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An overview on biological/oceanographic survey off Adelie Land, Antarctica in January-February 1996

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A set of biological/oceanographic surveys was conducted around the Antarctic Divergence (AD) off Adelie Land, Antarctica by R/T Vessel Umitaka-Maru III of Tokyo University of Fisheries in 1996 austral summer. Off Adelie Land is one of the least studied areas in the Antarctic Ocean partly due to its small Antarctic krill biomass, which means less economical and ecological interests. However, around 140° E of the area recently attracts much scientific attentions for its unique sea ice distribution dynamics. Sea ice condition could be one of the most important factor to control biological process in the Antarctic Ocean. Therefore, biological/oceanographic investigation of the area might present another type of Antarctic marine ecosystem different from what has been conventionally believed.

The operation plan of 1996 Antarctic ecological research cruise by the R/T Vessel Umitaka-Maru III was approved as a part of Japanese Antarctic Observation Program in June 1995. This survey was planned to reveal and identify biological/oceanographic characteristics of the AD area off Adelie Land by comparing new results to the previously obtained data. Moreover, the survey aims to increase our comprehensive knowledge on variability and dynamics of the whole Antarctic marine ecosystem.

The survey focused on six major study topics as follows:

1) Physical oceanographic study;
2) Primary production and related upper water environment;
3) Community structure of phytoplankton in relation to the AD
4) Community structure of zooplankton in relation to the AD;
5) Distribution of Antarctic krill;
6) Optical properties and development of bio-optical algorithm for near future use of ocean color remote sensing for monitoring phytoplankton biomass.

OUTLINE OF THE SURVEY

The survey was conducted off Adelie Land in the Southern Ocean from January 20 to February 3, 1996, during the 64th cruise of R/T Umitaka-Maru III. Four meridional research transects were set along 135, 140, 142 and 145 ° E between 62° S to 65° 30' S to cover the area in which the AD was expected to appear, and each transect was designated as the Line A, B, C and D, respectively. The survey grid and location of sampling stations are shown in Fig. 1.

A single or double CTD casts up to 2700 m deep were operated at 27 stations set along the four transects to obtain oceanic structure of the area with additional four casts between Fremantle, Australia, to the northern most station of the Line A. In addition, an XBT was cast every 10' or 20' in latitude along the survey grid to gain more precise water temperature profiles.

Seawater samples were collected from several layers between surface and the depth of euphotic layer that is 1 % penetration if incident photosynthetic available radiation (PAR) at each station, using Rosette Multi-Sampler (RMS) with Niskin Bottles mounted on a CTD frame, or a Van Dorn Water Sampler. Additionally, seawater was sampled from the layers up to 1000 m or deeper for measurements of DO and dissolved-silicate to detect behavior of deep seawater mass of the area.

Concentrations of nitrate, nitrite, phosphate and silicate in the water samples were analyzed. Nitrate and nitrite were measured by an autoanalyzer with a copper-cadmium reduction column following the method in Technicon Manual (1978). Silicate and phosphate were analyzed manually using a spectrophotometer (Shimazu UV-120) after Sugawara (1969) and Strickland and Parsons (1972), respectively.

As an indicator of the standing stock of phytoplankton, concentration of Chl *a* was determined fluorometrically using Turner Designs fluorometer (10R). Size composition of phytoplankton cell was also determined. Phytoplankton smaller than 10 μm was counted by the epifluorescence microscopic method after samples were fixed in 1% glutaraldehyde solution and collected on membrane filters (Millipore Type JG, pore size 0.2 μm) through filtration. Cells of 10 μm or larger were fixed in 1% neutral formaline, and observed and enumerated with an inverted microscope using a Throndsen's sedimentation/counting chamber.

Zooplankton samples were obtained at 24 stations by an ORI net (mesh size 2 mm, mouth diameter 1.6 m) equipped with a flow-meter and digital memory depth meter (RMD; Rigosha R). The net was towed obliquely at a ship speed of 3.8 km h^{-1} between 0 and 200 m depth. For collection of larvae of *Euphausia superba*, a NORPAC net (mesh size 0.33 mm, mouth diameter 45 cm) was towed vertically from 150 m deep at 19 stations. All zooplankton was preserved in 5% neutral formaline soon after collection. Animals were sorted and counted for 14 categorical taxa: polychaetes, copepods, decapods, euphausiid, amphipods, ostracods, chaetognaths, cnidarians,

thecosomatous pteropods, gymnosomatous pteropods, cephalopods, thaliaceans, appendicularians and fishes. For juveniles and adults *Euphausia superba*, size frequency and stage of maturity were examined. Larval *Euphausia superba* were stored and counted for each larval stage.

Photosynthetic activity of phytoplankton was measured at 8 stations by the stable ^{13}C isotope method. Water samples taken from the surface and euphotic depth were transferred into 1000 ml clear polycarbonate bottles after adding $NaH^{13}CO_3$. Samples were incubated for four hours at different light levels in a water bath which was controlled at surface water temperature under natural sunlight. After being filtered by precombusted glass fiber filters (Whatman GF/F), isotopic ratios of ^{12}C to ^{13}C in samples were determined by infrared absorption spectrometry with the ^{13}C analyzer (EX-130, JASCO). Photosynthetic activity was calculated by the equation of Hama *et al.* (1983), and the rate at each depth was calculated on the basis of P-I curve fitted to the model of Eilers and Peeters (1988). Primary production in water column was estimated by integrating the values obtained by multiplying photosynthetic activity by Chl *a* concentration at each depth over entire euphotic layer.

Bio-optical measurements were carried out at 21 stations. Spectral radiation was measured using the spectroradiometer MER-2020A (Biospherical Instruments Inc.) which have sensors for downwelling irradiance (E_d) and upwelling radiance (L_u) at seven wave lengths compatible with SeaWiFS and OCTS bands. PAR was measured using quantum sensors LI-190B and LI-192SB (LI-COR Inc.). Quantitative filter technique was used to obtain absorption coefficient of suspended materials. Optical density (OD) was measured by a spectrophotometer (UV-365, Shimazu) equipped with an integrating sphere, an absorption coefficient was calculated from OD using the algorithm suggested by Mitchell (1990).

Table 1 shows the summary of the survey conducted at each sampling station.

SUMMARY OF EACH TOPICAL STUDY

Oceanic structure

In the present area, convex pattern for the dissolved silicate concentration, which is appropriate for detecting upwelled-deep water, is not so clear in the meridional sections of the hydrographic data. A temperature section, however, from the close XBT observation along the Line C indicates that the center of the AD zones is supposed to be located from 64° S to 64° 30' S, because warm water (above 1℃) originated from Circumpolar Deep Water is (CDW) upwelled to the region around 65° S.

A water mass with oxygen-rich and low dissolved-silicate concentration was detected on the continental slope. Also, the density of the water mass is somewhat high (sigma-θ =27.873) at 1720

m depth of the Stn. C10. This water may be also regarded as the "slope water" which is formed by mixing of shelf water with the upper CDW. Existence of the slope water suggested an evidence for sinking of dense water from the shelf region. Thus the, present study area is considered to be important as one of the major sources for the Antarctic Bottom Water (AABW) although a formation mechanism has not been fully understood yet as few *in situ* observation have been conducted. The observation results are expected to be useful to reveal formation process of water masses in the Antarctic coastal region.

Primary production and related upper water environment

The mean Chl *a* concentrations within the euphotic layer ranged from 0.15 μg l^{-1} at Stn.C31 to 0.97 μg l^{-1} at Stn. C07. Chl *a* was highly concentrated near the AD, particularly in the western side of the survey area. Subsurface chlorophyll maximum was observed in the north of the AD through the survey area, which appeared deeper to the east (about 100 m along the Line D). The mean concentration of nitrate, phosphate and silicate within the euphotic layer varied between 25 to 33 μM, 1.4 to 2.1 μM and 27 to 61 μM, respectively. All the nutrients marked their maximum concentrations at Stn. C20. Obtained concentrations of Chl *a* and inorganic nutrients were consistent with those reported in the previous studies conducted in the similar latitudes off Adelie Land in austral summer (Yamaguchi and Shibata, 1982; Yamaguchi *et al.*, 1985)

Maximum photosynthetic rate in the studied area was less than 1.6 mgC(mg Chl *a*)$^{-1}h^{-1}$. P-I curves indicated the evidence of light/dark adaptation of phytoplankton. Daily primary production of water columns varied from 0.01 gC $m^{-2}d^{-1}$ at Stn. C31 to 0.26 gC $m^{-2}d^{-1}$ at Stn. C11. Mean production of these stations except Stn. C31 was 0.19 gC $m^{-2}d^{-1}$. This value is similar to the previous study in the Pacific sector of the Antarctic Ocean in January to February (0.17 gC $m^{-2}d^{-1}$; Holm-Hansen *et al.*, 1977), but lower than that reported near the Antarctic Peninsula in January (0.24-1.39 gC $m^{-2}d^{-1}$; Holm-Hansen and Mitchel, 1991) and in Ross Sea in January to February (0.15-2.63 gC $m^{-2}d^{-1}$; Smith Jr. *et al.*,1996).

Community structure of phytoplankton in relation to the AD

15 species belonging to ten genera of diatoms and ten species belonging to six genera of dinoflagellates were identified for phytoplankton of 10 μm or larger. Diatoms occupied more than 75% of phytoplankton cells of this size class through the survey area. *Fragilariopsis kergulensis, Thalassiothrix antarctica, Rhizosolenia hebetata* f. *hebetata* and *Chaetoceros criphilis* were most abundant species. Diatom abundance increased near the AD mostly due to high abundance of the former two species, and that was likely to contribute to high concentration of euphotic layer mean Chl *a* of the area. While the former two species appeared more or less at any depths at most sampling stations, the latter two species were observed only near the south of the AD. In particular,

appearance of *C. criophilus* was restricted around the depth of euphotic zone.

Dinoflagellates occupied less than 15% of the total cell number in the size class of 10 μm or larger, in which *Prorocentrum pyriforme, Dinophysis acuminata, Gyrodinium lachryma* and *Protoperidinium divergence* were dominant species. In contrast to the diatom species which were more or less broadly distributed through the survey area, the four dominant flagellates showed a patchy distribution pattern both horizontally and vertically. Abundance of both diatoms and dinoflagellates were considerably low along the line D.

Phytoplankton smaller than 10 μm was categorized into four groups: cyanobacteria (diameter about 2 μm), cryptophycean species (diameter 4-6 μm), other eucaryotic pico-phytoplankton (diameter 1-5 μm) and eucaryotic nanophytoplankton (diameter 5-10 μm). 1-5 μm size class consisted of various types of flagellates, while major components of 5-10 μm size class were flagellates, diatoms of the genera *Nitzchia* and *Thalassiosira*, and several centric diatoms. Cyanobacteria was distributed mainly in the north of the AD, and eminently abundant upper 30 m on the Line B and D (>1000 cells ml^{-1}) and around 50 m deep on the Line C (>5000 cells ml^{-1}) where euphotic zone mean Chl *a* was quite low (<0.1 $\mu g\ l^{-1}$) and other 1-5 μm size class cells were scarcely distributed. Cryptophycean species were less abundant through the survey area. Eucaryotic pico- or nanophytoplankton of both size classes occurred in high abundance of more than 1000 cells ml^{-1} at most stations. While peak abundance of 5-10 μm size class appeared mostly upper 30 m, that of 1-5 μm size class were revognized deeper. In contrast to large diatoms, there observed no tendency that abundance of phytoplankton smaller than 10 μm increased near the AD.

Community structure of zooplankton in relation to the AD

31 species belonging to 30 genera were identified. A single species of salp, *Salpa thompsoni*, dominated in zooplankton both numerically and by biomass. *S. thompsoni* accounted for 44% of total zooplankton abundance in terms of number of individuals per 1000 m^3, and its mean carbon biomass was 8.15 mgC m^{-3}. Copepods followed salps and occupied 40% of the total abundance with the mean carbon biomass of 1.34 mgC m^{-3}. The sum of euphausiids, pteropods, chaetognaths and amphipods were only 16%, and other taxa such as polychaetes and cnidarians were less than 1%. Among copepods, *Rhincalanus gigas, Calanus propinquus, Calanoides acutus* and *Metridia gerachei* occupied more than 90% of total abundance. The maximum abundance of salps (29873 inds. 1000 m^{-3}, at Stn. C29) was remarkably high in comparison with past records of salp bloom around in the Antarctic Peninsula.

Assuming the daily consumption of organic matter in January as 25% of body carbon, *S. thompsoni* could consume only 4% of daily primary production at Stn. C11 where phytoplankton was accumulated, while they could consume nearly 4 times of that at Stn. C31. In other stations (C08, C10, C23 and C27), *S. thompsoni* population could remov 20 to 60% of daily production,

suggesting that they have a large grazing impact to phytoplankton communities. Thus, besides the possible Fe or micronutrients deficiency, grazing by salps might have further enhanced the HNLC condition particularly at the stations along the Line C and D with the lowest Chl *a*.

Although *S. thompsoni* were considerably abundant, they were not uniformly distributed through the survey area; i.e., the species comprised more than 80% of total zooplankton abundance at Stns. C10, C17, C18 and C29 while less than 5% at Stns. C07, C13, C14 and C21. In particular, abundance of salps eminently dropped at stations near the AD, where copepods replaced them in a large portion of zooplankton biomass. Considering high abundance of large sized diatoms near the AD, observed spatially partitioning in distribution pattern of salps and copepods might have appeared as a result of difference in their feeding adaptations. The four dominant copepod species were known to selectively feed on large diatoms in an enriched food supply. On the other hand, salps are non-selective filter feeder which might die for clogging under high particle concentration and thus adapted to oligotrophic waters. We observed a considerable amount of salps in south of the AD, despite that Foxton (1966) reported that distribution of *S. thompsoni* was principally restricted to north of the AD. Possible cause and ecological consequences of salp bloom in the Antarctic Ocean are discussed in detail in Chiba *et al.* (in press).

Distribution of Antarctic krill

Adults, juveniles and larvae of *Euphausia superba* were collected only at several stations, majority of which were located in the south of the AD. The maximum abundance of adults and juveniles of 41 inds. 1000 m^{-3}, 2.9 mgC m^{-3} (35 mg m^{-3} in wet weight) was recorded at Stn. C23 which was the only location where a krill swarm was seen on acoustic fish finder (frequency ; 120 kHz). Even considering inefficiency of the ORI net for krill fishing because of low towing speed, the maximum abundance we observed was much lower in comparison to other net surveys: for example, 98 mgC m^{-3} (1.2 g m^{-3} in wet weight) at minimum in Matsuda *et al.* (1979). As for larvae, only calyptopis I and calyptopis II stages (max. 204 inds. 1000 m^{-3}) were collected while no calyptopis III and furcilias were caught.

From the bimodal distribution of the total length frequency, the mean total length of first year class individuals was assumed as 25 to 32 mm. A recruitment index, which is the ratio of 1st year class to whole population was estimated as 0.024. Maturity stages of females shows advaced stages, 3C and 3D, were most abundant. Comparing to data derived from the long term study of Siegel and Loeb (1995), the recruitment index and stage of maturity obtained in this survey imply relatively poor recruitment success and late spawning of the season, respectively.

Optical properties and development of bio-optical algorithm for near future use of ocean color remote sensing for monitoring phytoplankton biomass

Waters at the most stations were optically very clear with the maximum transparency in the studied area was 39 m at Stn. C16. Irradiance attenuation coefficient at 490 nm of the surface layer (0-10 m), which was obtained from total suspended matter, varied from 0.032 to 0.128 m^{-1}. While absorption spectra of phytoplankton pigment at Stns. C05, C07, C08, C10, C11, C12 and C29 showed clear absorption peak by Chl *a*, those at Stns. C06, C23, C25, C27 and C31 indicated an existence of degradation products of pigments.

Surface chlorophyll pigments C (Chl *a* + Phaeopigments) and radiance ratio, R (λ_1, λ_2) shows a strong correlation and practical coefficient. Bio-optical algorithm for this relationship forms

$$C\ (mg\ m\text{-}3) = 2.283 \times R(\lambda_1, \lambda_2) \qquad r^2 = 0.910\ (n = 20)$$

where λ_1 and λ_2 are 443 nm and 510 nm, respectively. The obtained algorithm approximately agrees with the result of Michel (1992) which was constructed based on the data from the polar seas. This result suggests that underestimation due to the pigment pakage effects may occur by using the global algorithm presented by Gordon *et al.* (1983).

CONCLUSION AND FUTURE SUBJECTS

The traditional view of Antarctic ecosystem in which a diatom-krill-dominant simple food web exists have gradually changed in these decades. Our study supported the idea that one should consider existence of an alternative Antarctic food web in which pico- or nanophytoplankton and salps may play fundamental role as primary producer and major grazers, respectively.

Our results show that production of large sized diatoms was enhanced near the AD. The observed coincidence of the areas of southern intrusion of warmer and high salinity sueface water mass, low primary productivity and high salp abundance suggested that change in hydrographic condition near the AD may basically contribute to an appearance of the alternative food web. Our study was based on data taken in only one austral summer. However, considering the previous reports on low abundance of *Euphausia superva* and on occasional blooms of *Salpa thompsoni* even to the south of the AD off Adelie Land, the environmental condition and ecosystem we observed might be a yearly consistent feature of the area rather than only a temporal incident.

After long term study near the Antarctic Peninsula, Siegel and Loeb (1995) and Loeb *et al.* (1997) reported a positive correlation between krill abundance and sea ice extension/concentration. Sea ice condition not only could alter the timing of spring bloom and control phytoplankton growth but also provide food and protection for wintering *E. superba*. Since the least extension and early retreat of sea ice around 140° E has been observed for these 20 years, existence of the alternative food web may be reduced to the peculiar sea ice condition of the sea.

In contrast to the classical diatom-krill-dominant food web, the quantitative carbon flow in the

pico-nanophytoplankton-salp-dominant food web remains poorly understood. Identificatioin of consumers of salps, grazing capacity and growth rates of salps, and eveluation of contribution of microbial loop are among subjects to be futher investigated.

The mechnism of formation of the characteristic sea ice appearance off Adelie Land is still less understood. So is the possible interaction between sea ice condition and function of upwelling at the AD which might be related to the observed southern intrusion of warmer surface water mass. Causes and effects of formation of AABW on sea ice condition is another subject to be investigated. How such an oceanic structure affects the biological environment, and possibly result in appearance of the alternative food web should be investigated by a long term monitoring study including satellite remote-sensing.

The recent trend of global warming is a world wide concern. Polar regions are well known as the area where its influence could appear first, and most eminently on the earth. In other words, Antarctic ecosystem is quite sensitive to global climate change. Since spatial and temporal extent of annual sea ice cover near the Antarctic Peninsula is reported to diminish yearly in this decade, one can consider that the ice dependent, krill-dominant food web is already being damaged regionally. Futher investigations on mechanisms of the unique biological/oceanographic features off Adelie Land will provide us with unsight to evaluate and predict various consequences of sea-ice reduction to whole Antarctic ecosystem.

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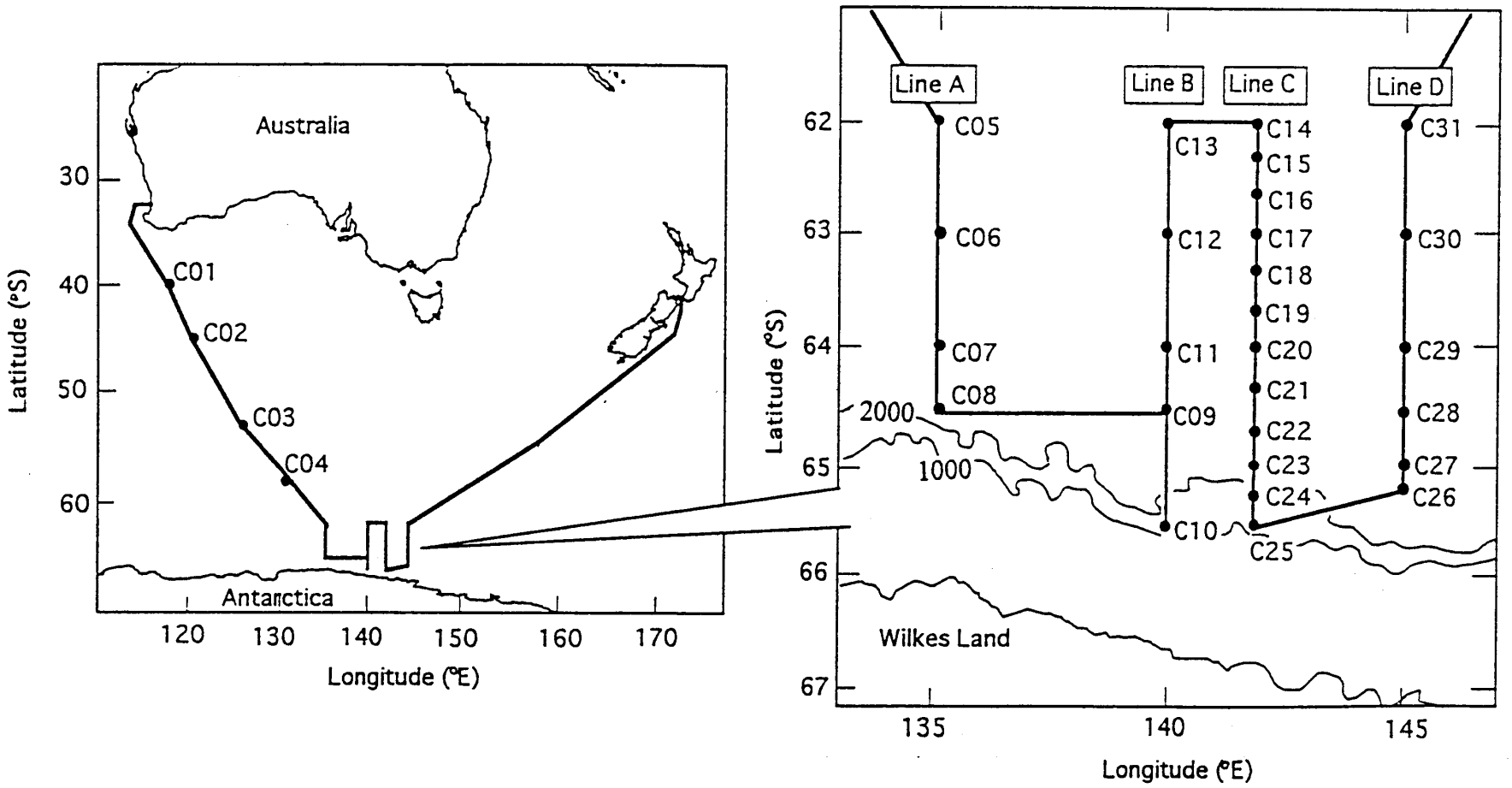

Fig. 1. Survey grid and sampling stations in the Southern Ocean during the 64th cruise of the R/T vessel Umitaka-Maru III. Contour lines indicate the depth (m).

Table 1. Summary of 1996 Umitaka-maru III Antarctic Ocean survey

Station	Date	Ship Position	CTD	Water Sampling		Optical Measurements						Water Analyses					Primary Production	Net Sampling	
				RMS	V.D.	Trans-parency	Water Color	OD	Quanta	MER	Absorption	DO	Nutrients	Chl *a*	Suspended Matter	HPLC		ORI	NORPAC
C01	Jan. 20	39° 59' 08" S 117° 48' 06" E	O	O		O	O			O		O	O	O					O
C02	Jan. 21	44° 11' 06" S 120° 24' 10" E	O	O		O	O			O			O	O					O
C03	Jan. 24	53° 38' 40" S 123° 30' 00" E	O			O	O			O			O	O					O
C04	Jan. 25	57° 50' 08" S 128° 40' 06" E	O			O	O			O			O	O					O
C05	Jan. 26	62° 00' 20" S 135° 00' 10" E	O	O	O	O	O	O	O	O	O		O	O	O	O	O		O
C06	Jan. 26	63° 00' 07" S 134° 59' 07" E	O	O	O	O	O			O	O		O	O	O	O		O	O
C07	Jan. 26	63° 59' 50" S 135° 00' 10" E	O	O	O						O	O	O	O	O			O	O
C08	Jan. 27	64° 33' 00" S 134° 58' 09" E	O	O	O	O	O			O	O		O	O	O	O	O	O	O
C09	Jan. 28	64° 30' 00" S 139° 59' 10" E	O	O	O								O	O	O			O	O
C10	Jan. 28	65° 29' 08" S 139° 59' 06" E	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O
C11	Jan. 29	64° 00' 00" S 140° 00' 40" E	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O
C12	Jan. 29	63° 00' 20" S 139° 59' 08" E	O	O	O	O	O	O	O	O	O	O	O	O	O	O		O	O
C13	Jan. 29	62° 00' 06" S 139° 59' 09" E	O	O	O							O	O	O			O	O	O
C14	Jan. 30	62° 00' 00" S 141° 59' 09" E	O	O		O	O						O	O				O	
C15	Jan. 30	62° 20' 10" S 142° 00' 40" E	O	O		O	O						O	O				O	
C16	Jan. 30	62° 40' 10" S 141° 59' 00" E	O	O		O	O						O	O				O	
C17	Jan. 30	62° 59' 08" S 141° 59' 40" E	O	O		O	O						O	O				O	
C18	Jan. 30	63° 19' 09" S 141° 59' 07" E	O	O		O	O						O	O				O	
C19	Jan. 30	63° 40' 00" S 145° 59' 07" E	O	O		O	O						O	O				O	

Table. 1 Continued.

Station	Date	Ship Position	CTD	Water Sampling		Optical Measurements						Water Analyses					Primary Production	Net Sampling	
				RMS	VD	Trans-parency	Water Color	OD	Quanta	MER	Absorption	DO	Nutrients	Chl *a*	Suspended Matter	HPLC		ORI	NORPAC
C21	Jan. 31	64° 20' 00" S 142° 00' 20" E	O	O									O	O				O	
C22	Jan. 31	64° 40' 00" S 142° 00' 20" E	O	O		O	O			O			O	O				O	
C23	Jan. 31	64° 59' 90" S 142° 00' 50" E	O	O	O	O	O	O	O	O	O		O	O	O	O	O	O	O
C24	Jan. 31	65° 14' 60" S 141° 59' 70" E	O	O		O	O			O			O	O				O	
C25	Jan. 31	65° 29' 80" S 141° 59' 90" E	O	O	O	O	O		O	O	O		O	O	O	O		O	O
C26	Feb. 2	65° 29' 40" S 145° 00' 00" E	O	O															
C27	Feb. 2	65° 00' 00" S 145° 00' 40" E	O	O	O	O	O	O	O	O	O		O	O	O	O	O	O	O
C28	Feb. 2	64° 30' 00" S 144° 59' 90" E	O	O															
C29	Feb. 2	63° 59' 90" S 145° 00' 50" E	O	O	O	O	O		O		O	O	O	O	O	O		O	O
C30	Feb. 2	63° 00' 10" S 144° 59' 90" E	O	O	O	O	O						O	O	O			O	O
C31	Feb. 2	62° 00' 50" S 144° 59' 70" E	O	O	O	O	O		O	O	O		O	O	O	O	O	O	O

RMS: Rosette Multi-Sampler; VD: Van Dorn Water Sampler; OD: Optical Density; MER: MER-2020A (spectroradiometer)