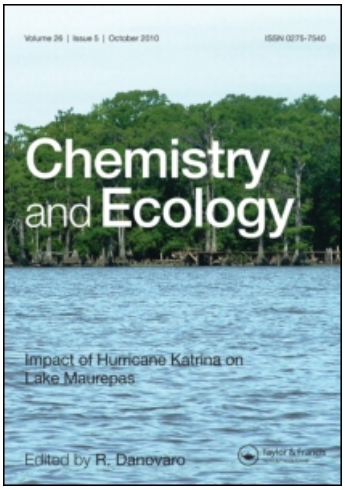

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SUSPENDED MATTER VARIABILITY IN RELATION TO WATER MASSES IN TERRA NOVA BAY (ROSS SEA—ANTARCTICA)

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The concentration (total particulate matter, TPM) and size of particulate matter collected during three oceanographic cruises carried out in the Ross Sea (Antarctica) in the frame of the Climatic Long-Term Interactions for the Mass-Balance in Antarctica (CLIMA) Project have been analysed in relation to the characteristics of the water masses present in the polynya of Terra Nova Bay (TNB). The water column was divisible into three layers: the surficial, which included the Antarctic Surface Waters (AASW); the intermediate, which sometimes included the Terra Nova Ice Shelf Waters (TISW); and the bottom, mainly consisting of High Salinity Shelf Waters (HSSW). The highest TPM concentrations were observed in the AASW, where the largest particles were also found; the lowest TPM concentrations were found in the bottom waters (HSSW). The TPM concentrations found in the water samples collected in the 1998 austral summer were almost twice as high as those found in 2001. In contrast, there was no difference in the size of the particles collected in 1998 and 2001, but there was a notable difference between those found in 1998 and 2001 and those found in 1997. The particulate input in the polynya waters is mainly related to ice melting processes and the variability in the TISW coming from the Nansen Ice Sheet and Drygalski and Campbell Ice Tongues.

Keywords: Water masses; Particulate matter; Antarctica; Polynya; Terra Nova Bay

1 INTRODUCTION

Most investigations carried out in the Ross Sea have focused on the organic components of the suspended particles in the sea water (Fabiano *et al.*, 1997; Carlson *et al.*, 2000; Gardner *et al.*, 2000; Gowing *et al.*, 2001; Asper and Smith, 2003); others have concentrated on the phytoplankton and zooplankton contribution to suspended loads (Smith and Nelson, 1986; Smith *et al.*, 1996; 2000; Fonda Umani *et al.*, 1998; 2002; Ducklow *et al.*, 2001; Smith and Asper, 2001). Few investigations have been carried out on the total suspended loads (Carter *et al.*, 1981; Fonda Umani *et al.*, 2002); hence, little is known about the transport and deposition of sedimentary particles within the Antarctic glaciomarine environment (Jaeger *et al.*, 1996).

During the CLIMA Project of the Italian National Research Program in Antarctica (PNRA), studies were carried out to investigate particulate matter. This was done using

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two methodologies: the coarser portion (150–400 μm), commonly dominated by faecal pellets (up to 70% by mass) and aggregate particles (Jaeger *et al.*, 1996), was measured using sediment traps (Dunbar *et al.*, 1998; Smith and Dunbar, 1998; Accornero *et al.*, 1999; Collier *et al.*, 2000; Langone *et al.*, 2000); the particulate matter slowly sinking and/or suspended (generally less than 100 μm) was measured by nephelometric instrumentation and by direct measurements of the TPM concentration (Chronis *et al.*, 2000). The combined data obtained by direct and nephelometric measurement provided an important insight into the spatial distribution of the TPM and often revealed the presence of high concentrations in patches and layers (McCave, 1986; Chronis *et al.*, 2000). There is a very close relationship between the dynamic of particles and the physical and hydrodynamic characteristics of the water mass (Anderson *et al.*, 1984; Dunbar *et al.*, 1984; Spezie *et al.*, 1993), and the sedimentation of suspended particles follows preferential lines of conveyance where there are well-defined masses of water (Jacobs *et al.*, 1970; Budillon *et al.*, 1999; Tucci *et al.*, 2000). Therefore, previous studies concentrated on the relationship between cold-water layers and increased water turbidity (Domack and Williams, 1990), concluding that the mid-water cold tongues and near-bottom turbidity can account for 87% of the total sedimentary load. The role of the seafloor nepheloid layer in eastern Antarctica, which has a TPM concentration up to $3.5\,\mathrm{mg\,l^{-1}}$, was also noted (Harris and O'Brien, 1998).

The goal of this study is to describe the variability in the concentration and particle size in relation to the physical characteristics of the water masses in which the matter is suspended (Dunbar *et al.*, 1984; Davey, 1987).

2 MATERIALS AND METHODS

The area selected for the evaluation of the water and particulate matter variability was the northwestern sector of the Ross Sea around Terra Nova Bay. All cruises were conducted during the austral summer, specifically during November–December 1997, January–February 1998, and January–February 2001 (Fig. 1).

Multiple samplings were made from the entire water column at the sampling stations, with four samplings at predetermined depths (surface, upper thermocline, intermediate water and near the bottom) and additional depths in well-defined water masses.

Conductivity–temperature–depth (CTD) profiles were taken with a Sea-Bird Electronics '9/11 plus' probe equipped with a standard sensor set, which included a double temperature–conductivity duct for optimized spike reduction by defined time alignment between temperature and conductivity measurements. Before each cruise, the CTD sensors were calibrated at the NATO Saclant Centre (La Spezia, Italy). The post-cruise calibration was performed after the eighteenth Antarctic cruise (2001). Additional checks were performed on board using two SIS RTM4200 digital reversing platinum thermometers. Several samples of water were collected at different depths at each station and analysed on board using an Autosal Guildline 6400 Salinometer, but only the bottom samples were used for the conductivity calibration. Scattering measurements were made with a Seapoint Turbidity Meter; this instrument measures scattered light (880 nm), 15–150° to the axis of the beam, from a small volume within 5 cm of the sensor windows. The sensor was factory adjusted for a consistent response to the Formazin Turbidity Standard measured in Formazin Turbidity Units (FTU). The sensitivity selected was $200\,\mathrm{mV\,FTU^{-1}}$ with a 25 FTU range. The TPM concentration in the samples collected during the 2001 cruise was determined using the turbidity sensor,

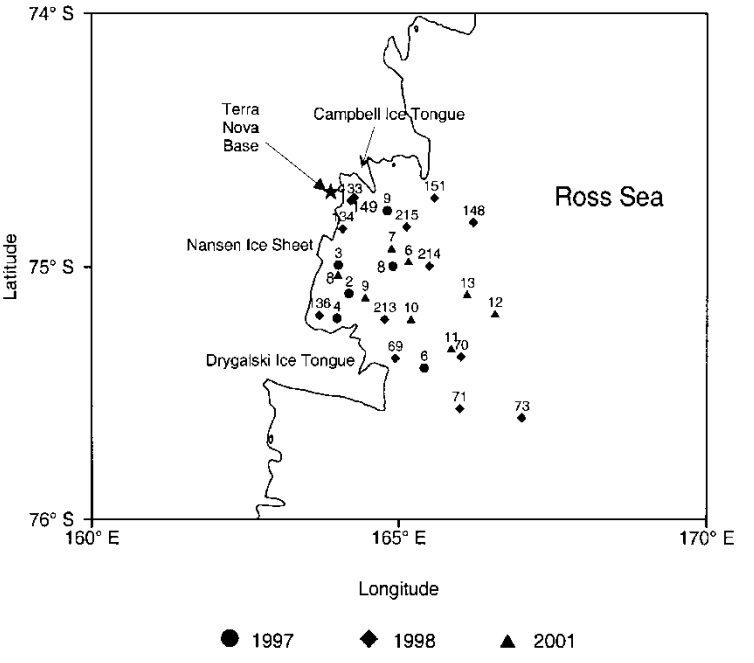

FIGURE 1 Location of the sampling stations.

which had been calibrated using the concentration (mg l^{-1}) of the same cruise samples. A plot of the transmissometer beam attenuation coefficient *vs.* sediment concentration (Fig. 2) exhibited linear regression of the data yields with a good correlation ($R^2 = 0.836$). The variability of the TPM between surface and bottom water samples was suggested as the cause of the scatter (Domack *et al.*, 1994).

The water samples were taken directly from the spigot of the Niskin bottle with a Teflon 10 l vessel; a known sample volume between 2 and 3 l was vacuum-filtered (200 mm Hg) through a Millipore HA 47 mm diameter with a nominal pore size of 0.45 μm and pre-weighed with a 10^{-5} g Scaltec SBC21 balance. After filtration, the membranes were rinsed with 60 ml of Milli-Q water to remove sea salt and then air-dried and stored in polystyrene Petri dishes at −20 °C until laboratory analysis.

In the laboratory, the filters were dried at 65 °C for 3 h and reweighed to obtain the TPM concentration; eventual variations due to varying atmospheric-environmental conditions were corrected using pre-weighed filters without samples for the correction (Pierce *et al.*, 1981); a control filter was used for every sampling station.

Afterwards, the filters were ashed for 3 h at 1100 °C, using some acetone drops (Carlo Erba®, minimum assay 99.8%) to remove the organic particulate fraction; the unburned fraction was weighed and used as the inorganic particulate fraction (Strickland and Parson, 1968; Piccazzo and Tucci, 1983). The particle size was obtained using a Coulter® Counter Multisizer II in the ship's laboratory. Water samples for particle size analysis were extracted from the spigots of the Multisampler bottles allowing the entire sample to fall directly and slowly into the analysis beaker. Analyses were performed using two tubes (diameter size of 30 and 140 μm), respectively, with a volume of 50 and 500 μl; the distribution curves were integrated using the multi-tube overlap program (Krank and Milligan, 1978).

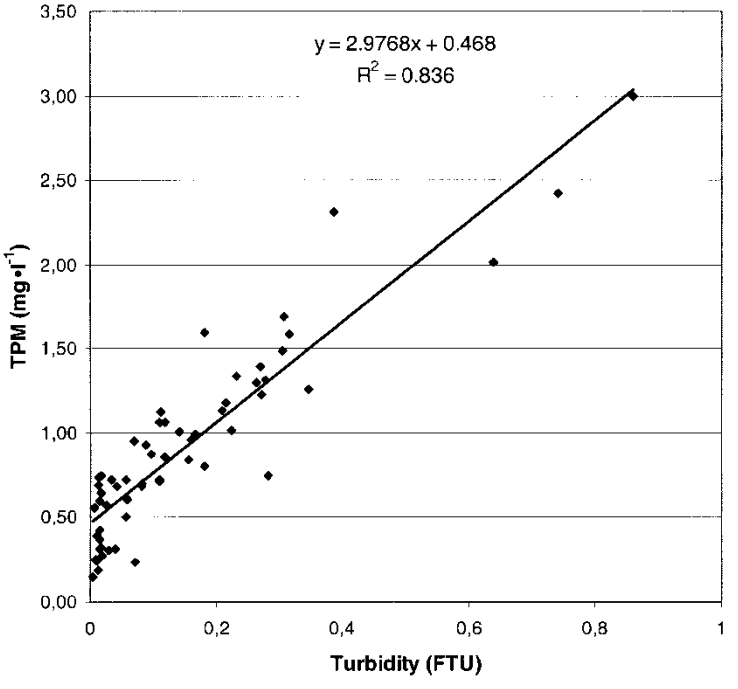

FIGURE 2 Calibration of nephelometer against TPM concentration ($mg\,l^{-1}$; cruise 2001).

3 RESULTS AND DISCUSSION

3.1 Hydrographic Conditions

The vertical structure of the water column in the Terra Nova Bay polynya is relatively simple. The greatest variability was observed in the surface layer extending to a depth of 50–150 m. Below this layer, the water column became isothermal, with its vertical stability preserved by the salinity that increased with depth. The vertical structure of the summer water column in Terra Nova Bay may therefore be considered as two-layered. In 1997–1998, these layers were separated by a pycnocline that occupied different depths at the beginning and at the end of the summer (deepening from November to February from 50–100 m to 150 m). The AASW was confined to the upper layer, which became fresher and warmer during the summer because it was influenced by sea ice melting and by the heat gained from solar radiation, which is the main constituent of the surface heat balance in summer in this region (Budillon *et al.*, 2000). Below this layer, the HSSW displayed a potential temperature close to the surface freezing point and $S > 34.7$ (Fig. 3).

In this near-isothermal layer of the HSSW, a water mass displaying temperatures lower than the surface freezing point ($T_f = -1.914\,^{\circ}C$ for $p = 0$ dbar and $S = 34.85$) (Fofonoff and Millard, 1983) has been detected at intermediate depths; this TISW (Budillon and Spezie, 2000) has been observed in the whole area of TNB, although characterized by different depths and thicknesses (Jacobs and Fairbanks (1985) mentioned the presence of a similar water mass in the Terra Nova Bay area, referring to unpublished data).

This water mass has an origin similar to the Deep Ice Shelf Water (Jacobs and Fairbanks, 1985), which is found in the southern sector of the Ross Sea, emerging beneath the Ross Ice Shelf, spreading to the shelf break and playing an important role in deep water formation (Bergamasco *et al.*, 2002; Budillon *et al.*, 2002; Rubino *et al.*, 2003). Actually, the most

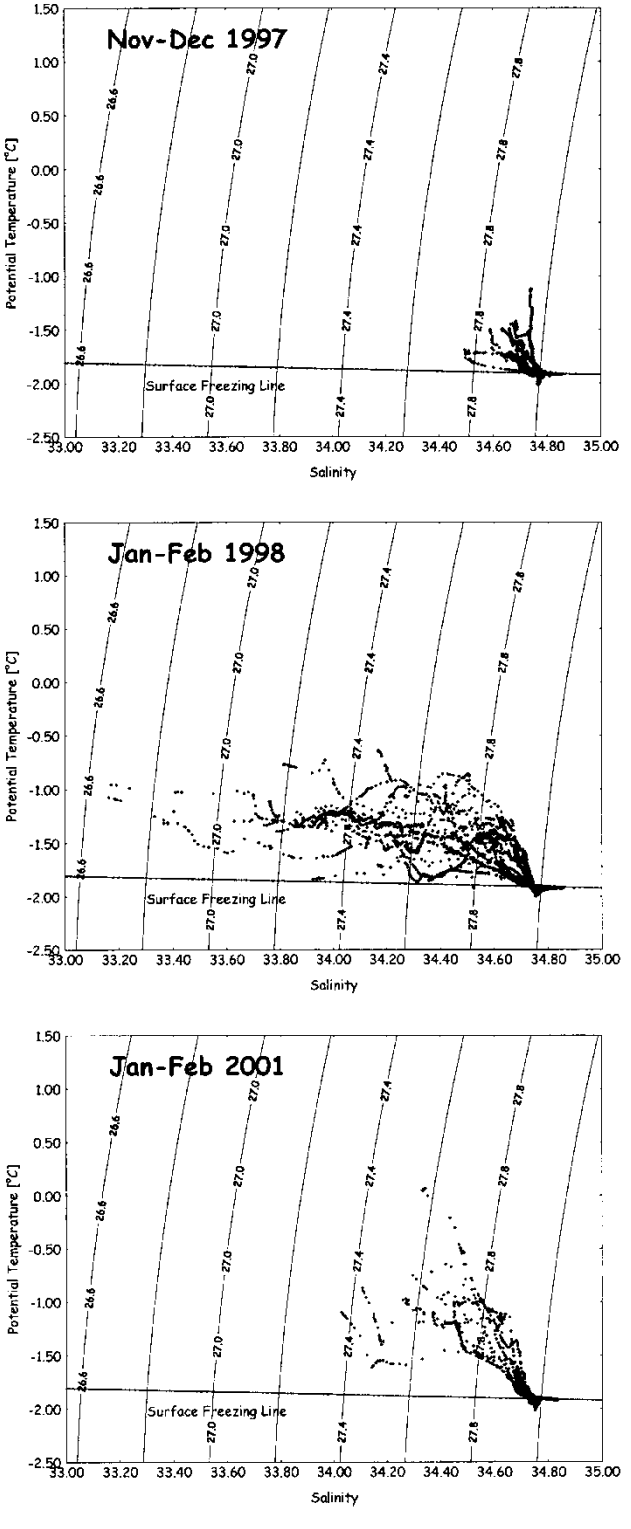

FIGURE 3 Potential temperature/salinity diagram (θ/S) of water masses in the Terra Nova polynya for the years 1997, 1998 (Budillon and Spezie, 2000, mod.) and 2001.

likely mechanism for the formation of this water mass is contact with the ice shelves or tongues of Terra Nova Bay. Because of the high salinity values detected in this TISW layer ($S > 34.7$), this water is primarily formed by the interaction of the salty HSSW with the base of the glacial ice (Budillon and Spezie, 2000).

The TISW was present in massive quantities in the western sector of Terra Nova Bay, indicating a north-eastwards flow of the TISW from beneath the Nansen Ice Sheet. Cold waters originating in the northern sector are then advected in the central region of Terra Nova Bay by the clockwise coastal circulation.

The northwards flow along the coast and to the central part of TNB agrees with the $\theta - T_f$ contours of the January–February 1998 cruise which showed the tongue of the TISW with a south-easterly direction (Fig. 4b), while during the November–December 1997 cruise, the area influenced by the TISW was close to the NIS (Fig. 4a). During the last cruise (Fig. 4c), the spreading of the TISW was not detectable: only the sector between the Nansen Ice Sheet and the Drygalski Ice Tongue was colder than the surface freezing values.

Actually, the summer water column of this sector in the southern part of Terra Nova Bay is often characterized by the higher temperature and salinities of the whole bay (Budillon and Spezie, 2000).

The TISW typically ranged from 30 to 600 m, being shallower in the north-west sector and deeper offshore, before its characteristics became undetectable after mixing with the surrounding waters. The depth thickness also changed considerably, from approximately 400 m (close to the coast) to 150 m in the central region of Terra Nova Bay.

3.2 Particulate Matter Concentration and Size

The TPM concentrations displayed clear interannual differences with a net increase in 1998. Concentrations of $0.6\,mg\,l^{-1}$ were found in November–December 1997, $1.9\,mg\,l^{-1}$ in January–February 1998 and $1.1\,mg\,l^{-1}$ in January–February 2001; these values are similar to those found by Yoon *et al.* (1998) in western Antarctica ($0.1–1\,mg\,l^{-1}$) and Domack *et al.* (1994) in an Antarctic fjord ($0.75–4.1\,mg\,l^{-1}$). The organic component showed percentage values of 65% in 1997, 74% in 1998 and 61% in 2001; the high values of this fraction encouraged us to evaluate the influence of biological processes on temporal and spatial changes of particulate matter in polynya areas; this study, conducted in collaboration with the Stazione di Biologia Marina of Trieste, was published in Fonda Umani *et al.* (2002).

The analysis of the size and number of particles in the different water masses provided the following average values:

- 1997: 190×10^6 particles l^{-1}, with mean size 10 μm and main mode 29 μm;
- 1998: 27×10^6 particles l^{-1}, with mean size 28 μm and main mode 56 μm;
- 2001: 12×10^6 particles l^{-1}, with mean size 21 μm and main mode 40 μm.

The typologies of the dimensional spectra relating dimension and volume were studied: the spectra were clearly divided into two groups (Fig. 5). The first group was characterized by bimodal spectra (B_L) and the second by polymodal spectra (P_M, P_S), with the following characteristics:

- bimodal histogram B_L: characterized by the presence of large particles with most values between 60 and 80 μm and a secondary grouping around 15 μm (Bimodal Large);
- polymodal histogram P_M and P_S: characterized by at least three types that could be divided into two subgroups; the first subgroup was characterized by medium-sized particles grouped around 4 μm, 12 μm and 20–40 μm (Polymodal Medium, P_M); the second subgroup was composed of small particles grouped around 1 μm, 3–4 μm and 15–20 μm (Polymodal Small, P_S).

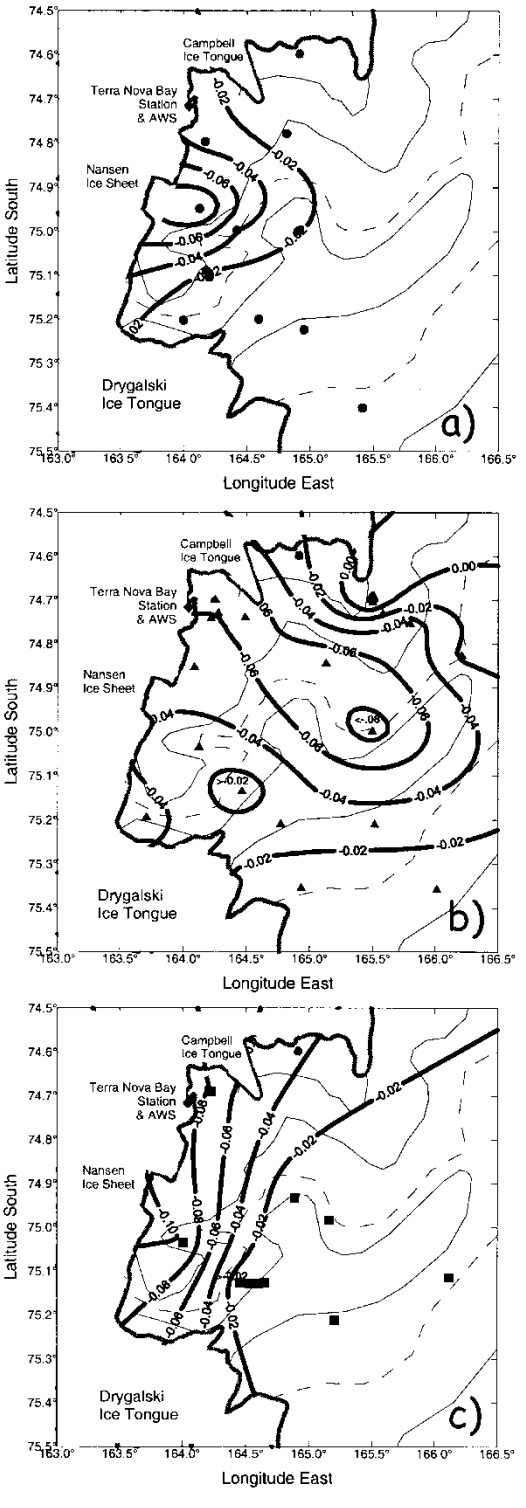

FIGURE 4 Distribution of the maximum anomaly (°C) between the *in situ* potential temperature and the surface freezing point ($S = 34.85$) for the three CLIMA cruises in Terra Nova Bay: (a) November–December 1997, (b) January–February 1998 and (c) January–February 2001. It must be stressed that these are not horizontal surfaces.

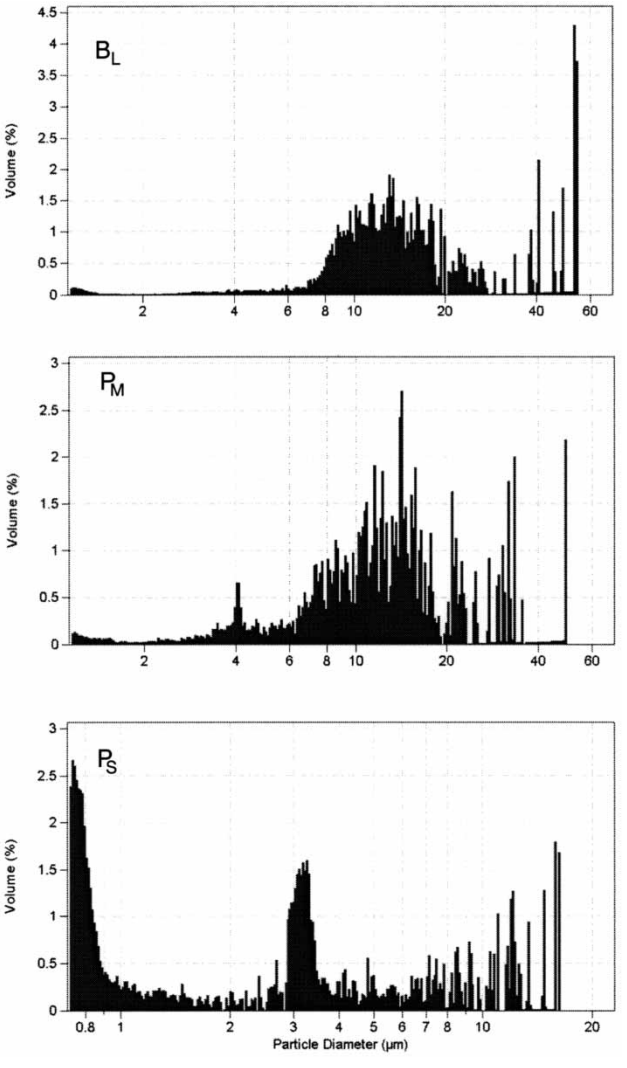

FIGURE 5 Dimensional analysis of particulate matter: spectral typology, top bimodal large (B_L), middle polymodal medium (P_M), bottom polymodal small (P_S).

The samples collected in November–December 1997, at the beginning of the austral summer, were characterized by polymodal spectra, with an important component of small size (P_S), in the entire water column. Instead the water column sampled in January and February of 1998 was characterized by bimodal spectra with large particles (B_L) and a reduced net component between 1 and 4 µm. The spectra that characterized January–February 2001 were always polymodal and grouped around 7, 12 and 20–40 µm (P_M); there was a tendency for the dimensions of the particles to increase as the season advanced.

We assigned a value of *S* and *T*, corresponding to the sampling depth, to each water sample, allowing us to discriminate between HSSW, TISW and AASW. The average values of two of the parameters (concentration and size) were associated with every water mass over the three years; the data are reported in Table I.

TABLE I Average concentration of TPM, IPM, OPM (%), mode, mean size and number of particles (NP).

	TPM (mg l^{-1})	*IPM (mg l^{-1})*	*OPM (%)*	*Mode (μm)*	*Mean size (μm)*	*NP (×10^6 l^{-1})*
AASW						
1997	0.9 ± 0.3	0.36 ± 0.25	60 ± 27	39 ± 18	13 ± 7	150 ± 60
1998	2.6 ± 1.3	0.56 ± 0.39	79 ± 9	63 ± 16	24 ± 11	46 ± 30
2001	1.4 ± 0.6	0.50 ± 0.29	64 ± 9	44 ± 18	18 ± 14	26 ± 18
TISW						
1997	0.7 ± 0.4	0.20 ± 0.19	72 ± 16	23 ± 14	9 ± 6	128 ± 104
1998	1.4 ± 0.9	0.31 ± 0.30	78 ± 23	54 ± 21	28 ± 13	26 ± 24
2001	1.2 ± 1.0	0.40 ± 0.30	56 ± 24	40 ± 27	28 ± 23	4 ± 3
HSSW						
1997	0.6 ± 0.2	0.15 ± 0.14	73 ± 21	24 ± 23	8 ± 7	294 ± 264
1998	1.5 ± 0.9	0.36 ± 0.25	73 ± 13	51 ± 23	32 ± 19	9 ± 4
2001	0.8 ± 0.3	0.29 ± 0.11	41 ± 15	37 ± 25	28 ± 25	5 ± 3

The highest TPM concentrations were found in the AASW, where the highest mode was also observed. The lowest TPM concentrations were found in the HSSW; a larger quantity of TPM was present in 1998, with values almost double those of 2001 in AASW and HSSW, while within the TISW, the main characteristics were the same in both years. This shows a constant organic input from the glacial tongues. The size of the particulate matter was similar in 1998 and 2001, but in 1997 differed in size and number throughout the water column.

The data that characterize the different areas show that in 1997 and 2001, the TPM concentrations in Terra Nova Bay coastal waters (AASW) were richer than those of the Drygalski Ice Tongue and Nansen Ice Sheet waters (1.7 mg l^{-1} *vs.* 0.7–0.8 mg l^{-1} in 1997, and 1.57 mg l^{-1} *vs.* 1.20 mg l^{-1} in 2001); in 1998, the richest were the Drygalski Ice Tongue surficial waters (2.7 mg l^{-1}). The underlying waters were always poor in particulate matter (0.2–0.3 mg l^{-1}), except for the TISW rich in TPM at the coastal stations near Terra Nova Bay in 1997 and in 1998 (0.5 mg l^{-1} and 1.1 mg l^{-1}) and in the waters off the Drygalski Ice Tongue in 2001 (0.6 mg l^{-1}). At a few stations, water near the bottom, associated with HSSW, was richer in TPM than that in the near-surface waters: station 9 in 1997 (0.9 mg l^{-1}), stations 70 (2.7 mg l^{-1}), 213 (1.5 mg l^{-1}) and 214 (3.4 mg l^{-1}) in 1998 and station 10 (3.0 mg l^{-1}) in 2001. All these results suggest an enrichment of the bottom waters off Terra Nova Bay due to the interaction of two processes: the sinking of particulate matter coming from the AASW and the lateral advection of particulate matter in the TISW towards the open sea, before reaching deep waters.

The physical characteristics of the water mass and those of the particulate matter were closely related, particularly for the TISW in 1997 and 1998. The Nansen Ice Sheet had a limited influence on the physical data and particulate concentration while the Drygalski Ice Tongue had a noticeable impact.

The relationship between the nephelometric data (FTU) on the water column and the TPM concentration in samples showed that the study area is generally characterized by low values (<1 FTU). High concentrations were observed in a surface nepheloid layer with a thickness of 200 m (values of 0.2–0.9 FTU *vs.* 0.5–3.0 mg l^{-1}). A second nepheloid layer was associated with the presence of the TISW; this intermediate layer was formed by contact with the lower side of the continental ice sheet and was detectable at stations 8, 10 and 12 at 400 m with a thickness of about 80 m (values of 0.6–0.7 mg l^{-1}). The bottom nepheloid layer was present in Terra Nova Bay (stations 6, 8 and 10) and at several offshore stations (11, 12 and 13) with concentration values of 0.7–1 mg l^{-1}. Concentration profiles were used to construct a section in front of the Nansen Ice Sheet (Fig. 6) including stations 8, 9, 10 and 11. Our results indicate an input of sediments in surficial water and at a depth of 400 m at station 8 (direct measurement of the TPM had

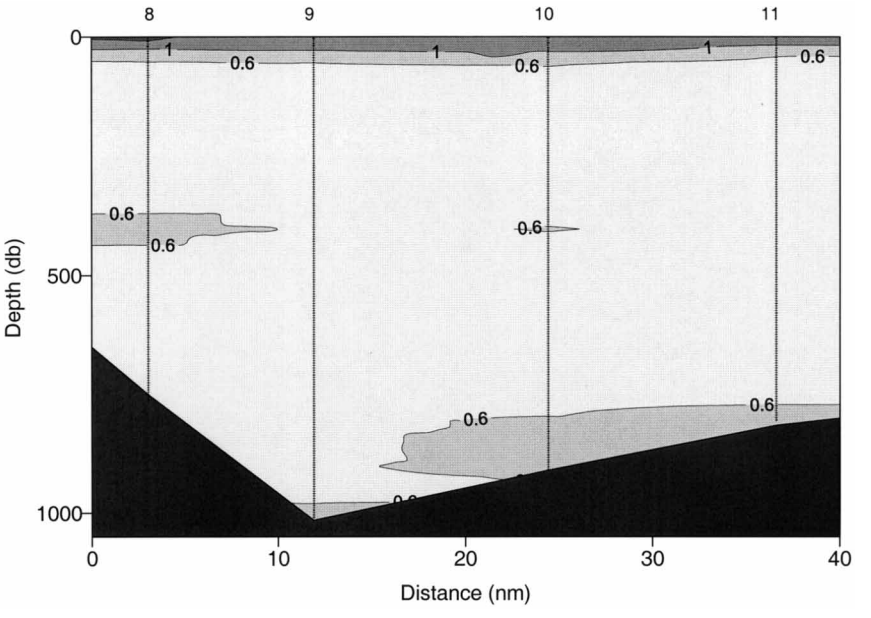

FIGURE 6 Vertical distribution of TPM ($mg\,l^{-1}$) in front of the Nansen Ice Sheet.

also indicated an increase at station 9), thereby confirming the physical data on the presence of the TISW only near the Nansen Ice Sheet in 2001. The offshore intermediate nepheloid layer, always located at 400 m, did not show any continuity with the coastal input and can therefore be ascribed to transport from outside our study area or, more likely, to transport from the Drygalski Ice Tongue. Unfortunately, this could not be confirmed because of a lack of sampling stations in that area.

4 CONCLUSIONS

The water column in Terra Nova Bay is formed by the AASW which extend from the surface down to 100–200 m; below this layer, the HSSW flow with a potential temperature close to the surface freezing point and a salinity >34.7. In this near-isothermal layer of HSSW, a water mass showing temperatures less than the surface freezing point was detected at intermediate depths. This water mass, called TISW, was observed in the whole area studied and was probably formed by contact with the ice shelves or tongues of Terra Nova Bay. The TISW was present in massive quantities in the western sector of Terra Nova Bay, suggesting that the TISW flows north-eastwards after leaving the Nansen Ice Sheet and the Drygalski Ice Tongue. Cold waters are then advected in the central region of Terra Nova Bay by a clockwise coastal circulation. During the last cruise, the spreading of the TISW over the whole area was not detectable: only the coastal sector, close to the Nansen Ice Sheet, was colder than the surface freezing values.

The total particulate matter concentrations, expressed as average values, showed concentrations of $0.6\,mg\,l^{-1}$ in November–December 1997, $1.9\,mg\,l^{-1}$ in January–February 1998 and $1.1\,mg\,l^{-1}$ in January–February 2001. The size of the particulate matter also varied, with a net prevalence of particles of small size at the beginning of the 1997 austral summer; during the middle and late summer periods of 1998 and 2001, the number of medium-sized particles increased, and the number of particles per litre decreased.

At the beginning of the 1997 austral summer, polymodal spectra with a large component of small size (P_S) dominated the entire water column. In 1998, bimodal spectra with large particles (B_L) and a net reduction in the component between 1 and 4 μm were observed. The spectra were polymodal again in 2001 with the presence of modes centred on 7–12 and 20–40 μm (P_M).

The correlation between the physical characteristics of the water mass and the characteristics of the particulate matter confirmed that the highest TPM values were found in the AASW, above all near Terra Nova Bay and the Drygalski Ice Tongue. The underlying waters, with HSSW characteristics, were poor in particulate matter near the coastal zone but richer offshore. Instead, the intermediate waters, with TISW characteristics, were rich in TPM at the coastal stations in 1997 and 1998 and in the waters off the Drygalski Ice Tongue in 2001. Offshore, the HSSW was sometimes very rich in TPM, and this enrichment is due to the settling of the particulate matter coming from the AASW and the suspended matter of the TISW that moves towards the open sea before reaching deep waters.

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