & Gorley 2006). Multivariate comparisons were made among years, locations, oceanographic zones and regions based on numbers of zooplankton in 12 of the 13 groups given in Table 2 namely: *Oithona similis*, Calanoid copepods, Copepod (other and unidentified), Amphipoda, Chaetognatha, Euphausiidae, Foraminifera, *Fritillaria* sp., *Oikopleura* sp., Ostracoda, Pteropoda and Salpa. The "Other" category (0.4% of total abundance on average) was not used in the PRIMER analysis because it was made up of different organisms in different areas. Counts per segment of silk were divided by segment length (normally five nautical mile equivalent) to give counts per nautical mile, and then averaged into 1° latitudinal bins for each of the 10 transits (on the basis of year and transit direction). This provided 203 RS region "samples"; each sample representing the mean abundance across 1° of latitude during one transit of the vessel between New Zealand and the Ross Sea or vice versa.

Abundances in the East Antarctic region were again scaled to counts per nautical mile and grouped simply by oceanographic zone: Sub-Tropical Zone (STZ), Sub-Antarctic Zone (SAZ), Polar Frontal Zone (PFZ), Permanent Open-Ocean Zone (POOZ), and the Sea Ice Zone (SIZ), with all years combined, yielding five East Antarctic region samples. The focus of the analysis was on variability in the Ross Sea region, with the East Antarctic data added for comparison only. Multivariate analysis in time, space and oceanographic zone of the East Antarctic CPR data was outside the scope of this report.

Matrices of Bray-Curtis similarities (or "resemblances") between samples were developed. Values closer to 1 indicate greater similarity between samples, and a value of 0 indicates complete dissimilarity. Bray-Curtis similarities are appropriate for species-abundance data such as CPR measurements because the metric is not affected by the scale of measurement and is insensitive to joint absences in the dataset (Clarke & Warwick 2001).

Two Bray-Curtis resemblance matrices were analysed: (1) based on untransformed (raw) zooplankton abundances and (2) based on abundances transformed using a log(1+x) transform. The former emphasises contributions of different taxa to overall zooplankton abundance so that abundant groups have substantially more influence on the ordination than less abundant groups. In contrast, analysis based on log transformed data increases the relative importance of less abundant groups and places more emphasis on zooplankton community structure than on the relative abundances of groups. Non-metric multidimensional scaling (MDS) was used to produce a two-dimensional ordination of relationships between samples (Shephard 1962; Kruskal 1964; Clarke & Warwick 2001). In MDS, "stress" gives an indication of goodness of fit.

The relative influence of each of the measured faunal variables in the final ordination was visualised by superimposing vectors proportional to their Pearson correlations with the 2-dimensional ordination. The same procedure was used to illustrate correlations with covariate ("environmental") factors: (1) latitude, (2) total zooplankton abundance, (3) within-year date (days since 1 January in that year), and (4, 5) satellite-derived measures of chlorophyll-*a* concentration and sea surface temperature (see Section 2.6).

Hierarchical clustering was used to provide indications of natural groupings in the data. Group-means were used to calculate clusters based on the untransformed and log(1+x) scaled Bray-Curtis resemblance matrices. These clusters were then superimposed on the MDS plots.

2.5.5 Regional comparison of zooplankton abundance using Boosted Regression Trees

In addition to comparing zooplankton abundance between the Ross Sea and East Antarctic regions in broad oceanographic zones, spatial models were used to test whether differences in abundances between the regions could be due to variations in environmental conditions between the regions. To do this, models of the relationship between environmental variables and zooplankton abundances were built based on CPR data from the East Antarctic region and used to predict abundances of key zooplankton groups in the Ross Sea region. Comparing these predictions of zooplankton abundance data measured using the CPR in the Ross Sea region gave an indication of the similarity in the species-environment relationships in the two areas. Modelling of species-environment relationships for zooplankton have hypothesized that variations in zooplankton abundances between regions can be related to different environmental characteristics in different areas (e.g. Pinkerton et al. 2010b). Such analyses assume (and can test this assumption to some degree) geographic stationarity in the species-environment relationship (i.e. the relationship does not vary with location), and the CPR Ross Sea dataset gives us an opportunity to test this further.

We used the multivariate statistical technique of Boosted Regression Trees (BRT: Elith et al. 2008) to extrapolate in situ measurements of the abundance of key zooplankton groups from East Antarctica to the Ross Sea. BRT is one of the modelling approaches developed recently to use multivariate statistical methods to relate sparse measurements of species abundance to environmental characteristics in order to investigate patterns of occurrence over large spatial scales (hundreds of km) and over extended periods (months–decades) (Guisan & Zimmermann 2000; Leathwick et al. 2006; Elith et al. 2007, 2008; Pinkerton et al. 2010b). The technique for prediction followed the methodology given in Pinkerton et al. (2010b) for *Oithona similis*. BRT models were developed for the East Antarctic region using long-term average environmental data, and the models were then used to predict zooplankton abundances in the Ross Sea region. Following many recent studies, we linked in situ measurements of relative abundance to long-term averages of physico-chemical environmental conditions, rather than to the environmental conditions at the moment of sampling (e.g. Leathwick et al. 2006; Pinkerton et al. 2010b). These predicted abundances were then compared to actual observations of abundance in the Ross Sea region made in this study.

The zooplankton groups chosen for analysis were: Amphipoda, Chaetognatha, Copepoda, euphausiids, Foraminifera, *Fritillaria* sp., *Oithona similis*, Ostracoda and Pteropoda. These groups were selected because they were well-sampled by the CPR; data validity was not compromised by variable levels of identification uncertainty; and BRT fitting was effective. Total zooplankton abundance was also compared.

2.6 Satellite data

Measurements of surface chlorophyll-*a* concentration (chl-*a*) and sea surface temperature (SST) from satellite ocean colour sensors were used to provide environmental oceanographic context for the zooplankton measurements. Chl-*a* is a proxy for primary production in the water column and is likely to limit the carrying capacity of the marine system, and hence affect zooplankton biomass. Ocean colour satellite measurements are not available under cloudy conditions, during the winter when light levels are too low, or where sea ice is present. Chl-*a* and SST data were taken from the NASA MODIS-Aqua sensor which commenced operation in May 2002 and continues to the present (NASA, 2013).

2.7 Data management and integration

The data generated in this study have been forwarded to the marine section of the SCAR Antarctic Biodiversity Information Facility (ANTABIF) where they can be used for the new SCAR Life Sciences programmes State of the Antarctic Environment (AntEco) and the Antarctic Thresholds -

Ecosystem Resilience and Adaptations (AnT-ERA). The SO-CPR data were also transmitted to the global CPR database managed by the Global Alliance of CPR Surveys (GACS), which produces an annual state of the environment report on ocean plankton. Data are available for use in the Southern Ocean Observing System (SOOS), Global Ocean Observing System (GOOS) and are available for use by the Commission for the Conservation of Antarctic Marine Living Resources (CCAMLR).

3 RESULTS

3.1 Ross Sea Sampling

The CPR tows carried out by the FV *San Aotea II* during transits from New Zealand's EEZ to the Ross Sea region and return from 2008–09 to 2012–13 are shown in Figure 3. This figure also shows the positions of the Sub-Tropical Front, (from Orsi et al. 1995); the Sub-Antarctic Front, Polar Front and the maximum extent of the Sea Ice Zone (SIZ) (Sokolov & Rintoul 2009), which were used to define the oceanographic zones for the analysis reported here. A summary of data collected as part of this survey is given in Table 3. Appendix 1 lists the individual tows that were completed as part of this project and their corresponding time, date, and position data.

Forty two individual tows of the CPR from the FV *San Aotea II* were carried out as part of this survey, comprising more than 2300 segments of silk and 11 900 nautical miles (more than 22 000 km) of towed distance. Zooplankton samples were collected between 44.5°S and 77.2°S.

In the laboratory, 856 700 individual zooplankton specimens were counted and identified as part of this project. The time of sampling was very consistent, with all south-bound tows taking place in November-December and all north-bound tows in January-February. In terms of towed distance, the proportion sampled in each year was 19% (2008–09); 20% (2009–10); 23% (2010–11); 17% (2011–12); and 21% (2012–13), providing an even temporal coverage important for detecting change in zooplankton composition over time.

For completeness, tows carried out by the RV *Tangaroa* in 2006, 2008, and 2010 are shown in Figure 4. A summary of data collected as part of these surveys is given in Table 4. Appendix 2 lists the tows that were completed by RV *Tangaroa* and their corresponding time, date, and position data.

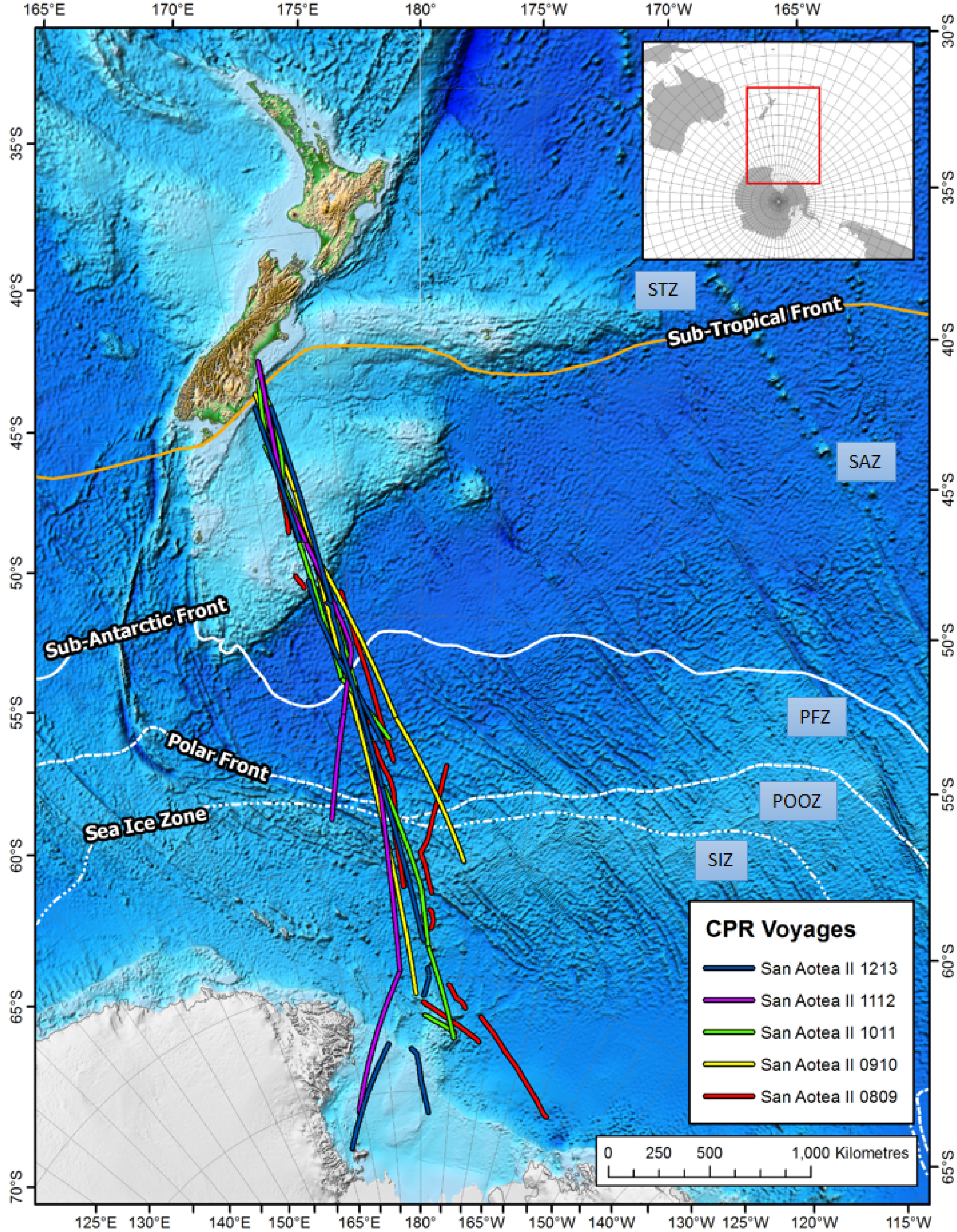


Figure 3: Ross Sea Continuous Plankton Recorder Tows. FV *San Aotea II* 2008–2013. The five latitudinal zones are shown: the Sub-Tropical Zone (STZ), the Sub-Antarctic Zone (SAZ), the Polar Frontal Zone (PFZ), the Permanent Open-Ocean Zone (POOZ) and the Sea Ice Zone (SIZ).

Table 3: Summary of FV *San Aotea II* CPR data collected as part of this project. Transit: S=southward (New Zealand to Ross Sea); N=northward (Ross Sea to New Zealand). A 'tow' is a single deployment and retrieval of the CPR. A 'segment' is a 5 nautical mile analysed section of the tow.

Season	Transit	Start date	End date	Number of tows	Number of segments	Distance towed (nmi)	Number zooplankton counts
2008–09	S	19-Dec-08	26-Dec-08	5	179	897	123 523
2008–09	N	23-Jan-09	2-Feb-09	6	282	1 413	56 242
2009–10	S	13-Dec-09	17-Dec-09	2	162	809	194 386
2009–10	N	9-Feb-10	17-Feb-10	4	306	1 527	84 154
2010–11	S	23-Nov-10	27-Nov-10	3	192	963	101 795
2010–11	N	15-Jan-11	23-Jan-11	7	349	1 740	104 557
2011–12	S	28-Nov-11	4-Dec-11	4	227	1 133	66 739
2011–12	N	22-Feb-12	26-Feb-12	2	177	884	32 329
2012–13	S	3-Dec-12	27-Jan-13	4	180	899	49 950
2012–13	N	14-Feb-13	24-Feb-13	5	324	1 614	42 980
Total				42	2 378	11 879	856 655

Table 4: Summary of the RV *Tangaroa* CPR data obtained from the SCAR SO-CPR Survey database which contributes to the Ross Sea Region data. A 'tow' is a single deployment and retrieval of the CPR. A 'segment' is a 5 nautical mile analysed section of the tow.

Season	Start date	End date	Number of tows	Number of segments	Distance towed (nmi)	Number zooplankton counts
2005–06	30-Jan-06	13-Mar-06	9	586	2 919	44 120
2007–08	31-Jan-08	18-Mar-08	8	488	2 434	49 080
2009–10	13-Dec-09	9-Feb-10	5	399	1 994	65 144
Total			22	1 473	7 347	158 344

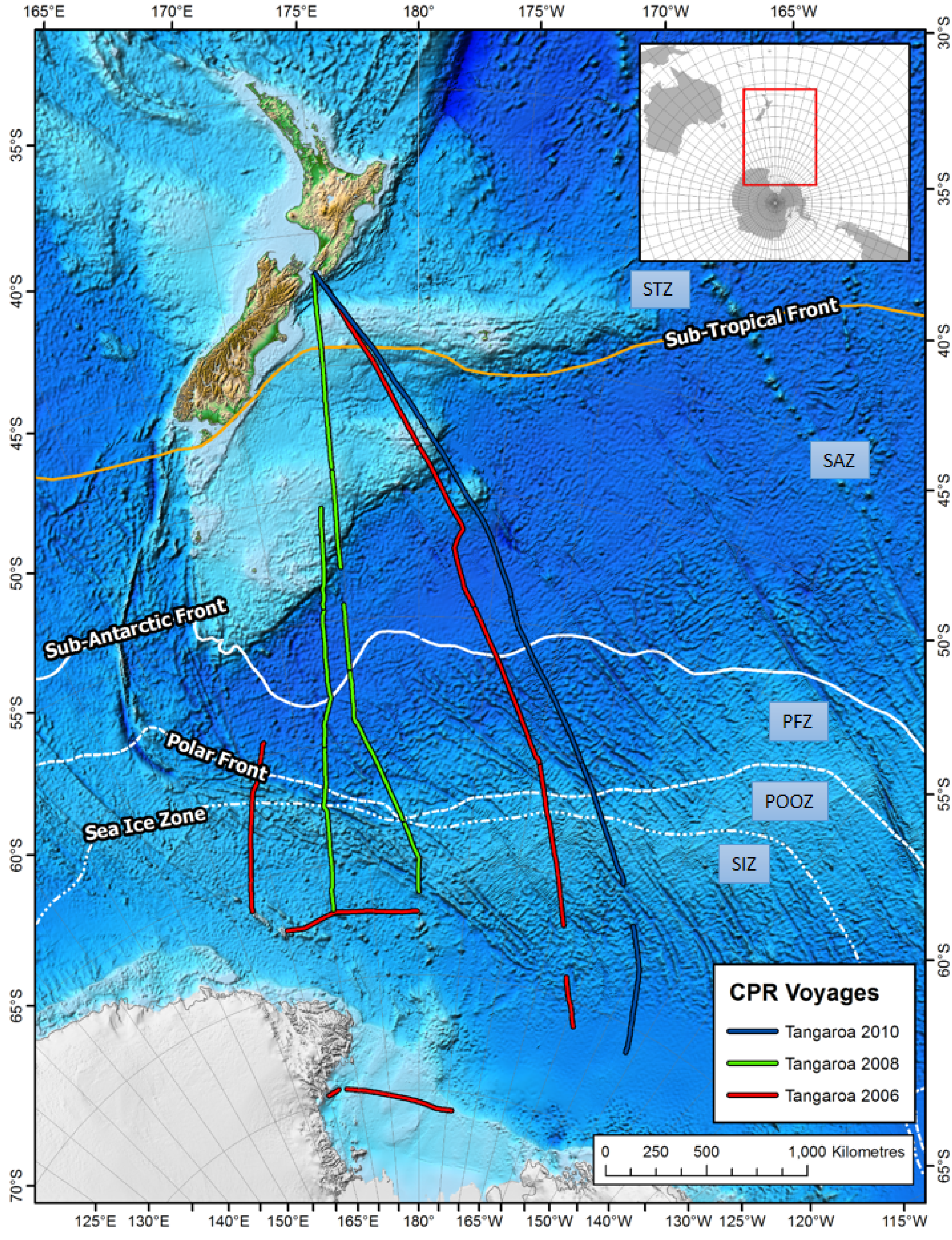


Figure 4: Ross Sea Continuous Plankton Recorder Tows. RV *Tangaroa* 2006–2010. The five latitudinal zones are shown: the Sub-Tropical Zone (STZ), the Sub-Antarctic Zone (SAZ), the Polar Frontal Zone (PFZ), the Permanent Open-Ocean Zone (POOZ) and the Sea Ice Zone (SIZ).

3.2 Sea surface temperature (satellite data)

Mean sea surface temperature (SST) data measured by the MODIS-Aqua sensor from 2002–2013 show latitudinal bands of water that correspond to the mean positions of oceanographic frontal zones (Orsi et al. 1995; Sokolov & Rintoul 2009) – Figure 5. Satellite data were extracted to summarise variations in SST in the region sampled by the Ross Sea CPR survey between 2008–09 and 2012–13 (Figure 6). SST measurements give a context within which to interpret changes in zooplankton abundances and communities between regions and years. For example, is the abundance of a given zooplankton group markedly different when SST is different from normal?

In general, variations in median SST in 1° latitude bins varied by a small amount (-0.68°C to +0.76°C) from the mean temperature during the sampling period. The overall median difference in SST from the mean of satellite-observed SST between 2002–2013 during the CPR sampling undertaken in this project was -0.03°C, suggesting that the period of sampling was broadly representative of oceanographic conditions in this region over this time period.

Variations in SST from the 2002–2013 mean values may indicate latitudinal excursions of the fronts, but will also be affected by changes in the timing of the annual warm-cool (summer-winter) cycle from year to year. The 2009–10 and 2012–13 years varied most from the 2002–2013 mean in terms of SST. Waters in the Sub-Antarctic Zone started the season much colder than normal (by up to 0.7°C) in November/December 2009. Later in this season, the waters seemed to warm more rapidly than normal, leading to higher than average SST in February 2010 (by about 0.4°C in the Sub-Antarctic Zone and Permanent Open-Ocean Zone). Waters north of the Sea Ice Zone were also warmer than normal in the 2012–13 sampling year. This period was also unusual compared to the 2002–2013 average in that southern waters in the Sea Ice Zone were especially cold at the end of the season (SST was 0.4°C colder than normal in February 2013).

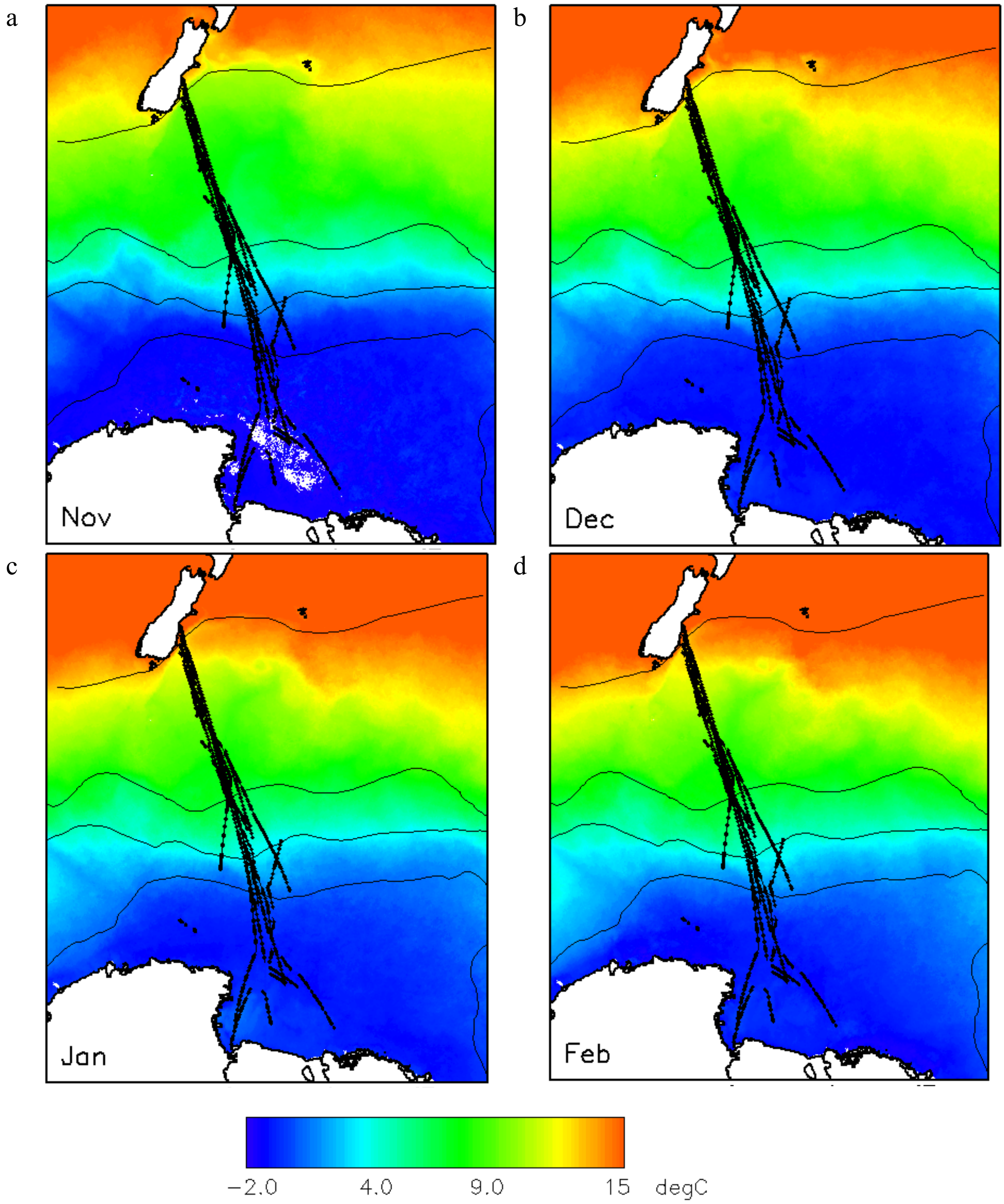


Figure 5: Climatological sea surface temperature (SST). Long-term (2002–2013) mean (climatological) monthly temperatures from the NASA MODIS-Aqua satellite sensor for the Ross Sea region. a: November; b: December; c: January; d: February. Fronts shown are (from top): Sub-Tropical Front, Sub-Antarctic Front, Polar Front, mean limit of sea-ice (Orsi et al. 1995; Sokolov & Rintoul 2009). CPR tracks from FV *San Aotea II* deployments are shown as black dots. White indicates land, ice-tongues or no data because of persistent cloud.

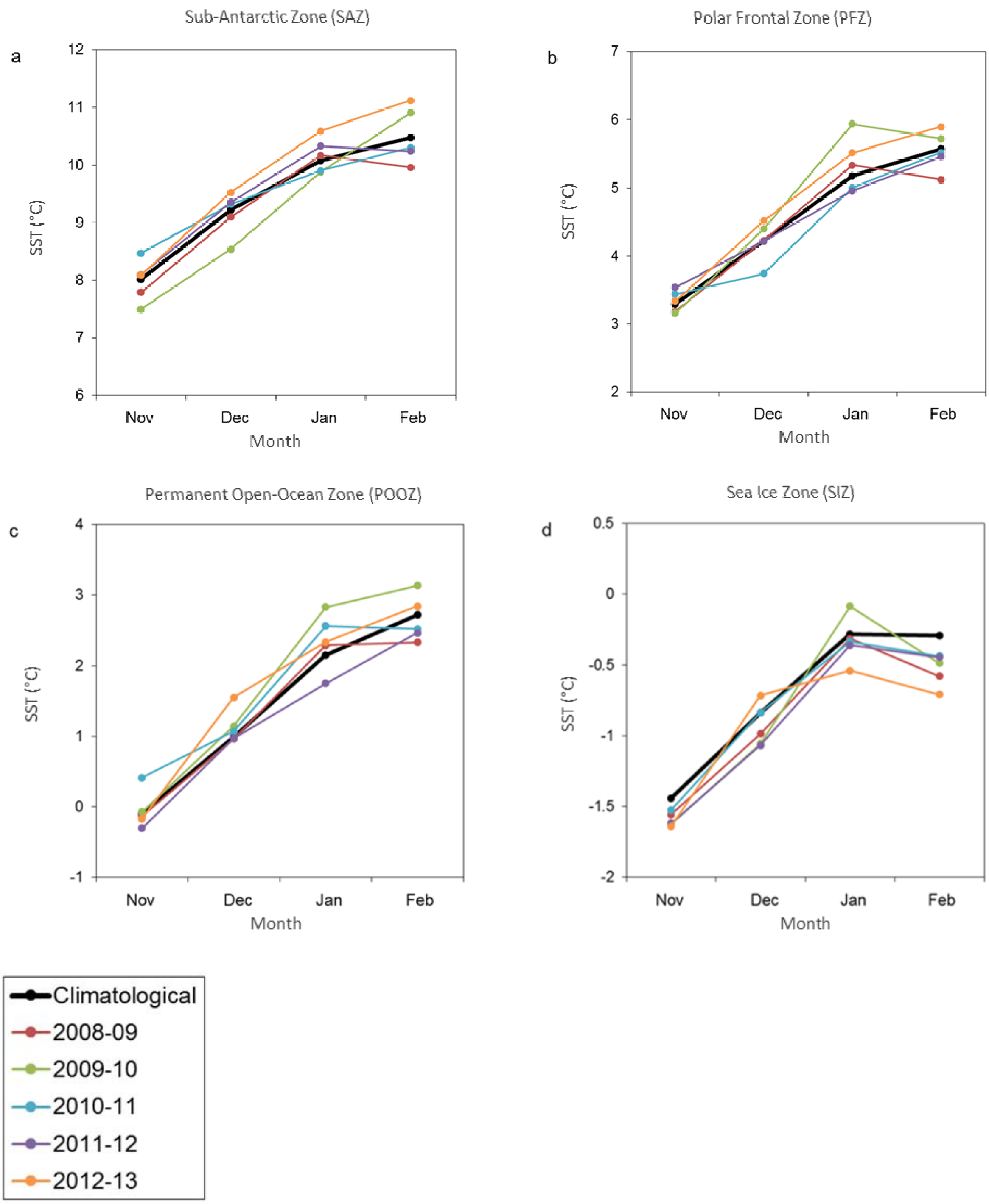


Figure 6: Sea surface temperature (SST). Climatological and seasonal mean monthly SST as measured by the NASA MODIS-Aqua satellite sensor for the Ross Sea region in four oceanographic zones. a: Sub-Antarctic Zone (SAZ); b: Polar Frontal Zone (PFZ); c: Permanent Open-Ocean Zone (POOZ); d: Sea Ice Zone (SIZ).

3.3 Chlorophyll-*a* concentration (satellite data)

As for sea surface temperatures, satellite measurements of chl-*a* concentration give a context to CPR measurements of zooplankton abundances and communities between regions and years. For example, how variable are chl-*a* distributions from year to year, and are there any clear relationships with zooplankton abundances or community composition? Long-term mean (i.e. "climatological") chl-*a* concentrations from the MODIS-Aqua sensor are shown in Figure 7, and monthly means for the five sampling years in which the CPR was deployed from the FV *San Aotea II* are shown below: 2008–09 (Figure 8), 2009–10 (Figure 9), 2010–11 (Figure 10), 2011–12 (Figure 11) and 2012–13 (Figure 12).

Differences between chl-*a* at the time of sampling and the climatological mean within the zones used here were between 0.34 and +0.46 mg m^{-3}. The overall median difference in chl-*a* from the climatological mean during the CPR sampling undertaken in this project was small (-0.03 mg m^{-3}), suggesting that the period of sampling was broadly representative of chl-a conditions in this region in general.

There were variations of chl-*a* in the Sub-Antarctic Zone from the climatological mean of between 0.13 and +0.10 mg m^{-3}, with the 2011–12 year having particularly low production compared to the others measured in this study (Figure 13). In the Polar Frontal Zone, most years measured in this study had lower than climatological chl-*a* concentrations, the exception being December 2009 where chl-*a* was 0.05 mg m^{-3} higher than normal. In the Permanent Open-Ocean Zone (POOZ), the first two years sampled (2008–09 and 2009–10) generally had higher than average chl-*a* concentrations. Chl-*a* concentration in the POOZ in December 2008 was a substantial 0.32 mg m^{-3} higher than average. In February 2010, chl-*a* was 0.32 mg m^{-3} higher than normal and the summer/autumn period of high production was longer than usual. In other years sampled in this study, chl-*a* in the Permanent Open-Ocean Zone was lower than normal. Higher values of chl-*a* between November 2009 and February 2010 also occurred in the Sea Ice Zone, with chl-*a* in December 2009 0.46 mg m^{-3} higher than normal. The December 2011 to February 2012 period was one of lower than average chl-*a* (by about 0.3 mg m^{-3}).

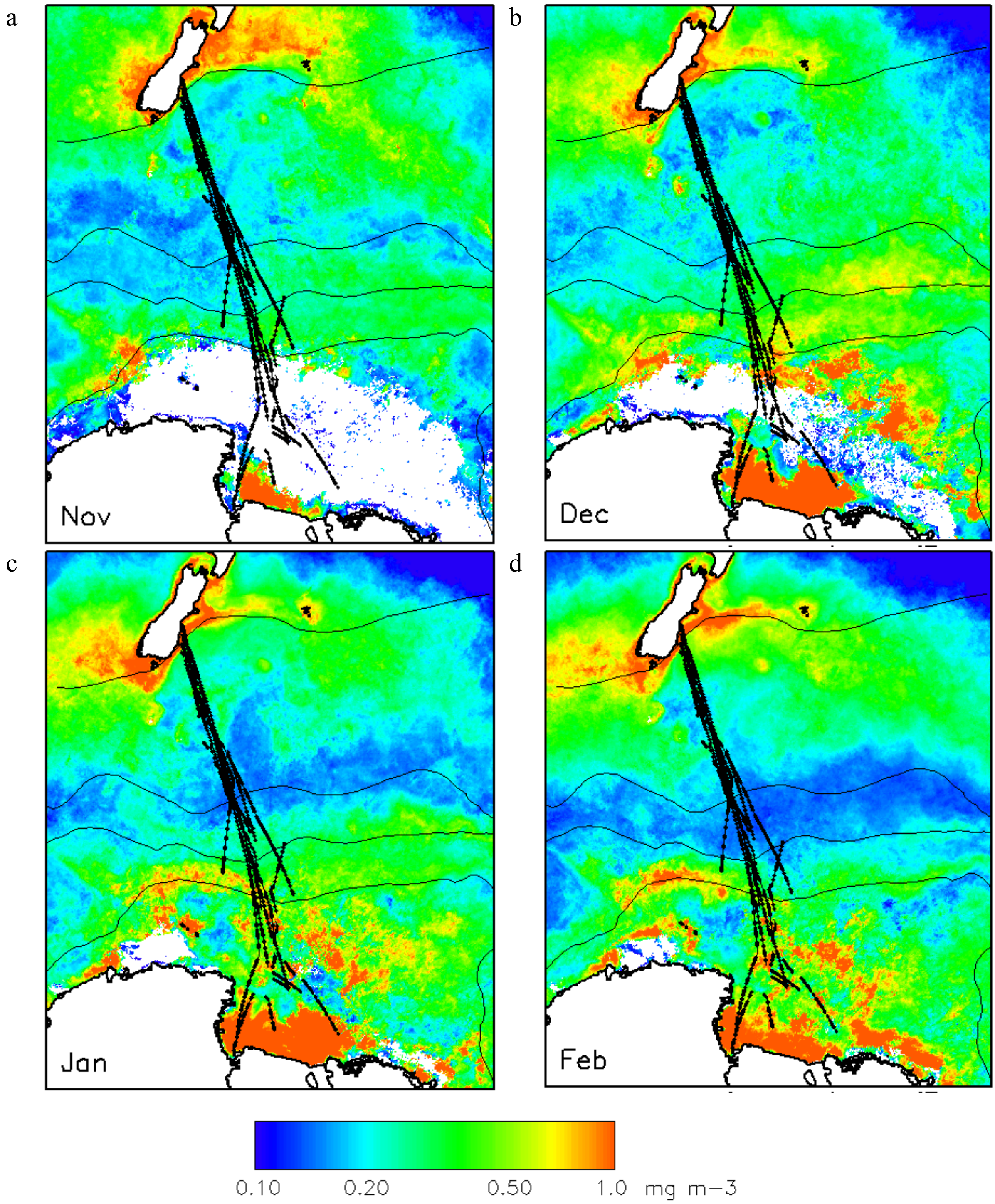


Figure 7: Climatological chlorophyll-*a* concentration (chl-a) – a proxy for primary productivity. Long-term (2002–2013) mean monthly (climatological) chl-a concentration as measured by the NASA MODIS-Aqua satellite sensor for the Ross Sea region. a: November; b: December; c: January; d: February. Fronts shown are (from top): Sub-Tropical Front, Sub-Antarctic Front, Polar Front, mean limit of sea-ice. CPR tracks from FV *San Aotea II* deployments are shown as black dots. White indicates land, ice-tongues or no data because of persistent cloud or sea-ice. Note the logarithmic scale.

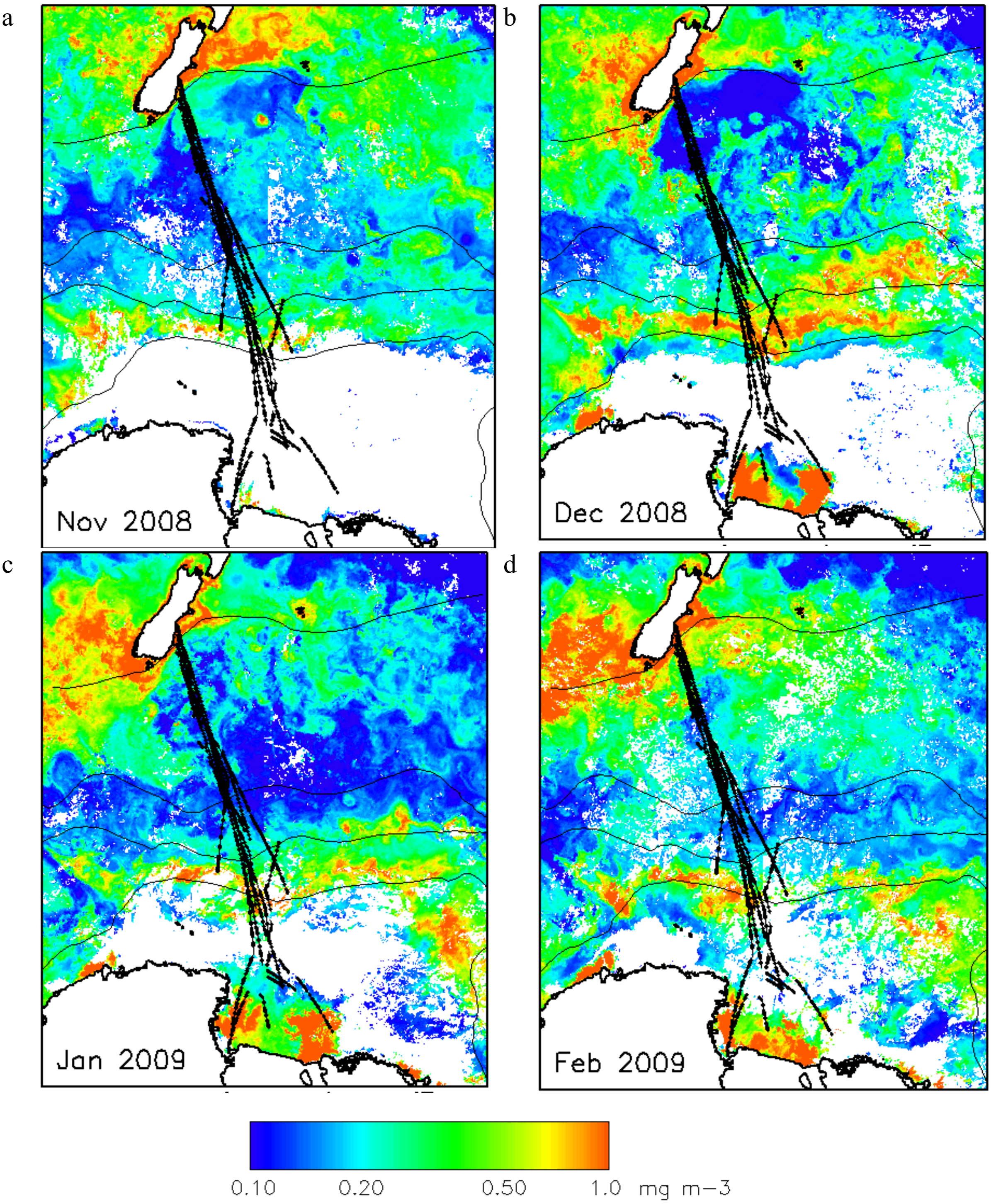


Figure 8: 2008–09 chlorophyll-*a* concentration (chl-*a*) – a proxy for primary productivity. Mean monthly chl-*a* as measured by the NASA MODIS-Aqua satellite sensor for the Ross Sea region. a: November; b: December; c: January; d: February. Fronts shown are (from top): Sub-Tropical Front, Sub-Antarctic Front, Polar Front, mean limit of sea-ice. CPR tracks from FV *San Aotea II* deployments are shown as black dots. White indicates land, ice-tongues or no data because of persistent cloud or sea-ice. Note the logarithmic scale.

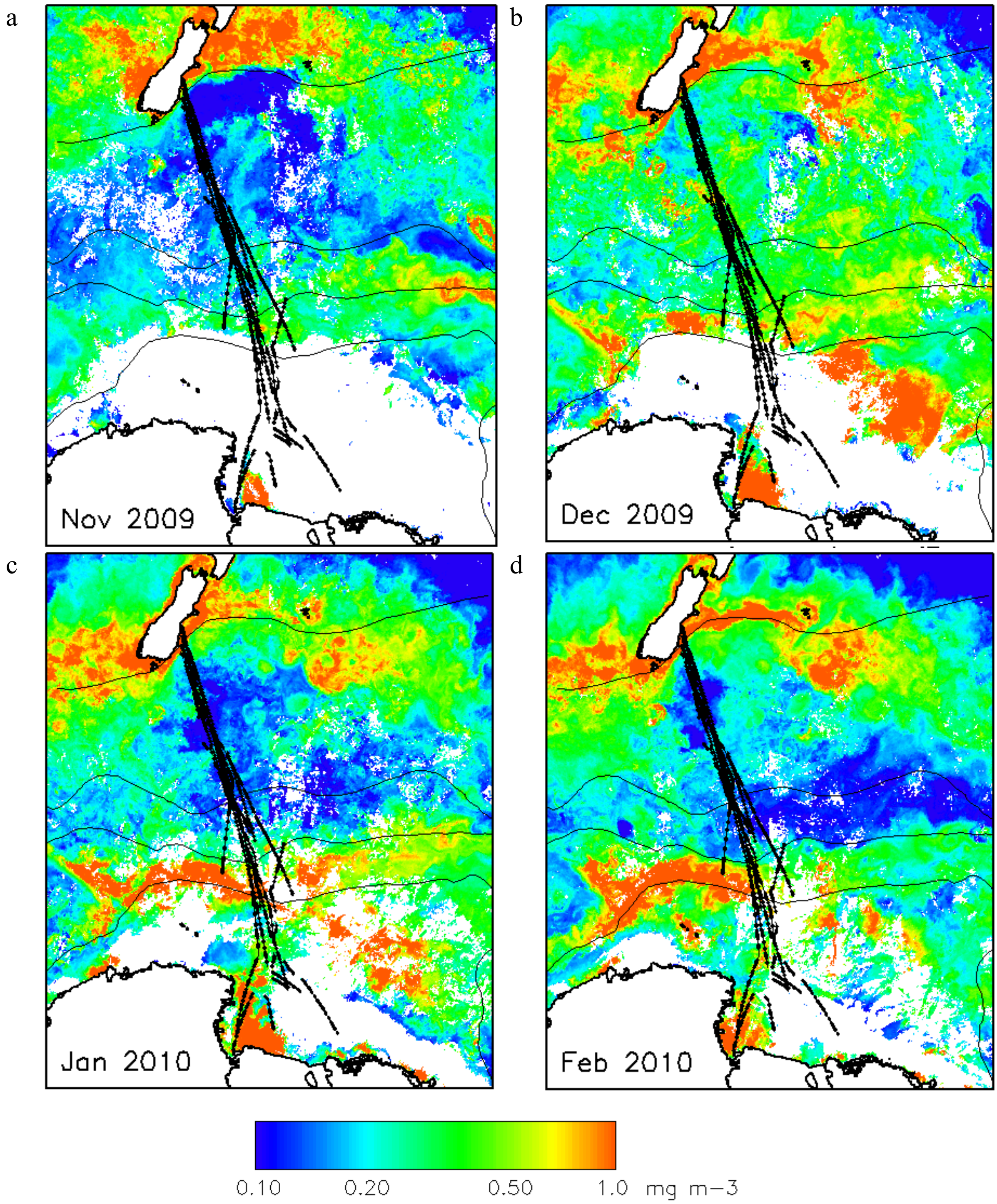


Figure 9: 2009–10 chlorophyll-*a* concentration (chl-*a*) – a proxy for primary productivity. Mean monthly chl-*a* as measured by the NASA MODIS-Aqua satellite sensor for the Ross Sea region. a: November; b: December; c: January; d: February. Fronts shown are (from top): Sub-Tropical Front, Sub-Antarctic Front, Polar Front, mean limit of sea-ice. CPR tracks from FV *San Aotea II* deployments are shown as black dots. White indicates land, ice-tongues or no data because of persistent cloud or sea-ice. Note the logarithmic scale.

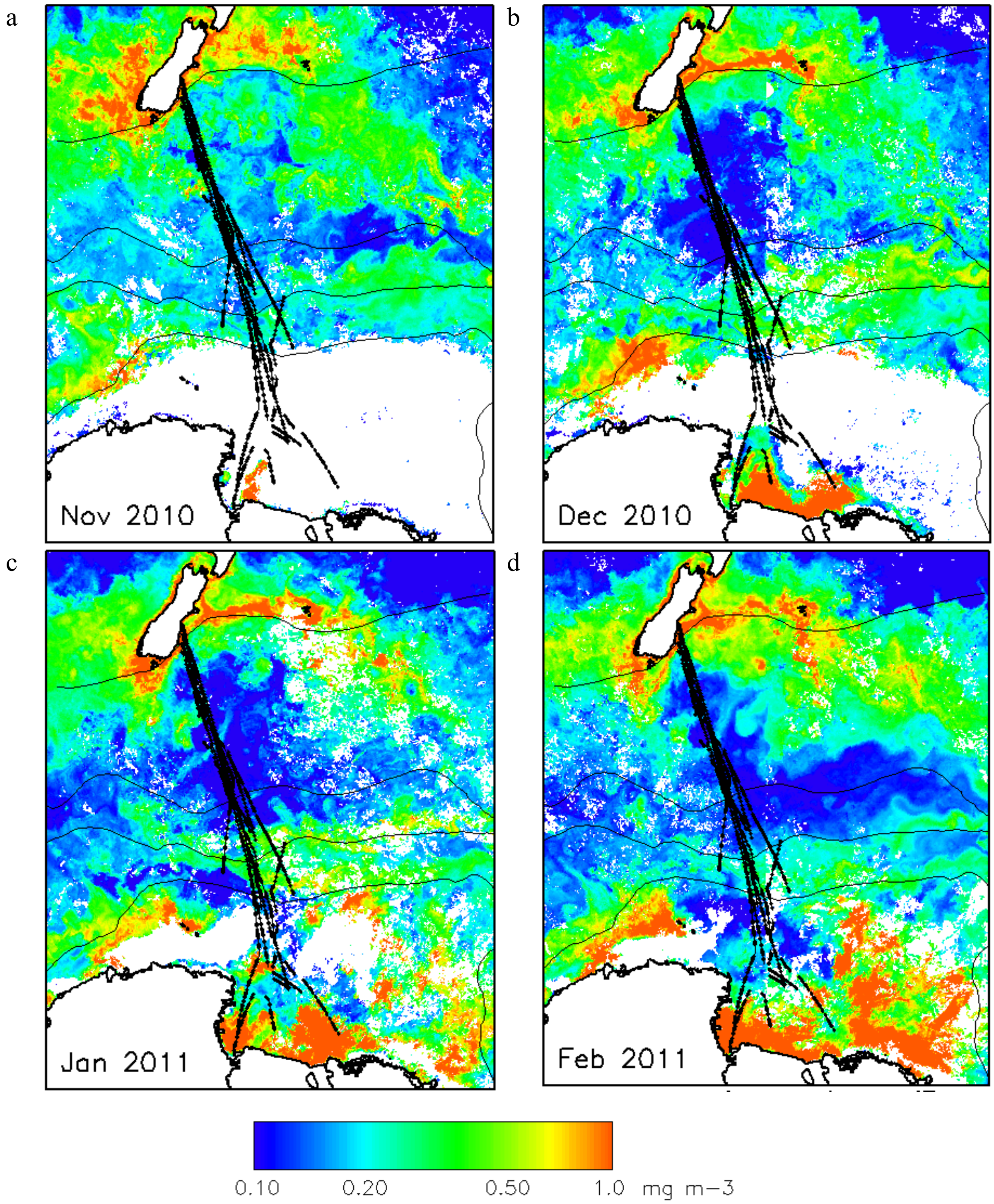


Figure 10: 2010–11 chlorophyll-*a* concentration (chl-*a*) – a proxy for primary productivity. Mean monthly chl-*a* as measured by the NASA MODIS-Aqua satellite sensor for the Ross Sea region. a: November; b: December; c: January; d: February. Fronts shown are (from top): Sub-Tropical Front, Sub-Antarctic Front, Polar Front, mean limit of sea-ice. CPR tracks from FV *San Aotea II* deployments are shown as black dots. White indicates land, ice-tongues or no data because of persistent cloud or sea-ice. Note the logarithmic scale.

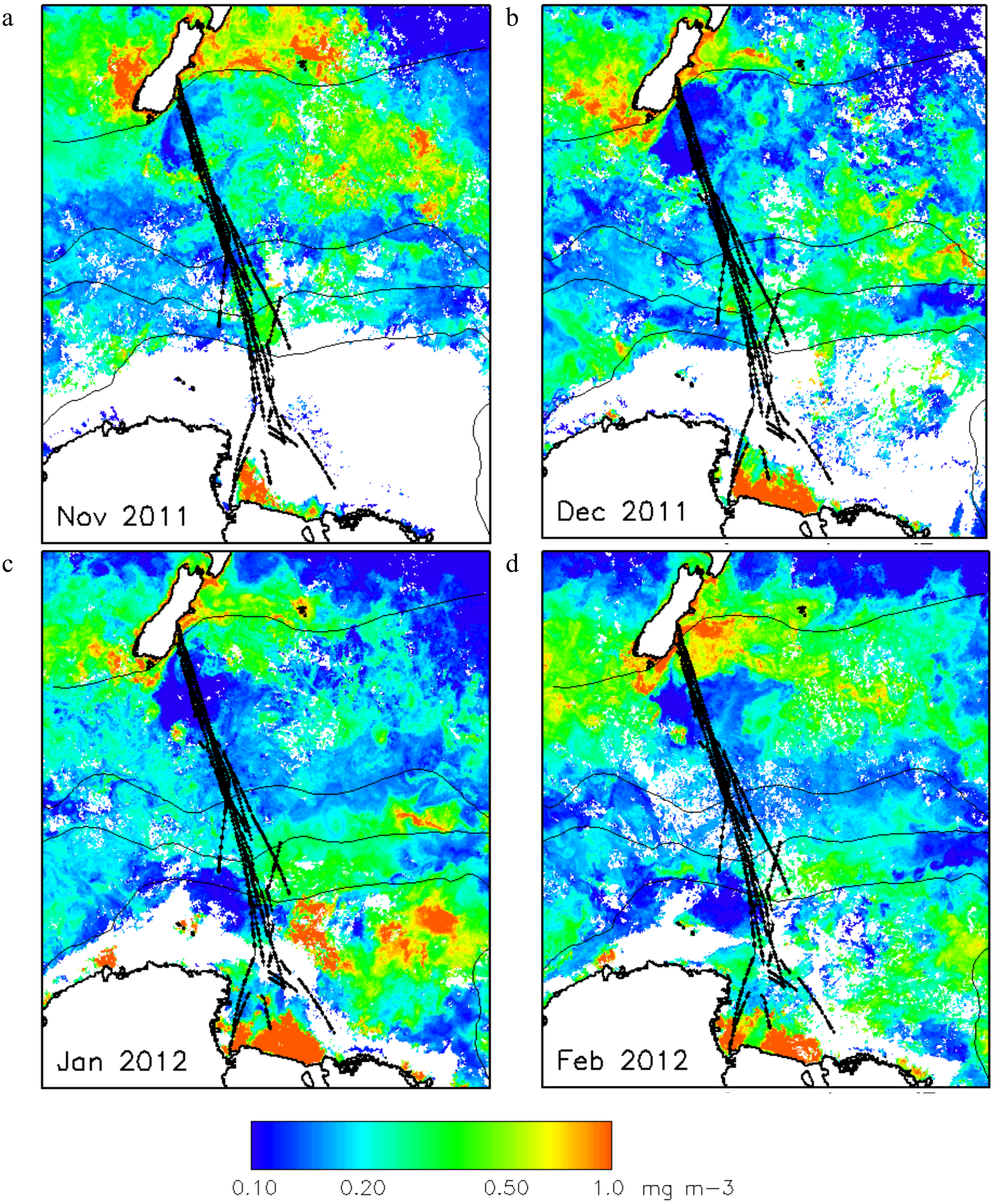


Figure 11: 2011–12 chlorophyll-*a* concentration (chl-*a*) – a proxy for primary productivity. Mean monthly chl-*a* as measured by the NASA MODIS-Aqua satellite sensor for the Ross Sea region. a: November; b: December; c: January; d: February. Fronts shown are (from top): Sub-Tropical Front, Sub-Antarctic Front, Polar Front, mean limit of sea-ice. CPR tracks from FV *San Aotea II* deployments are shown as black dots. White indicates land, ice-tongues or no data because of persistent cloud or sea-ice. Note the logarithmic scale.

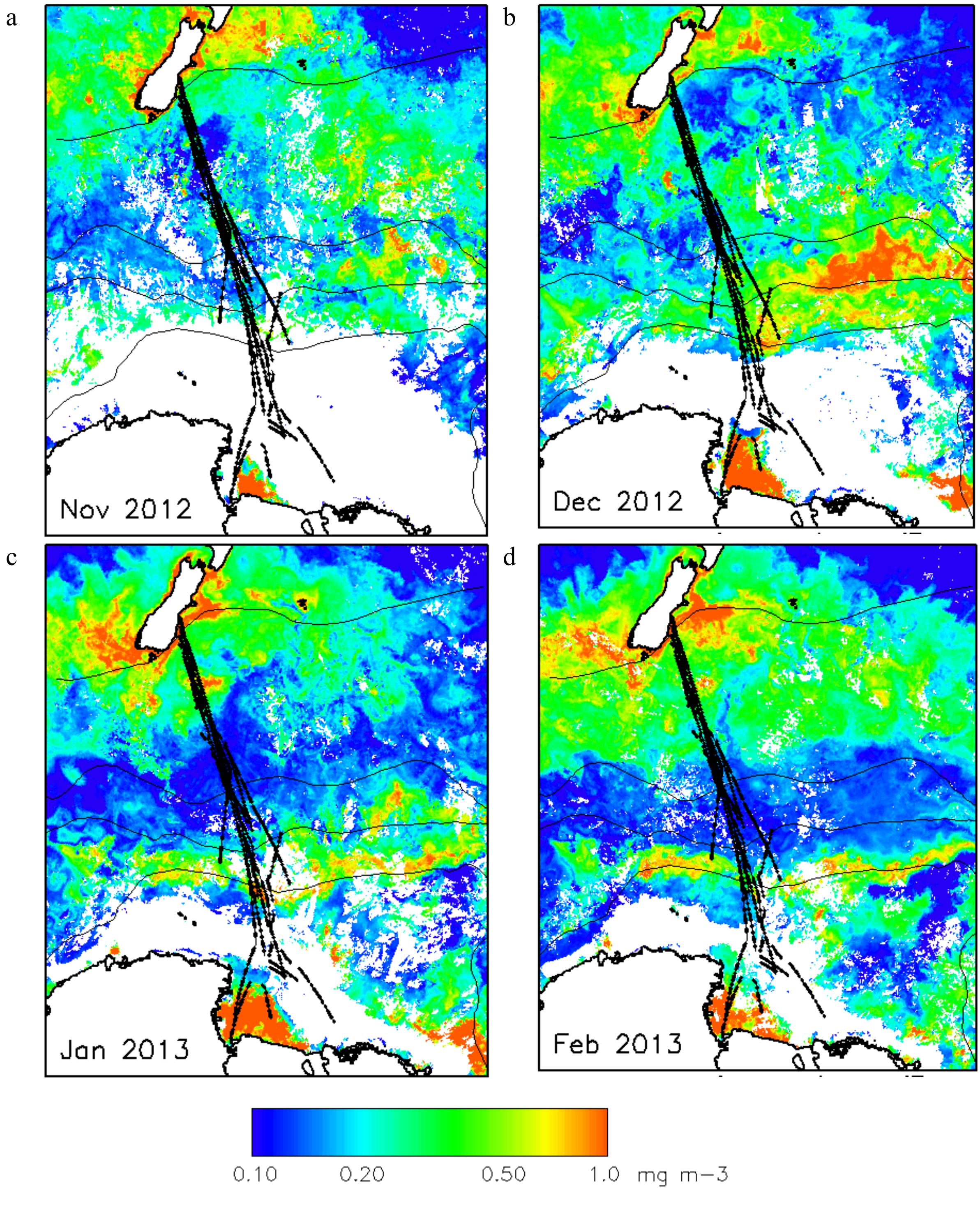


Figure 12: 2012–13 chlorophyll-*a* concentration (chl-*a*) – a proxy for primary productivity. Mean monthly chl-*a* as measured by the NASA MODIS-Aqua satellite sensor for the Ross Sea region. a: November; b: December; c: January; d: February. Fronts shown are (from top): Sub-Tropical Front, Sub-Antarctic Front, Polar Front, mean limit of sea-ice. CPR tracks from FV *San Aotea II* deployments are shown as black dots. White indicates land, ice-tongues or no data because of persistent cloud or sea-ice. Note the logarithmic scale.

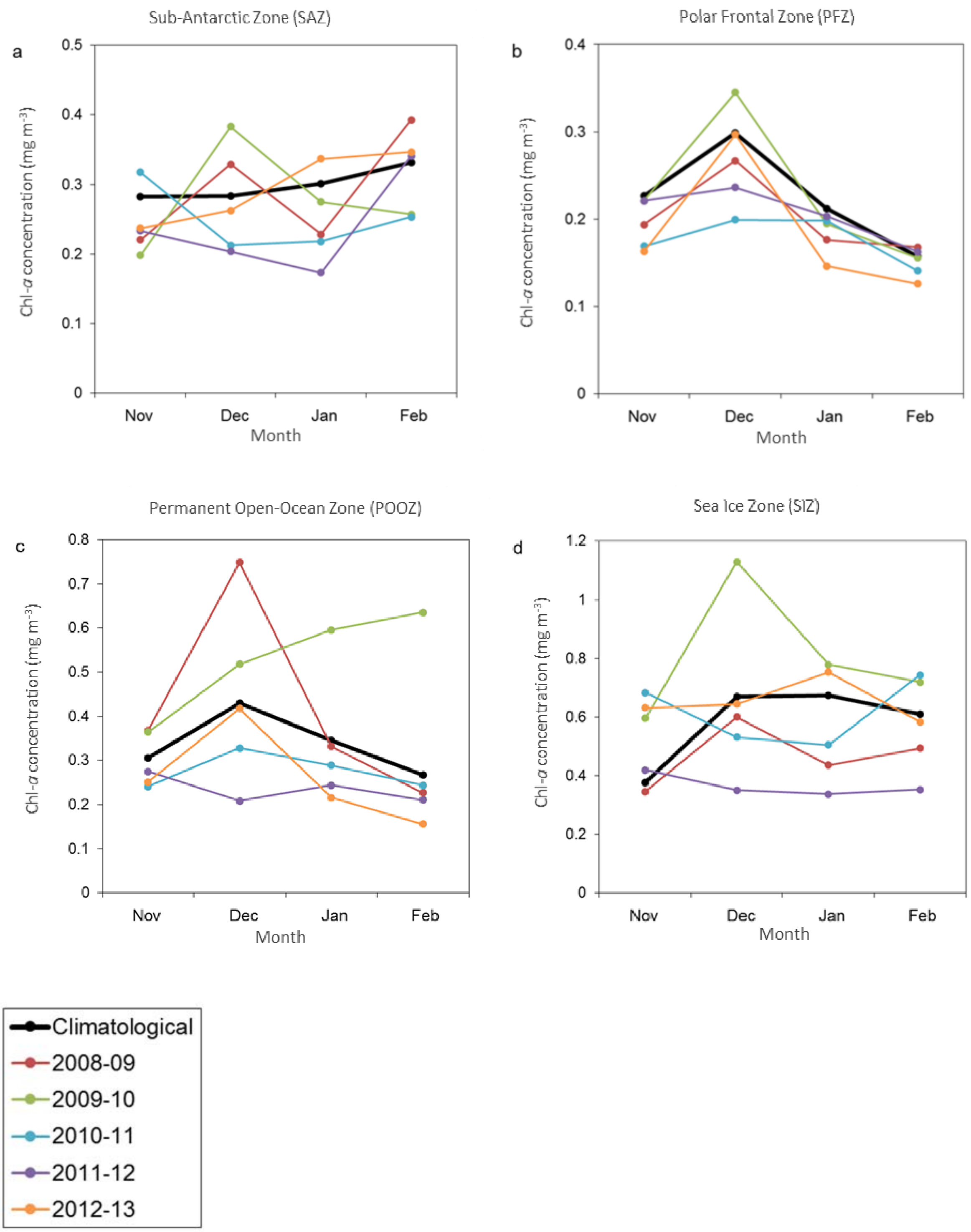


Figure 13: Chlorophyll-*a* concentration (chl-*a*) – a proxy for primary productivity. Climatological and seasonal mean monthly chl-a as measured by the NASA MODIS-Aqua satellite sensor for the Ross Sea region in four oceanographic zones. a: Sub-Antarctic Zone (SAZ); b: Polar Frontal Zone (PFZ); c: Permanent Open-Ocean Zone (POOZ); d: Sea Ice Zone (SIZ).

3.4 Phytoplankton abundance (CPR data)

Phytoplankton Colour Index (PCI) values from the Ross Sea CPR samples were compared to chlorophyll-*a* (chl-*a*) concentration derived from corresponding MODIS-Aqua satellite ocean colour satellite data at the same locations (Figure 14). Least-squares regression (PCI versus log chl-*a* concentration) indicated that the PCI explains about 21% of the variation in remotely-sensed chl-*a* concentration (T-test $p<0.01$). This suggests that the CPR Phytoplankton Colour Index is indicative of large-scale (multi-kilometre) variations in chl-*a* concentration, but that there are substantial differences between the two methods of estimating chl-*a* concentration.

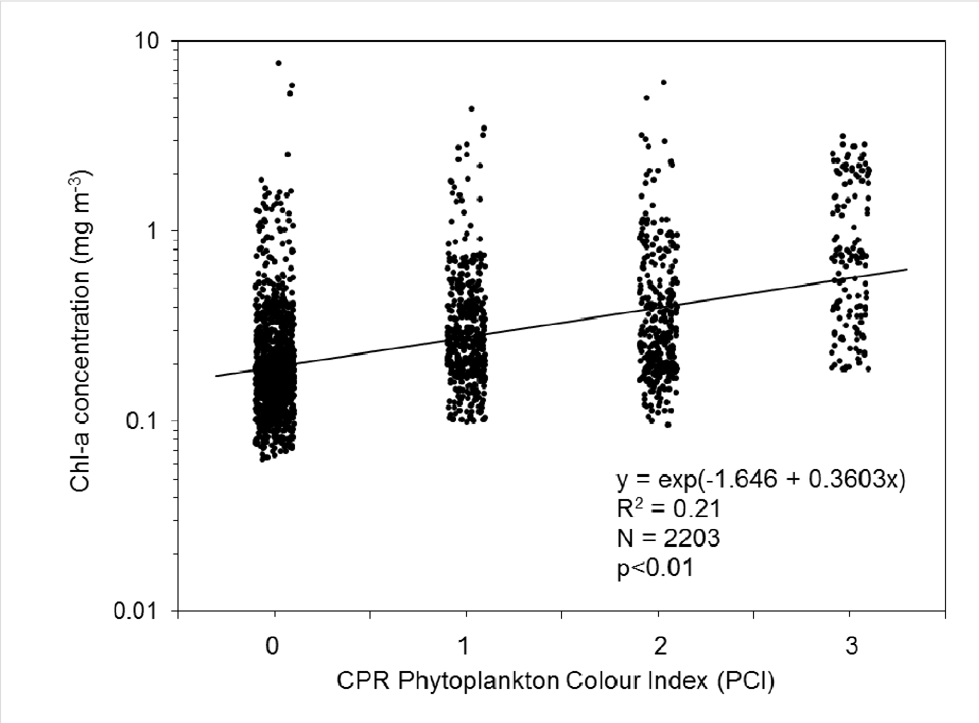


Figure 14: Phytoplankton Colour Index (PCI) from the Ross Sea CPR survey compared to chlorophyll-*a* (chl-*a*) concentration derived from corresponding MODIS-Aqua satellite ocean colour satellite data at the same location. PCI data are shown jittered by ±0.1 to indicate spread. The least-squares fitted regression line in ln(chl-*a*) vs PCI space is shown, together with the fitting information.

The Ross Sea region had consistently higher PCI scores in all oceanic zones compared with the East Antarctic region. The Sea Ice Zone consistently recorded the highest values of PCI in both regions, with the Ross Sea region more than double that of the East Antarctic region (Table 5). Chlorophyll-*a* concentration as measured by ocean colour satellite data was also higher on average in the Ross Sea region at the locations and times of CPR sampling than in the East Antarctic region (Table 5). The difference was quite small in the Sub-Antarctic Zone (about 8% on average), but was greater further south (Polar Frontal Zone: 28%, Permanent Open-Ocean Zone: 85%, Sea Ice Zone: 79%). The higher chl-*a* concentrations in the Ross Sea region compared to the East Antarctic region can also be seen in long-term satellite data of the region (Figure 15).

Table 5: Comparison between East Antarctic and Ross Sea regions by oceanographic zone: Phytoplankton Colour Index (PCI), mean chlorophyll-*a* concentration (chl-*a*, mg m^{-3}) at locations of CPR sampling (based on 2002–2013 ocean colour satellite observation), and mean zooplankton abundance since 2007-08. Sub-Antarctic Zone (SAZ); Polar Frontal Zone (PFZ); Permanent Open-Ocean Zone (POOZ); Sea Ice Zone (SIZ). Mean PCI values are averages of PCI values in each oceanographic zone.

	Eastern Antarctic region			Ross Sea region		
	Mean PCI	Mean chl-*a* (mg m^3)	Mean zooplankton abundance (m^3)	Mean PCI	Mean chl-*a* (mg m^3)	Mean zooplankton abundance (m^3)
SAZ	0.12	0.22	42.9	0.29	0.23	158.5
PFZ	0.21	0.19	86.7	0.63	0.25	311.0
POOZ	0.24	0.20	119.6	0.92	0.37	357.5
SIZ	0.44	0.37	80.3	0.99	0.67	90.7

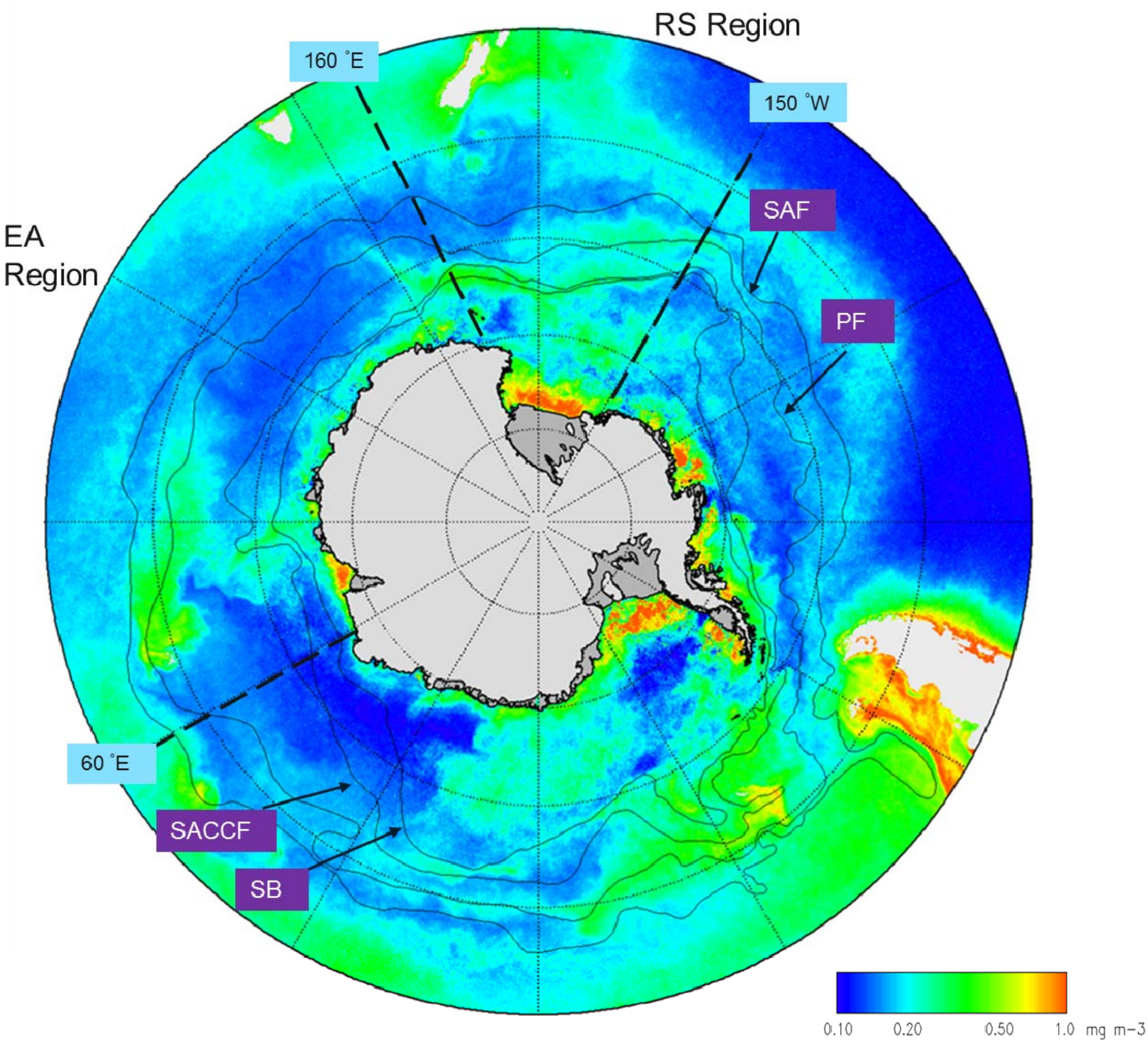


Figure 15: Mean summer chlorophyll-*a* concentration (chl-*a*) for the Southern Ocean derived from the MODIS-Aqua ocean colour sensor, 2002–2013. Warmer colours (more red) indicate higher concentration and cooler colours (more blue) lower concentration. East Antarctic region (EA) and Ross Sea region (RS) are indicated. Fronts shown as: Sub-Antarctic Front (SAF), Polar Front (PF), the Southern Antarctic Circumpolar Current Front (SACCF), and the southern boundary of the Antarctic Circumpolar Current (SB). Front positions were taken from Orsi et al (1995).

3.5 Zooplankton abundance (CPR data)

This section summarises CPR data across the Ross Sea region by oceanographic zone and includes data from the five FV *San Aotea II* voyages and the three RV *Tangaroa* research voyages. The Sub-Tropical Zone is a very narrow band which coincides with the continental shelf close to New Zealand, and has a low number of samples associated with it, as does the Permanent Open-Ocean Zone, which is also narrow in the area that the CPR transects cross (Table 6). The Sub-Antarctic Zone is the widest zone in the Ross Sea region and contributed the highest number of samples (1479) and taxa (122). In contrast the Polar Frontal Zone and Permanent Open-Ocean Zone had the highest overall abundances, but less diversity with 81 and 44 present, respectively.

Table 6: NZ-CPR statistics per oceanic zone in the Ross Sea Region including data from the FV *San Aotea II* 2008–2013 and the RV *Tangaroa* 2006, 2008 and 2010. Sub-Tropical Zone (STZ), Sub-Antarctic Zone (SAZ), Polar Frontal Zone (PFZ), Permanent Open-Ocean Zone (POOZ) and Sea Ice Zone (SIZ).

Zone	No. of Samples	No. of Taxa	Mean total zooplankton abundance (No. m^{-3})
STZ	156	85	66.0
SAZ	1479	122	158.5
PFZ	863	81	311.0
POOZ	99	44	357.5
SIZ	1254	75	90.7

For each of the zones in the Ross Sea region, the top 10 zooplankton taxa (before grouping) are shown as a percentage of total abundance in Figures 17 to 21. In the Sub-Tropical zone, coastal species including *Paracalanus* sp., *Calanus australi*s, *Noctiluca scintillans* and *Oithona similis* were present. Copepods were the dominant group in this zone making up 68% of the total zooplankton abundance. The Calanoid copepod indeterminate (indet.) group includes juvenile and damaged individuals, and small species that could not be positively identified to genus or species level (Figure 17).

The Sub-Antarctic Zone (Figure 18), had the highest taxon richness with 122 taxa, including Sub-Antarctic species such as *Neocalanus tonsus*, *Calanus simillimus*, and *Clausocalanus brevipes*. Calanoid copepods dominated the community, but *Oithona similis* (a cyclopoid copepod) was the most dominant species. The larvacean *Fritillaria* sp. and foraminiferan species were considerably more abundant in this zone than in the Sub-Tropical Zone. *Oithona similis, Fritillaria* sp. and Calanoid copepod indet. were the dominant groups in the Polar Frontal Zone and the Permanent Open-Ocean Zone (Figure 19 and Figure 20). *Oithona similis* remained the dominant species in the Sea Ice Zone, along with small indeterminate calanoid copepod species and the larvacean *Fritillaria* sp. (Figure 21). Characteristic high-latitude species including *Calanus propinquus*, *Calanoides acutus*, the Antarctic krill *Euphausia superba*, and the pteropod *Limacina* sp., were also recorded in Sea Ice Zone samples but not in high abundance.

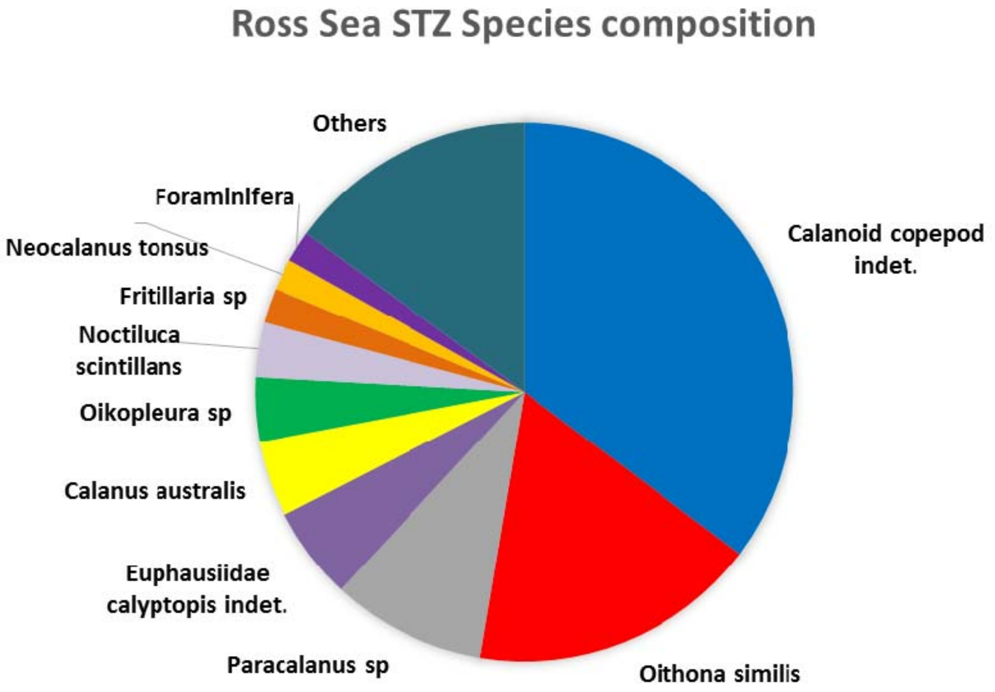


Figure 17: The ten most abundant zooplankton taxa collected in the Sub-Tropical Zone (STZ) in the Ross Sea region for combined FV *San Aotea II* and RV *Tangaroa* voyages. Calanoid copepod indeterminate (indet.) refers to animals that were damaged, juvenile or could not be positively identified to genus or species level.

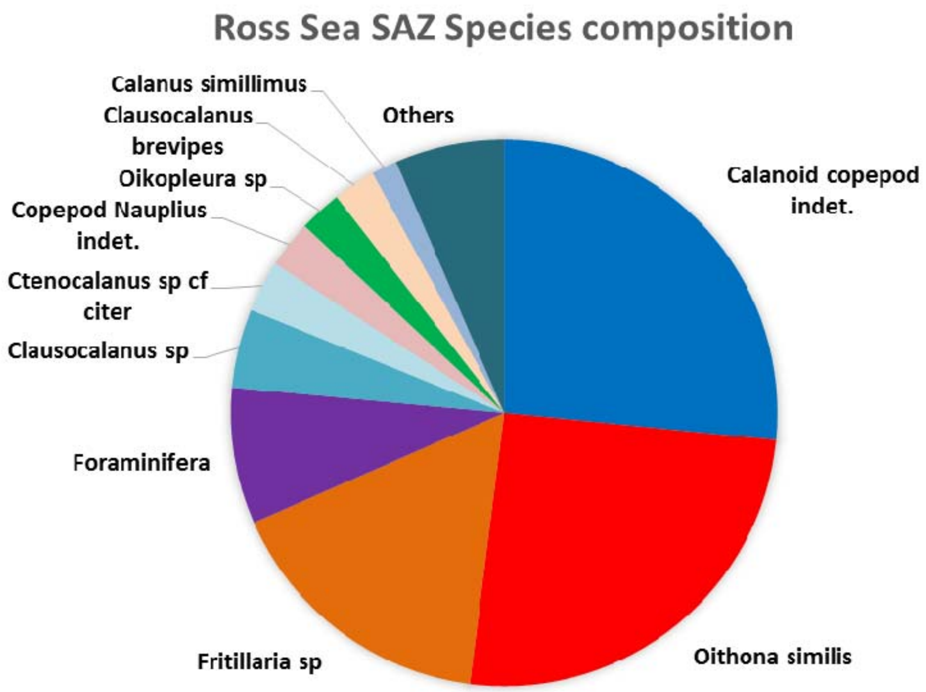


Figure 18: The ten most abundant zooplankton taxa collected in the Sub-Antarctic Zone (SAZ) in the Ross Sea region for combined FV *San Aotea II* and RV *Tangaroa* voyages. Calanoid copepod indeterminate (indet.) refers to animals that were damaged, juvenile or could not be positively identified to genus or species level.

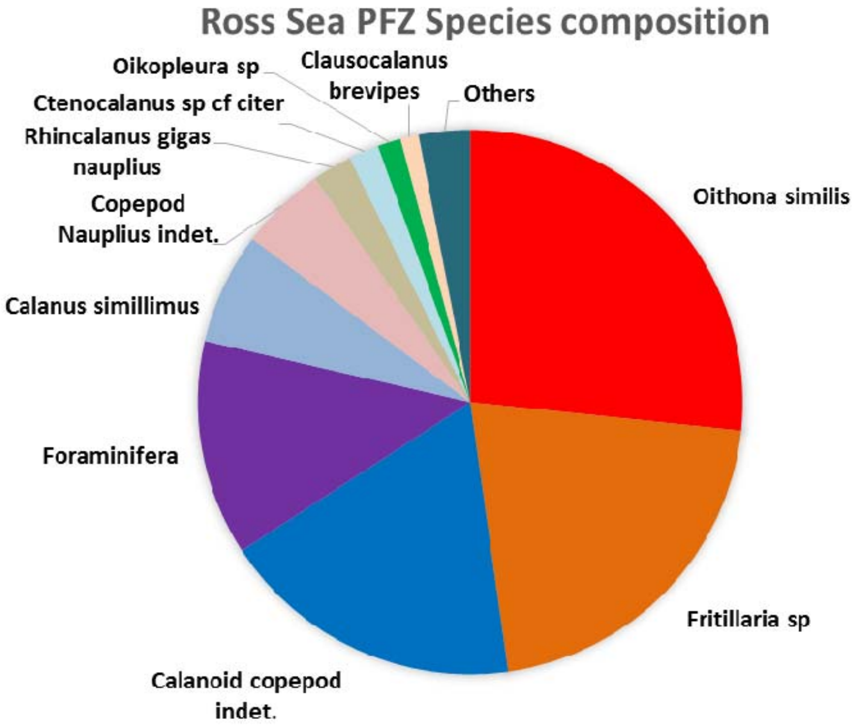


Figure 19: The ten most abundant zooplankton taxa collected in the Polar Frontal Zone (PFZ) in the Ross Sea region for combined FV *San Aotea II* and RV *Tangaroa* voyages. Calanoid copepod indeterminate (indet.) refers to animals that were damaged, juvenile or could not be positively identified to genus or species level.

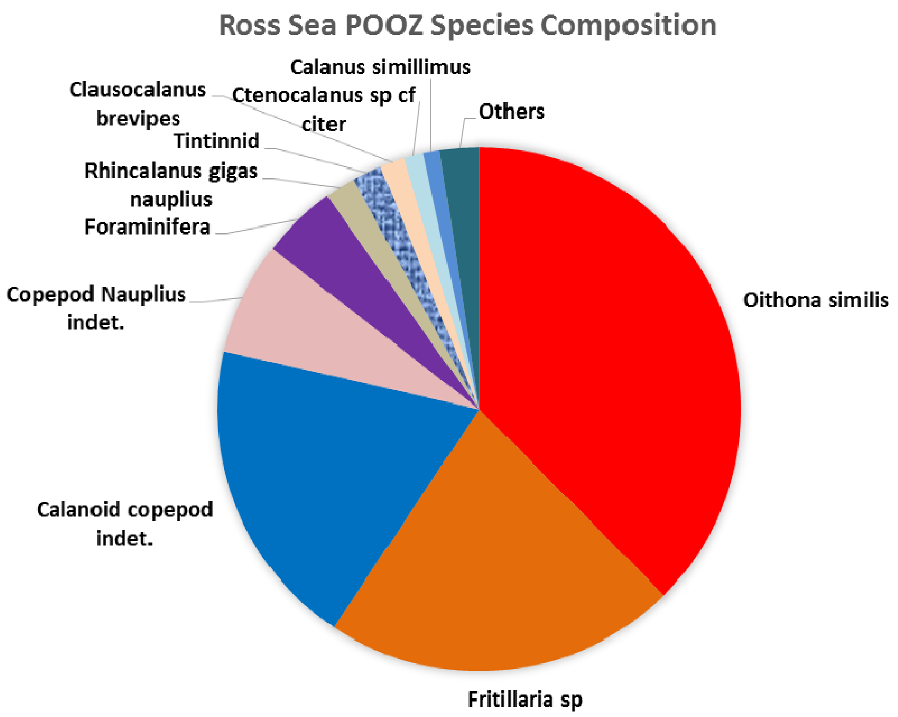


Figure 20: The ten most abundant zooplankton taxa collected in the Permanent Open-Ocean Zone (POOZ) in the Ross Sea region for combined FV *San Aotea II* and RV *Tangaroa* voyages. Calanoid copepod indeterminate (indet.) refers to animals that were damaged, juvenile or could not be positively identified to genus or species level.

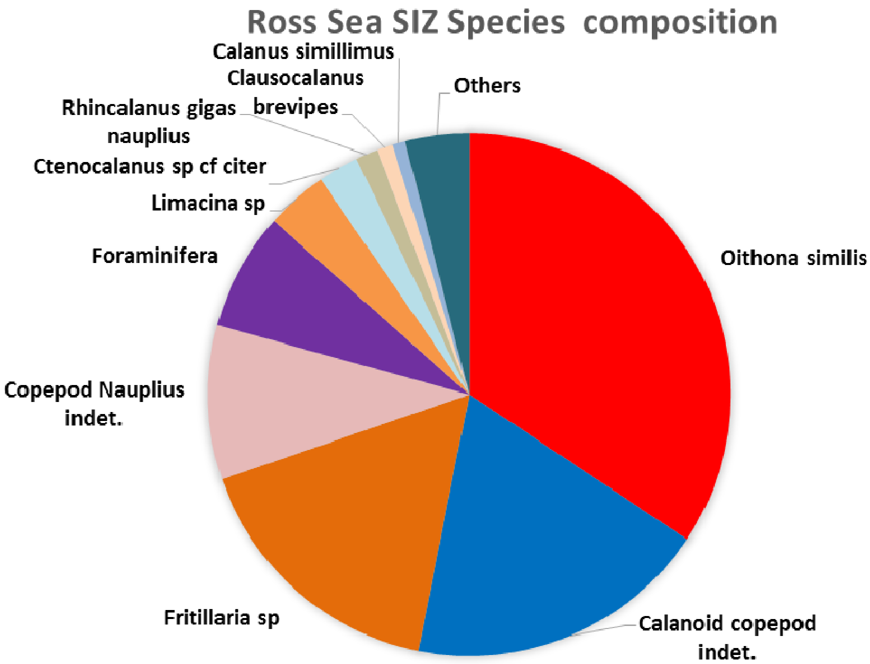


Figure 21: The ten most abundant zooplankton taxa collected in the Sea Ice Zone (SIZ) in the Ross Sea region for combined FV *San Aotea II* and RV *Tangaroa* voyages. Calanoid copepod indeterminate (indet.) refers to animals that were damaged, juvenile or could not be positively identified to genus or species level.

3.6 Latitudinal variation in the Ross Sea region

Total zooplankton abundance, relative abundances by taxonomic group (in 13 groups), and Phytoplankton Colour Index (PCI) index are shown in Figures 22 to 31. These data include only FV *San Aotea II* CPR deployments as these regular transects allow the most robust annual comparisons to be made. The figures also show satellite measurements of chl-*a* concentration and sea surface temperature (SST) extracted from the monthly-composite satellite data at the location of each CPR sample. These are shown against the climatological (10-year monthly-mean) value of chl-*a* and SST to identify anomalous oceanographic conditions that may have affected zooplankton abundance and/or community structure.

In broad terms, zooplankton communities at the same latitudes were similar from year to year with higher zooplankton abundances tending to occur north of the Polar Front in the Sub-Tropical Zone, the Sub-Antarctic Zone and the Polar Frontal Zone. Higher levels of zooplankton abundance tended to occur on the southward transects in the early parts of the summer season. The PCI scores show consistently high levels across all the sampling years, with high PCI values tending to be associated with the Sea Ice Zone except in January 2011 (Figure 27) where there was no colour present. This low PCI index was associated with very low zooplankton abundance.

The two most abundant groups overall were the single cyclopoid copepod species *Oithona similis* (28% of all counts overall) and calanoid copepods (30% overall), most of which (20% overall) were unidentified beyond order. These two groups tended to form the largest proportion of total zooplankton abundance at most latitudes and in most years. The other copepod group, “Copepod (other + unidentified)”, made up 6% of counts overall (about 5% of which were unidentified to order). Unidentified copepods were always of low abundance compared to *Oithona similis*, but occasionally were more abundant than the calanoid copepod group (2008–09, south transit at 65°S and 2009–10, south transit, at 61°S).

Calanoid copepods and, to a lesser extent *Oithona similis*, were responsible for high total abundances of zooplankton measured in the two main frontal zones, (Sub-Tropical Zone and Polar Frontal Zone), on some occasions. For example, there were elevated abundances of these two groups in the Sub-Tropical Zone (about 48°S) in December 2008 (Figure 22) and November 2010 (Figure 26). In both these instances, chl-*a* was close to the climatological mean. Sea surface temperatures were also very similar to the climatological mean at these times and locations. This suggests that the elevated abundances of the copepods may not have been directly related to primary production. In the Polar Frontal Zone (60°–63°S), there were higher zooplankton abundances measured in February 2010 (Figure 25) and January 2011 (Figure 27) and calanoid copepods and *O. similis* were the most abundant groups by far in both cases. In the former case, there was a suggestion in the satellite data that chl-*a* was higher than normal to the south of the high zooplankton abundances (about 65°S), but little difference from climatological mean chl-*a* at 60°–63°S. In January 2011, the high values of chl-*a* occur further north than in the 2002–2013 satellite mean (peak values at 60°S rather than the normal 67°S), and this may have been related to the higher zooplankton abundances measured on the CPR transect at this time. Sea surface temperatures were very similar to the climatological mean giving no indication of a change in the oceanic frontal positions.

The larvacean genus *Fritillaria* sp. comprised 21% of counts overall, and although always present in low numbers, a very substantial (more than 10-fold) increase in abundance above the 5-year mean from FV *San Aotea II* CPR data was observed in December 2009 over much of the latitudinal range measured, 53–65°S (Figure 24). The unusually high abundances of *Fritillaria* sp. in December 2009 correspond to the highest observed chl-*a* in December in the Sub-Antarctic Zone, Polar Frontal Zone and Sea Ice Zone over the 5 years of this study. This suggests that there were elevated levels of primary productivity occurring in these zones at this time. Sea surface temperatures were close to the climatological mean.

Foraminifera is the only other group that made up more than 2% of total abundance overall, comprising 10% of the overall counts. Foraminifera were more abundant in the 2008–09 season, over a wide range of latitudes, than in the other four years (Figure 23). However, abundances of Foraminifera were higher in the vicinity of the Sub-Tropical Front in November 2010 (Figure 26), and in the Polar Frontal Zone in January 2011 (Figure 27), increasing in line with the copepod abundances in these locations and times. Chl-*a* concentrations measured by satellite close to the Sub-Tropical Front (about 47°S) in November 2010 were close to the climatological mean, as were chl-*a* values in the Polar Frontal Zone at about 63°S in January 2011, giving no clue as to the causes of higher Foraminifera abundances at this time. Sea surface temperatures was also close to the climatological mean at these times and locations.

Overall abundances of the other groups were (in descending order): *Oikopleura* sp. (1.3% overall), Euphausiidae (1.0% overall), Pteropoda (0.6% overall), Salps (0.2% overall), Amphipoda (0.15% overall), Chaetognatha (0.14% overall) and Ostracoda (0.1% overall). The “other” group represents 0.4% of total counts overall, and includes samples which are wholly unidentified (0.1%), cephalopods, fish, fish eggs, isopods, “jellies” (ctenophores, siphonophores), mysids, polychaetes, protozoa and shrimps. Salps in this study will be under-represented for reasons given earlier.

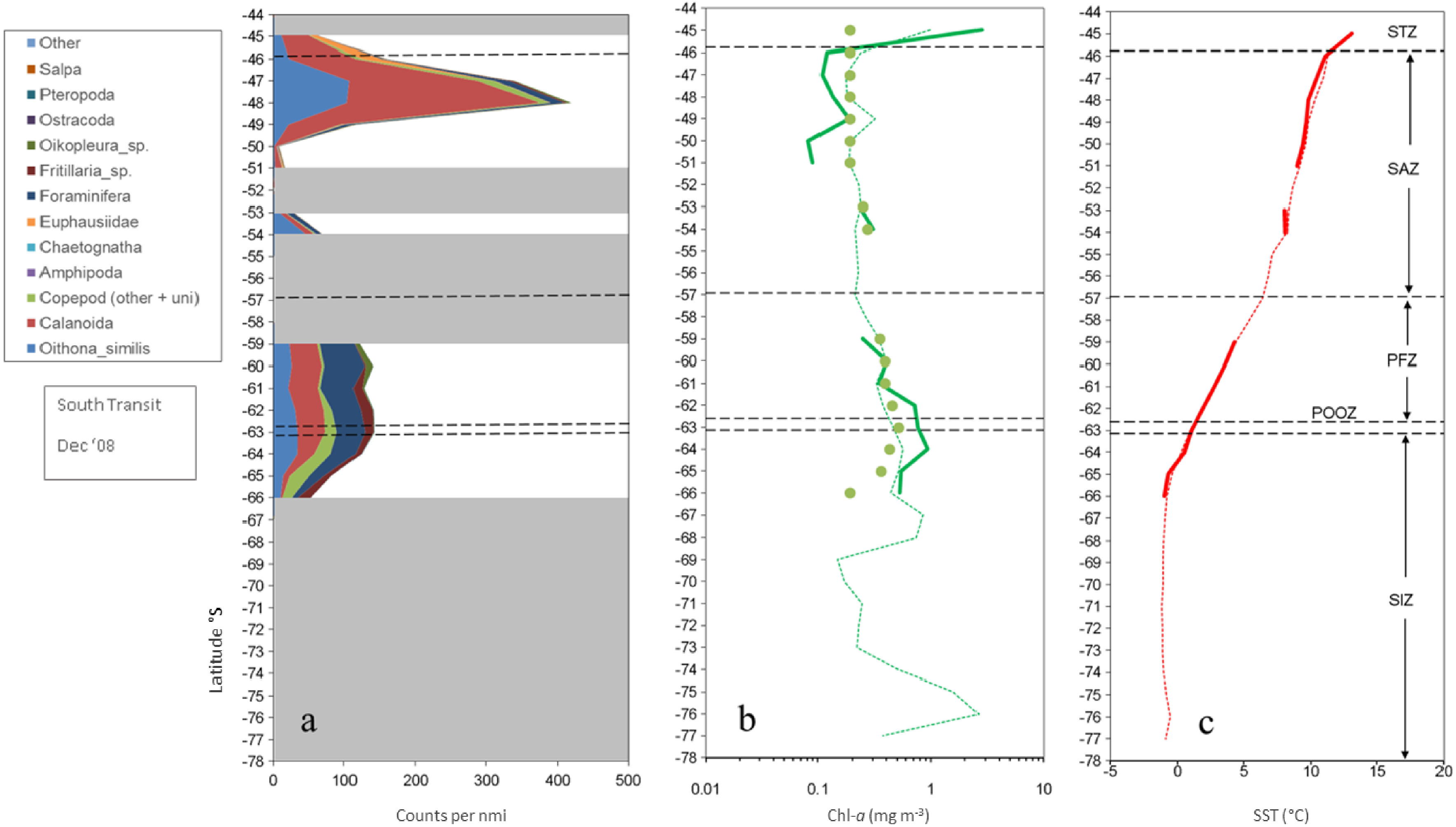


Figure 22: CPR tows 2008–09 (south transit, Dec 2008) a: Zooplankton abundance in 13 groups as shown in key on left (median values per 1° latitude bin). Grey indicates no CPR data. b: Chlorophyll-*a* concentration (Chl-*a*) at the time of CPR sampling from MODIS-Aqua (solid green line), long-term mean values from MODIS-Aqua 2002–2013 (dashed green line), and estimated from the mean CPR phytoplankton colour index (PCI) in 1° latitude bin using the scaling of Figure 14 (green dots). c: Sea surface temperature (SST) at the time of CPR sampling from MODIS-Aqua (solid red line) and long-term mean SST from MODIS-Aqua 2002–2013 (dashed red line). Black dashed lines show boundaries between oceanographic zones: Sub-Tropical Zone (STZ), Sub-Antarctic Zone (SAZ), Polar Frontal Zone (PFZ), Permanent Open-Ocean Zone (POOZ) and Sea Ice Zone (SIZ).

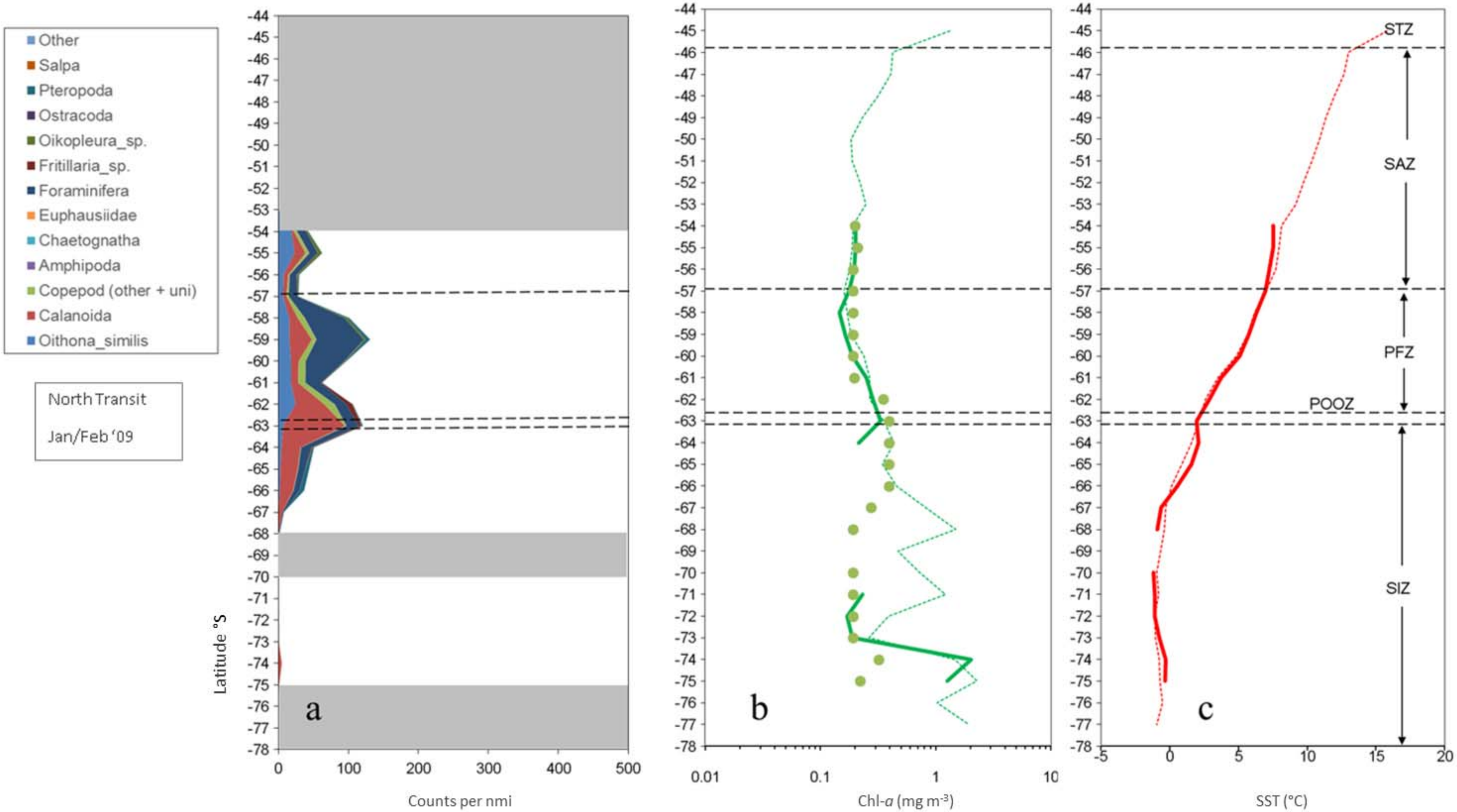


Figure 23: CPR tows 2008–09 (north transit, Jan/Feb 2009). Refer to Figure 22 for extended legend detail. a: Zooplankton abundance in 13 groups. Grey indicates no CPR data. b: Chlorophyll-*a* concentration (Chl-*a*) (solid green line), long-term mean Chl-*a* (dashed green line), mean Phytoplankton Colour Index (PCI) (green dots). c: Sea surface temperature (SST) (solid red line), mean SST (dashed red line). Black dashed lines show boundaries between oceanographic zones: Sub-Tropical Zone (STZ), Sub-Antarctic Zone (SAZ), Polar Frontal Zone (PFZ), Permanent Open-Ocean Zone (POOZ) and Sea Ice Zone (SIZ).

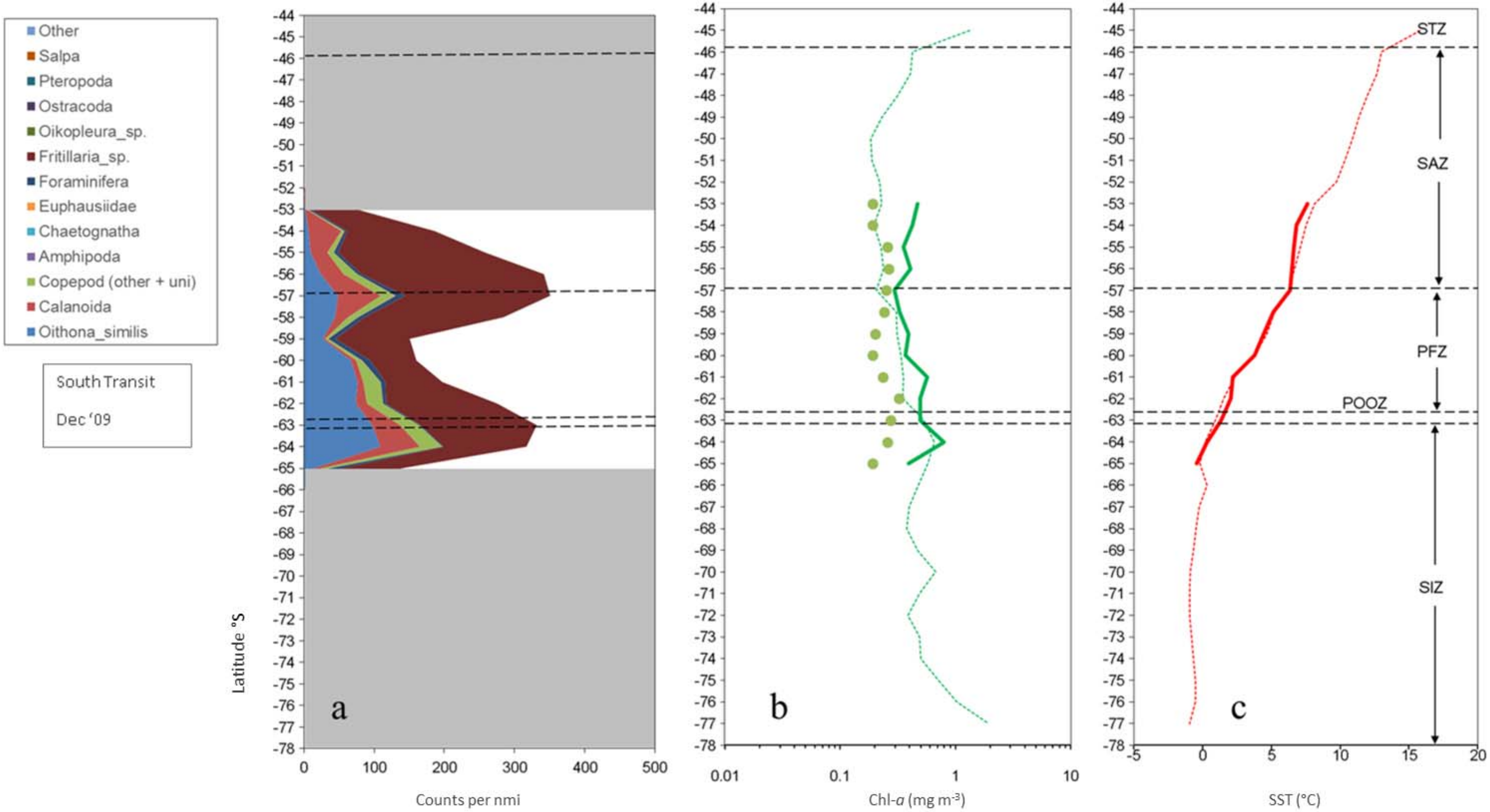


Figure 24: CPR tows 2009–10 (south transit, Dec 2009) a: Refer to Figure 22 for extended legend detail. a: Zooplankton abundance in 13 groups. Grey indicates no CPR data. b: Chlorophyll-*a* concentration (Chl-*a*) (solid green line), long-term mean Chl-*a* (dashed green line), mean Phytoplankton Colour Index (PCI) (green dots). c: Sea surface temperature (SST) (solid red line), mean SST (dashed red line). Black dashed lines show boundaries between oceanographic zones: Sub-Tropical Zone (STZ), Sub-Antarctic Zone (SAZ), Polar Frontal Zone (PFZ), Permanent Open-Ocean Zone (POOZ) and Sea Ice Zone (SIZ).

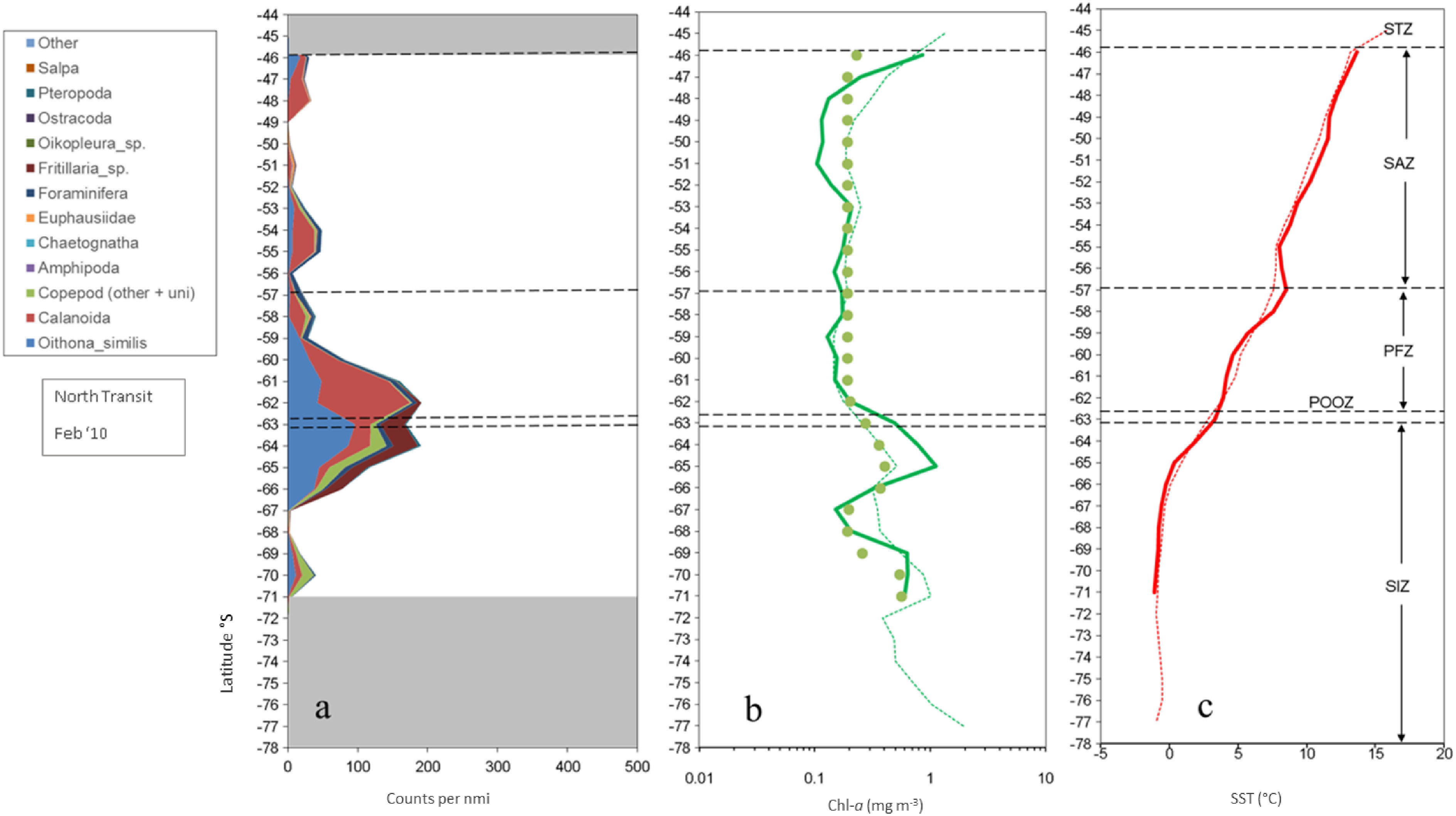


Figure 25: CPR tows 2009–10 (north transit, Feb 2010) a: Refer to Figure 22 for extended legend detail. a: Zooplankton abundance in 13 groups. Grey indicates no CPR data. b: Chlorophyll-*a* concentration (Chl-*a*) (solid green line), long-term mean Chl-*a* (dashed green line), mean Phytoplankton Colour Index (PCI) (green dots). c: Sea surface temperature (SST) (solid red line), mean SST (dashed red line). Black dashed lines show boundaries between oceanographic zones: Sub-Tropical Zone (STZ), Sub-Antarctic Zone (SAZ), Polar Frontal Zone (PFZ), Permanent Open-Ocean Zone (POOZ) and Sea Ice Zone (SIZ).

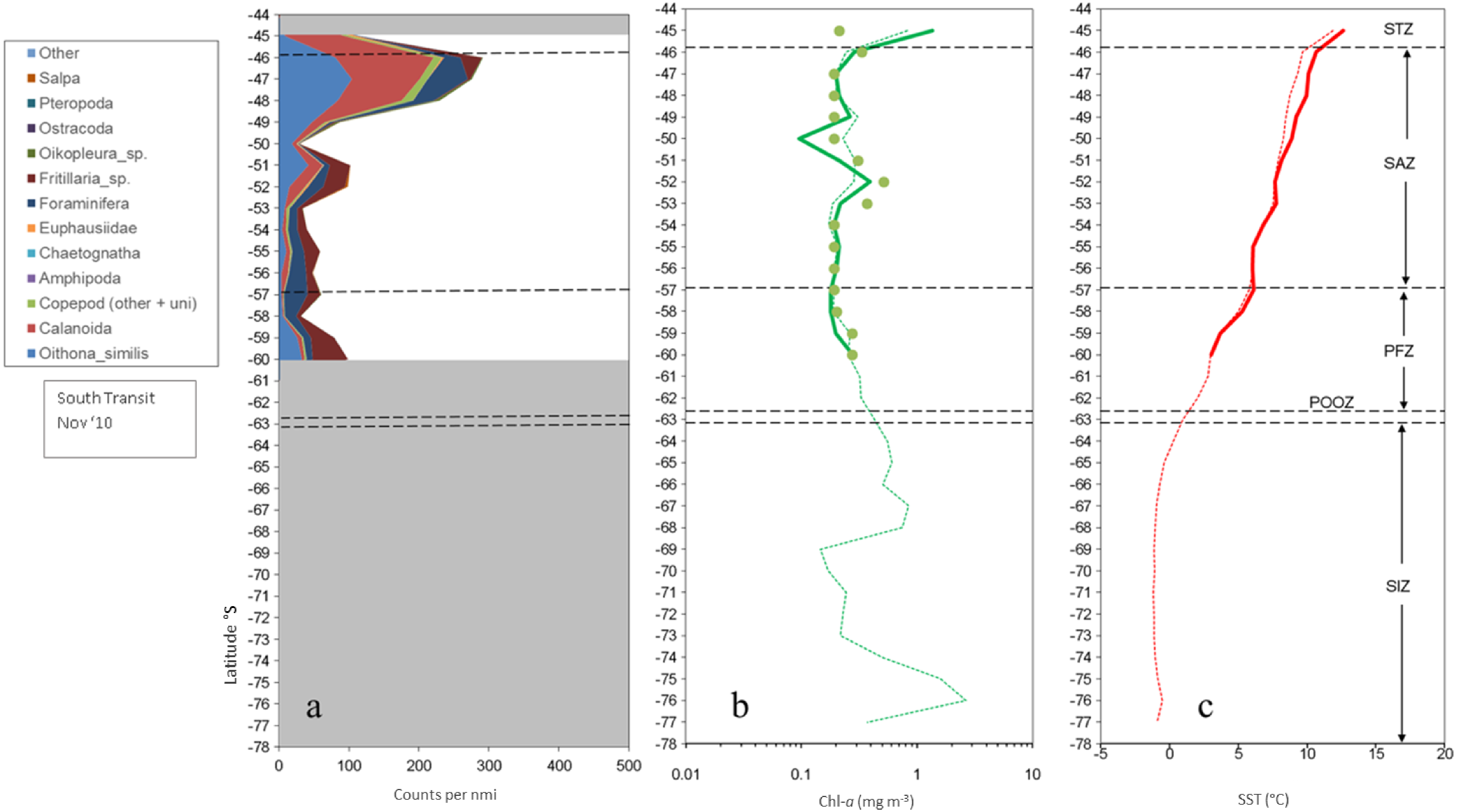


Figure 26: CPR tows 2010–11 (south transit, Nov 2010) a: Refer to Figure 22 for extended legend detail. a: Zooplankton abundance in 13 groups. Grey indicates no CPR data. b: Chlorophyll-*a* concentration (Chl-*a*) (solid green line), long-term mean Chl-*a* (dashed green line), mean Phytoplankton Colour Index (PCI) (green dots). c: Sea surface temperature (SST) (solid red line), mean SST (dashed red line). Black dashed lines show boundaries between oceanographic zones: Sub-Tropical Zone (STZ), Sub-Antarctic Zone (SAZ), Polar Frontal Zone (PFZ), Permanent Open-Ocean Zone (POOZ) and Sea Ice Zone (SIZ).

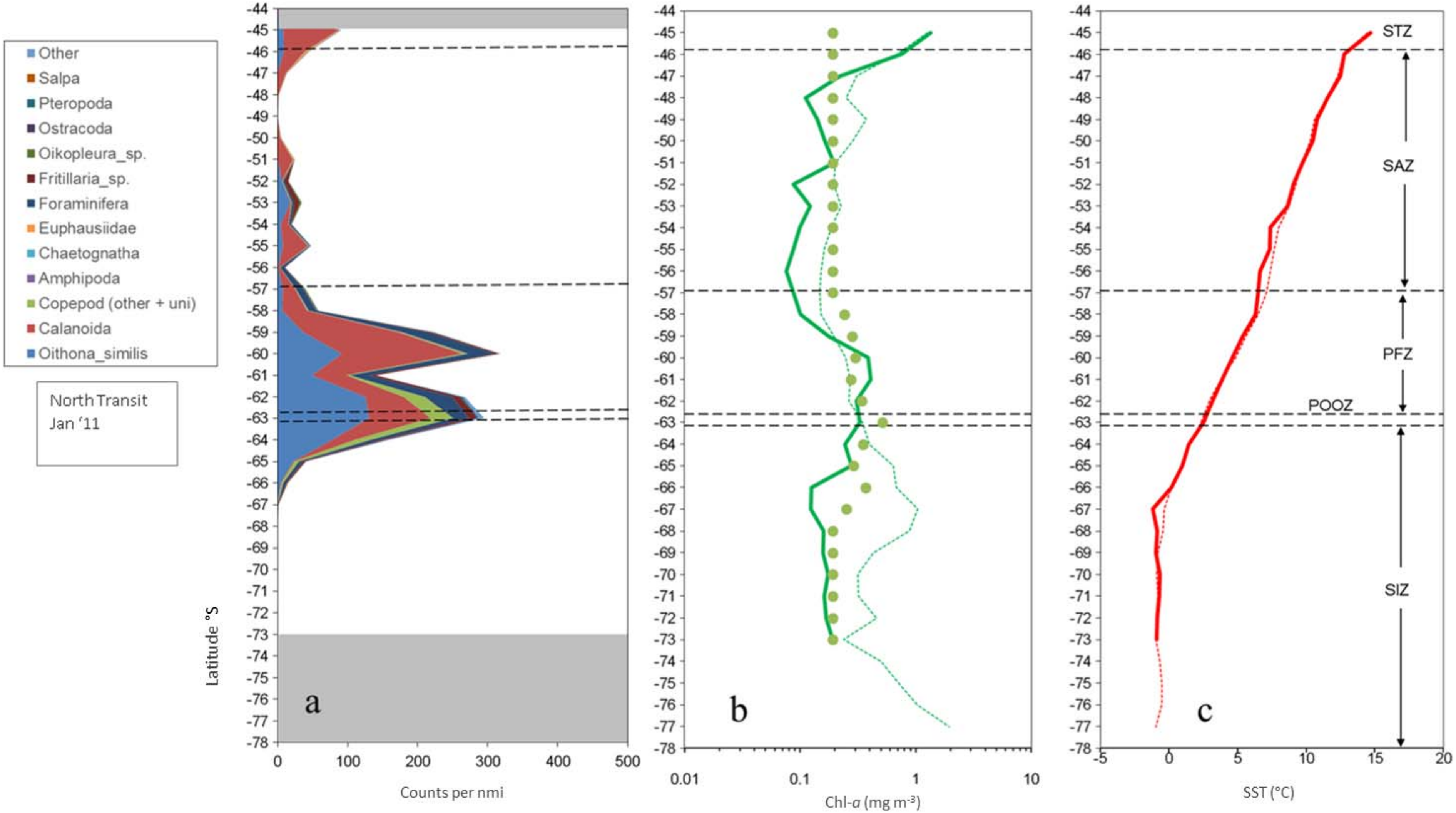


Figure 27: CPR tows 2010–11 (north transit, Jan 2011) a: Refer to Figure 22 for extended legend detail. a: Zooplankton abundance in 13 groups. Grey indicates no CPR data. b: Chlorophyll-*a* concentration (Chl-*a*) (solid green line), long-term mean Chl-*a* (dashed green line), mean Phytoplankton Colour Index (PCI) (green dots). c: Sea surface temperature (SST) (solid red line), mean SST (dashed red line). Black dashed lines show boundaries between oceanographic zones: Sub-Tropical Zone (STZ), Sub-Antarctic Zone (SAZ), Polar Frontal Zone (PFZ), Permanent Open-Ocean Zone (POOZ) and Sea Ice Zone (SIZ).

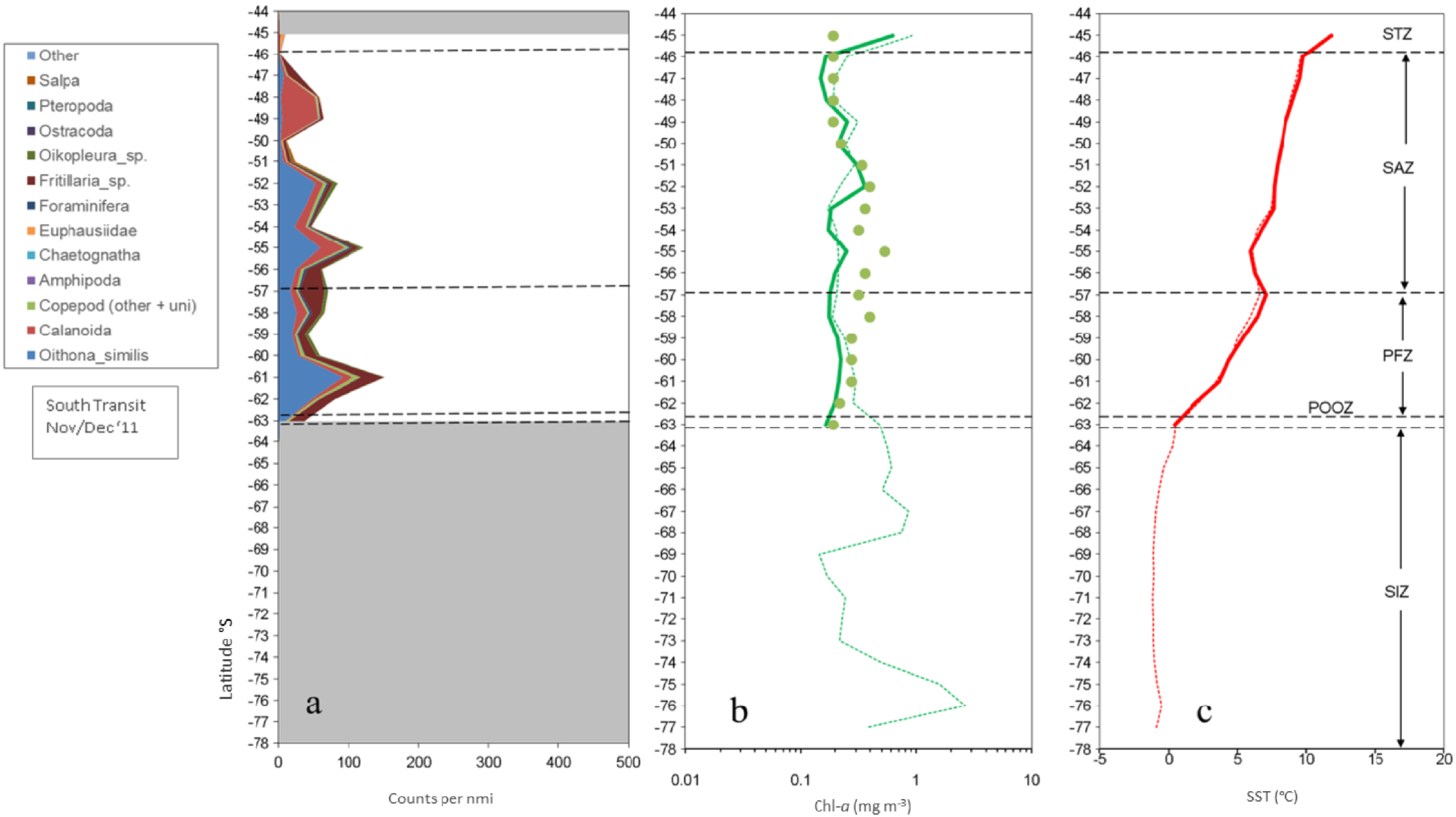


Figure 28: CPR tows 2011–12 (south transit, Nov/Dec 2011) a: Refer to Figure 22 for extended legend detail. a: Zooplankton abundance in 13 groups. Grey indicates no CPR data. b: Chlorophyll-*a* concentration (Chl-*a*) (solid green line), long-term mean Chl-*a* (dashed green line), mean Phytoplankton Colour Index (PCI) (green dots). c: Sea surface temperature (SST) (solid red line), mean SST (dashed red line). Black dashed lines show boundaries between oceanographic zones: Sub-Tropical Zone (STZ), Sub-Antarctic Zone (SAZ), Polar Frontal Zone (PFZ), Permanent Open-Ocean Zone (POOZ) and Sea Ice Zone (SIZ).

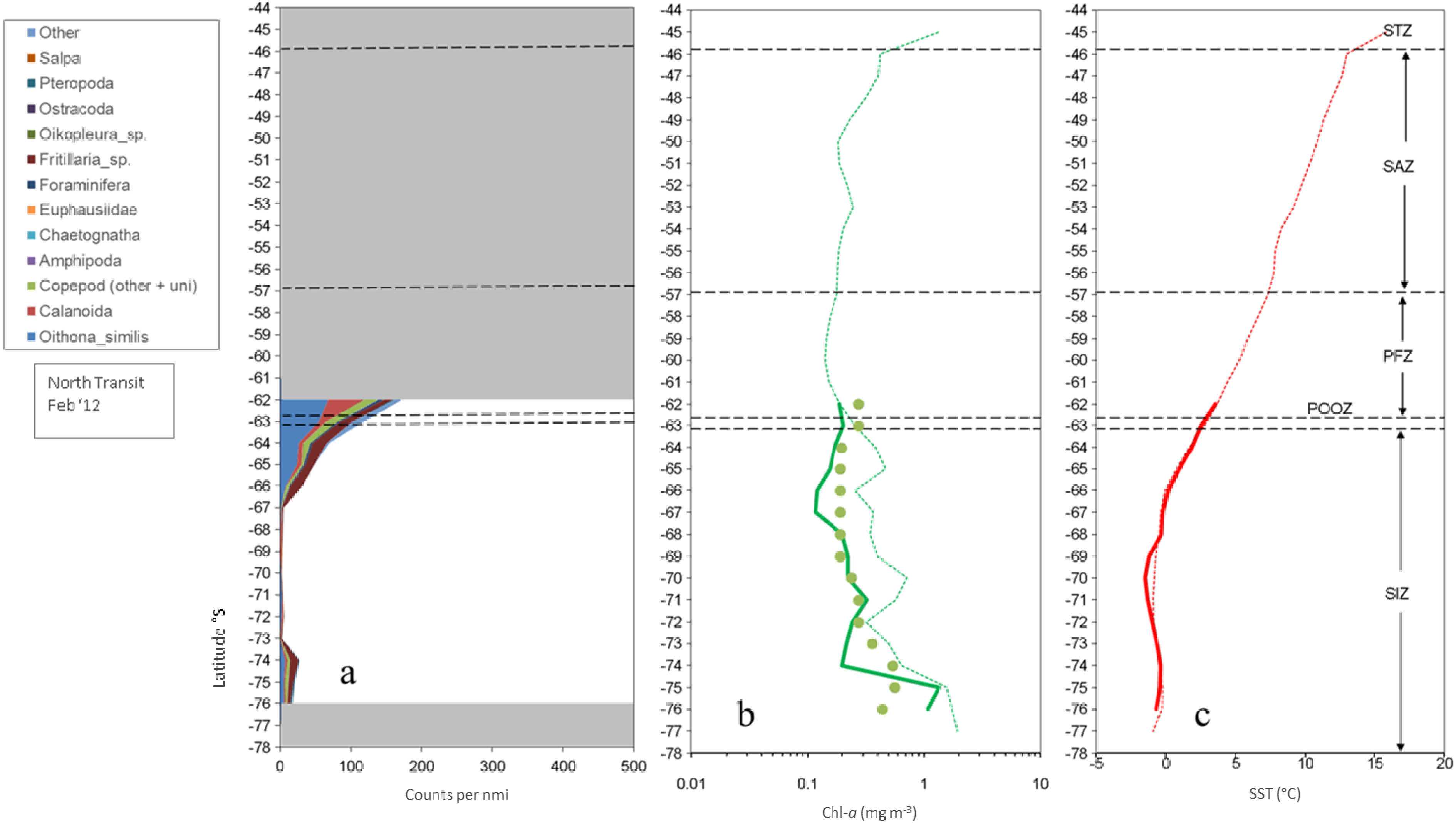


Figure 29: CPR tows 2011–12 (north transit, Feb 2012) a: Refer to Figure 22 for extended legend detail. a: Zooplankton abundance in 13 groups. Grey indicates no CPR data. b: Chlorophyll-*a* concentration (Chl-*a*) (solid green line), long-term mean Chl-*a* (dashed green line), mean Phytoplankton Colour Index (PCI) (green dots). c: Sea surface temperature (SST) (solid red line), mean SST (dashed red line). Black dashed lines show boundaries between oceanographic zones: Sub-Tropical Zone (STZ), Sub-Antarctic Zone (SAZ), Polar Frontal Zone (PFZ), Permanent Open-Ocean Zone (POOZ) and Sea Ice Zone (SIZ).

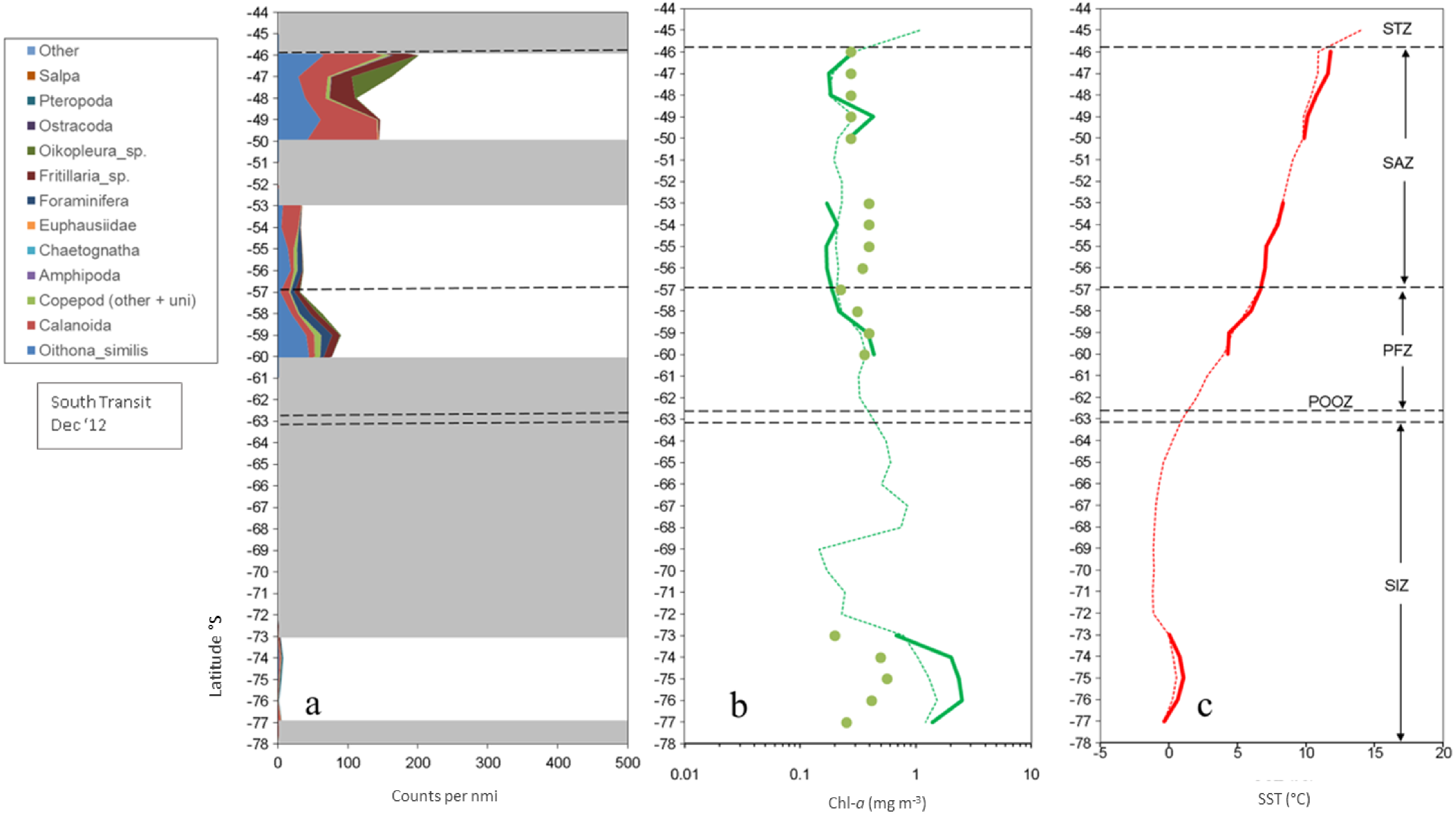


Figure 30: CPR tows 2012–13 (south transit, Dec 2012) a: Refer to Figure 22 for extended legend detail. a: Zooplankton abundance in 13 groups. Grey indicates no CPR data. b: Chlorophyll-*a* concentration (Chl-*a*) (solid green line), long-term mean Chl-*a* (dashed green line), mean Phytoplankton Colour Index (PCI) (green dots). c: Sea surface temperature (SST) (solid red line), mean SST (dashed red line). Black dashed lines show boundaries between oceanographic zones: Sub-Tropical Zone (STZ), Sub-Antarctic Zone (SAZ), Polar Frontal Zone (PFZ), Permanent Open-Ocean Zone (POOZ) and Sea Ice Zone (SIZ).

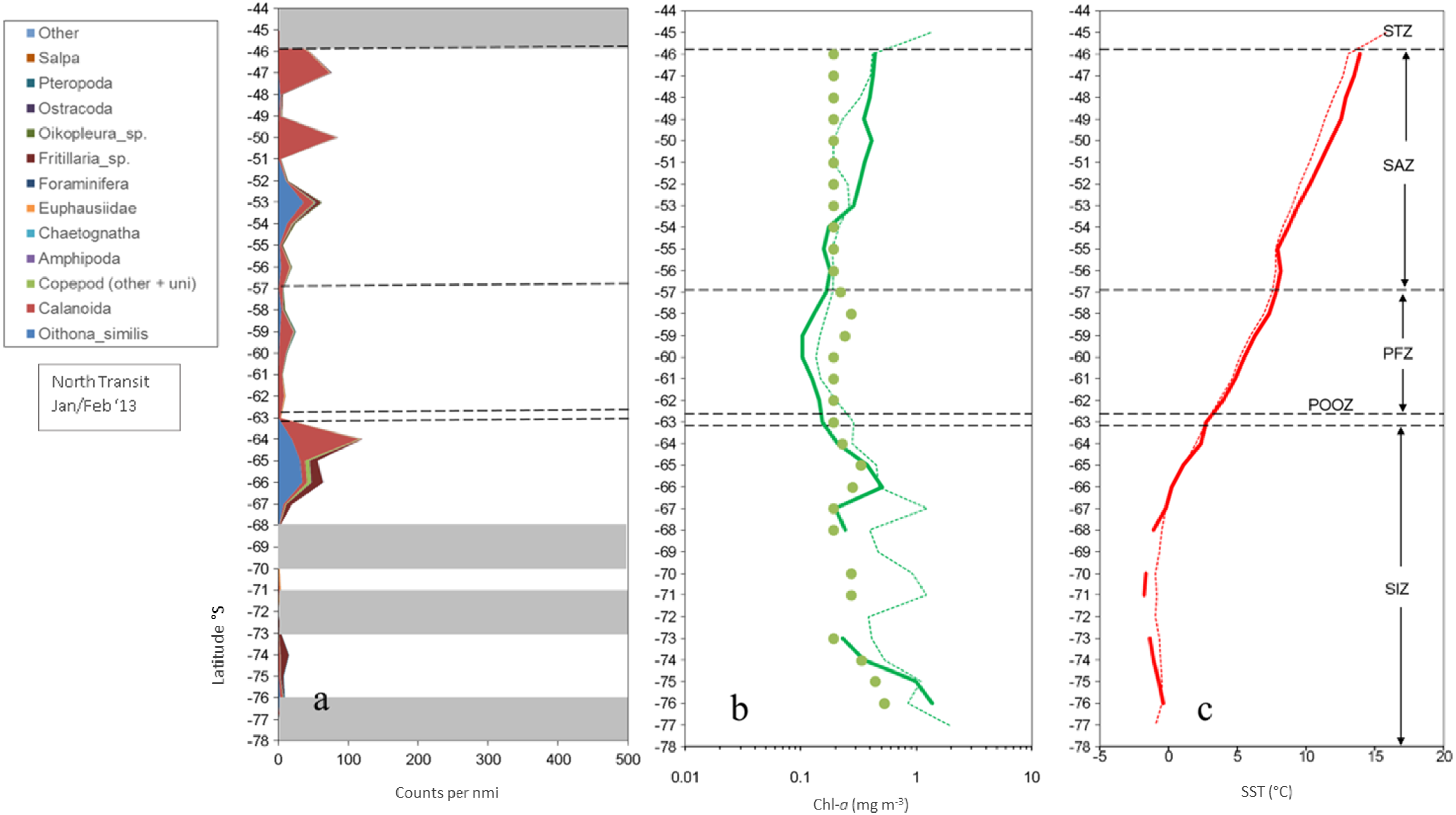


Figure 31: CPR tows 2012–13 (north transit, Jan/Feb 2013) a: Refer to Figure 22 for extended legend detail. a: Zooplankton abundance in 13 groups. Grey indicates no CPR data. b: Chlorophyll-*a* concentration (Chl-*a*) (solid green line), long-term mean Chl-*a* (dashed green line), mean Phytoplankton Colour Index (PCI) (green dots). c: Sea surface temperature (SST) (solid red line), mean SST (dashed red line). Black dashed lines show boundaries between oceanographic zones: Sub-Tropical Zone (STZ), Sub-Antarctic Zone (SAZ), Polar Frontal Zone (PFZ), Permanent Open-Ocean Zone (POOZ) and Sea Ice Zone (SIZ).

3.7 Latitudinal variation in zooplankton abundance

Comparisons of zooplankton abundance were made between the Ross Sea region, comprising the NZ CPR data, and the East Antarctic region which includes the Australian and Japanese CPR data. The Sub-Tropical Zone was not considered for comparison as it is not normally sampled by Australia or Japan in the East Antarctic region, therefore comparisons were based on four oceanic zones: The Sub-Antarctic Zone, the Polar Frontal Zone, the Permanent Open-Ocean Zone and the Sea Ice Zone.

On average, within the same oceanographic zone, total abundances of zooplankton in the Ross Sea region were substantially higher than those in the East Antarctic region (Figure 32). The overall mean zooplankton abundance in the Ross Sea region was also consistently higher than that of the East Antarctic region: note the 8-fold scale change in zooplankton abundance between Figure 33 and Figure 34. In the Ross Sea region, high overall abundances occurred in 2009–10 for all the zones (Figure 33). The Permanent Open-Ocean Zone showed high abundances in 2010–11, while the Polar Frontal Zone had increasing abundances over the sampling period in 2010–11 and 2011–12. Zooplankton abundances in the East Antarctic region showed a significant increasing trend with time ($p<0.05$), while the Ross Sea region showed no trend (Table 7).

The consistent timing of sampling in the Ross Sea region showed that variability in zooplankton abundance within a sampling season can be very great (Figure 33). The median reduced by a factor of about 3 from December to February in any given year in the Ross Sea region. In the Sub-Antarctic Zone in the 2009–10 year however, there was an 11-fold change in total zooplankton abundance between December 2009 and February 2010. Most of this change was due to changes in the abundance of *Fritillaria* sp. The cyclopoid copepod *Oithona similis* was abundant in all oceanic zones, but peaked in 2008–09 in the Sub-Antarctic Zone, and in the Polar Frontal and Permanent Open-Ocean Zones in 2010–11.

In the East Antarctic region, variations in total zooplankton abundance in zones between years ranged between −69% and +76% of the long-term (12 years) mean. The Sub-Antarctic Zone and Sea Ice Zone were more variable in terms of total zooplankton abundance than the Polar Frontal Zone and Permanent Open-Ocean Zone (mean absolute interannual variability of 26% and 33% compared to 14% and 17% respectively). In the Ross Sea region, mean annual variations in total zooplankton abundance ranged between −98% and +181% of the long-term (5 years) mean. Mean absolute interannual variability was greatest in the Sea Ice Zone (72%) and lowest in the Polar Frontal Zone (28%).

The greater variability in zooplankton abundance over a shorter period of sampling in the Ross Sea region, (5 years compared to more than 12 years in East Antarctic), suggests that zooplankton may be more variable in the Ross Sea region than in the East Antarctic region. However this conclusion should be treated with caution because the sampling was different in the two regions. In the Ross Sea region, the interannual variability is the “true” variability in zooplankton abundance in a given longitudinal strip. In contrast, the interannual variability in CPR data in the East Antarctic region includes differences in longitude as well as latitude because of the greater area of sampling.

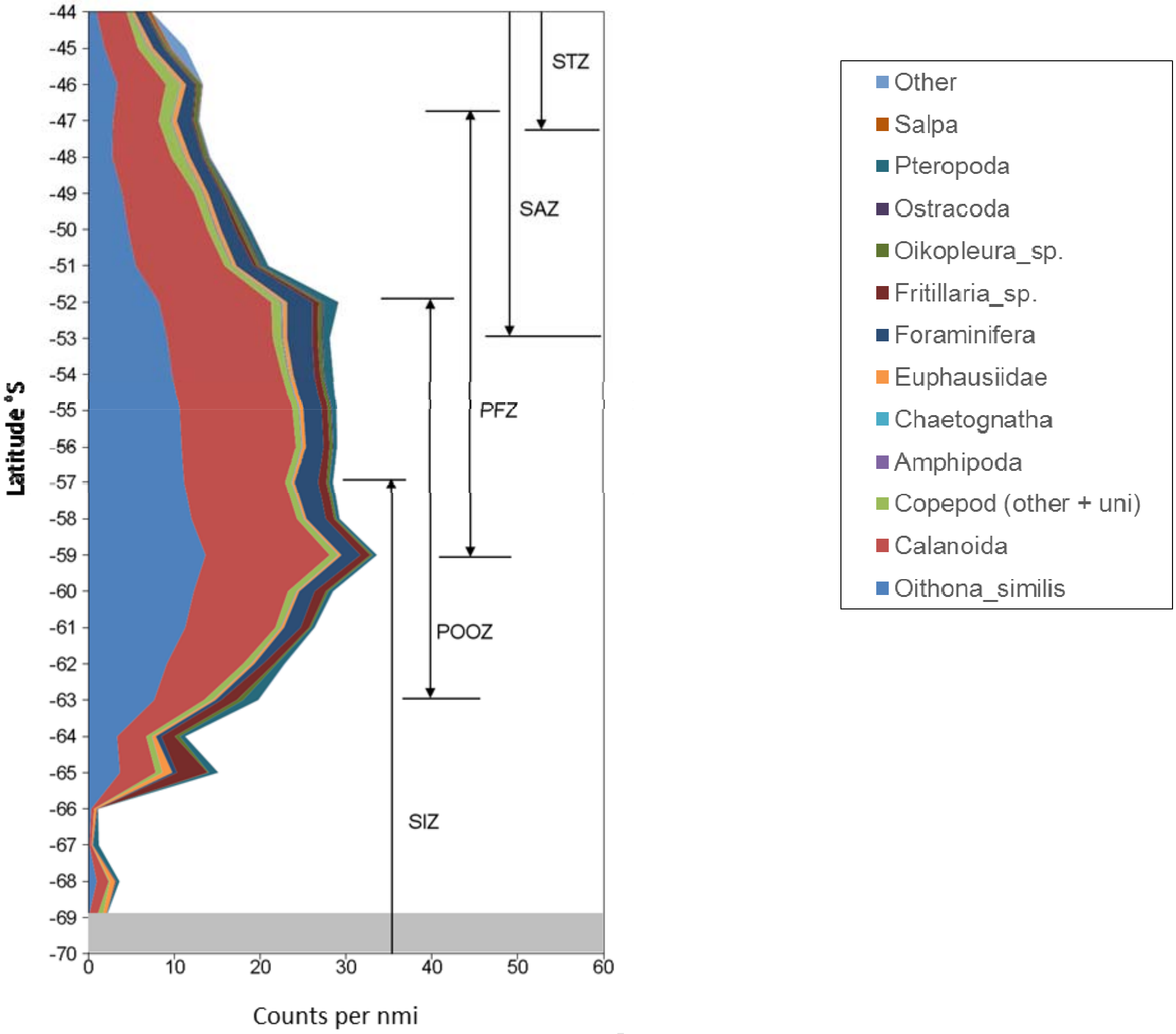


Figure 32: Abundance of 13 groups of zooplankton in the East Antarctica region shown as medians per 1° latitude bin. Note that this represents a wide longitudinal range of 60°E to 160°E, and includes all CPR data from many seasons and years (1995–2013). Black dashed lines show boundaries between oceanographic zones: Sub-Tropical Zone (STZ), Sub-Antarctic Zone (SAZ), Polar Frontal Zone (PFZ), Permanent Open-Ocean Zone (POOZ) and Sea Ice Zone (SIZ). These zones overlap because the frontal boundaries between them vary latitudinally across the East Antarctica region. Grey indicates no CPR data (no data south of 69°S).

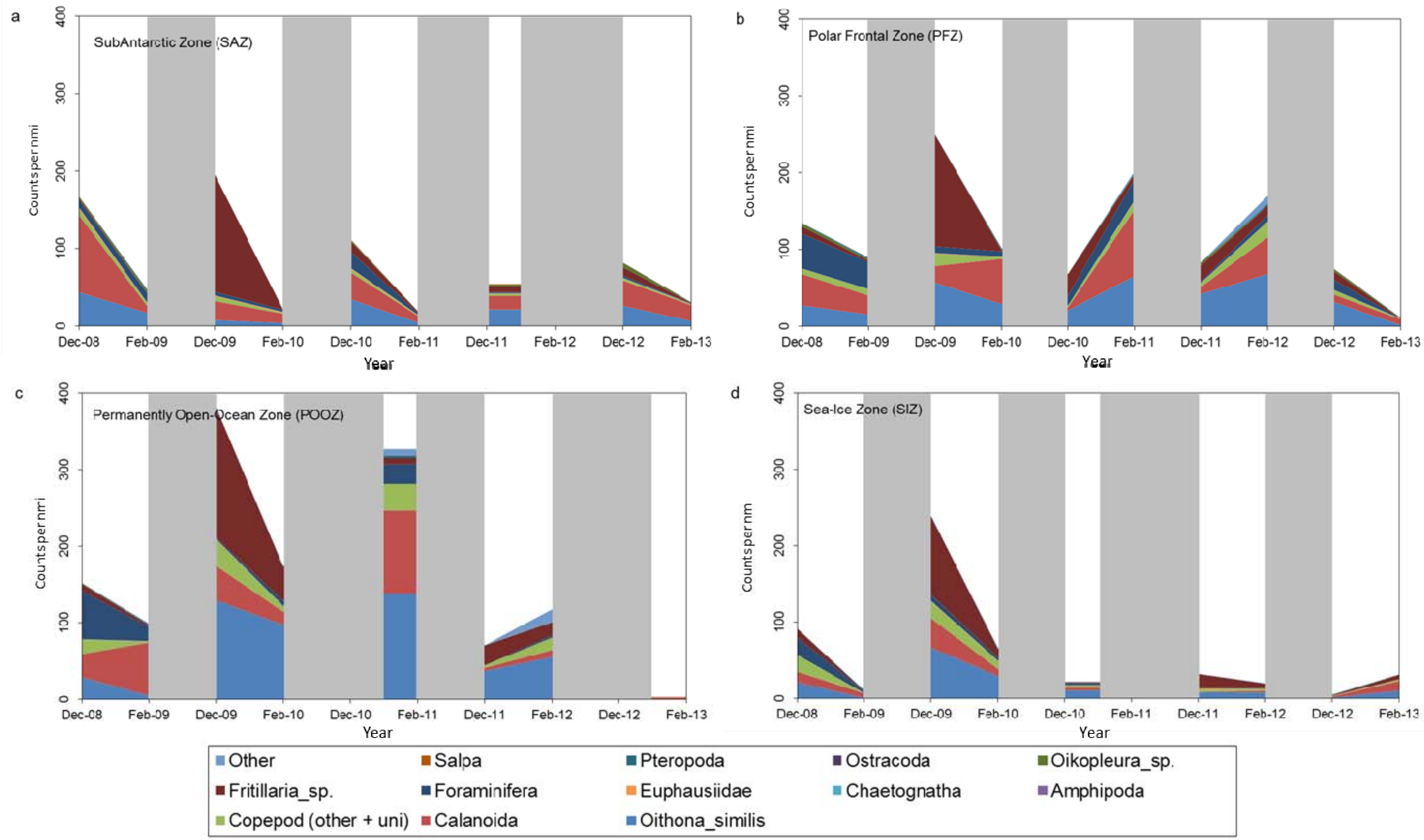


Figure 33: Variation in zooplankton abundance in the Ross Sea (RS) region over time (December 2008 – February 2013). a: Sub-Antarctic Zone (SAZ); b: Polar Frontal Zone (PFZ); c: Permanent Open-Ocean Zone (POOZ); d: Sea Ice Zone (SIZ). Grey areas indicate no data.

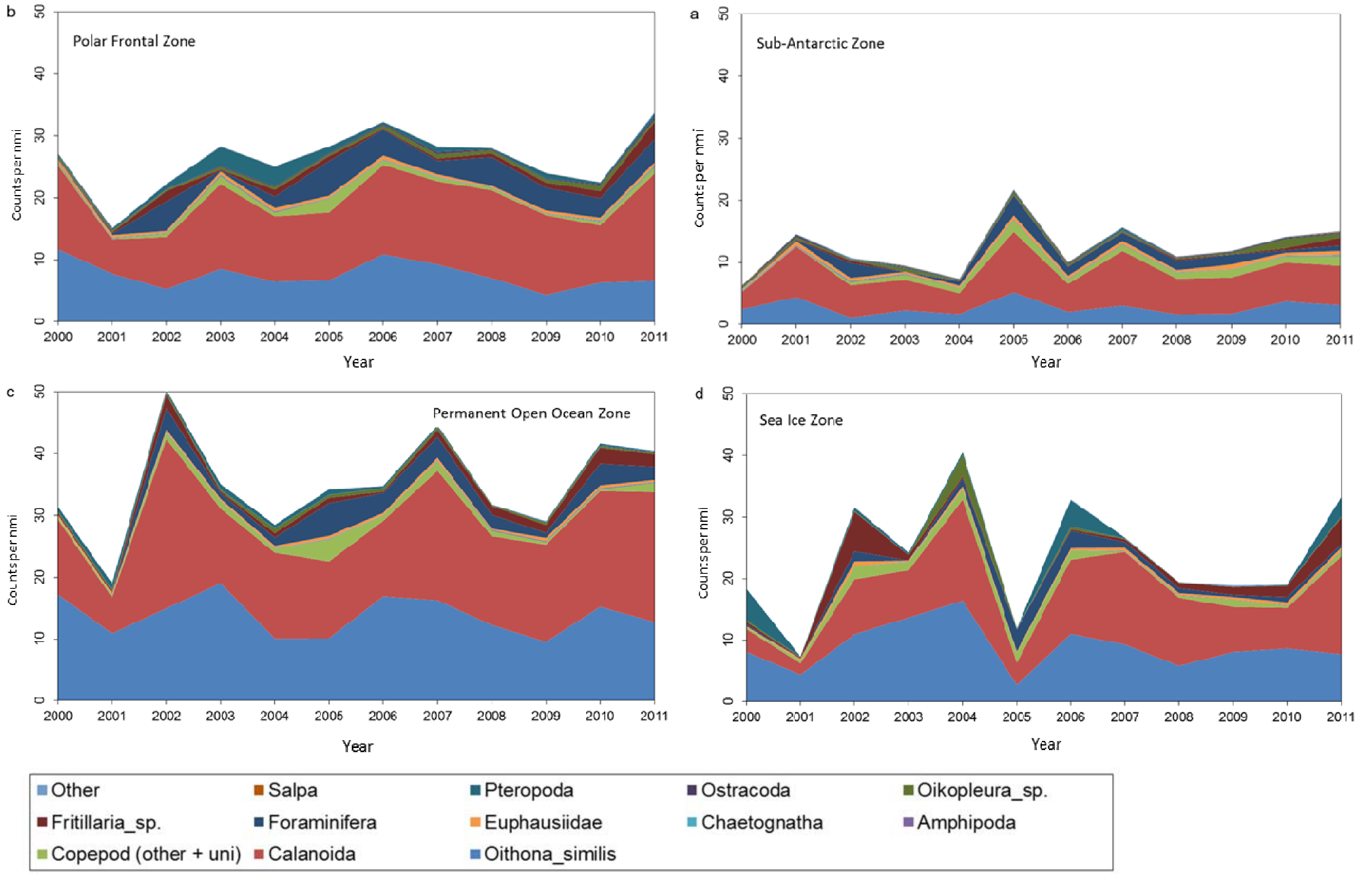


Figure 34: Variation in zooplankton abundances in the East Antarctic (EA) region over time (1999–2000 to 2010–2011 years). a: Sub-Antarctic Zone (SAZ); b: Polar Frontal Zone (PFZ); c: Permanent Open-Ocean Zone (POOZ); d: Sea Ice Zone (SIZ).

Table 7: Regression analysis of trends in mean total zooplankton abundance with time (year) in Ross Sea (RS) region including FV *San Aotea II* (2008–2013) and RV *Tangaroa* data (2006, 2008, 2010) and the East Antarctic (EA) region (1991–2011). Oceanographic zones are: Sub-Antarctic Zone (SAZ), Polar Frontal Zone (PFZ), Permanent Open-Ocean Zone (POOZ) and Sea Ice Zone (SIZ). p<0.05 is statistically significant.

Region	Oceanographic Zone	F Value	R^2	*P*	D.F.
East Antarctic (1991–2011)	SAZ	5.160	0.319	0.044	1,13
	PFZ	9.368	0.419	0.009	1,14
	POOZ	8.980	0.409	0.010	1,14
	SIZ	5.874	0.311	0.031	1,14
Ross Sea (2006–2013)	SAZ	0.600	0.107	0.474	1,6
	PFZ	0.639	0.113	0.460	1,6
	POOZ	0.183	0.035	0.687	1,6
	SIZ	0.115	0.023	0.748	1,6

3.8 Average Copepod Community Size (ACCS)

The ACCS in the oceanic zones of the East Antarctic region showed a steady increase in the average size of copepods from the mid-1990s to 2010 (Figure 35). This suggests a shift in dominance to larger species of copepods in that period. The Ross Sea region showed no significant trends from 2008 to 2013. This result should be treated with caution as the Ross Sea time series is still relatively short and the level of variability between years is high. All trends in the East Antarctic region were statistically significant (p<0.05) but none were significant in the Ross Sea region (Table 8).

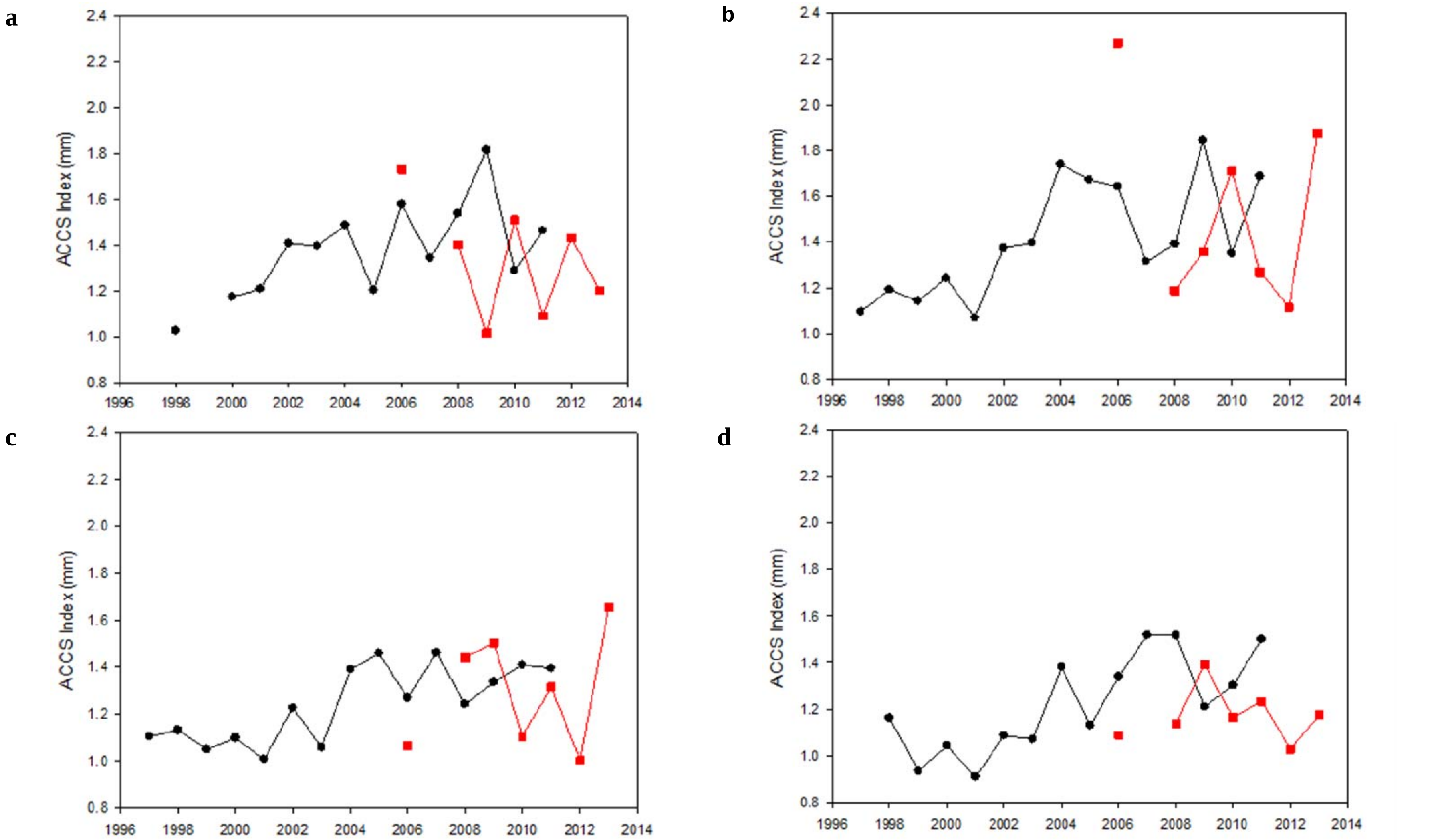


Figure 35: Average Copepod Community Size (ACCS) for the East Antarctic (black circles) and Ross Sea (red squares) regions in four oceanographic zones. a: Sub-Antarctic Zone (SAZ); b: Polar Frontal Zone (PFZ); c: Permanent Open-Ocean Zone (POOZ); d: Sea Ice Zone (SIZ). There are insufficient data for comparison in the Sub-Tropical Zone.

Table 8: Regression analysis of trends in the Average Copepod Community Size (ACCS) index between the Ross Sea (RS) region including FV *San Aotea II* (2008–2013) and RV *Tangaroa* data (2006, 2008, 2010) and the East Antarctic (EA) region (1991–2011). Oceanographic zones are: Sub-Antarctic Zone (SAZ), Polar Frontal Zone (PFZ), Permanent Open-Ocean Zone (POOZ) and Sea Ice Zone (SIZ). p<0.05 is statistically significant.

Region	Oceanographic Zone	F Value	R^2	*P*	D.F.
East Antarctic (1991–2011)	SAZ	7.435	0.403	0.020	1,13
	PFZ	11.681	0.473	0.005	1,14
	POOZ	17.426	0.573	0.001	1,14
	SIZ	15.153	0.558	0.002	1,13
Ross Sea (2006–2013)	SAZ	1.719	0.256	0.247	1,6
	PFZ	0.688	0.121	0.445	1,6
	POOZ	0.365	0.068	0.572	1,6
	SIZ	0.002	0.000	0.966	1,6

3.9 Multivariate analysis of zooplankton abundance and environmental variables

The non-metric multidimensional scaling ordination (MDS) of CPR zooplankton abundance data as described in Section 2.5.4 are shown in Figure 36 (untransformed abundances) and Figure 37 (log(1+x) transformed abundances). In the Ross Sea region, the average 1° latitude-average abundances vary by more than a factor of 300 (more than two orders of magnitude) between taxonomic groups (from 0.07 individuals per nautical mile for Ostracoda to 23 Calanoid individuals per nautical mile). Despite this, the MDS ordination results are very similar whether based on untransformed or log(1+x) transformed Bray-Curtiss resemblance matrices, implying robustness in the results.

The MDS stress levels (0.09 for untransformed and 0.11 for log transformed) indicate good ordination, and suggest that higher-dimensional ordination is not warranted (Clarke & Warwick 2001). The x-dimension of the MDS (shown in Figure 36 and Figure 37) is driven mainly by variations in total abundance of zooplankton across the Ross Sea region dataset. Strongest correlations on the x-axis with the "environmental" covariates were total abundance (r^2=0.55 untransformed, 0.34 log transformed), and within-season date (r^2=0.14, 0.10). Zooplankton abundances increase to the left on MDS axis 1 and in most cases this corresponds to earlier within-season date, consistent with Figure 33. In terms of zooplankton groups, the x-axis correlates most strongly with the following groups: *O. similis* (r^2=0.42 untransformed, 0.64 log transformed), Calanoid copepods (r^2=0.29, 0.46), Copepod other/unidentified (r^2=0.31, 0.45), Foraminifera (r^2=0.19, 0.37), *Fritillaria* sp. (r^2=0.16, 0.31). Samples in the Sea Ice Zone (SIZ) and in the 2008–09 (SIZ only) and 2010–11 (SIZ usually) years tended to have higher values on the x-axis.

The MDS y-axis is driven mainly by variations in zooplankton community with latitude (and SST) across the Ross Sea dataset. Latitude and SST increase upwards as represented in the MDS, so that northern samples tend to be toward the top of Figure 36 and Figure 37. Strongest correlations with environmental covariates with the y-axis were latitude (r^2=0.11 untransformed, 0.08 log transformed) and SST (r^2=0.16, 0.19). The higher correlation of zooplankton community similarity on the y-axis with sea surface temperatures rather than latitude suggests that this is showing a functional environmental link i.e. that zooplankton communities are responding to differences in upper ocean water temperature. In terms of zooplankton groups, y-axis correlates most strongly with groups: calanoid copepods (r^2=0.17, 0.21), Euphausiidae (r^2=0.08, 0.24), Ostracoda (r^2=0.12, 0.16), *Fritillaria* sp. (r^2=0.11, 0.17) and Amphipoda (r^2=0.10, 0.12). MDS y-axis hence corresponds to variations in the less dominant zooplankton groups. Zooplankton data in the 2009–10 southward transit in all zones, except the Sea Ice Zone stand out as being unusual, tending to lie low on the y-axis. This corresponds to the unusually high abundance of *Fritillaria* sp. measured here (Figure 34 and Section 3.7). There were no overall clear patterns in terms of variation by oceanographic zone or season on the y-axis.

Co-variation between zooplankton community and chl-*a* concentration was weak (r^2<0.01). There was little evidence here of ecological compensation among groups (i.e. one zooplankton group increasing at the expense of another); all zooplankton groups (including Chaetognatha, *Oikopleura* sp., Pteropoda and Salpa) varied in the same sense on x-axis and y-axis.

The cluster analysis was quite uninformative, identifying only three groups at the 30% resemblance level, and these were simply spread across the total abundance continuum (MDS axis 1). Clusters identified based on higher resemblance levels are similarly spread along the x-axis. The points to the right of the x-axis (low abundance) correspond mainly to zooplankton distributions measured in the Sea Ice Zone in the 2010–11 season, northward transit (Figure 27).

Zooplankton data for the East Antarctic region fall close to the centre of those for the Ross Sea region in Figure 36 and Figure 37, rather than forming a separate cluster in the MDS analysis. This is partly a result of the highly averaged nature of data from the East Antarctic region (five zonal averages compared to 203 for the Ross Sea region), but also indicates that the zooplankton communities between the regions are broadly similar. The fact that the East Antarctic data plot to the right of the majority of the Ross Sea data in Figure 36 and Figure 37 is consistent with the lower abundances of zooplankton in the East Antarctic region, and the predominant correlation of the x-axis with (decreasing) total zooplankton abundance.

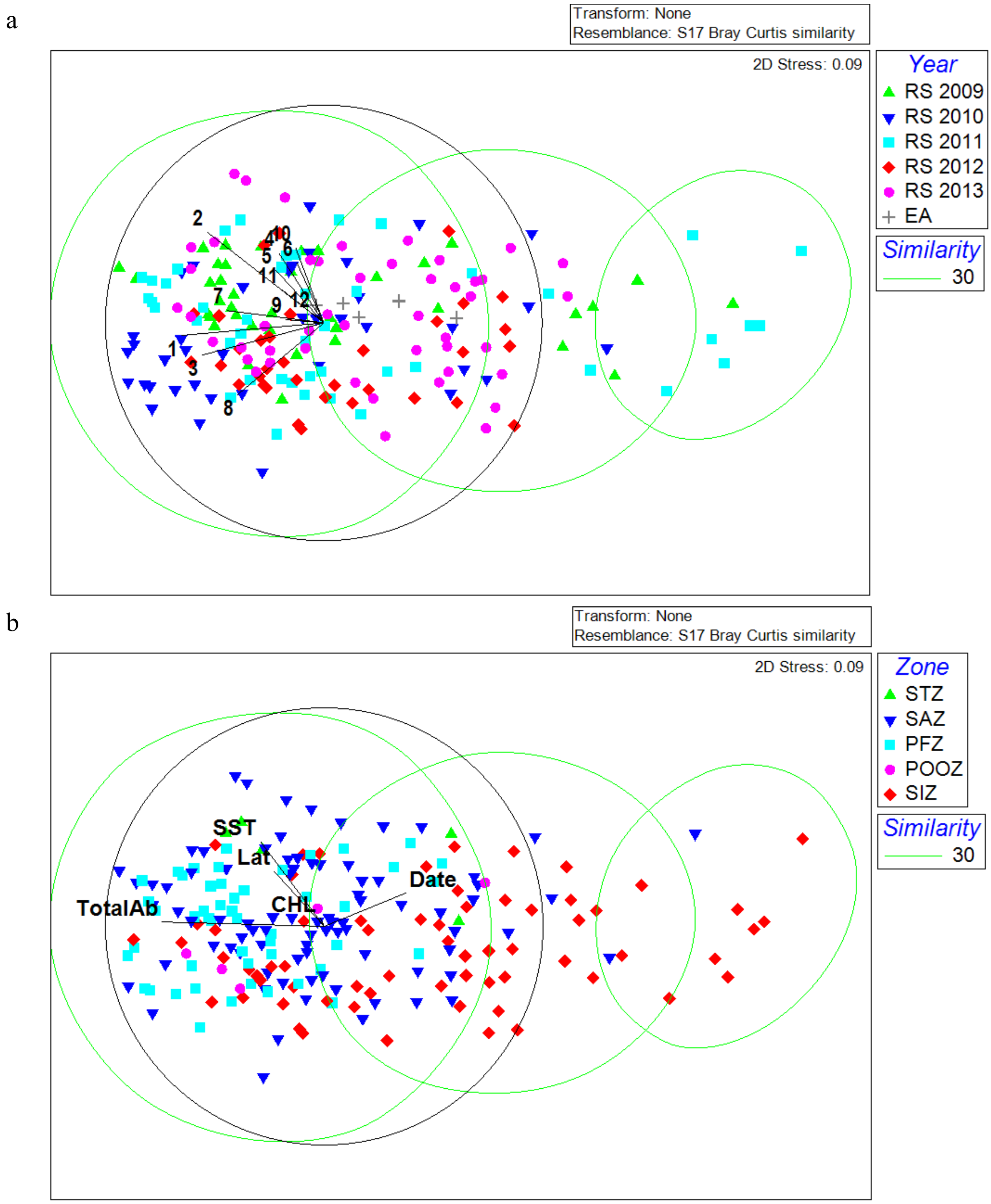
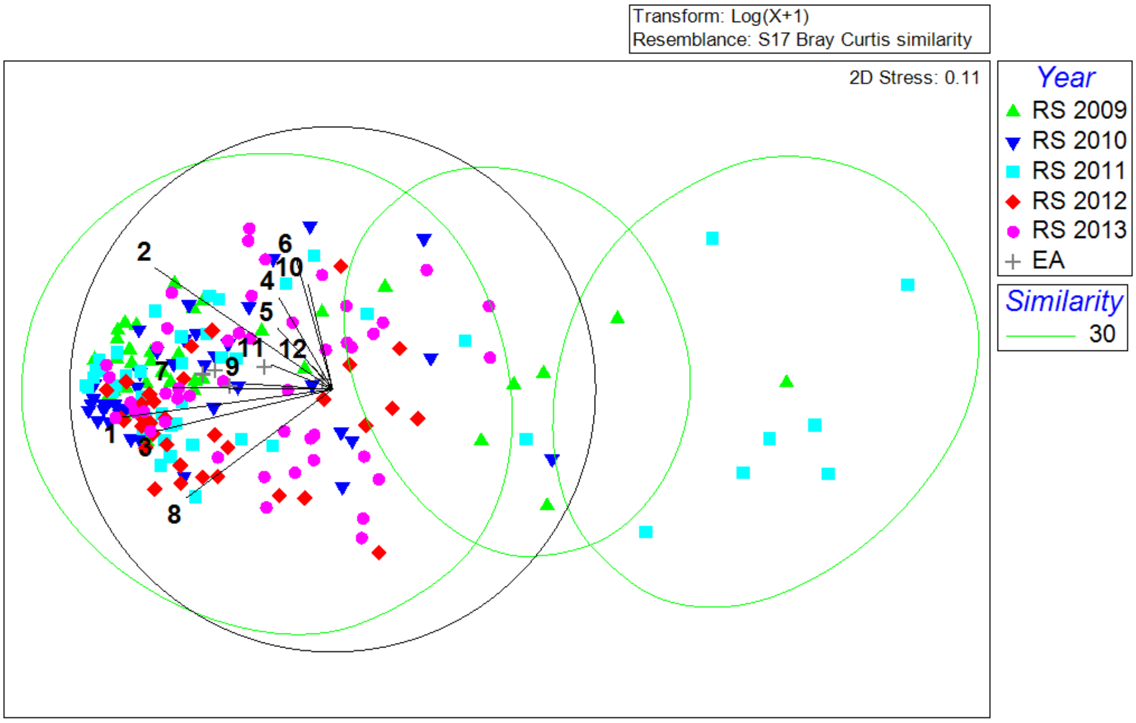


Figure 36: Non-metric multidimensional scaling ordination (MDS) of CPR untransformed zooplankton abundance data as described in Section 2.5.4. For the Ross Sea (RS) region, coloured points represent zooplankton communities in 1° latitude bins by year (e.g. 2008–09 sampling is labelled "2009"), and transit (north or south). Green circles indicate clusters superimposed on the MDS and enclose points with more than 30% similarity (group means). a: Data differentiated by year. Contributions by the 12 individual zooplankton groups (see Table 2 for key) are shown as black vectors within the unit correlation circle (black). Grey crosses represent East Antarctica (EA) data summarized into five oceanographic zones (Section 2.5.1). b: Data differentiated by oceanographic zone. Contributions by "environmental" covariates are shown as black vectors within the unit correlation circle (black): latitude ("Lat"), total zooplankton abundance ("TotalAb"), within season date (days since 1 January in that season, "Date"), satellite-derived chlorophyll-*a* concentration ("CHL") and sea surface temperature ("SST").

a



b

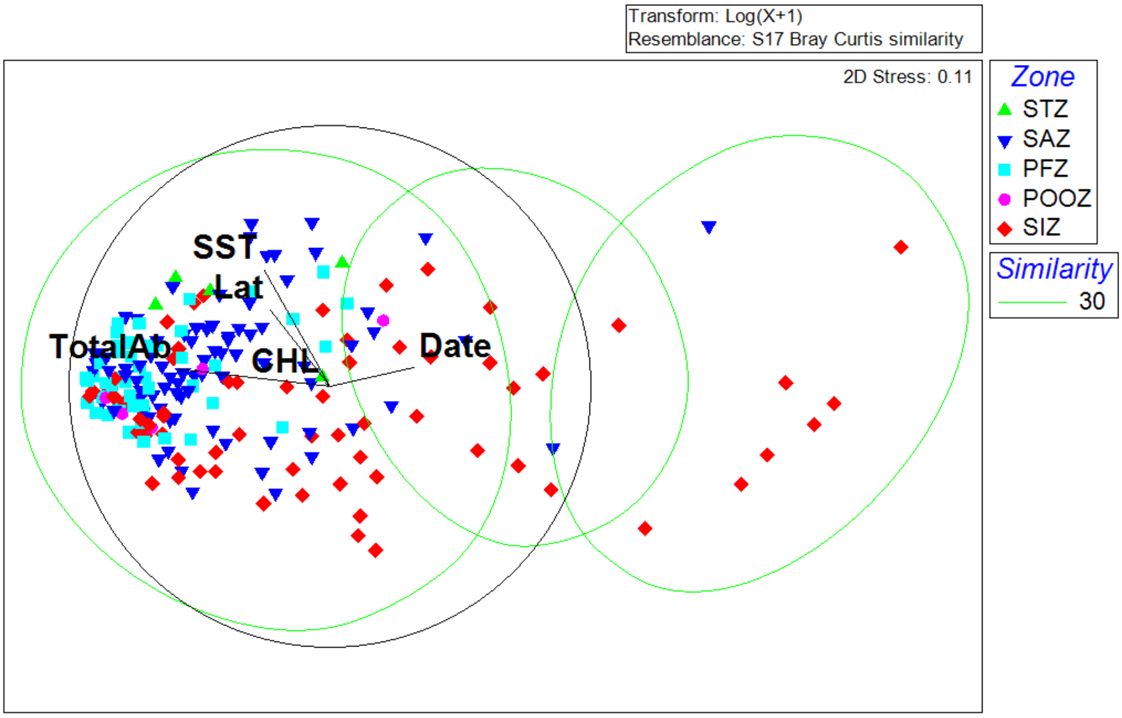
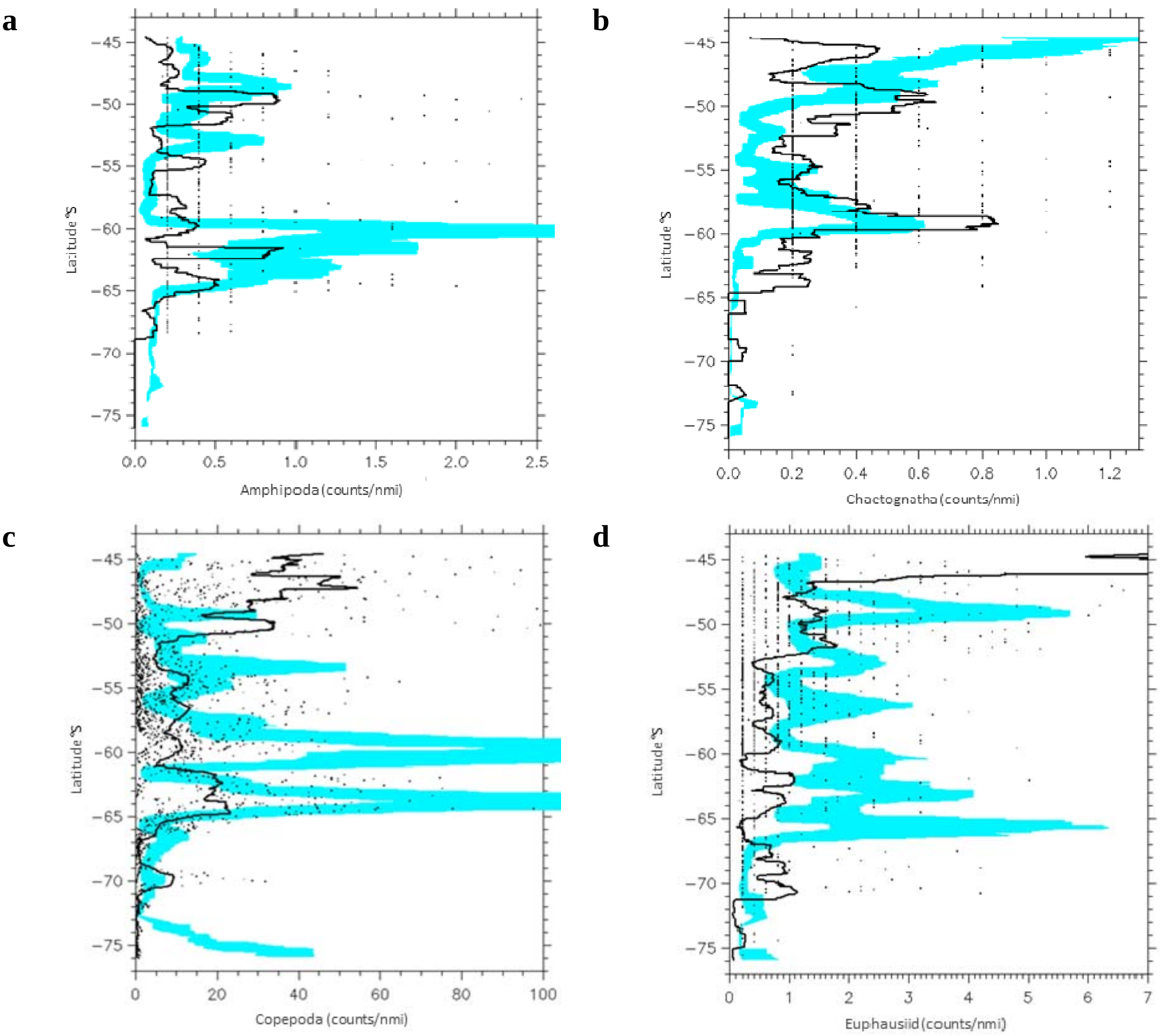


Figure 37: Non-metric multidimensional ordination (MDS) of CPR log(1+x) transformed zooplankton abundance data as described in Section 2.5.4. For the Ross Sea (RS) region, coloured points represent zooplankton communities in 1° latitude bins by year (e.g. 2008–09 sampling is labelled "2009"), and transit (north or south). Green circles indicate clusters superimposed on the MDS and enclose points with more than 30% similarity (group means). a: Data differentiated by year. Contributions by the 12 individual zooplankton groups (see Table 2 for key) are shown on black axes within the unit correlation circle (black). Grey crosses represent East Antarctica (EA) data summarized into five oceanographic zones (Section 2.5.1). b: Data differentiated by oceanographic zone. Contributions by "environmental" covariates are shown on black axes within the unit correlation circle (black): latitude ("Lat"), total zooplankton abundance ("TotalAb"), within season date (days since 1 January in that season, "Date"), satellite-derived chlorophyll-*a* concentration ("CHL") and sea surface temperature ("SST").

3.10 Boosted Regression Tree (BRT) model-based comparisons

For some species and in some latitudinal oceanic zones the predicted abundances of zooplankton in the Ross Sea region based on data from East Antarctic region were qualitatively similar to those measured in situ by the CPR in the present study (Figure 38). For example, the BRT model data reproduced the increased abundance of amphipods, chaetognaths, copepods, Foraminifera, *O. similis*, pteropods and total zooplankton abundance around the Polar Front (60–65°S). Also, similar relative magnitudes of abundances between the different groups were generally seen in the predicted and measured data (i.e. within a factor of 10). However, it is clear that in many cases the models are not qualitatively or quantitatively consistent with the data measured in situ by the CPR in this study. For example, the BRT models failed to capture the elevated abundances of copepods, *O. similis* or total abundance north of about 50°S. In some cases (especially Foraminifera, *Fritillaria* sp., and pteropods), there are some very substantial differences between patterns of abundance predicted based on East Antarctic data and measured locally using the CPR in this study. This suggests that using predictive models based on data from the East Antarctic does not completely reproduce the patterns of abundance seen using in-situ sampling within the Ross Sea region.



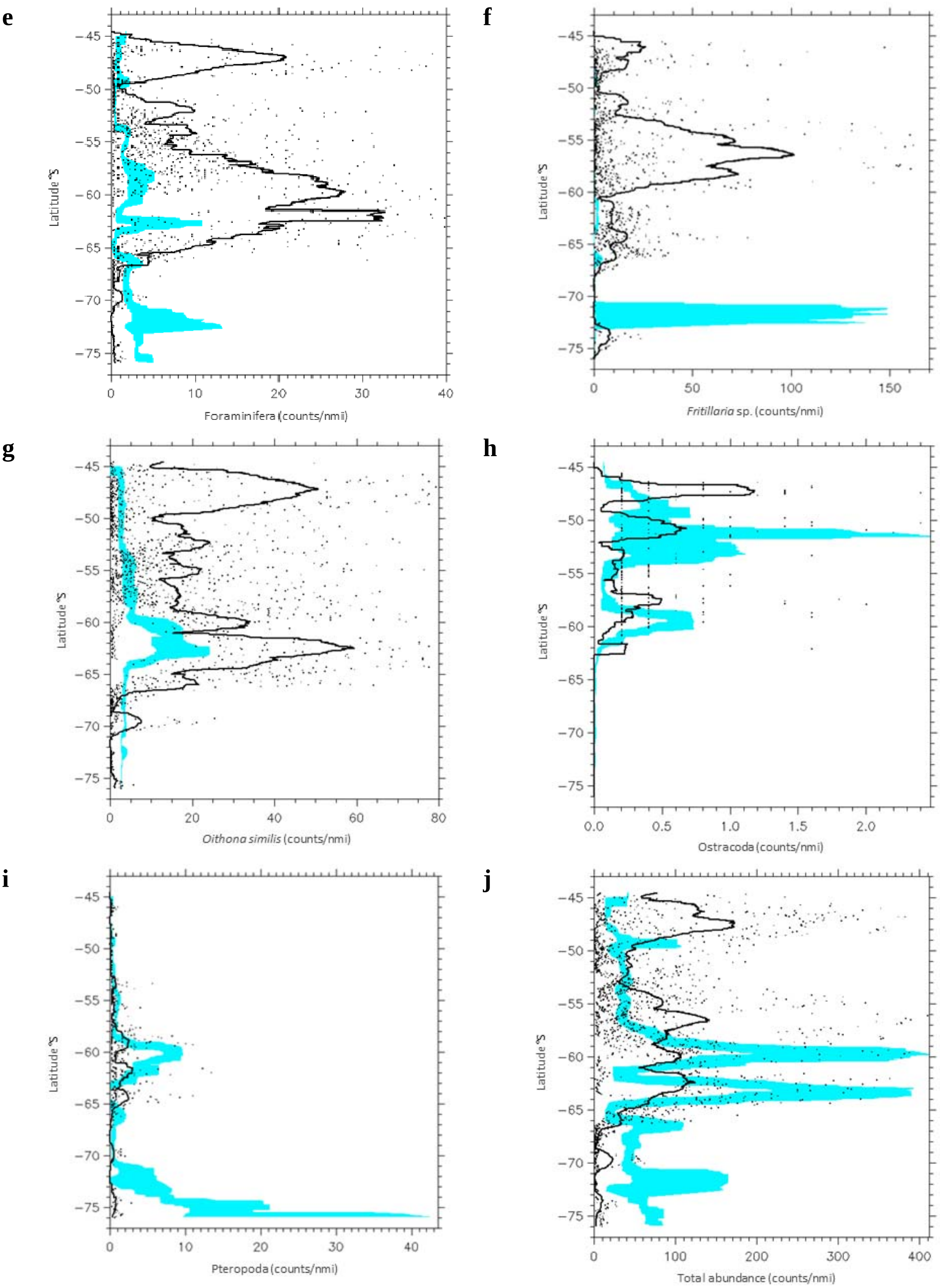


Figure 38: Comparisons of abundance (numbers per nautical mile) of zooplankton groups in the Ross Sea region. Blue shaded area: 10th – 90th percentiles of abundance predicted using a Boosted Regression Trees (BRT) species-environment model (see Pinkerton et al. 2010b) based predominantly on CPR data in East Antarctic region. Black dots: Abundance measured in the Ross Sea region in this study using the CPR deployed from FV *San Aotea II*. Black line: mean abundance measured in this study using FV *San Aotea II* data. a: Amphipoda; b: Chaetognatha; c: Copepoda; d: Euphausiids; e: Foraminifera; f: *Fritillaria* sp.; g: *Oithona similis*; h: Ostracoda; i: Pteropoda; j: total zooplankton abundance.

4 DISCUSSION

The Ross Sea Strategy commits New Zealand to stewardship of the Ross Sea region, allowing New Zealand to harvest marine living resources whilst protecting Southern Ocean ecosystems. Ecosystem-based management of human activities in the Ross Sea region requires an acknowledgement that global environmental changes can affect ecosystem structure and function. Monitoring for change in the lower trophic levels of the foodweb such as phytoplankton and zooplankton, as recorded through the NZ-CPR programme, provides context for New Zealand stewardship of the Ross Sea region.

The NZ-CPR transects from New Zealand to the Ross Sea have provided data relevant to the CCAMLR aim to evaluate and monitor change in the Southern Ocean in the context of developing a network of marine protected areas. This project aligns with the proposal to establish a marine protected area (MPA) in the Ross Sea and forms part of a monitoring and research plan to accompany the MPA proposal which included a priority to initiate and maintain: "*Continuous Plankton Recorder (CPR) monitoring of Ross Sea shelf using ships of opportunity (supply ships, tourist vessels, fishing vessels) and using research vessels (periodically, as available) for validation. The surveys should characterize and monitor surface zooplankton distributions, especially copepods, pteropods and species known to be prey of silverfish* (Delegations of New Zealand and the USA 2013).

This NZ-CPR project aligns with one of SCAR's previous Scientific Research Programmes - "Evolution and Biodiversity in the Antarctic", and the new Scientific Research Programmes - State of the Antarctic Ecosystem (AnT-Eco – www.scar.org/researchgroups/progplanning/#AntEco) and Antarctic Thresholds - Ecosystem Resilience and Adaptation (AnT-ERA – www.scar.org/researchgroups/progplanning/#AnT-ERA), which aim to understand the present biological processes and provide data to test future predictions of ecosystem change.

New Zealand's Antarctic and Southern Ocean Science Directions and Priorities 2010–2020 identified priorities as: (1) to assess population status for a range of species and their role within the Ross Sea ecosystem; (2) to improve understanding of the biodiversity and marine ecosystems in the Ross Sea region; (3) to improve understanding of the oceanography, bathymetry and hydrography of the Ross Sea; (4) to understand how the marine environment and marine food webs may respond to climate change and ocean acidification. The NZ-CPR Survey transects contribute to all four key priorities. Zooplankton were identified as being one of the groups with the largest overall effect on maintaining ecosystem structure and function in the Ross Sea region (Pinkerton et al. 2010a; Pinkerton & Bradford-Grieve 2012). Mixed trophic impact analysis (Ulanowicz & Puccia 1990; Libralato et al. 2006) indicated that mesozooplankton were between the first and third most trophically important groups in the Ross Sea foodweb. Other key groups in the ecosystems of the Ross Sea sector include Antarctic and crystal krill, both of which can be found in CPR datasets.

Any changes to zooplankton communities may have important flow-on effects to other species in the foodweb. For example, silverfish diet is known to include a substantial proportion of zooplankton in the Ross Sea (Pinkerton et al. 2012), with *Metridia gerlachei* and *Paraeuchaeta antarctica* (both copepods) being consumed in reasonably high proportions. Where silverfish have recently disappeared from Southern Ocean ecosystems (e.g. on the parts of the Antarctic Peninsula), there have been adverse effects on top predators that feed on silverfish (Torres, 2010). The reasons for changes to silverfish populations elsewhere are not known; had baseline time series of zooplankton abundance been available, more opportunities would have been available to investigate causes for such changes.

Zooplankton are known to be important prey species for seabird populations in the Southern Ocean, including flying birds (Raymond et al. 2010) and penguins. North of the Ross Sea proper, zooplankton support populations of myctophids (*Electrona* sp., *Gymnoloscopus* sp.) which are also prey for air breathing predators. In particular, the large Adelie and Emperor penguin populations in the Ross Sea are likely to feed heavily on zooplankton and myctophids when they disperse northwards from the Ross Sea outside the summer nesting season. Frontal zones are known to be important areas for seabird foraging, so monitoring the zooplankton abundances in these zones will assist in understanding changes to seabird populations. Monitoring zooplankton in these frontal zones may provide an early warning of climate-based effects on higher level species. The feeding (and hence ecological success) of marine mammals, such as southern elephant seals and southern right whales, in the Ross Sea sector are likely to be linked to zooplankton community characteristics and overall abundance also. Spatial maps of zooplankton community structure and abundance provide better information on areas that may be crucial for top predator foraging.

The NZ-CPR survey has in five years achieved more than other CPR surveys have done during their respective establishment periods. For example, the SCAR Southern Ocean CPR Survey (SO-CPR) produced 13 tows in its first five years and only 501 samples (*pers. comm.* G.W. Hosie). Funded by the present project, forty-two successful tows from the FV *San Aotea II* were completed, representing more than 22 000 km of towed distance conducted between 44.5°S and 77.2°S and producing more than 2378 individual 5 nautical mile CPR samples. Laboratory analysis of these samples over the 5 years of this study has involved identifying more than 850 000 zooplankton individuals into 220 taxonomic categories. The NZ-CPR survey has enhanced the knowledge of zooplankton biodiversity in the region between New Zealand and the Ross Sea and has laid the foundation for sustained routine observations of phytoplankton and zooplankton in the region. In particular, the regularity of the sampling, both in terms of location and timing of sampling provides a robust dataset with which to study and monitor variability and change in the regional ecosystem.

High abundances of total zooplankton were often observed just south of or in association with the Sub-Tropical Front (STF) in the Ross Sea Region (at about 45°S) (e.g. Figure 22). This region corresponds with the shelf waters of New Zealand immediately south of Timaru and Wellington, the respective starting ports for the FV *San Aotea II* and RV *Tangaroa* voyages, and the region between the South Island and the northern end of the Campbell Plateau. While lying in the northern part of the Sub-Antarctic Zone, the higher abundances are most likely due to local environmental effects including elevated primary production. The composition of the zooplankton community in the region south of the Sub Antarctic Front in the Ross Sea region (south of about 55°S) is qualitatively similar to other Southern Ocean regions surveyed by CPR, notably the East Antarctic region south and west of Australia where there has been the highest concentration of CPR sampling to date. For example, Hunt & Hosie (2005) showed that, in the region south of Tasmania, the Sub-Antarctic Front was a major biogeographic boundary for zooplankton with higher abundances and higher diversity of zooplankton species north of the front. South of the Sub-Antarctic Front in the Polar Frontal Zone in the East Antarctic region, abundances were elevated contrary to the paradigm that the Permanent Open-Ocean zone is oligotrophic (Hosie et al. 2003; Hunt & Hosie, 2005). The same pattern was observed for total zooplankton abundance and number of zooplankton species in the New Zealand CPR data. The CPR transects between New Zealand and the Ross Sea show a frequent peak of zooplankton abundance just north of the Sea Ice zone, i.e. north of the maximum sea-ice extent, which corresponds with zooplankton abundance in both the Polar Frontal Zone and the Permanent Open-Ocean Zone. Modelling by Pinkerton et al. (2010b) predicted a narrow band of high abundance of *Oithona similis* at much the same location, but the new CPR data has shown that the area of high abundance for total zooplankton is much broader than the predictive models (Figure 38g). Both the predictive models and observations show that the Sea Ice zone of the Ross Sea region has a much lower abundance of zooplankton than the other oceanic zones. The same has been seen in the East Antarctic region where abundances decrease quickly in the Sea Ice zone (Hosie et al. 2003). Reassessment and refinement of the zooplankton bio-regionalisation models for the Ross Sea region using the new dataset may be warranted.

The Ross Sea region as a whole has a higher abundance of zooplankton than the East Antarctic region. This is especially noticeable in the Antarctic Circumpolar Current (ACC), which incorporates the Polar Frontal Zone and the Permanent Open-Ocean Zone. This is despite the Ross Sea region of the ACC being downstream from the East Antarctic. Similarly, the Phytoplankton Colour Index (PCI) scores used as an estimate of phytoplankton production in the latitudinal oceanographic zones were higher in the Ross Sea region than the corresponding zones in the East Antarctic region, as were chl-*a* concentrations from ocean colour satellites. This indicates a higher standing stock or productivity in the Ross Sea region. The proportion of variance explained (r^2=21%) between PCI and satellite-measured (log) chl-*a* concentration was reasonably good considering the large differences in spatial scale, time and methodology between the two approaches to quantifying phytoplankton abundance. It is likely that the higher primary productivity in the Ross Sea region is responsible for the higher zooplankton abundance there.

Since 1991, the East Antarctic region has shown an increasing trend in total zooplankton abundance in the Sub-Antarctic Zone, Polar Frontal Zone, Permanent Open-Ocean Zone and the Sea Ice Zone. The five years of FV *San Aotea II* data, supplemented with the three RV *Tangaroa* voyages providing data since 2006, show no trends in any part of the Ross Sea region in terms of total zooplankton abundance. Total zooplankton abundance in the Ross Sea region varied markedly between years with large peaks in abundance occurring in 2008–09 in the Sub-Antarctic Zone, 2009–10 in the Sea Ice Zone and in 2010–11 in the other oceanographic zones. The cause of these peaks has yet to be determined. The large inter-annual variation in zooplankton abundance in the Ross Sea region contrasts with the observed patterns in the East Antarctic region where there is less inter-annual variation in total zooplankton abundance. Reasons for the higher variability in the Ross Sea region are not known at present.

The Average Copepod Community Size (ACCS) metric was used to compare dominance in copepod species between regions. There was no significant trend in the ACCS in the Ross Sea region during the sampling period. In the East Antarctic region, the ACCS metric showed a significant positive trend from 1991 to 2013, suggesting a shift towards larger copepod species (Figure 35). Reasons for this change are not known at present, however the same zooplankton species were present in the two regions.

Recommendations

Laboratory analysis methods used in the future must strike a balance between being achievable within resource constraints and giving high quality, reliable data over large areas. It would be useful to improve identification of the unidentified copepods and euphausiids. Attempting to better identify a subset of CPR data identified as “calanoid copepods and copepodites” would be informative. Although unknown at present, this group is expected to largely consist of small copepods of the genera *Microcalanus* sp. and *Ctenocalanus* sp. The “calanoid copepods and copepodites” group also contains a small proportion of larger species that are not identifiable because of damage during collection or are early copepodite stages (C1–C3). These proportions should be ascertained, at least at an indicative level. It may also be useful to distinguish generally between adults and developmental (copepodite) stages of major species of large calanoid copepods in order to investigate life cycles and possible phenological variation of these species. However, increasing the required identification level of samples will increase analysis time. Already, substantial additional resources for sample and data analysis were provided to this study from two MBIE projects (C01X1001 “Protecting Ross Sea Ecosystems” and C01X1226 “Ross Sea Ecosystems and Climate”). Hence, careful consideration of the value of any extended data analysis will be needed as this study continues.

We also recommend applying the spatial modelling techniques developed for *Oithona similis* by Pinkerton et al. (2010b) to the updated Southern Ocean CPR survey dataset which includes the new New Zealand - Ross Sea transects. The previous analysis (Pinkerton et al. 2010b) was based on data that included just one RV *Tangaroa* 2006 survey for the Ross Sea region. It is likely that the new larger dataset of zooplankton measurements collected by FV *San Aotea II* and RV *Tangaroa* in the Ross Sea region may improve predictions elsewhere in the Southern Ocean. The improvement may be especially marked in Southern Ocean regions which have elevated primary productivity levels, similar to the Ross Sea region. Modelled spatial and seasonal distributions of a number of common and ecologically important zooplankton taxa from this analysis, such as Antarctic Krill (*Euphausia superba*), other euphausiids, *Oithona similis*, *Calanus* species, salps and pteropods would contribute to a Southern Ocean zooplankton biogeographic atlas of predictive distributions. This would complement the Southern Ocean zooplankton atlas of observations in the East Antarctic region 1991 to 2008 published by McLeod et al. (2010).

5 SUMMARY OF CONCLUSIONS

1. Abundances of zooplankton were higher in the Ross Sea region between 2006–2013 than in similar oceanographic water masses in East Antarctic region. This suggests that the Ross Sea region is more productive than the East Antarctic.

2. There was high interannual variability in the abundance of zooplankton through the Ross Sea region over the course of the study. The interannual changes in total zooplankton abundance in the Ross Sea region observed in this study are apparently much greater than those that occur in East Antarctica. Reasons for the high variability in zooplankton observed in the Ross Sea are not known at present but are likely to affect other parts of the marine food-web, including fishes. For example, more variable zooplankton abundances may lead to more variable feeding strategies in planktivorous fish like myctophids, or more interannual variability in fish survival or breeding success.

3. Modelled predictions of abundances and distributions of key zooplankton groups in the Ross Sea based on data from East Antarctica are generally accurate for abundance order-of-magnitude, but poor for representing distributional patterns in time and space.

4. Local measurements of zooplankton in the Ross Sea region are required for monitoring change in the region. The Ross Sea CPR survey, using twice-annual transits of a fishing vessel on a single track, is an excellent approach for quantifying variability in zooplankton. Less regular (opportunistic) CPR sampling from research-vessels is complementary to the regular FV *San Aotea* CPR transits by providing zooplankton measurements in other areas (off the transit line), at other times of the year and with additional measurements (e.g. fish sampling and stomach analysis to improve understanding of feeding on zooplankton; zooplankton nets to provide samples for isotope analysis).

5. There was no significant trend in the Average Copepod Community Size (ACCS) metric in the Ross Sea region during the sampling period. In the East Antarctic region, the average copepod size increased significantly 1991 to 2013, suggesting a shift towards larger copepod species. Reasons for this change are not known at present. This will be addressed at a regional level by the SCAR SO-CPR survey and globally by the Global Alliance of CPR Surveys (GACS).

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8 APPENDIX 1

FV *San Aotea II* CPR Tow List 2008–2013 from the SCAR SO-CPR database.

Season	Voyage	Tow No.	Start Date	Start Time	Start Lat	Start Long	End Date	End Time	End Lat	End Long
2008–09	SA2-0809	1a	19-Dec-2008	07:11	-44.7217	171.3700	20-Dec-2008	19:29	-49.9167	171.5950
2008–09	SA2-0809	1b	21-Dec-2008	02:00	-49.9467	171.6350	21-Dec-2008	11:34	-51.2683	171.6550
2008–09	SA2-0809	2	21-Dec-2008	11:55	-51.2950	171.6550	22-Dec-2008	05:29	-53.5358	172.1355
2008–09	SA2-0809	3a	23-Dec-2008	20:00	-58.7650	174.9783	24-Dec-2008	00:14	-59.2518	175.8405
2008–09	SA2-0809	3b	24-Dec-2008	03:50	-59.3550	175.6750	26-Dec-2008	10:42	-66.1967	178.2270
2008–09	SA2-0809	4	23-Jan-2009	02:00	-71.0967	-179.7450	23-Jan-2009	20:29	-72.6883	-171.5467
2008–09	SA2-0809	5a	27-Jan-2009	10:05	-75.1450	-158.0133	28-Jan-2009	16:59	-71.6160	-171.7162
2008–09	SA2-0809	5b	28-Jan-2009	22:30	-71.3800	-173.8083	29-Jan-2009	06:19	-70.3745	-176.4358
2008–09	SA2-0809	6a	29-Jan-2009	22:00	-68.0517	-178.8267	30-Jan-2009	03:59	-67.2003	-178.9932
2008–09	SA2-0809	6b	30-Jan-2009	9:30	-66.5383	-178.7583	31-Jan-2009	22:00	-61.1067	-177.7768
2008–09	SA2-0809	7	31-Jan-2009	23:05	-60.9600	177.7000	02-Feb-2009	21:59	-53.8702	174.5947
2009–10	SA2-0910	2	13-Dec-2009	23:00	-52.6500	173.4300	15-Dec-2009	22:59	-59.0950	177.9787
2009–10	SA2-0910	3	15-Dec-2009	23:25	-59.1167	178.0000	17-Dec-2009	18:09	-65.0567	-175.6867
2009–10	SA2-0910	4	09-Feb-2010	19:45	-70.8667	179.4250	11-Feb-2010	18:58	-63.5950	176.4663
2009–10	SA2-0910	5	11-Feb-2010	19:02	-63.5933	176.4800	13-Feb-2010	21:59	-56.6267	174.0567
2009–10	SA2-0910	6	13-Feb-2010	22:03	-56.5767	174.0567	15-Feb-2010	20:14	-49.6850	172.3833
2009–10	SA2-0910	7	15-Feb-2010	20:30	-49.6833	172.3850	17-Feb-2010	04:40	-45.7500	170.9350
2010–11	SA2-1011	1	23-Nov-2010	02:08	-44.5933	171.3833	24-Nov-2010	18:35	-50.4367	171.7800
2010–11	SA2-1011	2	25-Nov-2010	00:54	-50.4433	171.8217	26-Nov-2010	23:39	-57.3500	174.0083
2010–11	SA2-1011	3	27-Nov-2010	00:00	-57.3617	174.0217	27-Nov-2010	21:39	-59.9800	177.4083
2010–11	SA2-1011	4a	15-Jan-2011	01:15	-71.6847	-179.6345	15-Jan-2011	12:50	-72.4062	-175.152
2010–11	SA2-1011	4b	15-Jan-2011	20:15	-72.7233	-175.1183	16-Jan-2011	22:14	-68.7583	-179.1217
2010–11	SA2-1011	5	16-Jan-2011	22:25	-68.7550	-179.1233	18-Jan-2011	19:14	-61.9467	176.7167

2010–11	SA2-1011	6a	18-Jan-2011	19:30	-61.9100	176.4533	18-Jan-2011	23:20	-61.3350	176.2017
2010–11	SA2-1011	6b	19-Jan-2011	22:50	-60.5917	176.0050	21-Jan-2011	12:59	-54.4600	173.8933
2010–11	SA2-1011	7	21-Jan-2011	13:12	-54.4450	173.8900	23-Jan-2011	08:29	-47.8067	171.2183
2010–11	SA2-1011	8	23-Jan-2011	08:40	-47.7783	171.2150	23-Jan-2011	23:19	-45.2383	171.2350
2011–12	SA2-1112	1a	28-Nov-2011	09:25	-44.4613	171.3420	29-Nov-2011	22:37	-49.5683	171.6667
2011–12	SA2-1112	1b	30-Nov-2011	05:36	-49.6850	171.7033	30-Nov-2011	18:48	-51.7067	172.6317
2011–12	SA2-1112	2	30-Nov-2011	19:06	-51.7517	172.6600	02-Dec-2011	20:40	-58.7933	173.8833
2011–12	SA2-1112	3	2-Dec-2011	21:00	-58.8337	173.8635	04-Dec-2011	03:23	-63.1033	171.7750
2011–12	SA2-1112	6	22-Feb-2012	04:21	-75.7533	168.9967	24-Feb-2012	03:30	-69.8000	177.4417
2011–12	SA2-1112	7	24-Feb-2012	03:30	-69.8000	177.4417	26-Feb-2012	10:30	-61.5500	176.3117
2012–13	SA2-1213	1	3-Dec-2012	08:16	-46.212	170.787	4-Dec-2012	21:30	-51.6333	172.2333
2012–13	SA2-1213	2	5-Dec-2012	21:30	-51.6333	172.2583	7-Dec-2012	09:40	-56.5500	173.9083
2012–13	SA2-1213	3	7-Dec-2012	09:47	-56.5850	173.9133	8-Dec-2012	12:14	-60.0850	176.8417
2012–13	SA2-1213	4	26-Jan-2013	03:13	-72.8367	175.4467	27-Jan-2013	18:00	-77.1667	166.4650
2012–13	SA2-1213	5a	14-Feb-2013	20:40	-76.0267	-178.5950	15-Feb-2013	16:47	-73.1750	178.6150
2012–13	SA2-1213	5b	16-Feb-2013	08:53	-70.9467	-179.6417	16-Feb-2013	18:55	-69.6900	-179.1483
2012–13	SA2-1213	6	17-Feb-2013	05:12	-68.5567	-179.5750	19-Feb-2013	03:15	-62.0333	176.6000
2012–13	SA2-1213	7	19-Feb-2013	10:00	-61.3033	176.4000	22-Feb-2013	04:50	-54.3000	173.8467
2012–13	SA2-1213	8	22-Feb-2013	05:03	-54.2800	173.8433	24-Feb-2013	11:55	-46.3483	171.6867

9 APPENDIX 2

RV *Tangaroa* Ross Sea CPR Tow List 2006–2010 from the SCAR SO-CPR database.

Season	Voyage	Tow Number	Start-Date	Start-Time	Start-Lat	Start-Long	End-Date	End-Time	End-Lat	End-Long
2005–06	TAN0506	1	30-Jan-2006	03:05	-41.9547	175.3277	31-Jan-2006	12:14	-48.1860	-179.9957
2005–06	TAN0506	2	31-Jan-2006	12:45	-48.2117	179.9867	02-Feb-2006	10:09	-54.5115	-176.1741
2005–06	TAN0506	3	2-Feb-2006	10:25	-54.5323	-176.1522	03-Feb-2006	20:22	-60.6170	-169.7127
2005–06	TAN0506	4	3-Feb-2006	20:34	-60.7150	-169.6333	05-Feb-2006	08:21	-67.0084	-163.9655
2005–06	TAN0506	5	5-Feb-2006	23:22	-69.0386	-162.0200	06-Feb-2006	11:31	-71.0207	-159.0176
2005–06	TAN0506	6a	18-Feb-2006	22:28	-74.7617	164.6600	19-Feb-2006	01:41	-74.5892	166.7394
2005–06	TAN0506	6b	19-Feb-2006	03:40	-74.6183	167.8217	20-Feb-2006	05:44	-75.8337	-174.1138
2005–06	TAN0506	7	6-Mar-2006	14:24	-67.2667	-179.9250	07-Mar-2006	21:14	-67.4035	165.2406
2005–06	TAN0506	8	11-Mar-2006	11:03	-66.2450	162.0707	13-Mar-2006	05:25	-59.4780	167.2468
2007–08	TAN0802	1	31-Jan-2008	06:47	-41.4769	174.8010	01-Feb-2008	20:49	-48.9130	174.8268
2007–08	TAN0802	2a	1-Feb-2008	21:18	-49.0016	174.8281	02-Feb-2008	17:41	-52.8838	174.8165
2007–08	TAN0802	2b	3-Feb-2008	03:00	-54.3049	174.8041	03-Feb-2008	17:37	-57.0200	174.7992
2007–08	TAN0802	3	3-Feb-2008	17:54	-57.0698	174.8029	05-Feb-2008	07:31	-63.3875	178.4859
2007–08	TAN0802	4	5-Feb-2008	09:00	-63.4883	178.5400	06-Feb-2008	03:31	-66.4459	-179.9723
2007–08	TAN0802	10	14-Mar-2008	02:35	-67.0105	170.6217	15-Mar-2008	23:15	-60.1235	172.1301
2007–08	TAN0802	11a	15-Mar-2008	23:25	-60.1072	172.1324	17-Mar-2008	06:04	-54.5508	173.3803
2007–08	TAN0802	11b	17-Mar-2008	06:19	-54.5047	173.4025	18-Mar-2008	02:31	-50.4634	173.9359
2009–10	Y1	1	02-Feb-2010	02:01	-41.3565	174.8030	03-Feb-2010	11:06	-47.4906	-179.6033
2009–10	Y1	2	03-Feb-2010	11:24	-47.5269	-179.5729	05-Feb-2010	03:14	-53.9869	-173.6855
2009–10	Y1	3	05-Feb-2010	03:25	-54.0000	-173.6900	06-Feb-2010	18:17	-60.1842	-166.2982
2009–10	Y1	4	06-Feb-2010	18:36	-60.2000	-166.2792	08-Feb-2010	00:56	-64.5422	-159.4490
2009–10	Y1	5	08-Feb-2010	11:25	-65.9962	-157.0154	09-Feb-2010	19:54	-71.0652	-151.2313

10 APPENDIX 3

Groupings of CPR zooplankton groups used in this study (note that the table is in two sets of columns). "Indet" = indeterminate. "o+u" = other and unidentified.

Group	CPR identification	Group	CPR identification
Amphipoda	Amphipod indet	Calanoida	*Acartia danae*
Amphipoda	*Brachyscelus crusculum*	Calanoida	*Acartia* spp
Amphipoda	*Cyllopus lucasii*	Calanoida	*Aetideus* sp.
Amphipoda	*Cyllopus magellanicus*	Calanoida	Calanoid cope & copepodites
Amphipoda	*Dairella latissima*	Calanoida	*Calanoides acutus*
Amphipoda	*Hyperia antarctica*	Calanoida	*Calanoides macrocarinatus*
Amphipoda	*Hyperia* sp.	Calanoida	*Calanus australis*
Amphipoda	*Hyperia spinigera*	Calanoida	*Calanus propinquus*
Amphipoda	*Hyperiella antarctica*	Calanoida	*Calanus simillimus*
Amphipoda	*Hyperiella dilatata*	Calanoida	*Calanus* sp.
Amphipoda	*Hyperiella* sp.	Calanoida	*Calocalanus* sp.
Amphipoda	Hyperiidae indet	Calanoida	*Candacia cheirura*
Amphipoda	*Hyperoche medusarum*	Calanoida	*Candacia falcifera*
Amphipoda	*Hyperoche* sp.	Calanoida	*Candacia maxima*
Amphipoda	*Parathemisto australis*	Calanoida	*Candacia* sp.
Amphipoda	*Parathemisto* sp.	Calanoida	*Centropages aucklandicus*
Amphipoda	*Phronima* sp.	Calanoida	*Centropages bradyi*
Amphipoda	*Platysceloidea* sp.	Calanoida	*Clausocalanus brevipes*
Amphipoda	*Primno macropa*	Calanoida	*Clausocalanus laticeps*
Amphipoda	*Scina* sp.	Calanoida	*Clausocalanus* sp.
Amphipoda	*Themisto australis*	Calanoida	*Ctenocalanus* sp. cf *citer*
Amphipoda	*Themisto gaudichaudi*	Calanoida	*Drepanopus* sp.
Amphipoda	*Vibilia antarctica*	Calanoida	*Euaugaptilus* sp.
Amphipoda	*Vibilia armata*	Calanoida	*Eucalanus* sp.
Amphipoda	*Vibilia* sp.	Calanoida	*Euchirella rostromagna*
Chaetognatha	Chaetognath indet	Calanoida	*Haloptilus oxycephalus*
Chaetognatha	*Eukrohnia hamata*	Calanoida	*Heterorhabdus austrinus*
Euphausiidae	*Euphausia crystallorophias*	Calanoida	*Heterorhabdus farrani*
Euphausiidae	*E. crystallorophias* calyptopis	Calanoida	*Heterorhabdus lobatus*
Euphausiidae	*E. crystallorophias* furcilia	Calanoida	*Heterorhabdus* sp.
Euphausiidae	*Euphausia frigida*	Calanoida	*Heterorhabdus spinifrons*
Euphausiidae	*Euphausia frigida* calyptopis	*Calanoida*	*Lucicutia sp.*
Euphausiidae	*Euphausia frigida* furcilia	Calanoida	*Mecynocera clausi*
Euphausiidae	*Euphausia hanseni* furcilia	Calanoida	*Mesocalanus tenuicornis*
Euphausiidae	*Euphausia longirostris*	Calanoida	*Metridia gerlachei*
Euphausiidae	*Euphausia longirostris* calyptopis	Calanoida	*Metridia lucens*
Euphausiidae	*Euphausia longirostris* furcilia	Calanoida	*Metridia* sp.
Euphausiidae	*Euphausia lucens*	Calanoida	*Microcalanus pygmaeus*
Euphausiidae	*Euphausia recurva*	Calanoida	*Onchocalanus* sp.
Euphausiidae	*Euphausia similis*	Calanoida	*Paracalanus* sp.
Euphausiidae	*Euphausia spinifera*	Calanoida	*Paraeuchaeta antarctica*
Euphausiidae	*Euphausia spinifera* calyptopis	Calanoida	*Paraeuchaeta barbarta*
Euphausiidae	*Euphausia spinifera* furcilia	Calanoida	*Paraeuchaeta biloba*
Euphausiidae	*Euphausia superba*	Calanoida	*Paraeuchaeta exigua*
Euphausiidae	*Euphausia superba* C1	Calanoida	*Paraeuchaeta* sp.
Euphausiidae	*Euphausia superba* C2	Calanoida	*Paralabidocera antarctica*
Euphausiidae	*Euphausia superba* C3	Calanoida	*Pleuromamma abdominalis*
Euphausiidae	*Euphausia superba* calyptopis	Calanoida	*Pleuromamma borealis*
Euphausiidae	*Euphausia superba* F1	Calanoida	*Pleuromamma gracilis*
Euphausiidae	*Euphausia superba* F2	Calanoida	*Pleuromamma piseki*
Euphausiidae	*Euphausia superba* F3	Calanoida	*Pleuromamma robusta*
Euphausiidae	*Euphausia superba* F4	Calanoida	*Pleuromamma* sp.
Euphausiidae	*Euphausia superba* F5	Calanoida	*Rhincalanus gigas*
Euphausiidae	*Euphausia superba* F6	Calanoida	*Rhincalanus gigas* nauplius

Euphausiidae	*Euphausia superba* furcilia
Euphausiidae	*Euphausia triacantha*
Euphausiidae	*Euphausia triacantha* calyptopis
Euphausiidae	*Euphausia triacantha* furcilia
Euphausiidae	*Euphausia vallentini*
Euphausiidae	*Euphausia vallentini* calyptopis
Euphausiidae	*Euphausia vallentini* furcilia
Euphausiidae	*Euphausiidae calyptopis* indet
Euphausiidae	*Euphausiidae furcilia* indet
Euphausiidae	Euphausiidae indet
Euphausiidae	Euphausiidae metanauplius indet
Euphausiidae	Euphausiidae nauplius indet
Euphausiidae	*Nyctiphanes australis*
Euphausiidae	*Nyctiphanes australis* calyptopis
Euphausiidae	*Nyctiphanes australis* furcilia
Euphausiidae	*Thysanoessa gregaria*
Euphausiidae	*Thysanoessa gregaria* calyptopis
Euphausiidae	*Thysanoessa gregaria* furcilia.
Euphausiidae	*Thysanoessa macrura*
Euphausiidae	*Thysanoessa macrura* C1
Euphausiidae	*Thysanoessa macrura* C2
Euphausiidae	*Thysanoessa macrura* C3
Euphausiidae	*Thysanoessa macrura* calyptopis
Euphausiidae	*Thysanoessa macrura* F1
Euphausiidae	*Thysanoessa macrura* F2
Euphausiidae	*Thysanoessa macrura* F3
Euphausiidae	*Thysanoessa macrura* F4
Euphausiidae	*Thysanoessa macrura* F5
Euphausiidae	*Thysanoessa macrura* F6
Euphausiidae	*Thysanoessa macrura* furcilia
Euphausiidae	*T. macrura* metanauplius
Euphausiidae	*Thysanoessa* sp.
Euphausiidae	*Thysanoessa* sp. furcilia
Foraminifera	Foraminifera
Foraminifera	*Globorotalia* sp.
Fritillaria_sp.	*Fritillaria* sp.
Oikopleura_sp.	*Oikopleura* sp.
Ostracoda	Ostracoda
Pteropoda	*Clio pyramidata*
Pteropoda	*Clione antarctica*
Pteropoda	Gastropoda indet
Pteropoda	*Limacina* sp.
Pteropoda	Pteropod
Pteropoda	*Spongiobranchaea australis*
Salpa	Doliolidae
Salpa	Pyrosomatidae indet.
Salpa	*Sagitta gazellae*
Salpa	*Sagitta marri*
Salpa	*Sagitta* sp.
Salpa	*Salpa fusiformis*
Salpa	*Salpa* spp.
Salpa	*Salpa thompsoni*
Salpa	*Thalia* spp.
Calanoida	*Rhincalanus* sp. copepodite
Calanoida	*Scaphocalanus ferrani*
Calanoida	*Scolecithricella minor*
Calanoida	*Scolecithricella* sp.
Calanoida	*Stephos longipes*
Calanoida	*Subeucalanus longiceps*
Calanoida	*Sulcanus conflictus*
Calanoida	*Temora turbinata*
Copepod (o+u)	Copepod indet
Copepod (o+u)	Copepod Nauplius indet
Copepod (o+u)	Crustacean nauplius indet
Copepod (o+u)	Cyclopoid nauplii
Copepod (o+u)	Harpacticoid
Copepod (o+u)	*Lubbockia* sp.
Copepod (o+u)	*Microsetella rosea*
Copepod (o+u)	*Microsetella* sp.
Copepod (o+u)	Nauplius indet (small)
Copepod (o+u)	*Neocalanus gracilis*
Copepod (o+u)	*Neocalanus tonsus*
Copepod (o+u)	*Oithona frigida*
Copepod (o+u)	*Oithona* sp.
Copepod (o+u)	*Oncaea antarctica*
Copepod (o+u)	Oncaea curvata
Copepod (o+u)	*Oncaea* sp.
Copepod (o+u)	Sapphirina sp.
Oithona similis	*Oithona similis*
Other	Alciopidae
Other	Appendicularian Indet
Other	Bivalve spat
Other	Branchiopoda
Other	*Chelophyes* sp.
Other	Cirripedia Nauplius
Other	Ctenophore
Other	Cumacean
Other	Decapod megalopa
Other	Decapod zoea indet
Other	Decapoda (natant) indet juv
Other	Decapoda nauplius indet.
Other	Echinoid larvae
Other	Egg indet.
Other	Egg mass
Other	*Evadne* sp.
Other	Fish egg
Other	Fish larvae
Other	*Iospilid* sp.
Other	Isopod
Other	*Maupasia* sp.
Other	Medusa indet
Other	*Munida gregaria*
Other	Myctophidae indet
Other	Mysidae indet.
Other	*Nematocarcinus longirostris* juv
Other	*Nematoscelis megalops*
Other	*Noctiluca scintillans*
Other	*Pelagobia longicirrata*
Other	*Phalacrophorous pictus*
Other	*Phalacrophus* sp
Other	*Pleurogramma antarcticum*
Other	Polychaete indet
Other	*Protomyctophum* sp.

Other	Radiolaria
Other	Sergestid
Other	Siphonophore nectophore
Other	*Solmundella bitentaculata*
Other	Squid indet
Other	*Squilla* sp.
Other	Tintinnid
Other	*Tomopteris carpenteri*
Other	*Tomopteris* sp
Other	*Travisiopsis* sp.
Other	*Typhloscolex mulleri*
Other	*Vanadis antarctica*
Other	*Vanadis longissima*

11 APPENDIX 4

Parameters used to calculate the Average Copepod Community Size index (ACCS) (Bradford-Grieve et al. 1999).

Copepod Species	Indicative total length of adult female CVI (mm)
Acartia danae	1.18
Acartia spp	1.18
Calanoid cope & copepodites	1.00
Calanoides acutus	4.60
Calanoides macrocarinatus	3.55
Calanus australis	3.10
Calanus propinquus	5.38
Calanus simillimus	3.23
Calanus sp.	3.90
Calocalanus sp.	0.85
Candacia cheirura	2.63
Candacia falcifera	3.81
Candacia maxima	3.72
Candacia sp.	3.39
Centropages aucklandicus	1.65
Centropages bradyi	2.25
Clausocalanus brevipes	1.43
Clausocalanus laticeps	1.46
Clausocalanus sp	1.45
Ctenocalanus sp cf *citer*	1.11
Drepanopus sp.	2.29
Euaugaptilus sp	3.86
Eucalanus sp	4.00
Euchirella rostromagna	6.05
Haloptilus oxycephalus	3.56
Heterorhabdus austrinus	3.36
Heterorhabdus farrani	3.94
Heterorhabdus spinifrons	2.35
Heterorhabdus lobatus	3.10
Heterorhabdus sp	3.22
Lubbockia sp	1.70
Lucicutia sp	2.33
Mecynocera clausi	1.07
Mesocalanus tenuicornis	2.10
Metridia gerlachei	3.82
Metridia lucens	2.66
Metridia sp	3.24
Microcalanus pygmaeus	0.86
Microsetella rosea	0.85
Microsetella sp.	0.85
Neocalanus gracilis	3.22
Neocalanus tonsus	3.75
Oithona frigida	1.22
Oithona similis	0.82
Oithona sp	1.02

Oncaea antarctica	1.21
Oncaea curvata	0.63
Oncaea sp	0.90
Onchocalanus sp.	7.54
Paracalanus sp	1.08
Paraeuchaeta antarctica	9.15
Paraeuchaeta barbarta	9.00
Paraeuchaeta biloba	5.85
Paraeuchaeta exigua	6.85
Paraeuchaeta sp	7.71
Paralabidocera antarctica	2.01
Pleuromamma abdominalis	3.05
Pleuromamma borealis	2.03
Pleuromamma gracilis	2.08
Pleuromamma piseki	1.85
Pleuromamma robusta	3.65
Pleuromamma sp.	2.53
Rhincalanus gigas	7.88
Rhincalanus gigas nauplius	7.88
Rhincalanus sp copepodite	7.88
Sapphirina sp	4.41
Scolecithricella minor	1.27
Scolecithricella sp	1.27
Stephos longipes	0.84
Subeucalanus longiceps	4.55
Sulcanus conflictus	1.55
Temora turbinata	1.33