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Distribution of dinoflagellate cysts in surface sediments of the Mackenzie Shelf and Amundsen Gulf, Beaufort Sea (Canada)

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Abstract

In order to document long-term climate cycles and predict future climate trends for the Arctic, we need to look at the geological records to establish the link between historical and pre-historical sea-surface parameters. Dinoflagellate cysts (dinocysts) are used as proxy indicators of sea-surface parameters (temperature, salinity, sea-ice cover, primary productivity) jointly with transfer functions and a modern dinocyst reference database, to reconstruct the evolution of sea-surface conditions at decadal and millennial timescales. Here we present the surface distribution of recent dinocyst assemblages from 34 surface sediment samples collected on the Mackenzie Slope/Amundsen Gulf during the 2004 CASES (Canadian Arctic Shelf Exchange Study) cruise. Dinocyst concentrations in surface sediments are relatively high outside the Mackenzie plume area and increase gradually eastward toward Amundsen Gulf. The cysts of autotrophic dinoflagellates are dominant throughout the study area, while the maximum abundance of heterotrophic taxa is found within the Mackenzie plume. Hierarchical clustering analyses allowed defining two dinocyst assemblages. Assemblage I is located on the Mackenzie Slope and southern Amundsen Gulf, while Assemblage II is located within the Cape Bathurst Polynya area in northern Amundsen Gulf. Both assemblages are dominated by *Operculodinium centrocarpum*, but are distinguished on the basis of the relative abundance of *Islandinium minutum*, a taxon generally associated with sea ice. *I. minutum* is found in lower abundance in the Cape Bathurst Polynya.

Keywords: Arctic; Dinoflagellate cysts; Beaufort Sea; Mackenzie Shelf; Amundsen Gulf; Surface sediments; Palynology; Climate; Sea-ice cover; Global warming

1. Introduction

Concerns have been raised during the past few decades about the future of our environment. Notable changes are already being observed and measured throughout the Arctic regions, but their extent and duration are still poorly understood. To achieve a better understanding of this global phenomenon, scientists tend to study those systems that have historically proven to be sensitive to variations in climate, with the goal of predicting the course that the climate of our planet will take in the years to come. One of these indicators of the planet's "pulse" is the Arctic ecosystem—more specifically, its ocean and its

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ice cover. A thinning of the multi-year ice cover (of approximately 0.1 m/year for the past ten years) and a decline in the area that it covers have been observed over the last few decades (Rothrock et al., 1999; Dumas et al., 2005).

Previous studies on the distribution of dinoflagellate cysts have shown that they are present in the overwhelming majority of surface sediments on the Arctic seas and their estuaries (Rochon et al., 1999; Mudie and Rochon, 2001; Voronina et al., 2001; Kunz-Pirrung, 2001; Grøsfjeld and Harland, 2001; Boessenkool et al., 2001; Radi et al., 2001). The use of micropalaeontological markers, such as dinoflagellate cysts (i.e. dinocysts), allows for the reconstruction of recent paleoceanographic conditions (temperature, salinity, duration of the sea-ice cover, primary production of the ecosystem) (de Vernal et al., 2001). The study of dinocyst assemblages collected from surface sediments of the Beaufort Sea during Leg 8 of the CASES (Canadian Arctic Shelf Exchange Study) cruise in the summer of 2004 allows us to determine the assemblages characteristic of the current modern conditions. These assemblages will be added to a reference database of modern dinocyst assemblages that is managed by GEOTOP (de Vernal et al., 2001).

The primary objective of this article is to establish the spatial distribution of dinoflagellate cyst assemblages and to assess their relationships with environmental parameters. Samples were collected on the shelf and slope of the Mackenzie Shelf (Beaufort Sea, Canada) and Amundsen Gulf; they fill a gap in the current dinocyst database. Maps of spatial distribution for major dinocyst species provide information on their relationships to one another and the sea-surface parameters.

2. Environmental setting

The Mackenzie Shelf is a coastal region of the Beaufort Sea located along the Arctic Ocean's Canadian coast, between Point Barrow in northern Alaska and the western part of the Canadian Arctic Archipelago (C.A.A.) (Mudie and Rochon, 2001; Wang et al., 2005). It is approximately 100 km wide, representing less than 2% of the total coast of the Arctic Ocean, and covers an area of approximately 64 000 km^2 (to the 200 m isobath) (Stein and Macdonald, 2004; O'Brien et al., 2006). The shelf is bordered to the west by the Mackenzie Trough and to the east by Amundsen Gulf (Fig. 1). The ice cover varies greatly from year to year. In general, the ice begins to form in mid-October and begins to break up at the end of May (Wang et al., 2005; O'Brien et al., 2006). If the winds allow, the shelf may be ice-free as early as mid-July. In the winter, landfast ice forms near the coast, beyond the 20 m isobath, and the stamukhi (i.e. a field of ice fragments), which contains ice and sediment mixed together, forms on the outer edge of the landfast ice. Beyond the stamukhi, one can observe a zone where the ice breaks up, with flaw leads forming intermittently across the pack ice, which tend to be moved westward by the Beaufort Gyre (Macdonald et al., 1995; O'Brien et al., 2006). To the east, near Amundsen Gulf, the ice-free zone forms part of

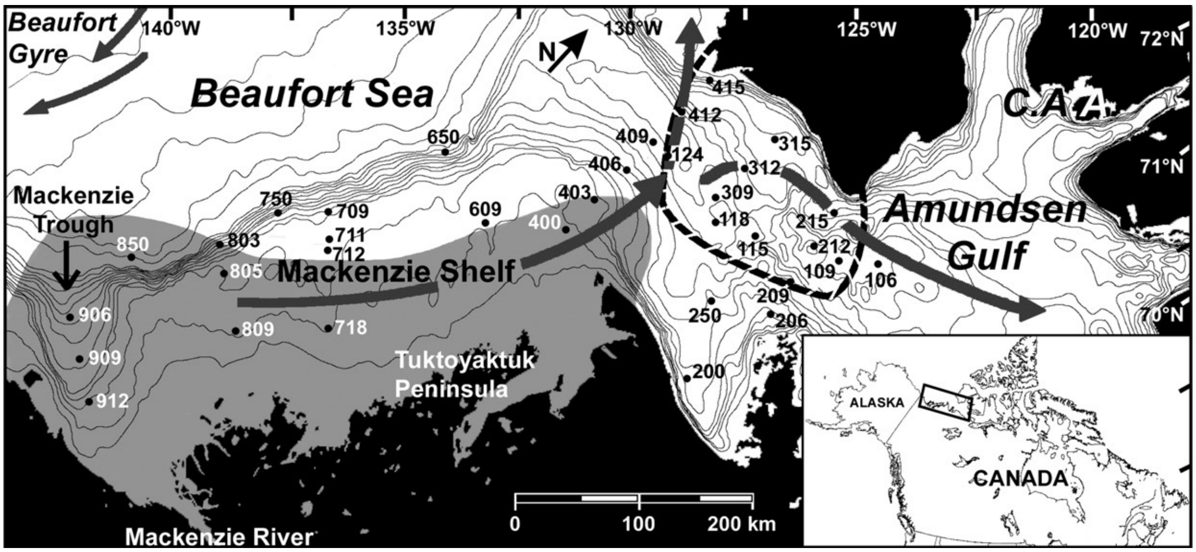

Fig. 1. Map of the Beaufort Sea and Amundsen Gulf illustrating the location of surface sediment samples used in our study. The thick arrows represent surface currents, the grey area represents the maximum extent of the Mackenzie River plume and the dashed line indicates the extent of the Cape Bathurst Polynya.

the Cape Bathurst Polynya (Arrigo and van Dijken, 2004). Polynyas are ice-free zones in the middle of the landfast ice, in both the Arctic and the Antarctic, that form in the winter under the action of winds, currents and upwellings of warmer water. They form every year at approximately the same location and are, in general, areas of high productivity.

The Mackenzie is the third largest Arctic river in terms of flow of fresh water, with an average flow of 4000 m^3/s (Melling, 2000; Dumas et al., 2005). It is also the largest in terms of sediment discharge, with approximately 127×10^6 Mt/year, which exceeds the total sediment discharge of all the other great Arctic rivers together (Macdonald et al., 2004; Stein and Macdonald, 2004; O'Brien et al., 2006). The Mackenzie River drainage basin, which is the source of the sediment and other materials carried by the river, covers a vast area (1.8×10^6 km^2) (Hill et al., 2001; Wang et al., 2005; Abdul Aziz and Burn, 2006). This basin drains the northern Rockies Mountains through the Athabasca and Peace rivers, and the Mackenzie Mountains through the Nahanni, Liard and Peel rivers. The current system dates from the end of the Wisconsinian Glaciation and results from erosion by the Laurentide Ice Sheet, which shifted the eastward-flowing drainage system toward the north. The main part of the delta fills a glacial valley that runs the width of the Mackenzie Trough. This trough is composed of more than 200 m of glacial sediments from the end of the Pleistocene, covered with deltaic deposits from the end of the Pleistocene and the Holocene (Blasco et al., 1990; Hill, 1996; Hill et al., 2001).

The Mackenzie River flows into the Beaufort Sea. The oceanic circulation of the Beaufort Sea is dominated by the anticyclonic Beaufort Gyre, which pushes the currents along the continental shelf. All along the coast, the currents are influenced by the wind direction, which alternates between eastward in the Canadian Archipelago and westward beyond the Mackenzie Trough (Vilks et al., 1979; Mudie and Rochon, 2001). The transport of suspended sediments within the plume of the Mackenzie can be affected by the ice cover, winds and currents (Fig. 1). In winter, the river carries sediments on a shorter distance, and its flow rate is reduced near the coast, below the landfast ice (Macdonald et al., 1995). In summer, the plume's position is greatly affected by the winds. Those coming from the northeast push the plume along Tuktoyaktuk Peninsula (Giovando and Herlinveaux, 1981), while the winds from the southeast push the plume westward, beyond the Mackenzie Trough (MacNeill and Garrett, 1975). As a result, the highest rates of accumulation are found in the Mackenzie Trough and on the nearby continental slope. As we move farther to the east, the rates of accumulation decline up to Amundsen Gulf, where sediment hardly accumulates at all (Hill et al., 1991; Macdonald et al., 1998; Blasco, unpublished results).

3. Materials and methods

3.1. Sampling

Sampling in the Beaufort Sea and Amundsen Gulf was carried out in the summer of 2004 during Leg 8 of the CASES (Canadian Arctic Shelf Exchange Study) cruise. A series of 34 surface samples were collected using a boxcorer, and the first 5 mm of the sediment's surface were collected. Each sample was then processed according to the standard palynological method described by Rochon et al. (1999).

3.2. Sieving

Approximately 5 cm^3 were taken from each sample and the volume measured in a graduated cylinder by water displacement. The weight (in gram) of this 5 cm^3 of sediment is also measured. A tablet of *Lycopodium clavatum* spores of known concentration (12,100 spores/tablet) is added to each sample. They serve as a palynological marker that enables us to calculate the concentration of palynomorphs in each sample. In order to determine the percentage of water in our samples, a small amount of sediment was collected and weighted before and after a period of at least 12 h in an incubator (60 °C). Sieving was performed using Nytex® sieves of 100 μm and 10 μm mesh, to eliminate coarse sand, fine silt and clay. The fraction between 10 μm and 100 μm was preserved in a conical tube with a few drops of phenol for subsequent chemical processing.

3.3. Chemical processing

The 10 μm to 100 μm fractions were processed with repeated treatments of hydrochloric acid (4 treatments with 10% HCl) and hydrofluoric acid (3 treatments, one of which was performed overnight, with 49% HF) in order to dissolve carbonates and silicates, respectively. These acid treatments were performed with heat in order to increase the rate of reaction. The remaining fraction was rinsed with distilled water to eliminate traces of acid before a final sieving at 10 μm that was performed to eliminate fine particles. The sample was mixed in the Vortimixer, and a few drops of the supernatant were drawn off and added to glycerin jelly to be mounted between slide and cover slip.

3.4. Palynomorph counts

Palynomorphs (pollen, spores, dinoflagellate cysts, acritarchs, and freshwater palynomorphs) were counted using an optical microscope (Nikon Eclipse I-80) under transmitted light, with magnification factors ranging from 200× to 400×. A minimum of 300 dinoflagellate cysts were counted in most samples, with the exception of two samples for which the counts were of 148 and 256 individuals. This method gives a sufficient representation of all the taxa present in the sample. The dinocyst concentration per unit of dry weight (cysts/g) and the relative abundance of each species (% dinocyst sp.) were calculated for each sample. The spatial distribution maps are obtained by linear interpolation between stations.

The dinocyst nomenclature is conformed to that of Rochon et al. (1999), Head et al. (2001) and the index of Lentin and Williams (Fensome and Williams, 2004). With respect to *Echinidinium* spp., there were only few specimens in some slides and they were not identified at the species level.

3.5. Statistical treatment

The sampling sites were arranged in a hierarchical clustering according to the dinocyst assemblages that characterizes them. We used the software PRIMER v5 (Plymouth Routines In Multivariate Ecological Research; Clarke and Gorley, 2001). The analysis was based on the non-transformed values of the dinocyst concentrations per dry weight (cysts/g). First, the program organized our data in a similarity matrix based on a measure of Euclidean distance. Next, a cluster was built on the basis of this matrix.

Table 1
Geographical coordinates, water depth (in meters), number of cysts counted, cyst concentrations (cysts/g) and hydrographic data for samples shown in Fig. 2

Station number	Lab number	Latitude	Longitude	Water depth	Count	Concentration	T_{feb}	S_{feb}	T_{aug}	S_{aug}	Ice
2004-804-106	140.5	70°. 36.0 N	122°. 37.8 W	122	301	4645	0.4	31.8	5.3	28.0	8.8
2004-804-109	140.3	70°. 39.600 N	123°. 25.824 W	569	300	7352	0.3	31.9	5.2	27.0	8.8
2004-804-115	139.6	70°. 50.910 N	125°. 03.010 W	352	314	2873	−0.1	32.5	6.7	28.7	8.6
2004-804-118	139.5	70°. 56.64 N	125°. 51.02 W	388	308	3191	−0.1	32.5	6.6	28.3	8.6
2004-804-124	138.1	71°. 23.368 N	126°. 43.112 W	442	311	5255	−1.4	32.7	4.5	28.1	9.8
2004-804-200	139.2	70°. 02.7 N	126°. 17.8 W	236	303	3319	−0.4	32.5	6.2	27.8	8.6
2004-804-206	139.3	70°. 19.248 N	124°. 50.320 W	95	319	3910	0.1	32.4	5.9	26.8	8.6
2004-804-209	139.4	70°. 32.319 N	124°. 21.95 W	241	312	3590	0.1	32.4	5.3	27.0	8.6
2004-804-212	140.1	70°. 45.429 N	123°. 53.429 W	430	354	6563	0.3	31.9	5.4	27.9	8.6
2004-804-215	140.2	70°. 58.450 N	123°. 24.900 W	297	306	6303	0.3	31.9	4.2	28.2	8.8
2004-804-250	140.4	70°. 27.095 N	125°. 25.386 W	193	319	3237	0.1	32.4	3.7	28.2	8.6
2004-804-309	138.5	71°. 07.52 N	125°. 50.01 W	397	389	6541	−0.1	32.5	6.3	28.5	8.6
2004-804-312	138.6	71°. 18.115 N	125°. 11.534 W	307	360	6292	0.3	31.9	6.0	28.3	8.6
2004-804-315	139.1	71°. 29.155 N	124°. 32.583 W	224	333	7018	0.3	31.9	2.9	27.9	8.6
2004-804-400	137.4	70°. 54.991 N	128°. 55.987 W	36	312	1029	−1.4	30.4	5.3	26.1	8.9
2004-804-403	137.5	71°. 06.777 N	128°. 18.302 W	59	310	1399	−1.6	32.5	4.8	27.0	8.9
2004-804-406	137.6	71°. 18.66 N	127°. 41.91 W	179	314	5508	−1.6	32.7	4.3	28.4	8.9
2004-804-409	138.2	71°. 30.70 N	127°. 05.53 W	387	301	4869	−1.6	32.7	3.3	28.7	9.8
2004-804-412	138.3	71°. 41.992 N	126°. 28.649 W	390	332	4457	−1.4	32.7	3.2	28.5	9.8
2004-804-415	138.4	71°. 54.455 N	125°. 52.092 W	56	334	4058	−1.4	32.7	3.0	28.3	9.8
2004-804-609	137.2	70°. 56.58 N	130°. 31.38 W	44	256	1857	−1.4	30.4	5.3	26.1	8.9
2004-804-650	137.1	71°. 18.558 N	131°. 37.148 W	241	318	4529	−1.4	31.3	4.1	27.0	8.9
2004-804-709	135.6	70°. 57.811 N	133°. 47.025 W	87	335	2194	−1.5	30.7	5.2	21.6	8.9
2004-804-711	135.5	70°. 49.427 N	133°. 48.199 W	77	326	3488	−1.5	30.7	5.8	21.9	8.9
2004-804-712	135.4	70°. 41.37 N	133°. 40.84 W	70	310	2593	−1.5	30.7	6.0	21.4	8.9
2004-804-718	135.3	70°. 10.196 N	133°. 32.047 W	45	305	1784	−1.5	30.7	6.3	19.8	8.9
2004-804-750	137.3	71°. 20.753 N	134°. 08.609 W	1087	304	2720	−1.6	30.8	2.7	19.2	10.0
2004-804-803	135.2	70°. 38.169 N	135°. 55.041 W	237	307	2626	−1.4	30.4	5.9	19.2	10.0
2004-804-805	133.6	70°. 23.571 N	135°. 25.214 W	66	148	2118	−1.4	30.4	6.3	18.2	10.0
2004-804-809	135.1	70°. 05.7 N	135°. 20.48 W	42	301	609	−1.4	30.4	6.5	18.1	10.0
2004-804-850	133.4	70°. 32.889 N	137°. 36.00 W	1071	301	2821	−1.2	30.3	4.9	18.9	9.6
2004-804-906	133.3	70°. 01.145 N	138°. 35.817 W	272	303	2959	−1.5	30.3	4.4	17.8	9.0
2004-804-909	133.2	69°. 45.16 N	138°. 16.296 W	169	304	2496	−0.7	30.0	4.9	15.2	9.0
2004-804-912	133.1	69°. 29.25 N	137°. 56.43 W	54	305	964	−0.7	30.0	5.6	15.1	9.0

Temperature and salinity are in °C and psu (practical salinity units) respectively. Ice is the number of months with more than 5/10 sea-ice coverage.

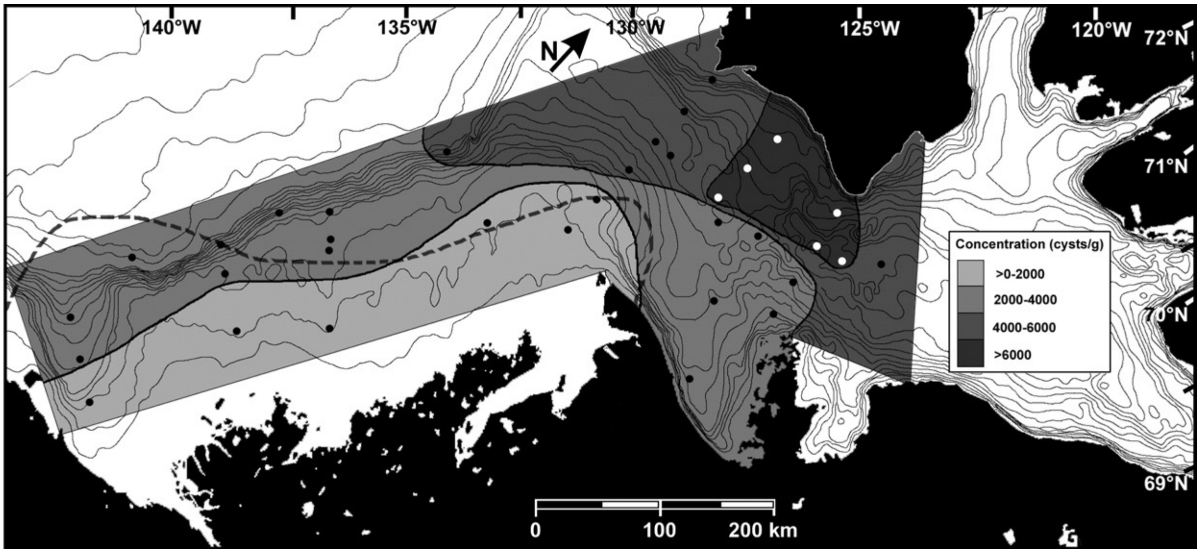

Fig. 2. Distribution map of dinocyst concentrations (cysts/g) in the study area. The dashed line illustrates the maximum extent of the Mackenzie River plume.

We then performed a Canonical Correspondence Analysis (CCA) to establish the relationships between the dinocyst species and the sea-surface parameters. The same data used for the hierarchical clustering was used in the CCA, in addition to environmental data from Table 1.

3.6. Environmental data

The hydrographic data collected during the CASES cruise represent only a limited survey of the conditions on the Mackenzie Shelf. We used surface temperature and salinity data from the World Ocean Atlas (2001) of the National Oceanographic Data Center (NODC) in order to obtain a multi-year representation of data, without any transformation (Table 1). When there were no data for a site, we used the NOAAZ interpolation grid built from NOAA 2001 (National Oceanic and Atmospheric Administration). The ice cover data comes from the National Climate Data Center in Boulder (NCDC) and cover the years 1953–2000. These data are an annual average of environmental conditions; thus the impact of the year-to-year variability in the area is reduced (de Vernal et al., 2001; de Vernal et al., 2005).

4. Results and discussion

The region of the Mackenzie Shelf shows a concentration of dinocysts between 600 and 7000 cysts/g, with an average of about 3681 cysts/g. The minimum concentrations (between 600 and 1860 cysts/g) are found in the plume area of the Mackenzie River (Fig. 2). The concentrations increase toward the slope and to the east in Amundsen Gulf, where the highest concentrations (between 6300 and 7000 cysts/g) are recorded. Using the ^{210}Pb measurements performed on short sediment cores from the Mackenzie Trough (Richerol et al.,

Table 2
List of dinoflagellate taxa present in our samples, and their code name

Dinocyst name	Code name
Ataxiodinium choane	Acho
Brigantedinium spp.	Bspp
Brigantedinium cariacoense	Bspp
Brigantedinium simplex	Bspp
Echinidinium spp.	Espp
Impagidinium pallidum	Ipal
Islandinium minutum	Imin
Islandinium minutum var. *cezare*	Imic
Nematosphaeropsis labyrinthus	Nlab
Operculodinium centrocarpum	Ocen
Operculodinium centrocarpum short spines	Ocen
Operculodinium centrocarpum var. *arctic*	Ocen
Pentapharsodinium dalei	Pdal
Polykrikos spp.	Pspp
Polykrikos var. *arctic*	Parc
Polykrikos quadratus	Parc
Polykrikos schwartzii	Psch
Protoperidinium americanum	Pame
Selenopemphix quanta	Squa
Spiniferites spp.	Sspp
Spiniferites elongatus	Selo
Spiniferites frigidus	Selo
Spiniferites ramosus	Sram
Votadinium spp.	Vspp

Table 3
Relative abundance (%) of dinoflagellate cyst taxa in our samples

Station number	Acho	Ipal	Nlab	Ocen	Pdal	Sram	Selo	Sspp	Imin	Imic	Espp	Pame	Bspp	Squa	Vspp	Parc	Psch	Pspp
2004-804-106	0.0	0.0	0.0	20.9	71.8	0.0	0.7	0.0	2.0	0.3	0.0	0.0	4.3	0.0	0.0	0.0	0.0	0.0
2004-804-109	0.0	0.0	0.0	36.3	51.3	0.0	3.0	0.0	1.0	1.0	0.0	0.0	5.0	0.0	0.0	1.7	0.7	0.0
2004-804-115	0.0	0.0	0.0	56.7	26.8	0.0	2.9	0.0	4.5	1.0	0.0	0.0	5.4	0.0	0.0	2.9	0.0	0.0
2004-804-118	0.0	0.0	0.0	66.9	18.2	0.3	5.2	0.0	1.3	1.0	0.0	0.0	5.5	0.0	0.0	1.6	0.0	0.0
2004-804-124	0.0	0.0	0.0	39.2	29.9	0.3	4.5	0.0	10.0	11.9	0.0	0.3	2.6	0.0	0.0	0.6	0.6	0.0
2004-804-200	0.0	0.0	0.0	50.5	33.0	0.0	4.6	0.0	3.3	1.0	0.0	0.3	6.3	0.0	0.0	1.0	0.0	0.0
2004-804-206	0.0	0.0	0.0	48.9	36.4	0.0	2.5	0.0	2.5	1.6	0.0	0.0	7.5	0.0	0.0	0.6	0.0	0.0
2004-804-209	0.0	0.0	0.0	57.7	25.0	0.0	3.8	0.0	2.6	2.9	0.0	0.0	6.4	0.0	0.0	1.3	0.3	0.0
2004-804-212	0.0	0.0	0.0	48.9	35.9	0.0	2.3	0.0	4.2	2.3	0.0	0.3	3.1	0.0	0.0	1.1	1.7	0.3
2004-804-215	0.0	0.7	0.0	46.4	33.0	0.0	7.8	0.0	3.3	1.3	0.0	0.0	4.6	0.0	0.0	2.3	0.7	0.0
2004-804-250	0.0	0.0	0.0	39.2	24.5	0.0	2.2	0.3	8.2	3.8	0.3	0.0	18.5	0.0	0.0	2.8	0.3	0.0
2004-804-309	0.0	0.0	0.0	47.3	33.2	0.0	4.1	0.0	7.2	1.5	0.0	0.0	4.9	0.0	0.0	1.3	0.0	0.5
2004-804-312	0.0	0.0	0.3	53.3	29.7	0.3	2.8	0.3	5.8	1.4	0.0	0.0	3.9	0.0	0.0	1.9	0.3	0.0
2004-804-315	0.0	0.0	0.0	63.7	21.3	0.0	8.1	0.0	3.0	0.6	0.0	0.0	2.1	0.0	0.0	0.6	0.3	0.3
2004-804-400	0.0	0.0	0.0	20.2	55.4	0.0	0.6	0.0	16.0	3.5	0.0	0.0	4.2	0.0	0.0	0.0	0.0	0.0
2004-804-403	0.0	0.0	0.0	37.7	19.4	0.0	3.5	0.0	16.8	9.7	0.0	0.6	8.4	0.0	0.0	1.9	1.9	0.0
2004-804-406	0.0	0.0	0.0	33.4	37.9	0.0	3.5	0.0	11.5	4.8	0.0	0.0	6.1	0.0	0.0	0.6	0.3	1.9
2004-804-409	0.0	0.3	0.0	48.5	23.9	0.0	3.3	0.0	13.0	5.0	0.0	0.0	5.0	0.0	0.0	0.3	0.3	0.3
2004-804-412	0.0	0.3	0.0	41.3	36.4	0.0	3.6	0.0	9.9	3.3	0.0	0.0	3.3	0.0	0.0	1.2	0.0	0.6
2004-804-415	0.0	0.0	0.0	54.2	25.7	0.3	6.0	0.0	5.7	1.5	0.9	0.0	4.8	0.0	0.0	0.9	0.0	0.0
2004-804-609	0.0	0.0	0.0	46.1	23.4	0.0	4.7	0.0	7.0	3.1	0.0	0.0	13.7	0.0	0.0	1.6	0.4	0.0
2004-804-650	0.0	0.0	0.0	31.4	44.0	0.0	4.1	0.0	5.0	6.0	0.0	0.0	8.2	0.0	0.0	0.3	0.6	0.3
2004-804-709	0.0	0.0	0.0	39.1	26.9	0.0	5.1	0.3	17.0	1.8	0.0	0.0	8.1	0.0	0.0	0.6	1.2	0.0
2004-804-711	0.0	0.0	0.0	37.7	19.0	0.0	2.8	0.0	18.4	4.3	0.0	0.0	15.6	0.0	0.3	1.8	0.0	0.0
2004-804-712	0.0	0.0	0.0	39.7	21.9	0.0	3.5	0.0	17.1	2.3	0.0	0.0	12.6	0.0	0.0	2.9	0.0	0.0
2004-804-718	0.0	0.0	0.0	40.7	34.8	0.0	3.3	0.0	6.2	2.3	0.0	0.0	12.5	0.0	0.0	0.3	0.0	0.0
2004-804-750	0.0	0.3	0.0	37.5	22.0	0.0	5.6	0.0	15.8	3.9	0.0	0.0	13.5	0.0	0.0	1.3	0.0	0.0
2004-804-803	0.3	0.3	0.0	50.5	19.2	0.0	2.6	0.0	9.8	5.5	0.0	0.3	10.4	0.0	0.0	0.7	0.3	0.0
2004-804-805	0.0	0.7	0.0	40.5	27.0	0.0	4.1	0.0	8.1	2.7	0.0	1.4	14.2	0.0	0.0	1.4	0.0	0.0
2004-804-809	0.0	0.0	0.0	39.9	18.3	0.0	2.7	1.7	21.3	1.7	0.0	0.0	14.6	0.0	0.0	0.0	0.0	0.0
2004-804-850	0.0	0.0	0.0	46.8	21.6	0.0	2.7	0.3	15.6	6.6	0.0	0.0	5.6	0.0	0.0	0.3	0.3	0.0
2004-804-906	0.0	0.0	0.3	47.2	34.3	0.0	1.3	0.7	9.6	1.7	0.0	0.0	5.0	0.0	0.0	0.0	0.0	0.0
2004-804-909	0.0	0.0	0.0	49.0	23.4	0.0	3.9	0.0	8.6	3.9	0.0	0.0	10.5	0.3	0.0	0.3	0.0	0.0
2004-804-912	0.0	0.0	0.0	45.07	21.4	0.0	1.6	2.0	18.1	1.6	0.0	0.0	9.2	0.0	0.0	0.3	0.3	0.3

unpublished results) and the data from Cochrane and Amiel (2006, unpublished results) on the Mackenzie Shelf and Slope, we can estimate sediment accumulation rates for our region, which range between 0.011 and 0.119 cm/year (0.051 cm/year on average) for the Mackenzie Shelf, and up to 0.226 cm/year (average of 0.081 cm/year) for the Mackenzie Trough, and between 0.004 and 0.037 cm/year (0.023 cm/year on average) for Amundsen Gulf. This enables us to estimate average dinocyst fluxes on the order of ~33 cysts/cm^2/year on the Mackenzie Shelf (~86 cysts/cm^2/year for the Mackenzie Trough) and ~34 cysts/cm^2/year in Amundsen Gulf. The Labrador Sea and Gulf of St. Lawrence are considered as high dinoflagellate productivity area, and the estimated dinocyst fluxes for these regions vary between 10 and 100 cysts/cm^2/year (de Vernal and Giroux, 1991; Rochon and de Vernal, 1994). In contrast, the dinocyst fluxes in central Baffin Bay and south-central Labrador Sea are very low, less than 1 cyst/cm^2/year (Rochon and de Vernal, 1994). Therefore, the dinocyst fluxes from our study area are among the higher in the Arctic and Subarctic areas. Moreover, the study area is dominated by the cysts of autotrophic dinoflagellates. The maximum abundance of cysts of heterotrophic dinoflagellates is found on the Mackenzie River Plume.

As for reworked palynomorphs, the highest concentrations are found in Amundsen Gulf (~221 reworked palynomorphs/g), primarily in the area of Cape Bathurst Polynya (~251 reworked palynomorphs/g). On the Mackenzie Shelf (~179 reworked palynomorphs/g), the concentrations gradually increase from the coast to the slope. Nonetheless, relatively high values (~178 reworked palynomorphs/g) are found in association with the Mackenzie River plume.

A total of 24 dinocyst taxa were identified in the samples (Table 2). Yet, 6 taxa make up more than 95% of the total dinocyst counts (Table 3; Fig. 3): *Operculodinium centrocarpum* s.l., *Pentapharsodinium dalei*, *Spiniferites*

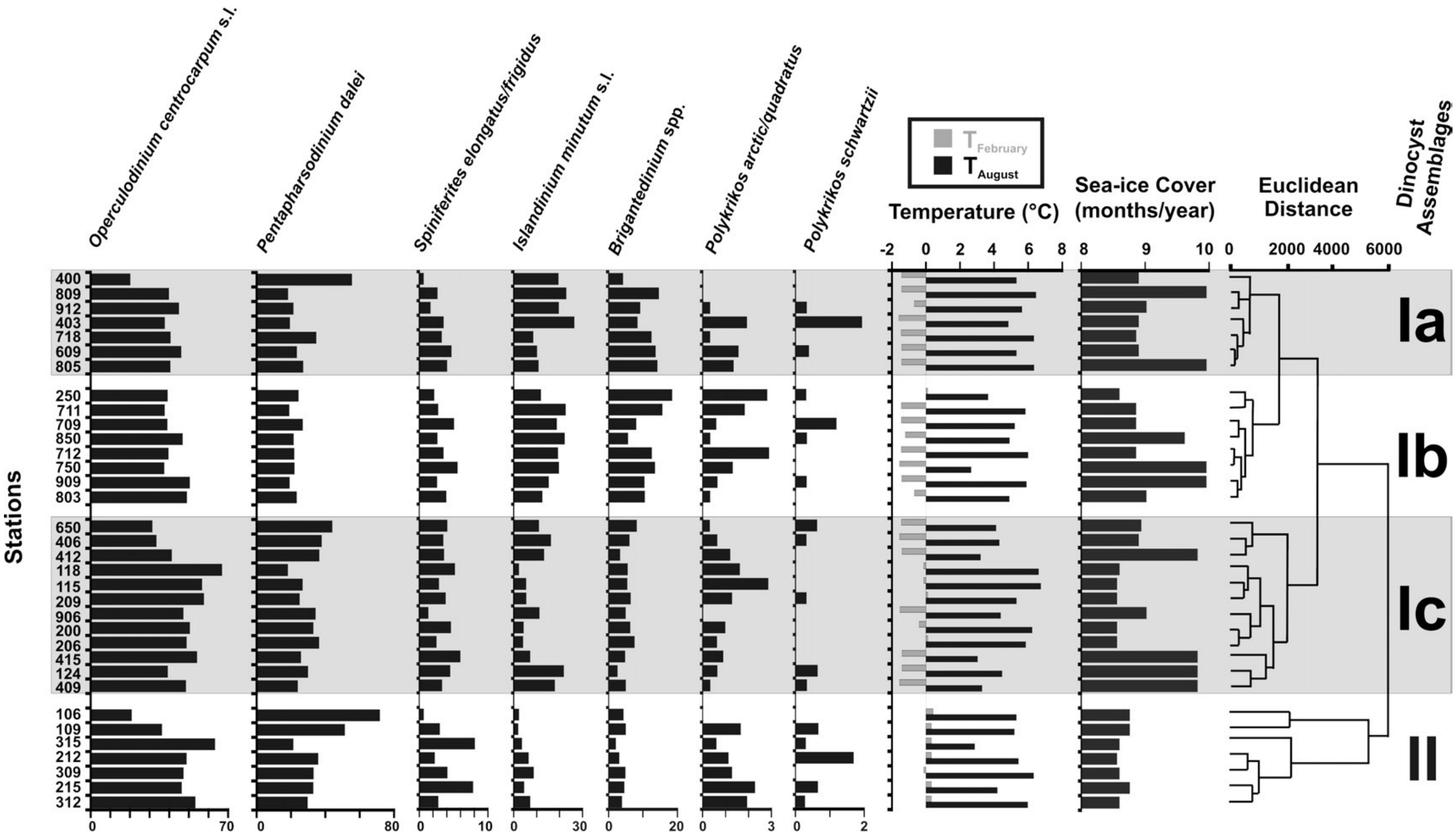

Fig. 3. Relative abundance of major dinoflagellate cyst taxa, sea-surface parameters (temperature and sea-ice cover) and hierarchical clustering of surface sediment samples used to determine dinocyst assemblages.

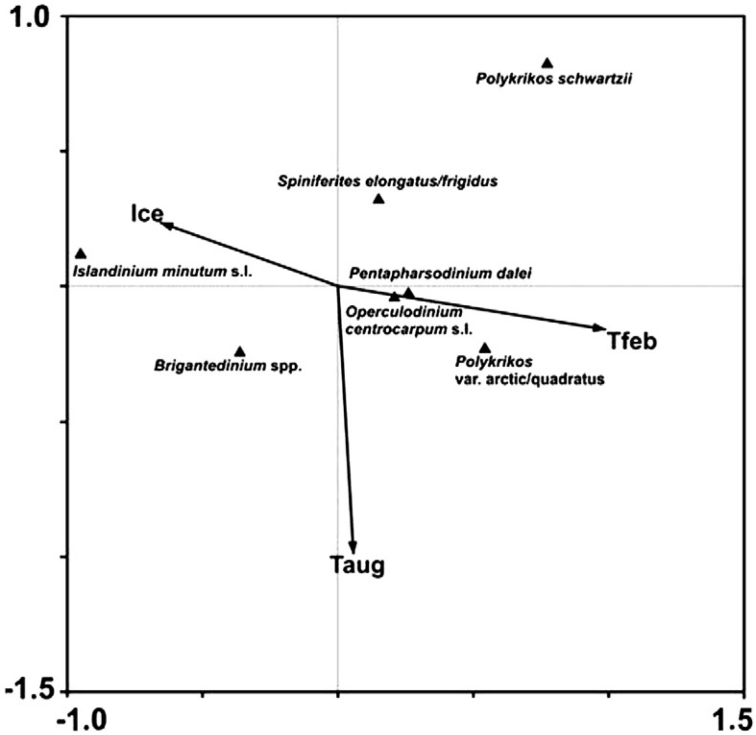

Fig. 4. Graph of the Canonical Correspondence Analysis (CCA) between the dinocyst species and the sea-surface parameters. Tfeb = sea-surface temperature of February; Taug = sea-surface temperature of August; Ice = sea-ice cover duration.

elongatus/frigidus, *Islandinium minutum* s.l., and *Brigantedinium* spp. We have combined them in the same way than the dinocyst database of the GEOTOP. *O. centrocarpum* s.l., includes *O. centrocarpum sensu* Wall and Dale 1966, *O. centrocarpum* short spines (with short, truncated processes), and *O. centrocarpum* var. arctic, according to de Vernal et al. (2001). Of the three morphotypes, *O. centrocarpum sensu* Wall and Dale 1966 was the most abundant. *S. elongatus/frigidus* are grouped together because they have a similar distribution,

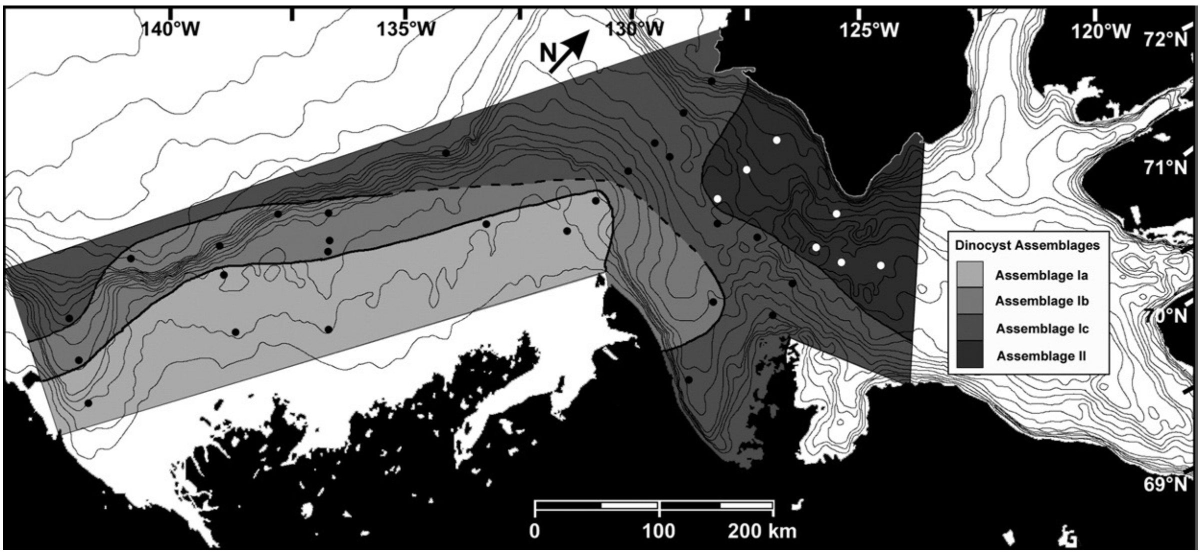

Fig. 5. Surface distribution of dinocyst assemblages in the study area. The dashed lines indicate uncertainties in defining assemblage zones.

S. frigidus being the most abundant. Moreover they seem to show a morphological gradation (the flange between the processes is more developed in *S. frigidus*). *I. minutum* s.l. includes the varieties *minutum* and *cezare*, the latter being the less abundant. *Brigantedinium* spp. includes *B. simplex* and *B. cariacoense*, two species that are distinguishable by the shape of the archeopyle, in addition to specimens of round brown cysts for which the archeopyle was not visible on the slides.

Statistical analyses with PRIMER v5 enabled us to determine the presence of two main assemblages and three sub-assemblages (Fig. 3). The first assemblage (I) includes the stations of the Mackenzie Shelf and Slope, with some stations in Amundsen Gulf. It is made up of three sub-assemblages (Ia, Ib, Ic). The abundances of *O. centrocarpum* s.l. and *P. dalei* are the highest in this first assemblage, but it is mostly characterized by the onshore–offshore decrease of *I. minutum* s.l. and *Brigantedinium* spp. abundances. Assemblage Ia includes the stations located near the coast, which are under the influence of the river's plume. It is characterized primarily by the maximum abundance of *I. minutum* s.l. and *Brigantedinium* spp. Assemblages Ib and Ic consist of the stations for which the plume's influence is lower and in which marine influence is dominant. Assemblage Ib is characterized by the species *I. minutum* s.l., *Brigantedinium* spp. and *Polykrikos* sp. Arctic morphotypes I and II (quadratus) *sensu* de Vernal et al., 2001. We distinguish the Arctic morphotypes I and II (quadratus) by the shape of the cyst, the latter being characterized by a thinning in the equatorial area and by processes concentrated at the polar extremities of the cyst. The Assemblage Ic is characterized by a lower abundance of *I. minutum* s.l. and *Brigantedinium* spp. and an increase in the abundance of *O. centrocarpum* s.l., *P. dalei* and *Polykrikos* var. arctic/quadratus. The second assemblage (II) consists of the stations in Amundsen Gulf, which are more specifically located in the Cape Bathurst Polynya. We found the highest abundances of *O. centrocarpum* s.l., *P. dalei*, *S. elongatus/frigidus* and *Polykrikos schwartzii* in this second assemblage. It is characterized by the lowest abundance of *I. minutum* s.l. and *Brigantedinium* spp. and by the highest abundance of *P. schwartzii*. The latter is distinguished from other *Polykrikos* species by having more developed and evenly distributed processes.

The distribution of dinoflagellate cyst assemblages is closely linked to that of sea-surface parameters (Fig. 3, 4). For instance, for Assemblage II, which is located in the Cape Bathurst Polynya (Fig. 5), the surface temperatures in February are >0 °C, which is not the case for the other assemblages. A few other stations in Assemblage Ic (118, 115, 209 and 206) and one station in Assemblage Ib (250) are also characterized by temperatures above the freezing point in winter (February) and lie at the southern limit of the polynya. Likewise, these stations and those of Assemblage II show the lowest sea-ice duration (between 8.50 and 8.75 months/year), which is consistent with the presence of a polynya. The CCA (Fig. 4) illustrates a positive correlation between the abundance of *I. minutum* s.l. and the sea-ice cover. This correlation is weaker with *Brigantedinium* spp., which has a worldwide distribution and is not directly influenced by the presence of sea ice. Their association with sea ice in this particular situation is most likely due to the relationship between its food source

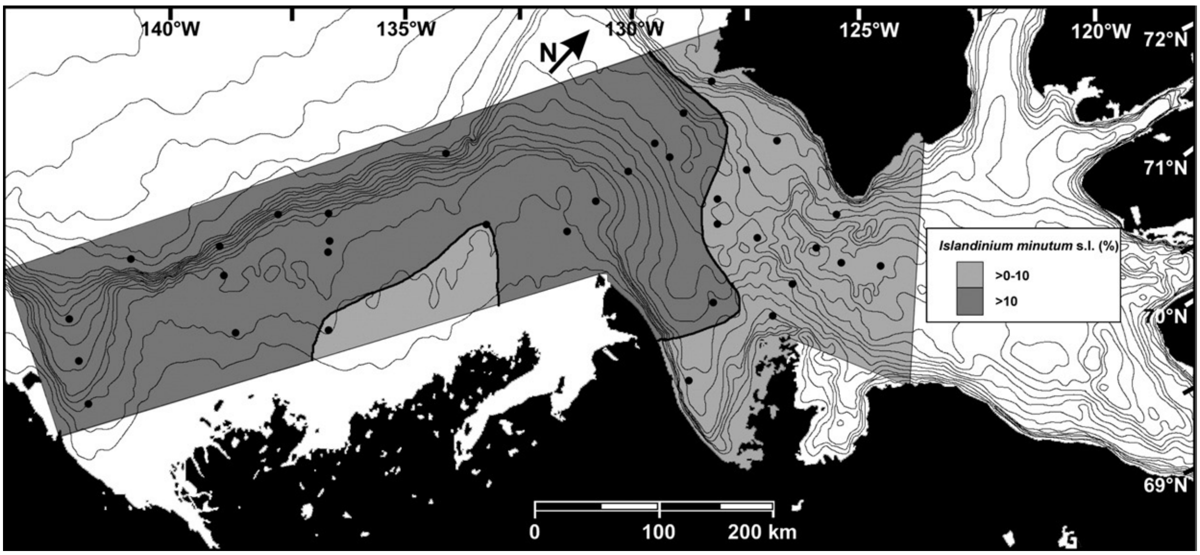

Fig. 6. Distribution map of the relative abundance of *Islandinium minutum* s.l. in surface sediments from the study area.

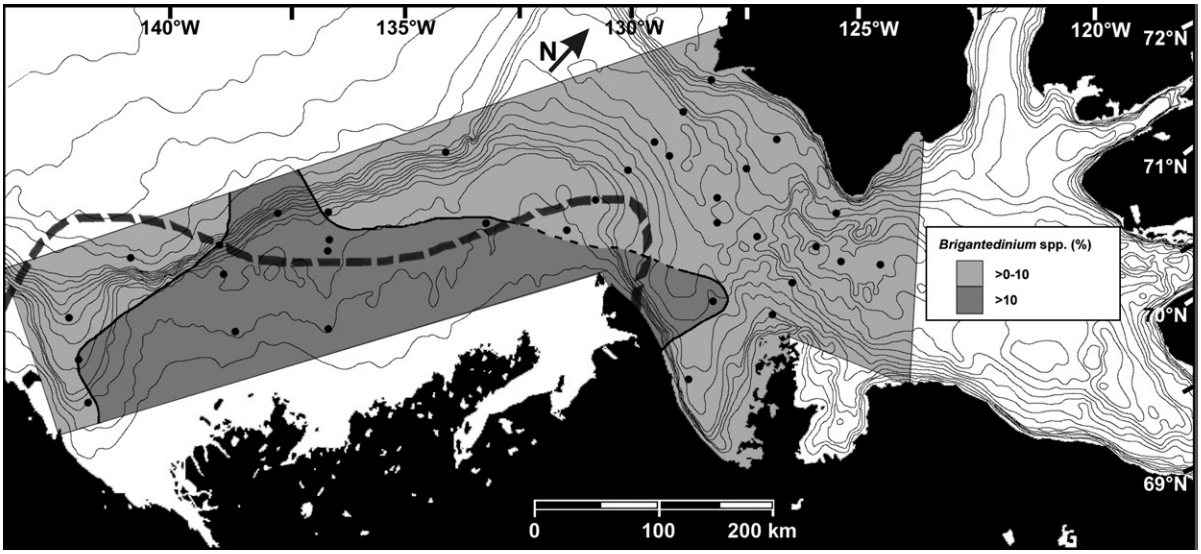

Fig. 7. Distribution map of the relative abundance of *Brigantedinium* spp. in surface sediments from the study area. The thin dashed lines indicate uncertainties in defining percentage zones, and the thick dashed line indicates the maximum extent of the Mackenzie River plume.

(e.g. ice algae) and sea ice. The decrease of these two groups of dinocysts is consistent with a decrease of sea-ice cover and increased February temperatures (Fig. 3).

The distribution of the cysts of heterotrophic taxa is shown in Figs. 6, 7, and 8. *I. minutum* s.l. is the most abundant on the Mackenzie Shelf, mostly on the slope, and at the mouth of Amundsen Gulf (~16.5% relative abundance), with a maximum relative abundance of 26.5%. The lowest abundances are recorded along the Tuktoyaktuk Peninsula (~9.3%) and at the head of Amundsen Gulf (~6.1%). The maximum abundance of *Brigantedinium* spp. (~18.5%) is found under the influence of the Mackenzie River plume. *Polykrikos* var. arctic/quadratus is found throughout the study area, but presents a very low abundance (maximum of ~2.9%).

The cyst distribution of the autotrophic taxa is shown in Figs. 9, 10, and 11. *O. centrocarpum* s.l. has a maximum abundance (~66.9%) in Amundsen Gulf, in the area of the Cape Bathurst Polynya. Its minimum

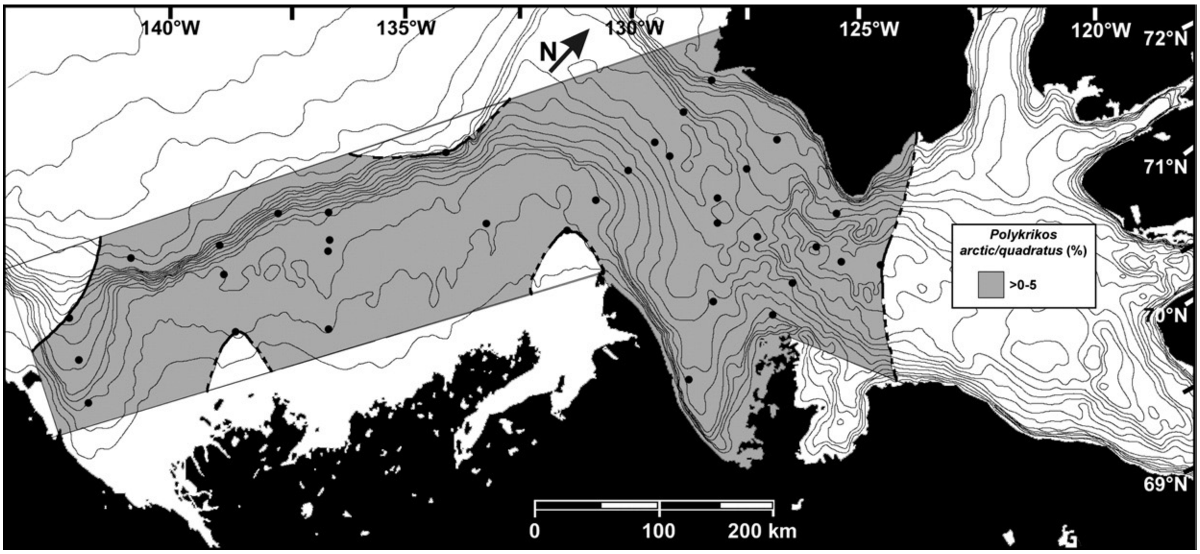

Fig. 8. Distribution map of the relative abundance of *Polykrikos* arctic/quadratus in surface sediments from the study area. The dashed lines indicate uncertainties in defining percentage zones.

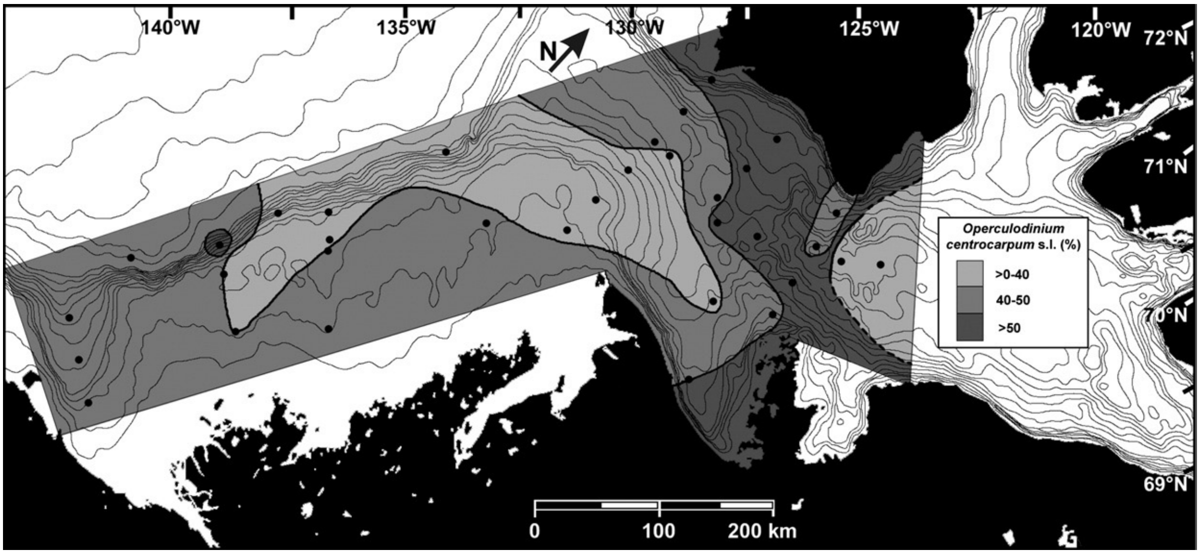

Fig. 9. Distribution map of the relative abundance of *Operculodinium centrocarpum* s.l. in surface sediments from the study area. The dashed lines indicate uncertainties in defining percentage zones.

abundance is approximately 20.2% in the central part of Amundsen Gulf and along the slope, just outside Amundsen Gulf. *P. dalei* seems to have a distribution that depends primarily on distance from the coast. The lowest abundances (~23.3%) are recorded near the coast and under the influence of the Mackenzie River plume. The highest abundance (~71.8%) is found in the central and innermost part of Amundsen Gulf. The species *S. elongatus/frigidus* are present in low abundance throughout the study area (~3.6%), and are found mostly along the shelf edge in Amundsen Gulf with maximum values of more than 5% in the polynya.

In general, the abundance of autotrophic taxa is higher than that of heterotrophic taxa throughout the study area. A closer examination of the distribution of the Autotrophic/Heterotrophic (A/H) ratio (Fig. 12) indicates that it increases away from the mouth of the Mackenzie River. On the Mackenzie Shelf, the A/H ratio is approximately 3; it is greater than 5 in Amundsen Gulf, with a maximum of 14 in the Cape

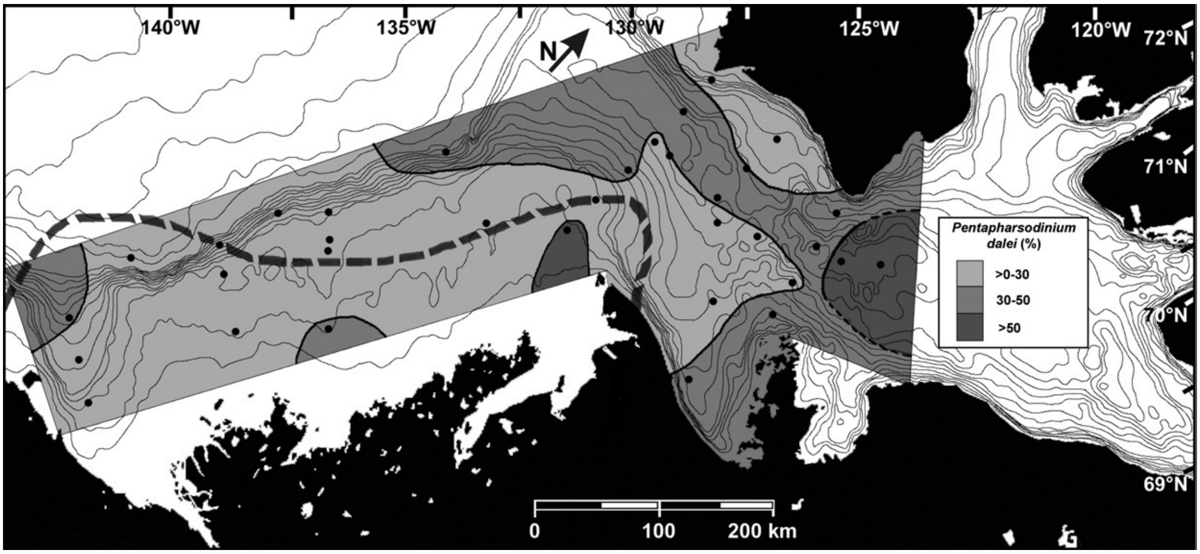

Fig. 10. Distribution map of the relative abundance of *Pentapharsodinium dalei* in surface sediments from the study area. The thin dashed lines indicate uncertainties in defining percentage zones, and the thick dashed line indicates the maximum extent of the Mackenzie River plume.

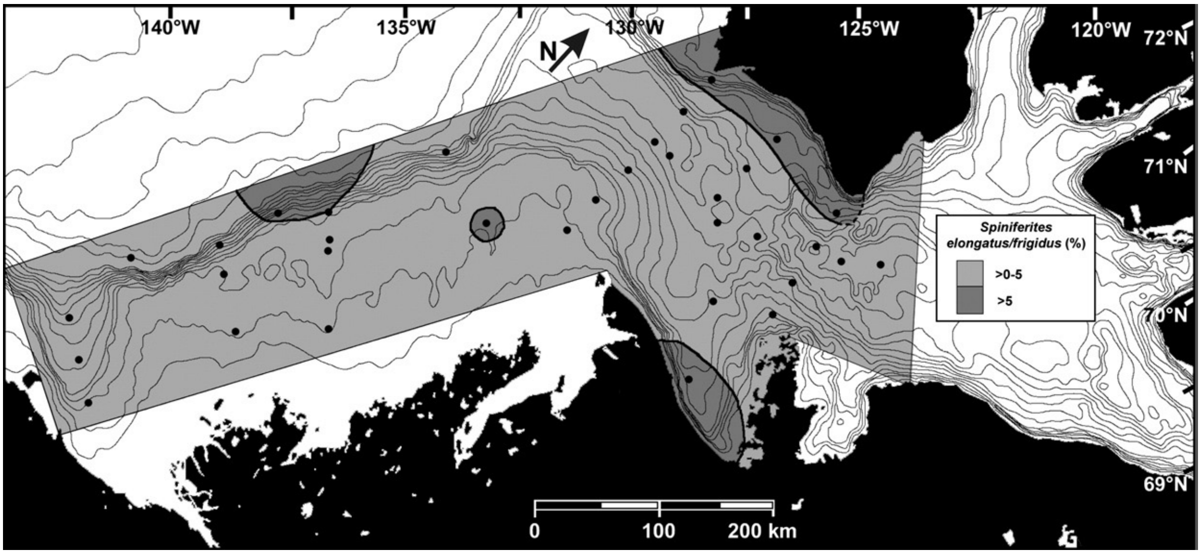

Fig. 11. Distribution map of the relative abundance of *Spiniferites elongatus/frigidus* in surface sediments from the study area. The dashed lines indicate uncertainties defining percentage zones.

Bathurst Polynya. In this area, the reduced sea-ice cover and upwelling of warmer water stir up the nutrients that have precipitated onto the bottom. This phenomenon promotes the development of phytoplankton blooms, including autotrophic dinoflagellates (Arrigo and van Dijken, 2004). Because of the competition between diatoms and autotrophic dinoflagellates, polynyas are usually characterized by the dominance of heterotrophic dinoflagellates (Lewis et al., 1990; Hamel et al., 2002; Radi and de Vernal, 2004; Radi et al., 2007). However, in some polynyas, like that of Cape Bathurst, blooms occur in cold water and there is a decrease of the grazing rate due to the low temperatures and the food-web is predominantly under "bottom-up" control. So, the productivity of the polynya is controlled by the resource limitation (the nutrients), which results in the dominance by autotrophic dinoflagellates and consequently, their cysts (Arrigo and van Dijken, 2004). Although dominant throughout the area, the autotrophic taxa have the highest abundance in Amundsen Gulf, in the Cape Bathurst Polynya, where the annual ice cover is the lowest and turbidity is minimum. The productivity

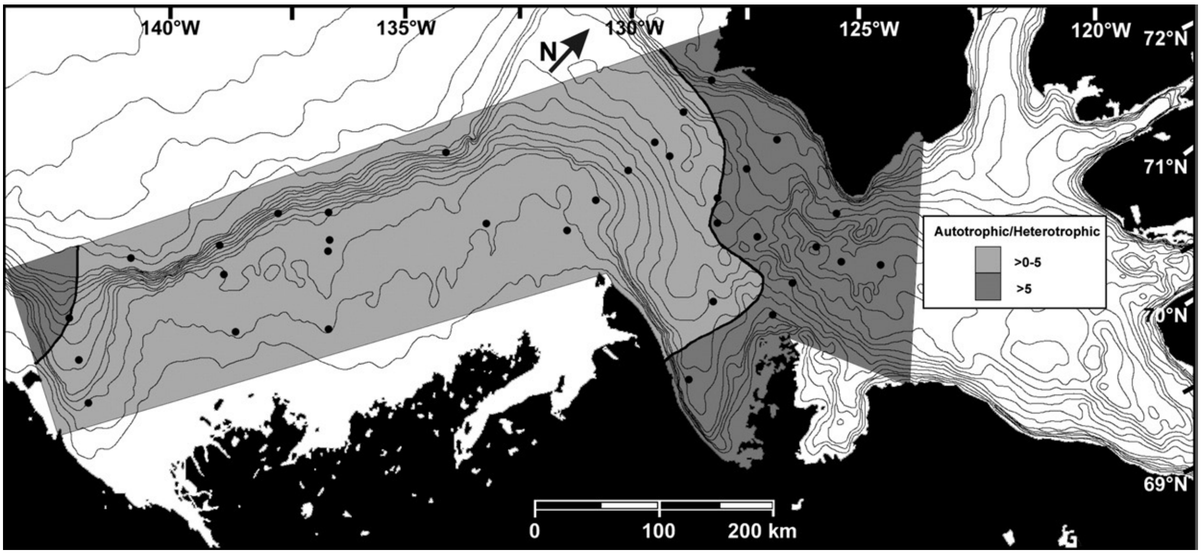

Fig. 12. Distribution map of the Autotrophic/Heterotrophic ratio.

of the polynya varies from year to year (between 90 and 175 g C/m^2/year from 1998 to 2002); however, it can be ranked among the most productive polynyas of pelagic Arctic marine ecosystems (Arrigo and van Dijken, 2004).

The distribution of nutrients on the Mackenzie Shelf varies substantially from season to season, as does productivity. The main source of nutrient influx in the area is the Mackenzie River. During the winter, because of the ice cover, the nutrients carried by the river lie under the ice, at the mouth of the river, and are used primarily by ice algae, which grow on the underside of the ice (Carmack et al., 2004). In spring and summer, the main primary producers are diatoms and flagellates (e.g. *Euglena* sp., *Chlamydomonas* sp.; Hsiao et al., 1977; Hill et al., 2005), while dinoflagellates account for only 5% of the total primary production (Horner, 1984). A relatively important primary production by marine diatoms was measured at the mouth of the Mackenzie River (~10 mg C/m^3/h) in early June after the ice melted (Parsons et al., 1989). Diatoms are mostly found in the nutrient-rich surface waters near the mouth of the river. This productivity decreases with increasing distance from shore. In addition, the turbidity of the plume interferes with the penetration of light for autotrophic species, thus creating conditions that tend to favor the heterotrophic dinoflagellate species. For example, *Brigantedinium* spp. is a group of ubiquitous, and probably opportunistic, species from epicontinental environments (de Vernal et al., 2001). That may explain why their maximum abundance (~18.5%; Fig. 7) is under the influence of the Mackenzie River plume where they can feed. Heterotrophic dinoflagellates feed primarily on diatoms and other dinoflagellates (Hsiao et al., 1977; Subba Rao and Platt, 1984; Jacobson and Anderson, 1986; Parsons et al., 1988; Parsons et al., 1989; Jacobson and Anderson, 1992). Therefore, the productivity from diatoms (~50 g C/m^2; Macdonald et al., 1998) would provide an easily accessible food supply for them. A similar situation was also observed in the Laptev Sea in the western Arctic (Cremer, 1998; Kunz-Pirrung, 2001). After the ice melt, nutrients carried by the river are in surface waters, within the plume, and they gradually become trapped below the thermocline further offshore (Hsiao et al., 1977). So, productivity from diatoms occurs after the ice melt, near the surface, but decrease offshore where the nutrients are not available below the thermocline and the euphotic zone.

Macdonald et al. (1998) estimated the burial of organic carbon within the Mackenzie Shelf/Slope sediments. They showed that less than 10% of the annual production of the delta and ~2% of that of the shelf are incorporated in the sediment. The rest is either recycled within the water column or in the sediment, or exported offshore in the deeper part of the basin. Even though dinoflagellates contribute only a minor fraction to the organic carbon flux toward the sediment, they constitute a relatively important fraction of the organic carbon preserved in marine sediments (Parsons et al., 1984; Hillaire-Marcel et al., 1994), which is mostly due to their membrane composed of dinosporine, a highly-resistant polymer. As such, they constitute an important indicator of primary production and will prove extremely helpful in future works on the recent paleoceanography and paleoproductivity of the area.

5. Conclusion

The study of dinocysts assemblages from 34 surface sediment samples from the Mackenzie Shelf and Amundsen Gulf has produced the following informations:

- Dinocysts concentrations are minimum on the Mackenzie Shelf and gradually increase toward the slope and Amundsen Gulf, where maximum values are recorded.
- Two main assemblages were identified statistically:
  - Assemblage I, which occupies most of the study area, with the exception of the Cape Bathurst Polynya, displays the maximum abundance of heterotrophic taxa. Their abundance decreases gradually away from the plume, along a South to North and West to East gradient.
  - Assemblage II, which is characterized by the maximum abundance of autotrophic taxa, is located in the Cape Bathurst Polynya, which is characterized by a lower sea-ice cover and a higher productivity.
- The dinocysts of autotrophic taxa are dominant throughout the study area. Nevertheless, the maximum concentration of heterotrophic taxa is observed in the area influenced by the Mackenzie River plume, where turbidity interferes with light penetration for autotrophic taxa, and diatoms released by the ice melting increases feeding opportunities for heterotrophic taxa.
- Dinoflagellate cysts constitute an important part of the preserved organic carbon in the sediment, even though they contribute for only a minor fraction to the organic carbon flux to the sea floor.

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