

# Distribution of dinoflagellate cysts in the Canadian Arctic marine region

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**ABSTRACT:** The Canadian Arctic is a major gateway for transport of freshwater from the Arctic Ocean to the North Atlantic. This region comprises the Beaufort Sea, the Canadian Arctic Archipelago (CAA) and northern sections of Baffin and Hudson bays. Subregional differences include major freshwater runoff to the Beaufort Sea and Hudson Bay, presence of Pacific and Atlantic Intermediate water in the west, and Atlantic Water in Baffin and Hudson bays. Principal component analysis of 50 core-top samples shows four subregional dinoflagellate cyst assemblages. Outer Beaufort Shelf Assemblage I is co-dominated by *Operculodinium centrocarpum* s.l. and *Brigantedinium* spp., with minor cysts of *Pentapharsodinium dalei*, *Algidasphaeridium? minutum* s.l. and cysts of *Polykrikos* spp. Assemblage II in the Canadian Arctic Archipelago is co-dominated by *Brigantedinium* spp., *A.? minutum* s.l. and cysts of *Polykrikos* spp., including two Arctic morphotypes. Assemblage III in the North Water polynya exclusively comprises *A.? minutum* s.l. and *Brigantedinium* spp. Assemblage IV in Baffin Bay is dominated by *O. centrocarpum* s.l. and *Spiniferites* spp., with *Brigantedinium* spp. on the shelves. The ratio of gonyaulacoid to protoperidinioid cysts (G:P) generally decreases with increased sea-ice cover, but it may also decrease in river plumes and in polynyas. Copyright © 2001 John Wiley & Sons, Ltd.



**KEYWORDS:** Canadian Arctic channels; Beaufort Sea; North Water polynya; dinoflagellate cysts; primary productivity.

## Introduction

The Canadian Arctic comprises about 25% of the continental shelf region surrounding the Arctic Ocean and includes the Beaufort Sea, the Canadian Arctic Archipelago (CAA), Baffin Bay and the northern part of Hudson Bay, with its outflow through Hudson Strait (Fig. 1). Although a smaller region than the Russian Arctic, it receives proportionally more freshwater as runoff from the Mackenzie River (third largest Arctic river). The transport of freshwater as ice (>0.8 Sv) and low salinity surface water (>1 Sv) is greater than through the shallow (<60 m) Bering Strait (ca. 0.83 Sv) and about 20–50% of the volume transport through the deep (>1000 m) Fram Strait (Melling, 2000).

Previous studies of dinoflagellate cyst (= dinocyst) distribution in the Arctic Ocean and adjacent circum-Arctic basins north of 60°N showed that these palynomorphs are present in surface sediments of almost all Arctic marine and estuarine environments (Mudie and Short, 1985; Mudie 1992; Rochon

*et al.*, 1999 and references therein). Although species diversity decreases with increasing length of sea-ice cover, Mudie (1992) found that dinocyst diversity and abundance are sufficiently varied in the Arctic Ocean and shelfal seas to allow qualitative distinction among perennial pack-ice, 1–2 year ice and estuarine subenvironments. In contrast, the diversity of planktonic foraminifers is very low in the Arctic Ocean (e.g. Kipp, 1976; Vilks, 1986) and calcareous species may undergo severe dissolution. The work of Bujak (1984) and Mudie (1992) also pointed to the potential importance of dinocysts as tracers of palaeoproduction and trophic systems because there is a correlation between duration of ice-cover and concentrations of cysts produced by heterotrophic 'peridinioids' (defined as protoperidinioid plus polykrikoid species). This observation led to the use (Mudie, 1992) of the ratio of photosynthetic gonyaulacoid to heterotrophic 'peridinioids' (G:P) as a qualitative measure of ice cover in high-latitude environments. More recently, a similar correlation was made for dinocysts from transects off the McMurdo Sound region of Antarctica (Harland *et al.*, 1998).

In order to allow quantitative reconstruction of past changes in sea-surface temperature (SST) for February and August ( $T_{\text{Feb}}$ ,  $T_{\text{Aug}}$ ), surface salinity ( $S_{\text{Feb}}$ ,  $S_{\text{Aug}}$ ) and duration of annual sea-ice cover (SIC), subsequent studies were made of 371 samples from the circum-Arctic basins and shelves in Hudson Bay, east Greenland and Barents seas (Rochon *et al.*, 1999)

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**Figure 1** Map of the Canadian Arctic Archipelago from Beaufort Sea to northern Baffin Bay, showing the locations of the main places mentioned in the text

in order to develop palaeobiotic transfer functions with a precision comparable to that of the oceanographic data base of the National Oceanic and Atmospheric Administration (NOAA). These transfer functions recently have been applied, using a 540 sample data base, to a centennial-scale dinocyst record from the North Water polynya (NOW; Levac *et al.*, 2001), which shows that there have been several major oscillations in  $T_{\text{aug}}$  (+2°C) and SIC (1–2 months more open water) during the past 7000 yr. To improve the resolution of these estimates, however, more reference samples are required for different regions of the Arctic shelves, particularly with regard to salinity gradients and areas with more variable sea-ice cover than Baffin Bay and the Barents and Greenland shelves.

The main objectives of this paper are to report on new dinocyst data from the various regions of the Canadian Arctic, with particular focus on possible differences between the assemblages in the truly polar sector of the Canadian Arctic Archipelago (CAA) compared with the Beaufort Sea and Baffin Bay. Comparison also will be made with assemblages in Hudson Bay (Rochon *et al.*, 1999) because this sea receives more freshwater runoff than the Beaufort, but contains no Pacific water and very little Atlantic water (Carmack, 2000). We also will examine the G:P ratio of the cyst assemblages relative to that found in the phytoplankton as reported by Hsiao (1983) in order to further validate the usefulness of this index for understanding Arctic trophic systems.

## Environmental Setting

### Beaufort Sea

The Beaufort Sea (Fig. 1) is located in the western Arctic Ocean, between Point Barrow in northern Alaska and the western Canadian Arctic Archipelago (CAA). The water circulation is dominated by the anticyclonic Beaufort Gyre that drives currents along the shelf margin. Along the coast, however, currents are driven by summer wind direction, alternating between eastward flow into the CAA and westward flow over Mackenzie Trough (see Matthiessen *et al.*, 2000, Vilks *et al.*, 1979). The wind direction also changes the location of the Mackenzie River plume and the salinity of the surface water in the Beaufort Sea. During winter (November–April), strong radiative cooling, upward heat flux and brine formation during freeze-up result in a deep mixed layer (ca. 100 m deep), with  $T$  and  $S$  values of about  $-1.7^{\circ}\text{C}$  and 32 psu. In summer, freshwater discharge, mostly from the Mackenzie River, amounts to a total runoff of about  $420 \text{ km}^3 \text{ y}^{-1}$ . This results in strong vertical stratification, with a shallow layer of warm ( $1\text{--}10^{\circ}\text{C}$ ), low-salinity Arctic surface water (5–30) and strong thermo- and haloclines between ca. 25 and 125 m above the deeper saline (34.9–35). Atlantic water layer (ca. 50–700 m depth). This intermediate Atlantic water has its origin as surface water in the eastern North Atlantic Ocean (see

Vilks, 1986; Mudie, 1992; Carmack, 2000). In western Beaufort Sea, there also is a layer of Pacific Ocean water (from mixing of Bering Sea and Alaskan coastal water) at about 60–80 m depth (Carmack, 2000), which is not always distinguishable on the Canadian sector of the Beaufort shelf (Chu *et al.*, 1999).

## Canadian Arctic Archipelago and North Water polynya

The CAA is a series of large islands on the polar continental shelf, which are separated by a network of marine channels that link the Arctic Ocean with Baffin Bay and the Labrador Sea in the northwest Atlantic (Fig. 1). It covers about 20% of the circum-Arctic shelf region (Carmack, 2000). The major channels are about 50–100 km wide and 300–800 m deep, but throughflow is constrained by relatively shallow sills (150–200 m) and narrows in the central sector of the CAA (e.g. at Barrow Strait in Parry Channel), and in central Nares Strait, at Smith Strait.

The oceanography of the CAA (Fig. 2) differs from that of the other Arctic shelves in that here low salinity (ca. 30–32) surface water moves onshore rather than offshore as found in the estuarine Beaufort and Siberian seas (Carmack, 2000). Flow through the channels also is influenced by three unique mechanisms:

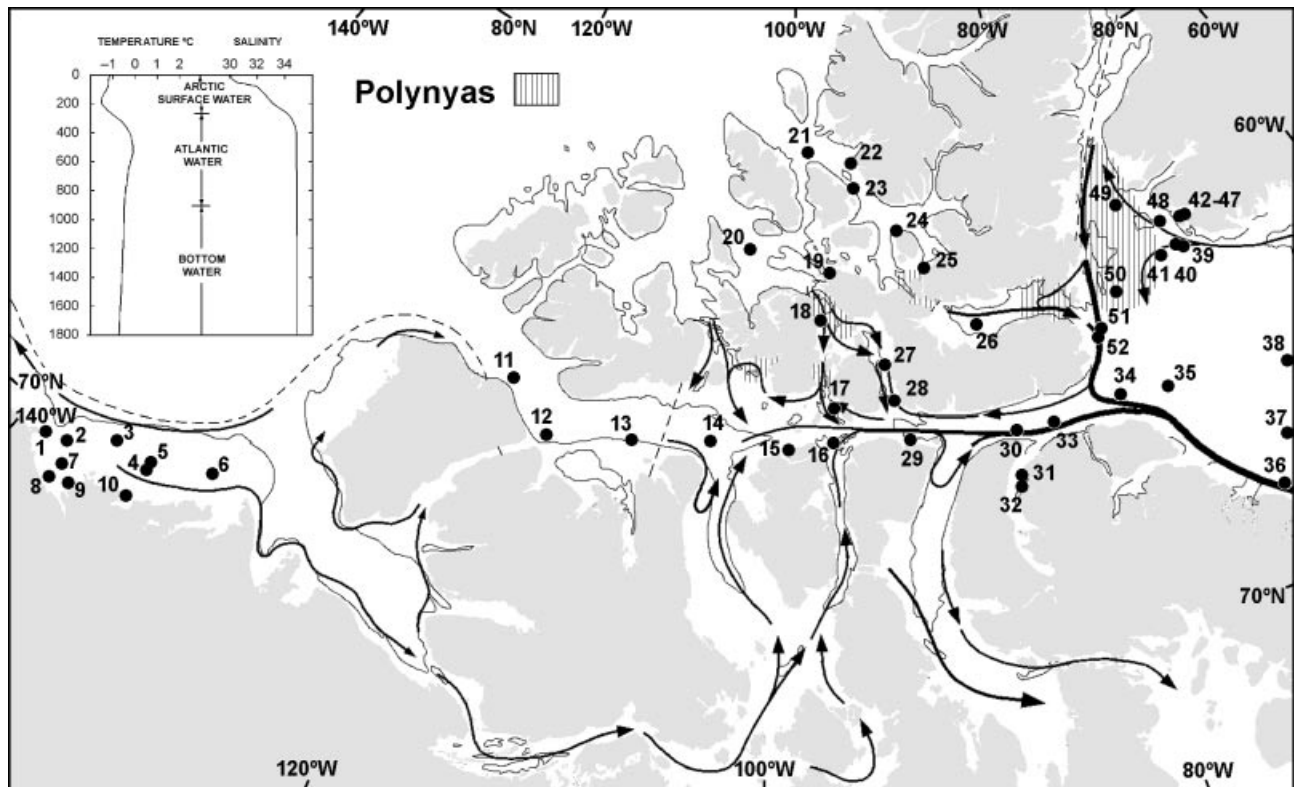
- 1 selective withdrawal of the stratified, relatively low salinity Arctic surface water at the shallows, so that there is no throughflow of either Pacific or Atlantic water from the Arctic Ocean;
- 2 formation of buoyancy boundary currents that confine less saline water on the north side of the channels, creating a horizontally stratified estuarine system;

- 3 recirculation of waters within sub-basins of the channels as a result of mixing at the boundaries and shallows (Melling *et al.*, 1984; Carmack, 2000; Melling, 2000).

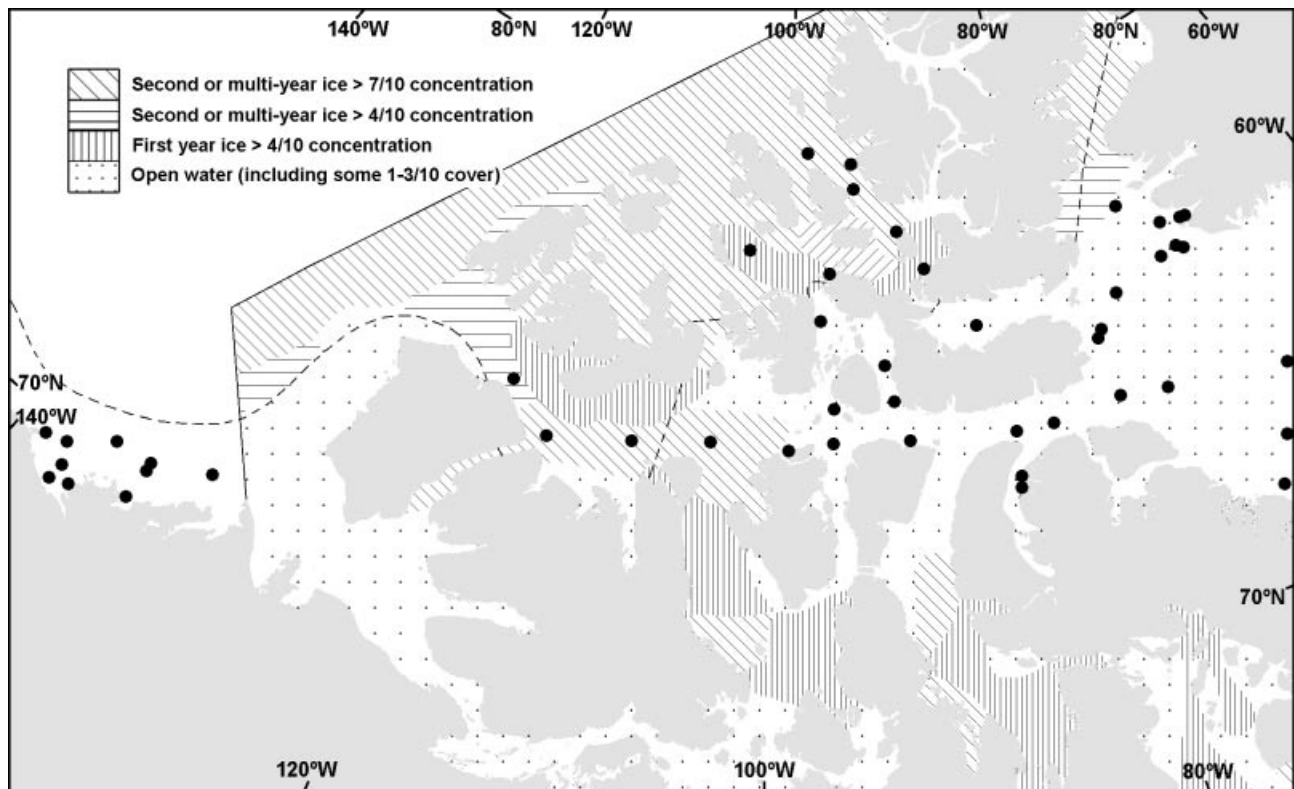
Another notable feature of the CAA is the frequency of polynyas (see Fig. 2). In addition to the large North Water polynya, there are 10 small polynyas, which are maintained by strong tidal currents in narrows joining wider shallow basins. Two larger coastal flaw polynyas are leads formed in the pack-ice off Cape Bathurst and off Cumberland Sound because of internal stresses that are maintained by the Beaufort Gyre and Davis Strait currents, respectively.

Outside of the polynyas, all of the CAA channels are seasonally covered by multiyear ice and various amounts of young ice, with freeze-up beginning in September–October and with break-up starting in May–June (Dickins, 1978; Vilks, 1986). In mid-winter, multiyear fast ice fills Nares Strait north of Kane Basin and westward along the polar continental shelf, including western Viscount Melville Sound (Taylor and McCann, 1983). First-year fast ice fills the other channels west of Peel Sound and Barrow Strait, while moving first-year ice covers Baffin Bay, Foxe Basin, Hudson Strait and Hudson Bay. The extent of open water varies interannually, but in a good year (Fig. 3), open water (defined as less than four-tenths cover of first-year ice) extends throughout the area south of 70°N, westward to Victoria and Melville islands and northward to Kane Basin, southern Axel Heiberg and Ellef Ringnes islands (Taylor and McCann, 1983). North of this area, the channels contain greater than four-tenths second- or multiyear ice and, on the polar margin, pack-ice and greater than seven-tenths multiyear ice. There are no icebergs in the CAA except at the entrance to Lancaster Sound and in Nares Strait, and the depth of the channels limits ice-scour to the shorelines.

Temperature and salinity data for the CAA are very sparse because of the difficulty of accessing the channels by ship prior



**Figure 2** Map of the Canadian Arctic Archipelago and Beaufort Sea showing the locations of the core-top samples (black dots), flow directions of the surface currents (arrows), the average ice limit in summer (dashed lines), and the locations of polynyas (vertical hachure). The inset, upper left, shows the average temperature–salinity profile of the Arctic Ocean off the Beaufort Sea (from Vilks *et al.*, 1979)



**Figure 3** Map of the Canadian Arctic Archipelago and Baffin Bay showing the distribution of various categories of sea-ice in a minimum ice summer (after Taylor and McCann, 1983)

to 1997 (see Melling, 2000), and no synoptic studies have yet been published. Temperature–salinity ( $T-S$ ) profiles from the major channels of the Northwest Passage (Vilks, 1986) and various polynyas (Topham *et al.*, 1983) show that SST ranges from at or near freezing ( $-1.82^{\circ}\text{C}$ ) during the period of ice-cover to values between  $-1.6$  and  $+5^{\circ}\text{C}$  after the summer break-up. Average surface salinity (SS) ranges in winter from about 32–33 and in summer, from 30–31 in the west to 32–33 in the east.

The data in Table 1 are from the new GEOTOP 677-sample dinocyst data base (see de Vernal *et al.*, this issue). They are interpolated from hydrographical data compiled by NODC (1994). Most of these values seem reasonable for SST and SS at 0 m. However, some values  $<30$  from the channels west of Ellesmere Island appear to be much lower than the average reported for the CAA; likewise, SSTs of  $>0^{\circ}\text{C}$  also appear to be too high. On the other hand, new data (Carmack, 2000) show a thin shallow (0–10 m) buoyancy current of low salinity ( $<27$ ) water along the south shore of Barrow Strait during the summer of 1997, so it is clear that there can be large interannual variations.

### Baffin Bay

Baffin Bay is a small, deep (ca. 2000 m) ocean basin located between Greenland and the CAA south of Nares Strait, and north of Davis Strait, which is a deep (ca. 500–800 m) sill separating it from the Labrador Sea (Mudie and Short, 1985). The deep sill allows the penetration of a large volume of Atlantic water known as the West Greenland Current, which flows counterclockwise along the slope between ca. 150 and 1200 m, and mixes with the southward flowing Arctic overflow water in the Baffinland Current off eastern Baffin Island.

There is a strong density gradient at ca. 10–20 m depth, which separates a surface layer of variable salinity from an upper Arctic water layer at ca. 20–150 m depth (see Mudie and Short, 1985 and references therein). In winter, this surface layer has a temperature of ca.  $-1.8^{\circ}\text{C}$  and a salinity of ca. 32 throughout the Bay. However, in summer, SST and SS range from ca.  $3-6^{\circ}\text{C}$  and 32–33 in the West Greenland Current and from  $-1$  to  $2^{\circ}\text{C}$  and 30–31 in the Baffinland Current, with lower salinities (20–29) in some fjords during periods of meltwater discharge. The underlying Arctic layer has a  $T-S$  of about  $-1$  to  $4^{\circ}\text{C}$  and a salinity of 31–34, indicating some mixing of Arctic surface and Atlantic waters. From 150 to 1200 m there is a relatively warm ( $0-2^{\circ}\text{C}$ ), saline (34–34.5) intermediate Water layer formed by cooling and mixing of Atlantic and Arctic water over Davis Strait.

Most of Baffin Bay and western Davis Strait are ice-covered in winter, but areas of open water are found in the NOW Polynya and in the Cumberland Sound flaw polynya off southeastern Baffin Island (see Mudie and Short, 1985, fig. 10). Break-up begins earlier in Davis Strait (April) than in the CAA and most of the Bay is open by mid-July (Dickins, 1978), although ice remains until August on the central Baffin Island Shelf. Baffin Bay differs from most other areas of the Canadian Arctic in the presence of icebergs, mostly from West Greenland glaciers north of Disko Bay. Icebergs in summer may temporarily lower the surface water temperature to  $-1^{\circ}\text{C}$ .

### Hudson Bay and Hudson Strait

Hudson Bay is a large shallow ( $<250$  m) inland sea connected to the CAA by Hudson Strait in the east and Foxe Basin in the north. The total annual runoff to Hudson Bay is  $709\text{ km}^3\text{ yr}^{-1}$ , which is more than twice that of the Mackenzie River

**Table 1** Geographical co-ordinates, water depths (in metres), number of cysts counted, cyst concentrations (cysts cm<sup>-3</sup>) and hydrographic data for samples shown in Fig. 2. Temperature and salinity are in °C and psu (practical salinity units), respectively. Ice is number of months with more than 5/10 sea-ice cover. The data in Table 1 are derived by interpolation from the new GEOTOP 677-sample dinocyst data base (see de Vernal *et al.*, this issue)

Station number	Core number	Latitude	Longitude	Water depth	Count	Concentration	$T_{\text{feb}}$	$S_{\text{feb}}$	$T_{\text{aug}}$	$S_{\text{aug}}$	Ice
1	LSSL-004 HH	65°45.00 N	138°81.00 W	47	32	435	-0.1	29.6	4.8	18.6	8.9
2	NAH-82	69°11.00 N	137°49.50 W	75	37	2569	n.a.	n.a.	n.a.	n.a.	n.a.
3	Kopanoar I-44	70°30.00 N	135°41.00 W	58	51	4722	-0.8	30.5	4.1	20.7	9
4	S9722-10	70°20.90 N	133°48.00 W	70	292	2059	-0.9	31.1	4.7	21.6	9.1
5	Nerlek B	78°28.00 N	133°30.00 W	55	48	870	-0.8	25.9	4.6	21.3	9.1
6	LSSL-002A	70°53.40 N	130°32.40 W	33	257	3089	n.a.	n.a.	n.a.	n.a.	n.a.
7	87N04	69°25.00 N	137°32.00 W	15	200	491	n.a.	n.a.	n.a.	n.a.	n.a.
8	87N114	69°20.00 N	137°25.00 W	8	50	65	n.a.	n.a.	n.a.	n.a.	n.a.
9	9101	69°30.00 N	135°38.00 W	6	200	284	n.a.	n.a.	n.a.	n.a.	n.a.
10	10B	69°40.00 N	134°10.00 W	5	75	259	n.a.	n.a.	n.a.	n.a.	n.a.
11	JOS 33-3ab	74°42.178 N	117°32.908 W	472	28	191	-1.4	22.4	0.2	16.3	11.8
12	LSSL-006B	74°02.00 N	114°43.00 W	511	54	364	-0.1	19.2	1.5	15.4	11.9
13	S9722-08	74°22.50 N	109°04.80 W	425	96	359	-0.8	15.7	0.2	12.2	11.9
14	S9722-05	74°40.00 N	104°04.80 W	203	240	1075	-1.3	18.8	-0.2	16.4	11.6
15	JOS 29-3	74°32.925 N	99°28.177 W	221	90	1585	-1	23.6	0.3	30.9	11.5
16	S9722-03	74°48.80 N	97°11.10 W	272	482	4830	-0.8	27	0	30.7	11.4
17	JOS 10-4	75°10.005 N	97°00.019 W	245	271	4609	-1.3	32.8	-1.5	31.1	11.4
18	JOS 11-4	76°59.820 N	98°00.421 W	307	156	1340	-1.3	28.8	0	29.6	11.4
19	JOS 12-3	77°15.835 N	96°31.560 W	267	149	2358	-1.3	30.8	0	29.5	11.7
20	LSSL-009A	78°30.00 N	104°00.00 W	77	196	1361	-1.7	29.8	-0.5	26.8	12
21	JOS 15-4	79°24.67 N	98°39.48 W	635	4	66	n.a.	n.a.	n.a.	n.a.	n.a.
22	JOS 14-4	79°01.627 N	95°05.326 W	530	17	363	-1	23.8	-0.1	20.6	11.9
23	JOS 13-4	78°45.38 N	94°56.99 W	292	11	195	n.a.	n.a.	n.a.	n.a.	n.a.
24	JOS 16-3	77°44.914 N	91°59.028 W	492	43	498	-1.2	30.3	0.7	27.5	11.7
25	JOS 17-3	77°04.564 N	89°31.488 W	370	61	672	-1.4	32.4	0.5	22.5	10.5
26	LSSL-011b	76°12.00 N	86°47.00 W	626	197	1929	-0.9	31.2	1.9	31.3	10.5
27	JOS 18-4	75°44.577 N	93°30.547 W	252	187	2541	-1.4	33.3	0	31.9	10.9
28	JOS 19-4	75°00.141 N	93°00.141 W	215	283	3401	-1.4	30.4	1	30.9	10.9
29	S9722-01	74°30.00 N	92°34.80 W	209	363	3314	-0.7	31	1.7	30	9.1
30	JOS 20-3	74°15.068 N	85°59.173 W	550	106	1274	-0.9	31.2	1.9	31.3	8.8
31	JOS 22-4	73°29.738 N	85°00.586 W	674	84	1567	-0.9	32.6	1	30.8	8.8
32	JOS 23-4ab	73°06.961 N	84°51.237 W	318	218	1401	-0.9	32.6	1	30.8	8.8
33	JOS 21-3	74°14.877 N	83°04.127 W	760	336	2947	-0.9	31.1	2	30.8	8.8
34	70-028-089	74°15.00 N	78°30.00 W	720	100	2600	n.a.	n.a.	n.a.	n.a.	n.a.
35	70-028-086	74°05.00 N	75°30.00 W	805	100	2730	n.a.	n.a.	n.a.	n.a.	n.a.
36	NP-2	69°45.00 N	137°53.00 W	400	107	4053	-0.1	29.6	4.8	18.6	10.1
37	70-028-074	72°30.00 N	69°30.00 W	1900	95	1716	n.a.	n.a.	n.a.	n.a.	n.a.
38	77-027-05	73°21.10 N	67°49.42 W	2200	100	633	n.a.	n.a.	n.a.	n.a.	n.a.
39	91-039A-010D	76°11.94 N	71°03.87 W	608	130	853	-1.1	34.2	2.6	31.6	8.6
40	91-039A-013E	76°20.45 N	71°38.80 W	660	65	781	-1.1	34.2	2.7	31.7	8
41	91-039A-009B	76°13.42 N	74°39.46 W	432	246	2500	-1.1	33.4	2.9	32.7	8.1
42	91-039A-015I	76°34.98 N	69°04.99 W	187	108	1250	-1.1	32.8	2.5	31.2	8.6
43	91-039A-019D	76°32.43 N	69°04.71 W	206	100	822	-1.1	32.8	2.4	31.2	8.6
44	91-039-020E	76°30.79 N	69°17.18 W	226	96	635	n.a.	n.a.	n.a.	n.a.	n.a.
45	91-039B-022D	76°33.77 N	69°12.45 W	202	186	803	-1.1	32.8	2.5	31.2	8.6
46	91-039B-023F	76°31.77 N	69°07.78 W	207	164	736	-1.1	32.8	2.4	31.2	8.6
47	91-039-024I	76°31.61 N	69°05.92 W	212	148	624	-1.1	32.8	2.5	31.2	8.6
48	91-039-011D	76°48.00 N	71°51.00 W	200	84	1010	n.a.	n.a.	n.a.	n.a.	n.a.
49	91-039-007D	77°16.00 N	74°20.00 W	200	341	3193	n.a.	n.a.	n.a.	n.a.	n.a.
50	91039A-003D	75°51.25 N	76°26.43 W	226	246	800	-1.1	33.2	3.6	32.6	8.5
51	91-039A-026C	75°13.49 N	78°43.02 W	450	100	3906	-1.1	31.8	2.8	31.7	8.4
52	91-039-006D	75°13.49 N	78°43.02 W	571	356	2399	-1.1	31.8	3.2	32.6	8.4

(Carmack, 2000). Likewise, a significant volume of ice forms and melts within this bay, amounting to an additional ca. 2 mm of fresh water. Circulation in the bay is counterclockwise and it is strongly stratified in summer, with surface salinities ranging from <15 in the south to ca. 31 in the north. Summer

temperature ranges from -1.8 to 7.8°C. Northern Hudson Bay receives some North Atlantic water through transport in Hudson Strait to Foxe Basin. Here, Labrador Sea water (a mixture of West Greenland and Baffinland current water), forms a buoyancy boundary current with a salinity of ca. 33.5

on the north side of the strait. In Foxe Basin, mixing with CAA water and winter freezing results in formation of cold, very saline ( $>34$ ) bottom water that flows south into Hudson Bay. Mixing of this Foxe Basin water and warmer, fresher Hudson Bay water results in surface salinities of about 30.6 to 31.2.

Ice formation in Hudson Bay varies interannually (Bursa, 1961b), but fast ice forms only along the shoreline and most of the Bay is 80–90% covered by first-year ice, which melts in place by late summer (Dickins, 1978; Carmack, 2000). Ice cover in Hudson Strait is similar to that in the bay, but also includes iceberg fragments from Baffin Bay.

## Materials and methods

About half the sediment samples used for the palynological studies of the Beaufort Sea region were obtained in 1991 from push cores or gravity cores on Richards Island and in the outer active delta (see Table 1, numbers 1–21 in Matthiessen *et al.*, 2000). Most of the Beaufort offshore samples are from gravity cores or Shelby tube cores provided by petroleum exploration companies. The amount of sediment missing from these coretops is unknown. Samples 1, 4 and 6, however, are reliable surface samples from box cores collected from the *CCGS Louis S. St. Laurent* in 1997 and 2000. All other CAA samples (Table 1) are from box cores taken during the 1997 SHEBA, 1998 JOIS and TUNDRA 2000 expeditions of *CCGS Louis S. St. Laurent*.

The sediment samples were processed in the laboratory using standard palynological procedures (Rochon *et al.*, 1999), which include the following treatments:

1 wet sieving at 10 and 120  $\mu\text{m}$  mesh to remove sand and silt particles;

- 2 treatments in hydrochloric (HCl 10%) and hydrofluoric (HF 49%) acids to remove carbonate and silicates, respectively;
- 3 addition of *Lycopodium* tablets before the first HCl treatment in order to determine palynomorph concentrations;
- 4 a final sieving at 10  $\mu\text{m}$  is done in order to remove the fluorosilicates;
- 5 mounting of the residue on slides with glycerin jelly.

The slides were counted on a Zeiss transmitted light microscope at 250 and 400 magnification. A minimum of 100 dinocysts was counted on one or two slides when possible. Actual counts vary between 4 and 356 dinocysts (Table 1).

The statistical package of Guiot (1990) was used for principal component analysis, which was done on log-transformed percentage data, in order to enhance the representation of minor taxa. Surface sediment samples containing  $\geq 50$  dinocysts were used in the principal component analysis, and 30 taxa were considered in the analysis (cf. de Vernal *et al.*, this issue). Systematic treatment is that used by Rochon *et al.* (1999), except where noted in the text.

## Results

### Beaufort Sea, CAA and NOW

Dinocyst concentrations in this subregion range from ca. 10 to 4800 cysts  $\text{cm}^{-3}$  (Table 1), with an average of 1634 cysts  $\text{cm}^{-3}$ . The lowest concentrations ( $<400$  cysts  $\text{cm}^{-3}$ ) occur in Parry Sound and M'Clure Strait in the northeastern and central CAA, respectively (Fig. 4). Sedimentation rates in these channels are relatively low ( $\leq 50$   $\text{cm kyr}^{-1}$ ; MacLean *et al.*, 1989; Andrews *et al.*, 1991), therefore these low numbers probably reflect low productivity. Some samples from beneath the pack-ice on the

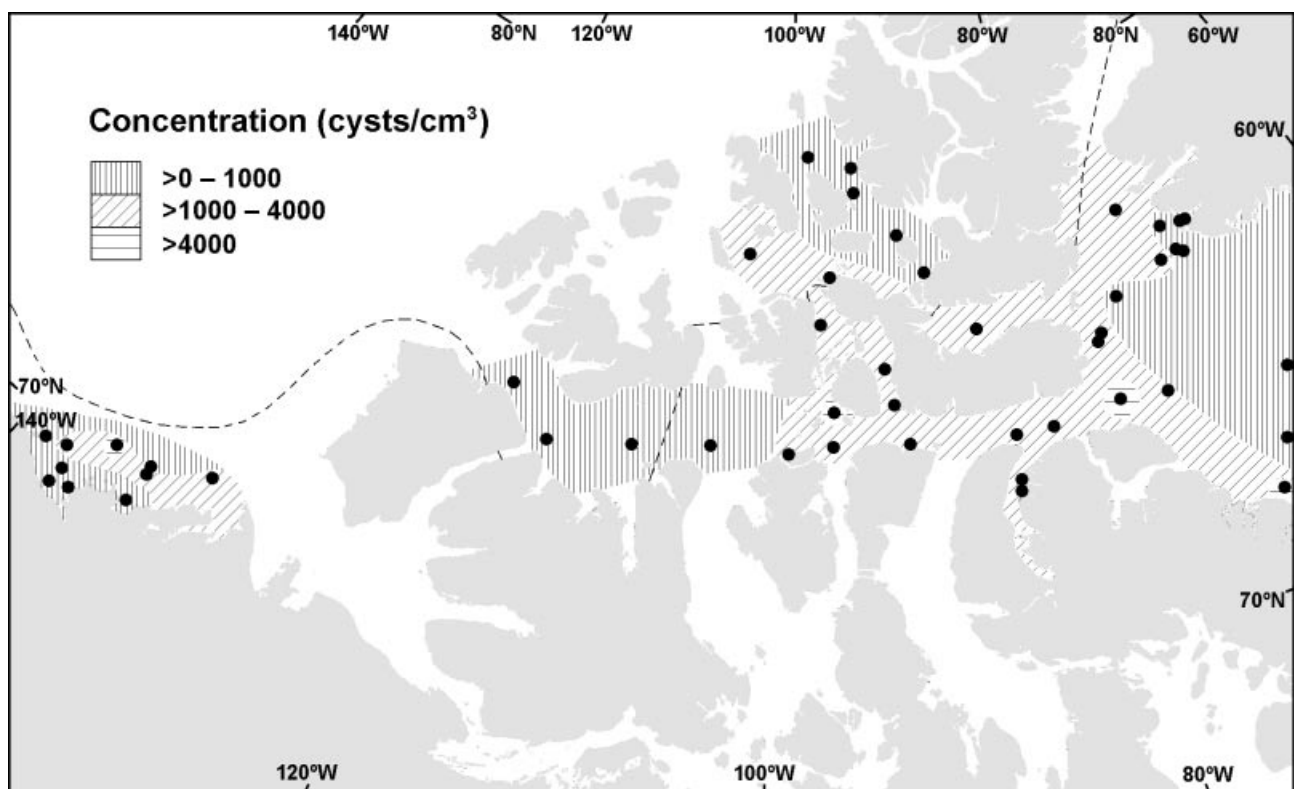


Figure 4 Map of variations of dinocyst concentrations in the Canadian Arctic study region

polar margin and in Parry Sound contained no Quaternary dinocysts; samples from the shallow shelf around Banks Island also contained no dinocysts. Samples from the intertidal area of Mackenzie Delta were barren of dinocysts although they contained abundant acritarchs, Zygnematalean spores and common Chlorococcalean coenobia (see Matthiessen *et al.*, 2000).

Average concentrations are 2300 cysts  $\text{cm}^{-3}$  in most of the region, with maxima of >3000–4600 cysts  $\text{cm}^{-3}$  in the outer Beaufort Shelf, eastern Lancaster Sound and off Cumberland Sound. These highly productive areas are either upwelling regions (outer Beaufort Sea) or large coastal polynyas. Lower cyst concentrations (625–1000 cysts  $\text{cm}^{-3}$ ) in northern Baffin Bay and the eastern section of the NOW polynya may reflect dilution by diatoms in the polynya (Hargraves *et al.*, 2001), and the deposition of ice-rafted detritus and/or distal turbidites in Baffin Bay (see Mudie and Short, 1985; de Vernal *et al.*, 1987).

### Ratio of gonyaulacoid to protoperidinioid dinocysts

In shelfal regions, the G:P ratio can be used to characterise the dominant trophic mode and the level of primary productivity, as long as the redox potential of the bottom water is quite uniform (McCarthy *et al.*, 2000). The NOW polynya, Ellesmere and Baffin shelves and CAA channels are all marked by low G:P values (0–0.1), indicating predominance of heterotrophic productivity (Fig. 5). Heterotrophic assemblages also dominate in the Mackenzie Delta, where suspended particulate matter is very high and light penetration is low (Matthiessen *et al.*, 2000). In the remainder of the Beaufort Sea, G:P values range from 0.16 to 0.84, with a peak along the margin of the Mackenzie River plume where both nutrients and light penetration are high, favouring the gonyaulacoid autotrophs. An anomalous small area of relatively high G:P values in the

ice-infested waters at the east end of M'Clure Strait probably indicates long-distance transport in either Beaufort Sea water or Atlantic intermediate water.

High G:P values (0.1 to >0.5) also are found in central Baffin Bay, where they may reflect the inflow of North Atlantic Drift water, which is dominated by gonyaulacoid cysts (Mudie, 1992). However, mild oxidation of the bottom sediments may bias the assemblages towards the more resistant Gonyaulacoid genera such as *Impagidinium*, *Nematosphaeropsis* and *Spiniferites* (Zonneveld *et al.*, 1997), so caution is needed in interpreting these deep-water assemblages.

### Species diversity

In Arctic and circum-Arctic regions, dinocyst species diversity (number of species per sample) shows a strong correlation with presence of persistent ice-cover (Mudie, 1992). In our study area, 15 species and a total of 21 taxa (including varieties and distinctive morphotypes) were found. There generally is a good correlation between low species number ( $N = 1-5$ ) and persistent pack-ice in summer (Figs 6 and 4). However, anomalies are found along the western edge of the NOW polynya, where *Brigantedinium* cysts make up >60% of the assemblages, and in the southern Barrow Strait area. Highest diversity ( $N = 11-15$ ) is found at the edge of the Mackenzie River plume.

### Distribution of dinocyst assemblages and species

The dinoflagellate cyst assemblages in the CAA are characterised by relatively low species diversity, with the exception of the outer Beaufort shelf. Sixteen species were identified

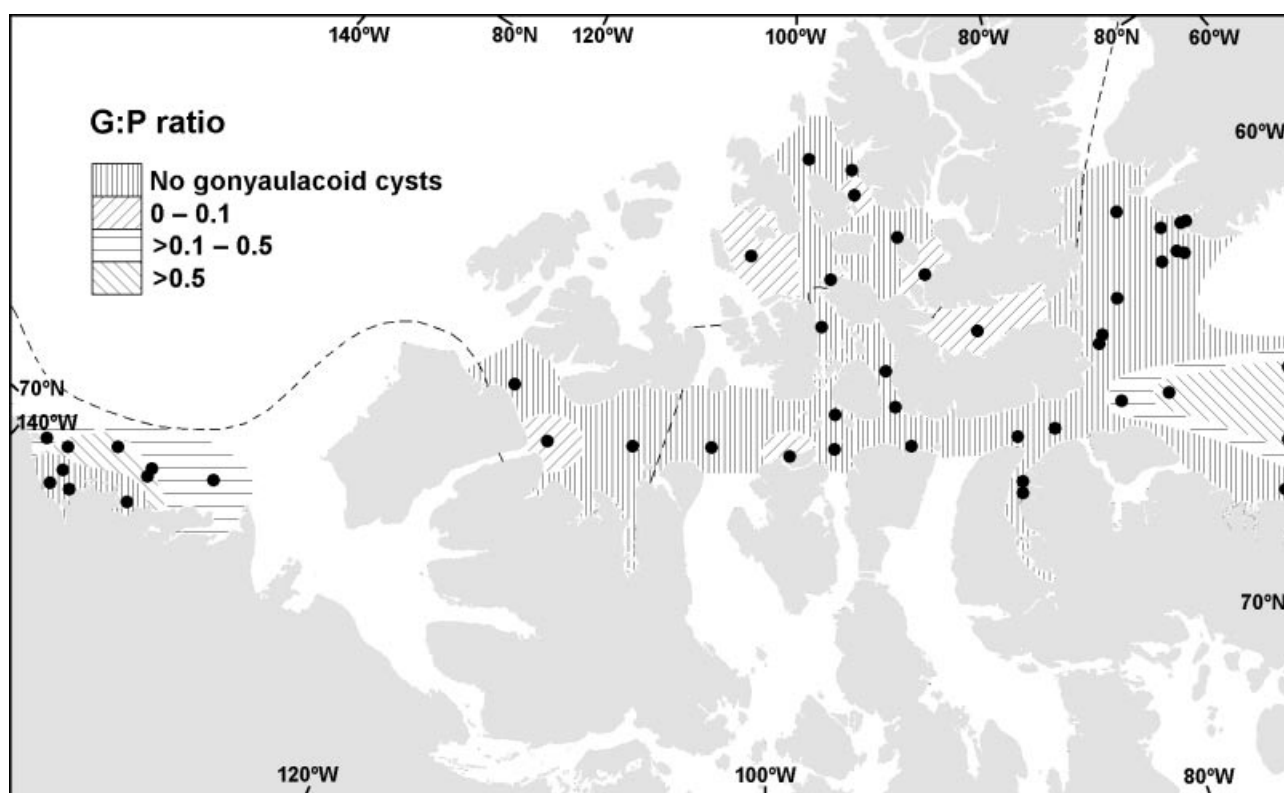


Figure 5 Map of variations in the ratio of Gonyaulacoid to peridinioid (G:P) cysts in the Canadian Arctic study region

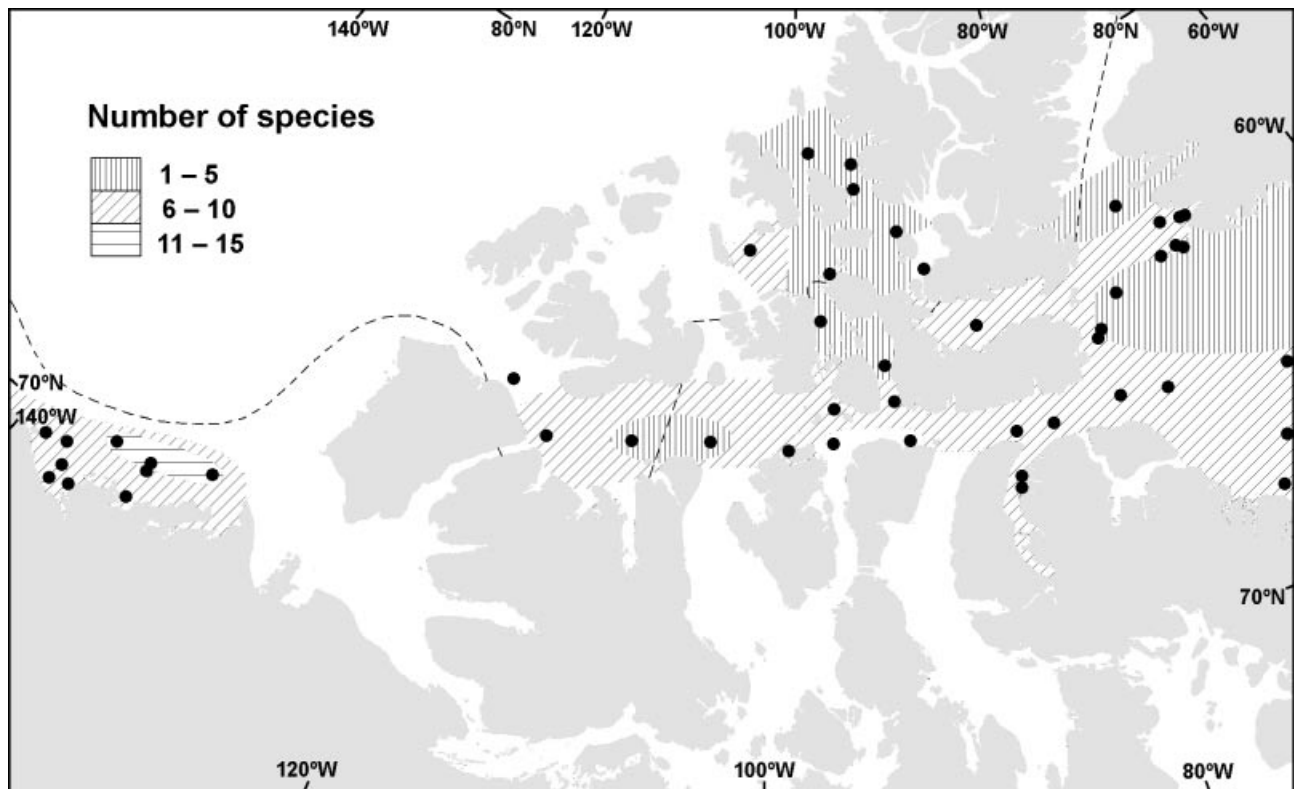


Figure 6 Map of variations in the number of dinocyst species in the Canadian Arctic study region

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

Dinocyst name	Code name
<i>Algidasphaeridium?</i> <i>minutum</i> var. <i>minutum</i>	Amin
<i>Algidasphaeridium?</i> <i>minutum</i> var. <i>cezare</i>	Amic
<i>Bitectatodinium tepikiense</i>	Btep
<i>Brigantedinium</i> spp.	Bspp
<i>Brigantedinium simplex</i>	Bspp
<i>Impagidinium pallidum</i>	lpal
<i>Nematosphaeropsis labyrinthus</i>	Nlab
<i>Operculodinium centrocarpum</i>	Ocen
<i>Operculodinium centrocarpum</i> morphotype arctic	Ocen
<i>Operculodinium centrocarpum</i> var. <i>truncatum</i>	Ocen
Peridinioid (unidentified Protoperidinioid cyst)	Peri
Cyst of <i>Polykrikos schwartzii</i>	Psch
Cyst of <i>Polykrikos</i> sp. morphotype 1 of Kunz-Pirrung 1998	Parc
Cyst of <i>Polykrikos</i> sp. morphotype 2 of Kunz-Pirrung 1998	Parc
Cyst of <i>Pentapharsodinium dalei</i>	Pdal
<i>Pyxidinosopsis reticulata</i>	Pret
<i>Selenopemphix nephroides</i>	Sele
<i>Selenopemphix quanta</i>	Squa
<i>Spiniferites elongatus</i>	Selo
<i>Spiniferites frigidus</i>	Selo
<i>Spiniferites ramosus</i>	Sram

in the samples, and a total of 21 different taxa are included in the counts (Table 2). However, four taxa constitute more than 90% of the assemblages: *Algidasphaeridium?* *minutum* s.l., *Brigantedinium* spp., *Operculodinium centrocarpum* s.l. and *Polykrikos* spp. *Algidasphaeridium?* *minutum* s.l. includes the varieties *minutum* and *cezare* (Table 3). They both have similar distributions in the CAA and occur together in samples, but the variety *cezare* is less abundant. *Operculodinium centrocarpum* s.l. includes *O. centrocarpum sensu* Wall and

Dale 1966, *O. centrocarpum* var. *truncatum* of Mudie (1992), with very short blunt processes, and the Arctic morphotype of *O. centrocarpum* of de Vernal *et al.* (this issue). The different varieties and morphotypes are relatively difficult to differentiate, therefore we have grouped all *O. centrocarpum* morphotypes for this paper. Cysts of *Polykrikos* spp. comprise *P. schwartzii*, and the Arctic taxa *Polykrikos* sp. morphotypes 1 and 2 described by Kunz-Pirrung (1998; plate 3, figs 6, 8–13 and figs 4 and 5, respectively). *Polykrikos* sp.



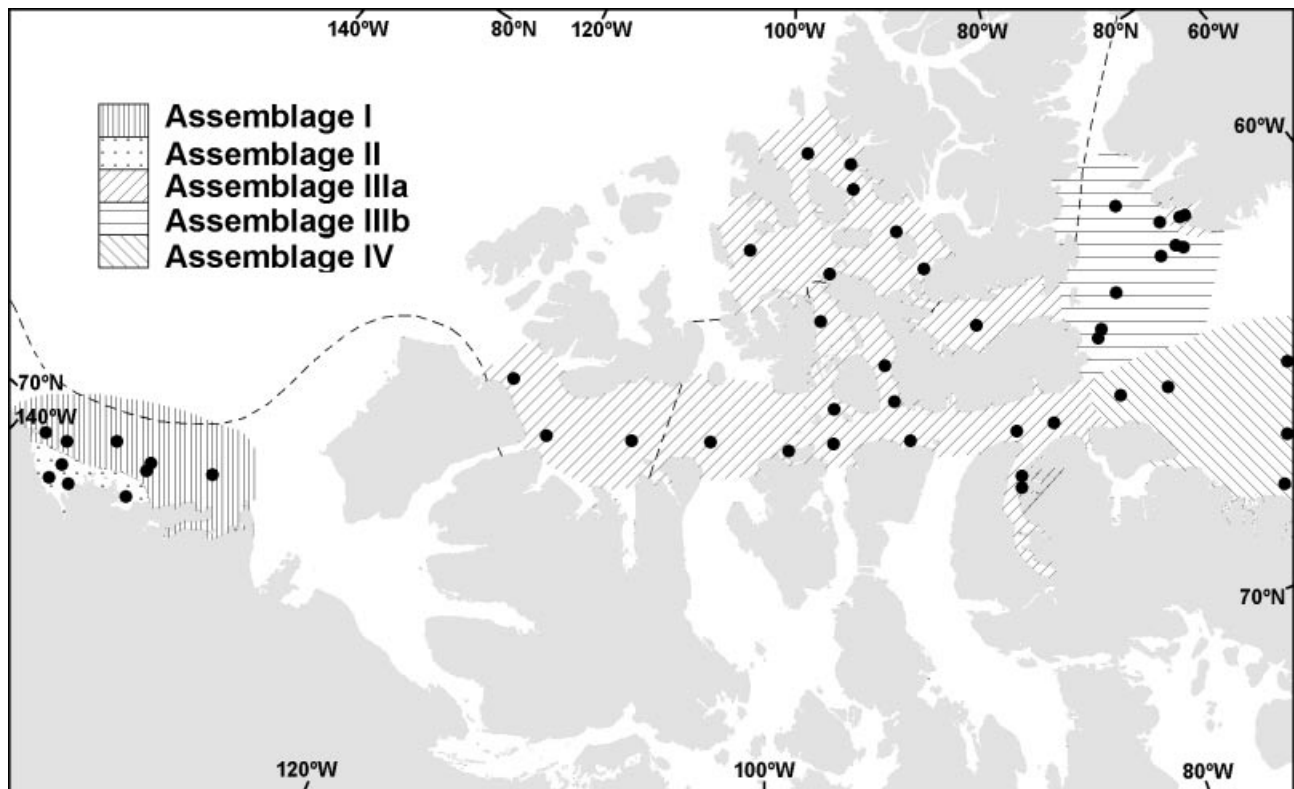
**Table 3** Relative abundance (%) of dinoflagellate cyst taxa in our samples

Station number	Core number	Btep	Ipal	Nlab	Ocen	Pret	Selo	Sram	Pdal	Amin	Amic	Bspp.	Peri	Sele	Squa	Psch	Parc
1	LSSL-004 HH	0.0	0.0	0.0	28.1	3.1	3.1	0.0	0.0	6.3	9.4	34.4	0.0	0.0	0.0	0.0	12.5
2	NAH-82	0.0	0.0	0.0	10.8	2.7	0.0	0.0	2.7	8.1	0.0	67.6	8.1	0.0	0.0	0.0	0.0
3	Kopanoar I-44	0.0	0.0	0.0	18.0	2.0	6.0	0.0	0.0	30.0	4.0	32.0	4.0	0.0	0.0	0.0	4.0
4	S9722-10	0.0	0.0	0.0	56.8	0.0	3.1	0.0	15.4	11.6	1.4	11.6	0.0	0.0	0.0	0.0	0.0
5	Nerlek B	0.0	2.3	0.0	36.4	0.0	2.3	0.0	2.3	6.8	0.0	43.2	0.0	0.0	0.0	2.3	4.5
6	LSSL-002A	2.0	0.4	0.0	40.9	0.0	1.6	0.0	0.0	26.1	5.1	23.0	0.0	0.0	0.0	0.0	0.0
7	87N04	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	11.0	2.0	82.0	4.5	0.0	0.0	0.0	0.0
8	87N114	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	12.7	0.0	85.0	0.0	0.0	0.0	0.0	0.0
9	9101	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	9.0	0.0	89.0	0.0	0.0	0.0	0.0	0.0
10	10B	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	7.5	0.5	92.0	0.0	0.0	0.0	0.0	0.0
11	JOS 33-3ab	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
12	LSSL-006B	0.0	0.0	0.0	7.4	0.0	1.9	0.0	0.0	7.4	1.9	81.5	0.0	0.0	0.0	0.0	0.0
13	S9722-08	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	46.9	1.0	42.7	0.0	0.0	0.0	0.0	9.3
14	S9722-05	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	74.6	0.0	22.5	0.0	0.0	0.0	0.0	0.3
15	JOS 29-3	0.0	0.0	0.0	2.2	0.0	0.0	0.0	0.0	48.3	0.0	41.6	0.0	0.0	0.0	1.1	6.7
16	S9722-03	0.0	0.0	0.0	0.4	0.0	0.0	0.0	0.0	58.0	3.1	38.5	0.0	0.0	0.0	0.0	0.0
17	JOS 10-4	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	25.4	0.4	70.6	0.0	0.0	0.0	0.0	3.6
18	JOS 11-4	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	38.1	0.6	51.0	0.0	0.0	0.0	0.0	10.3
19	JOS 12-3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	36.1	0.7	60.4	0.0	0.0	0.0	0.0	2.8
20	LSSL-009A	0.0	0.5	0.0	2.0	0.0	0.0	0.0	0.0	14.8	3.1	69.9	1.5	0.0	0.0	0.0	8.2
21	JOS 15-4	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	25.0	0.0	75.0	0.0	0.0	0.0	0.0	0.0
22	JOS 14-4	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	52.9	5.9	35.3	0.0	0.0	0.0	0.0	5.9
23	JOS 13-4	0.0	0.0	0.0	0.0	0.0	9.1	0.0	0.0	36.4	0.0	54.5	0.0	0.0	0.0	0.0	0.0
24	JOS 16-3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	45.2	0.0	47.6	0.0	0.0	0.0	0.0	7.1
25	JOS 17-3	0.0	0.0	0.0	1.6	0.0	0.0	0.0	0.0	50.8	0.0	37.7	0.0	0.0	0.0	0.0	9.8
26	LSSL-011b	0.0	0.5	0.0	0.0	1.0	0.0	0.0	0.0	20.8	1.0	54.3	0.5	0.0	0.5	8.6	12.7
27	JOS 18-4	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	21.8	0.0	71.5	0.0	0.0	0.0	0.0	6.7
28	JOS 19-4	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	18.0	0.0	77.7	0.0	0.0	0.0	0.0	4.3
29	S9722-01	0.0	0.0	0.0	0.3	0.0	0.0	0.0	0.0	50.8	4.7	42.5	0.0	0.0	0.0	0.0	1.7
30	JOS 20-3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	40.8	1.9	43.7	0.0	0.0	1.0	0.0	12.6
31	JOS 22-4	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	14.3	0.0	76.6	0.0	0.0	0.0	0.0	9.1
32	JOS 23-4ab	0.0	0.0	0.0	1.8	0.0	0.0	0.0	0.5	18.9	3.2	66.8	0.0	0.0	0.9	1.4	6.5
33	JOS 21-3	0.0	0.0	0.0	2.7	0.0	0.7	0.0	0.0	41.9	0.7	50.7	0.0	0.3	0.0	0.0	3.0
34	70-028-089	0.0	0.0	0.0	19.0	0.0	4.7	0.2	0.0	58.0	0.0	17.0	0.5	0.0	0.0	0.0	0.0
35	70-028-086	0.0	0.0	0.0	60.0	0.0	8.0	1.0	0.0	18.0	0.0	18.0	0.0	0.0	0.0	0.0	0.0
36	NP-2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	73.8	1.9	14.0	2.8	0.0	0.0	0.0	7.5
37	70-028-074	0.0	0.0	0.0	76.0	0.0	8.0	1.0	0.0	0.0	0.0	15.0	0.0	0.0	0.0	0.0	0.0
38	77-027-05	0.0	0.0	0.5	67.0	0.0	12.0	1.5	0.0	0.0	0.0	19.0	0.0	0.0	0.0	0.0	0.0
39	91-039A-010D	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	67.1	0.0	32.9	0.0	0.0	0.0	0.0	0.0
40	91-039A-013E	0.0	0.0	0.0	0.0	0.0	2.6	0.0	2.6	76.3	2.6	13.2	0.0	0.0	2.6	0.0	0.0
41	91-039A-009B	0.0	0.0	0.0	1.2	0.0	0.0	0.0	0.0	66.9	0.0	32.0	0.0	0.0	0.0	0.0	0.0
42	91-039A-015I	0.0	0.0	0.0	3.7	0.0	0.0	0.0	0.0	45.8	2.8	44.9	0.0	0.0	0.0	0.9	1.9
43	91-039A-019D	0.0	0.0	0.0	1.0	0.0	1.0	0.0	0.0	55.1	1.0	40.8	0.0	0.0	0.0	1.0	0.0
44	91-039-020E	0.0	0.0	0.0	2.1	0.0	0.0	0.0	0.0	22.9	0.0	74.0	0.0	0.0	0.0	0.0	1.0
45	91-039B-022D	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	40.9	0.0	57.0	0.0	0.0	0.0	0.0	2.2
46	91-039B-023F	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	34.9	0.0	63.2	0.0	0.0	0.0	0.0	2.0
47	91-039-024I	0.0	0.7	0.0	0.0	0.0	0.0	0.0	0.0	48.9	0.0	46.7	0.0	0.0	0.0	0.0	3.7
48	91-039-011D	0.0	0.0	0.0	4.0	0.0	1.0	0.0	2.0	52.5	3.0	37.6	0.0	0.0	0.0	0.0	0.0
49	91-039-007D	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	43.4	0.0	56.6	0.0	0.0	0.0	0.0	0.0
50	91039A-003D	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	45.2	0.0	54.8	0.0	0.0	0.0	0.0	0.0
51	91-039A-026C	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	63.0	2.0	34.0	0.0	0.0	1.0	0.0	0.0
52	91-039-006D	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	60.5	0.0	39.5	0.0	0.0	0.0	0.0	0.0

morphotype 1 has an elongate ovoidal body ca. 50–60 µm in length, with a well developed reticulation pattern (ca. 5 µm in height) in the apical and antapical regions. The ornamentation is reduced (lower) or absent in the sulcal area. The latter is constricted, which gives the cyst a distinctive 'figure 8 shape' appearance. Morphotype 2 has an ovoidal body ca. 50–60 µm in length, with a reduced (ca. 1–2 µm in height) reticulation pattern distributed evenly over the

entire surface of the cyst. The sulcal area is weakly constricted.

Four assemblages are distinguished based on a principal component analysis of the relative abundance of the dinocyst taxa (Fig. 7). The analysis was performed on the 46 samples that have counts of  $\geq 50$  dinocysts. The first three principal components explain 78% of the total variance, and they show the opposition between autotrophic (*O. centrocarpum*



**Figure 7** Map of the distributions of dinocyst assemblages in the Canadian Arctic study region

s.l., *Spiniferites* spp. and *N. labyrinthus*) and heterotrophic taxa (*A.? minutum* s.l., *Brigantedinium* spp. and *Polykrikos* Arctic morphotypes). Principal component 1, which explains 46.2% of the variance, shows a weak correlation with the August temperature ( $R = 0.54$ ). Principal components 2 and 3, which explain respectively 21.6 and 10.1% of the variance, do not show good correlation ( $R \leq 0.20$ ) with the interpolated GEOTOP environmental data, derived from hydrographical data compiled by NODC (1994). Other factors, such as the type of sea-ice, distribution of nutrients, or feeding behaviour probably play an important role in the distribution of dinocyst assemblages.

- 1 Assemblage I is characterised by co-dominance of *O. centrocarpum* s.l., *Brigantedinium* spp. and *A.? minutum* s.l., accompanied by (<5%) *Impagidinium pallidum*, cyst of *Pentapharsodinium dalei*, cyst of *Polykrikos* sp. morphotype 1, *Pyxidinosia reticulata* and *Spiniferites elongatus/frigidus*. This assemblage is centered on the Beaufort Shelf.
- 2 Assemblage II is characterised by the dominance (>80%) of *Brigantedinium* spp. and rare *A.? minutum* s.l.; freshwater palynomorph coenobia are common. This assemblage occurs on the inner Beaufort Shelf off the Mackenzie Delta.
- 3 Assemblage IIIa is characterised by the co-dominance of *Brigantedinium* spp. and *A.? minutum* s.l., accompanied by cysts of *Polykrikos* sp. morphotypes 1 and 2, and cysts of *P. schwartzii*. It occurs throughout the CAA west of the entrance to Lancaster and Jones sounds, and in the eastern NOW polynya. Assemblage IIIb is composed almost exclusively of *A.? minutum* var. *minutum*, accompanied by *Brigantedinium* spp. and rare *A.? minutum* var. *cezare*. It is found in the central and western NOW polynya, extending southwestward to the entrance of Jones Sound.
- 4 Assemblage IV is characterised by the co-dominance of *O. centrocarpum* s.l., *Brigantedinium* spp. and *Spiniferites*

spp. (mostly *S. elongatus-frigidus* intergrades), with rare *S. ramosus* and *Nematosphaeropsis labyrinthus*. This assemblage is centred in north-central Baffin Bay and extends west into the deep water (>200 m) entrances to Lancaster and Cumberland sounds.

The distributions of the main heterotrophic dinocyst species are shown in Figs 8 and 9. *Brigantedinium* spp. (Fig. 8a) is common and ubiquitous, being found at <20% only off the Mackenzie Delta, and in north-central Baffin Bay. This species is absent only in intertidal areas of the Mackenzie Delta (Solomon *et al.*, 2000) and at some sites beneath the pack-ice on the polar margin (Mudie, 1992). It is notable, however, that maximum abundances (60%) are associated with the Mackenzie freshwater plume in the Beaufort Sea, and with the areas of greater than four-tenths ice-cover in the CAA. In contrast, *Algidasphaeridium? minutum* s.l. (Fig. 8b) is most abundant (>40%) in areas of summer open water and is more common in the Atlantic-dominated eastern regions of the Canadian Arctic. Cysts of *Polykrikos* spp. (Fig. 8c) are common (>5%) only in two of the small polynyas of the CAA, and they are notably absent in the NOW polynya, north-central Baffin Bay and the Mackenzie Delta area of the Beaufort Sea. The Arctic morphotypes of *Polykrikos* (Fig. 9) have more restricted distributions, with morphotype 1 (Fig. 9a) being more common in the eastern CAA.

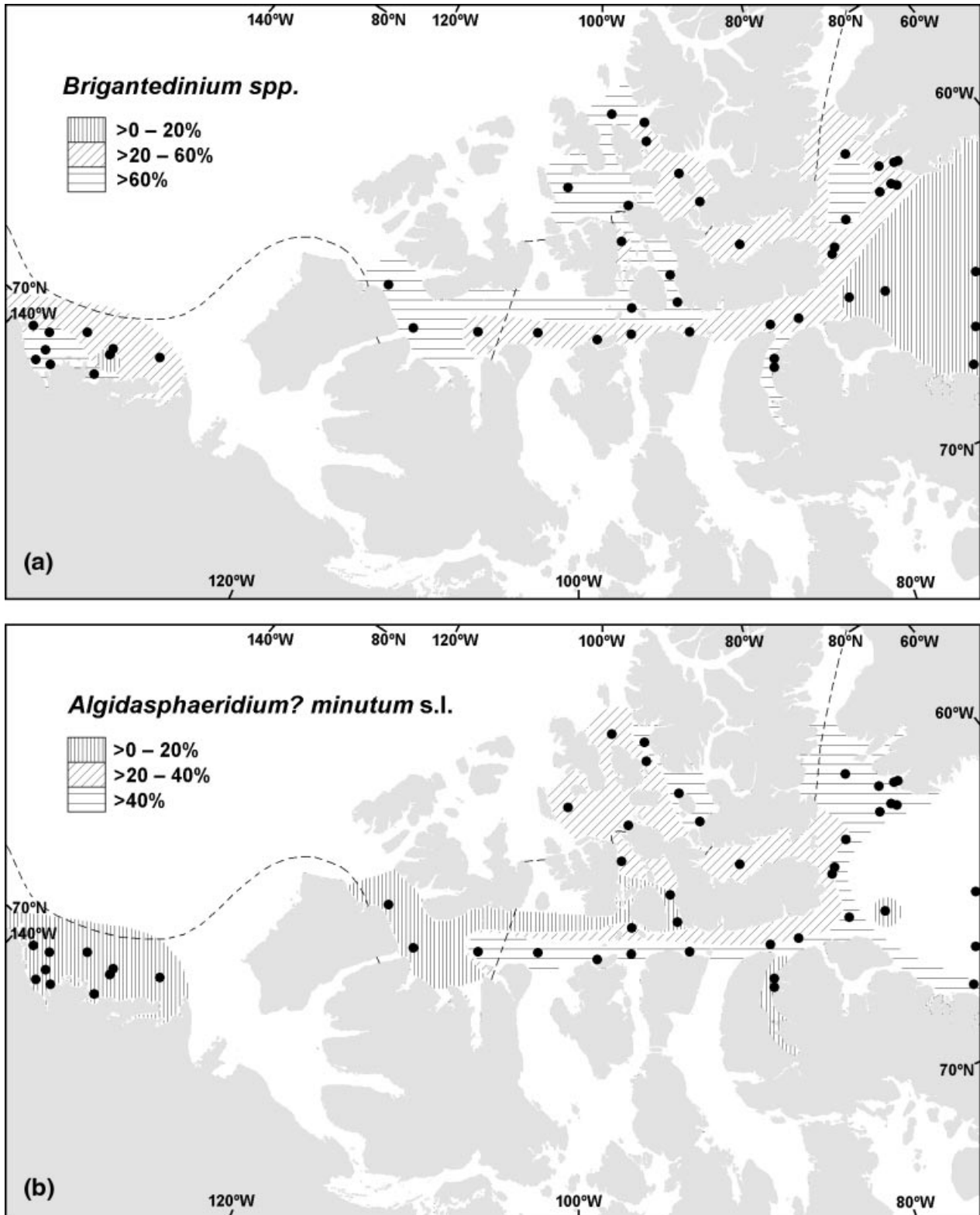
The distributions of the autotrophic gonyaulacoid species, *O. centrocarpum* s.l. and *Spiniferites* spp., are shown in Fig. 10. Both taxa essentially are restricted to the outer Beaufort Shelf and the deep-water areas of northern Baffin Bay. *Operculodinium centrocarpum* s.l. (Fig. 10a) is more widespread, being common in the southern part of the NOW polynya and being present in the small CAA polynyas and at a few sites in Parry Channel. In contrast, *Spiniferites* spp. (Fig. 10b) is found at only one site at the western entrance to Parry Sound.

## Baffin Bay

Q-mode factor analysis of the relative abundance of dinocysts in 50 core-top samples from Baffin Bay and the deep water at the entrance to Lancaster Sound (Mudie and Short, 1985) showed the presence of three assemblages.

- 1 *A. minutum* s.l. and *Brigantedinium* spp. are co-dominant on the eastern Baffin Island shelf, with rare occurrences of

cysts of *Polykrikos* spp. This assemblage is very similar to the CAA assemblage III, differing only in the presence of minor occurrences of cysts of *Polykrikos* spp. *Algidasphaeridium? minutum* var. *minutum* is the main variety of *Algidasphaeridium* present in most samples, but *A. minutum* var. *cezare* and other undescribed morphotypes with recurved process tips (*Protoperidinium* sp. A of Mudie and Short, 1985) are common around the entrance to Lancaster Sound.



**Figure 8** Maps of the distributions of major heterotrophic dinocyst species in the Canadian Arctic study region. (a) *Brigantedinium* spp. (b) *Algidasphaeridium? minutum* s.l. (c) *Polykrikos* spp.

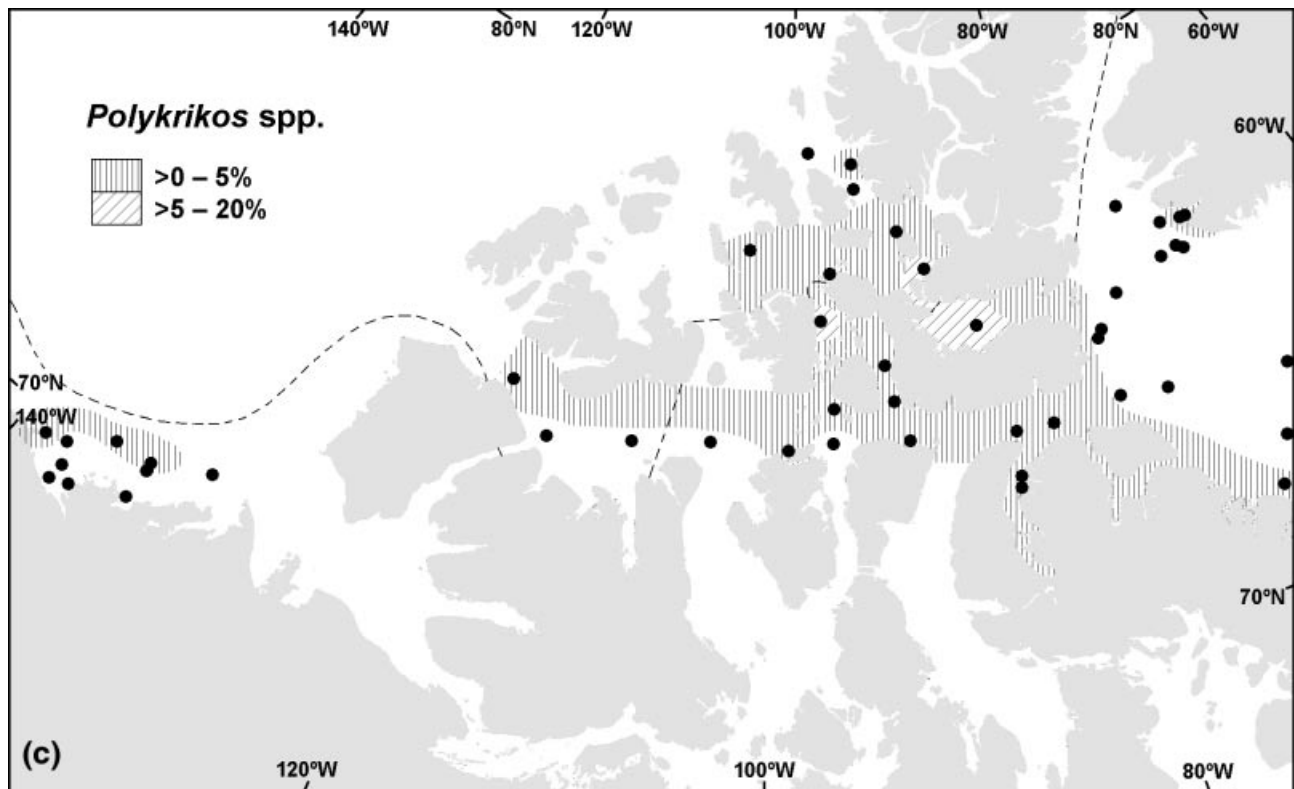


Figure 8 (Continued)

- 2 Assemblages with >60% *Brigantedinium* spp. and minor amounts of *A.? minutum* s.l., *O. centrocarpum* s.l. and *Spiniferites* spp. characterise samples from the West Greenland shelf between Davis Strait and Disko Bay. This is a nutrient-rich area of upwelling at the margin of the Kangeruaq glacier-field.
- 3 Assemblages dominated by *O. centrocarpum* s.l. (>60%) with significant amounts of *S. frigidus/S. elongatus* and minor *S. ramosus* and *A.? minutum* s.l. characterise the samples from central Baffin Bay and the largest Baffin Island fjords that are connected to the basin by deep (>200 m) transverse troughs. De Vernal *et al.* (1987) reported similar surface assemblages for the deep basin. This assemblage is very similar to assemblage IV of the CAA, but differs in that *Spiniferites membranaceus*, *Nematosphaeropsis labyrinthus*, *Impagidinium sphaericum* and *I. pallidum* also are sometimes present, and *Brigantedinium* is virtually absent.

### Hudson Bay and Hudson Strait

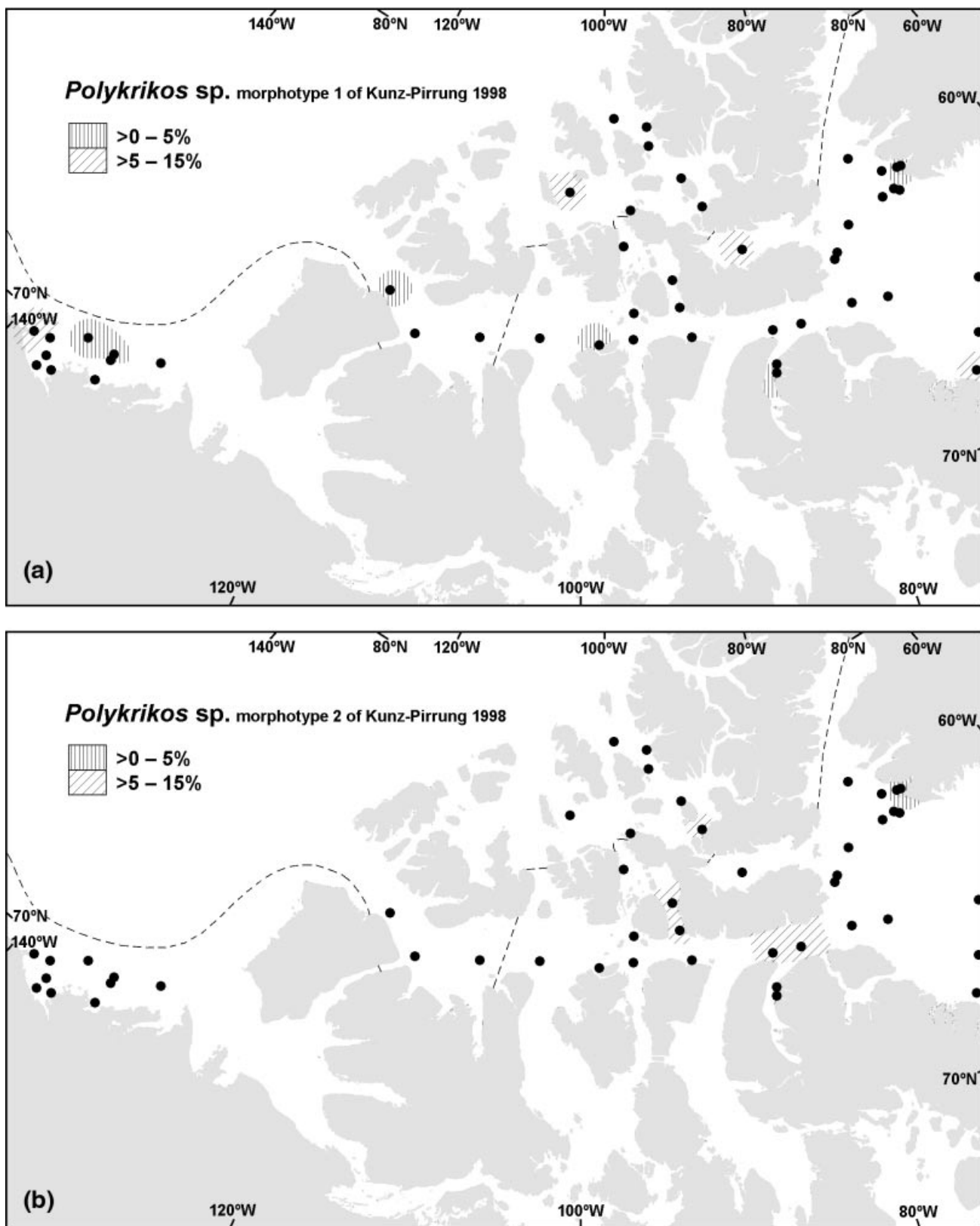
Previous studies (Rochon *et al.*, 1999; Hill *et al.*, 1999) have shown that Hudson Bay is characterised by two distinct dinocyst assemblages. There is a southern assemblage in James Bay and off the estuaries of the large rivers draining into the southern bay. The cysts of *P. dalei* dominate this assemblage almost exclusively ( $\leq 95\%$ ) at most of the southern sites and their abundance decreases gradually northwards. They are accompanied by *Algidasphaeridium? minutum* vars. *minutum* and *cezare*, and by *Spiniferites elongatus* and *S. ramosus*. The northern assemblage is characterised by the co-dominance of *Brigantedinium* spp., *O. centrocarpum* s.l. and *A.? minutum* var. *minutum*. *Spiniferites elongatus*, *S. ramosus* and *Impagidinium pallidum* also are present.

### Discussion

#### Canadian Arctic assemblages and correlation with temperature, salinity and sea-ice cover

We compared the sea-surface parameters of the three subregions of our study area (eastern Beaufort Sea (samples 1–10), CAA channels (samples 11–33) and NOW polynya (samples 34–52) in order to explain the differences among the dinocyst assemblages observed. Despite the scarcity and limitations regarding the present reliability of sea-surface data, each subregion is distinct with regard to summer temperature and salinity, and duration of sea-ice cover (see Table 1). Cold SST characterises all subregions in winter (February), with values ranging from  $-0.65$  to  $-1.8^\circ\text{C}$ . The surface waters of the Beaufort shelf are the warmest, at  $4.55^\circ\text{C}$  in summer, whereas the CAA and NOW are  $0.55$  and  $2.74^\circ\text{C}$  respectively. Summer salinity is relatively low on the Beaufort shelf and in the CAA ( $<15$ – $20.55$  and  $26.54$  respectively), and it averages  $31.72$  in the NOW area. The higher salinity in NOW is because of its distance from large rivers and possibly because of some Atlantic water input via the West Greenland Current (see Hargrave *et al.*, 2001). All three subregions are characterised by heavy SIC conditions during most of the year. The CAA has the most sea-ice, with  $10.8$  months  $\text{yr}^{-1}$ , whereas the Beaufort shelf and NOW polynya have  $9.0$  and  $8.45$  months  $\text{yr}^{-1}$  of sea-ice, respectively.

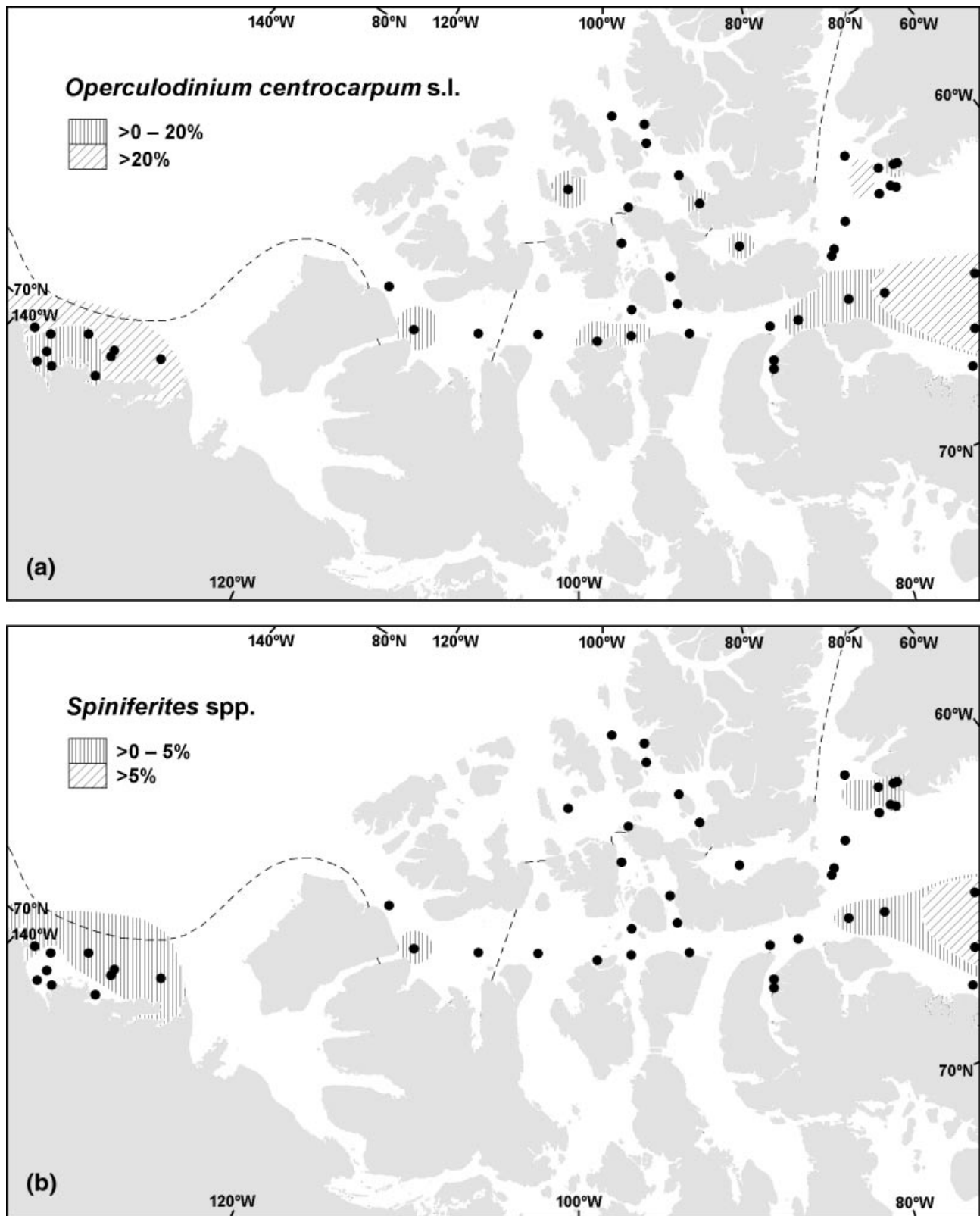
The CAA is the coldest of the three subregions. The distribution of cysts of *Polykrikos* sp. morphotype 1 of Kunz-Pirrung (1998) in that area is characteristic of High Arctic shelf environments with sea-ice cover of  $8$ – $12$  months  $\text{yr}^{-1}$ , including the Laptev Sea (Kunz-Pirrung, this issue). The Beaufort shelf area is under the influence of the freshwater Mackenzie plume, and has strong salinity gradients in summer (Matthiessen *et al.*, 2000). That, combined with high nutrient



**Figure 9** Maps of the distributions of Arctic morphotypes of *Polykrikos* in the Canadian Arctic study region. (a) Morphotype 1 of Kunz-Pirrung, 1998. (b) Morphotype 2 of Kunz-Pirrung, 1998

input and upwelling in canyons and on the shelf edge, probably accounts for the relatively high dinocyst concentrations and the high G:P ratio values on the outer shelf. The NOW region is dominated by a heterotrophic dinocyst assemblage, probably owing to the abundance of diatoms. In fact, most of the samples from the western polynya are devoid of autotrophic dinocysts. Dinoflagellate primary productivity is restricted to

a few species, most of which do not produce fossilisable resting cysts (see Table 4). It is presently not possible to determine if the relatively low dinocyst production is related to sustained competition from diatoms in the ice-free, nutrient-rich water of the polynya, or to some other critical factor, such as competition from blooms of autotrophic gymnodinioids (C. Lovejoy, personal communication, May 2001).



**Figure 10** Maps of the distributions of major autotrophic dinocyst species in the Canadian Arctic study region. (a) *Operculodinium centrocarpum* s.l. (b) *Spiniferites* spp.

### Comparison of CAA and Hudson Bay dinocyst assemblages

The *Brigantedinium*–*O. centrocarpum* assemblage from northern Hudson Bay is similar to Assemblage I from the outer Beaufort shelf. The dominant and accompanying taxa are the same, but their percentages are slightly different. The

outer Beaufort shelf assemblage also has low percentages of the cysts of *Polykrikos* sp. morphotype 1 and *Pyxidinopsis reticulata*, which are absent from Hudson Bay. In contrast, *Spiniferites ramosus* is absent from Beaufort Sea (only present in northern Baffin Bay) and percentages of *Spiniferites elongatus* are slightly lower than in northern Hudson Bay. Both assemblages are under the influence of Arctic surface water

**Table 4** Number of dinoflagellate species reported for the Russian and Canadian Arctic regions (see text for data sources) and the ratios of gonyaulacoid peridinioid dinoflagellates (G:P) reported. + presence is small amount

	GIN	Barents	White	Kara	Laptev	E. Siberian	Chukchi	Arctic Basin	Russian
Gymnodiniales	6	34	20	20	0	2	13	0	41
Gonyaulacales	2	30	15	17	8	1	13	2	33
Peridinales	13	57	38	52	28	8	44	9	86
Dinophysiales	2	14	9	13	5	2	7	0	19
Prorocentrales	3	5	3	2	0	0	1	0	8
Phytodinales	0	0	1	0	0	0	0	0	1
Blastodinales	0	0	0	0	0	0	1	0	1
N	26	140	86	104	41	13	79	11	189
G:P	0.15	0.52	0.39	0.33	0.28	0.12	0.29	0.22	0.38
	Baffin B.	Hudson B&S	Frobisher B.	NOW	NW Passage	E. Beaufort	W. Beaufort	Canad. Basin	Canadian
Gymnodiniales	19	2	3	29	4	1	3	1	29
Gonyaulacales	12	13	1	14	10	1	1	1	14
Peridinales	30	34	3	11	20	5	2	2	43
Dinophysiales	4	9	0	1	2	1	2	0	6
Prorocentrales	5	1	2	4	1	0	1	0	9
Phytodinales	0	0	0	+	0	0	0	0	0
Blastodinales	0	0	0	+	0	0	0	0	0
N	70	59	9	59	37	8	8	4	101
G:P	0.4	0.38	0.33	1.27	0.5	0.2	0.5	0.5	0.32

with similar summer sea-surface temperatures (ca. 4.55 °C for the Beaufort shelf and ca. 5.7 °C for northern Hudson Bay). The entire Beaufort shelf is influenced by the low salinity (5–15) freshwater plume from the Mackenzie River (Vilks *et al.*, 1979), and the salinity conditions are highly variable. When north-westerly winds deflect the plume toward the east, surface salinity on the inner shelf is low. During periods of easterly winds, the circulation on the shelf is reversed, and the eastern shelf is flooded with saline water. In our data base, the averaged salinities range from 18.6 to 28.7; however, it is likely that much lower salinities are found periodically at these sites. Despite the large inflow of fresh water in Hudson Bay (Carmack, 2000), only the southern part has low surface salinities (<15). Northern Hudson Bay has surface salinities of 30.6 to 31.2 as a result of the mixing with North Atlantic water and brine injection from ice formation in Foxe Basin. The seasonal duration of sea-ice cover also is quite different in the two subregions: the Beaufort shelf is ice-covered for 9 months yr<sup>-1</sup>, whereas northern Hudson Bay is covered by ice only ca. 7.5 months yr<sup>-1</sup>.

The southern Hudson Bay assemblages dominated by high percentages of the cysts of *P. dalei* are not similar to any of the CAA assemblages. Such high percentages of cysts of *P. dalei* are found elsewhere in areas of oceanic fronts such as in the southern Iceland Sea, and in the northern Pechora Sea (see Rochon *et al.*, 1999). Cysts of *P. dalei* also are dominant in the Chukchi Sea (Radi *et al.*, this issue), where relatively warm low-salinity (30–33) Bering Sea (Pacific) water mixes with colder, Arctic estuarine water (26.7–28). Low percentages of cysts of *P. dalei* on the Beaufort shelf probably reflect the strong salinity gradients observed in this area, and possible mixing of Pacific water by upwelling.

### Comparison with the eastern Arctic

The *Algidasphaeridium*–*Brigantedinium*–*Polykrikos* assemblages of the CAA are most similar to those described for the Laptev Shelf in the eastern Arctic (Kunz-Pirrung, 1998).

This similarity appears surprising given that salinities are much lower throughout the Laptev Sea (<30) than the CAA (ca. 30–32), but the two Arctic shelf regions are both fully polar in the sense of Kunz-Pirrung (this issue).

It is also interesting that the Canadian Arctic estuary, the Beaufort Sea, has a greater dominance of gonyaulacoid dinocysts than the estuarine Laptev Sea, where *O. centrocarpum* s.l., *N. labyrinthus*, *I. pallidum* and *Spiniferites* spp. are restricted to the slope and basinal sediments. There also is a greater abundance of *A. minutum* s.l. associated with the freshwater plumes in the inner Laptev Sea in contrast to the virtually monospecific *Brigantedinium* assemblages found in the inner Beaufort Sea.

The Beaufort Sea differs from the Laptev Sea in a number of ways that could have an important impact on the dinocyst assemblages. The Beaufort Sea is further south (69–71 °N) and is much smaller than the Laptev Sea, with the average width being less than one-fifth of the 500-km-wide Laptev Shelf. However, despite the more southerly location and warmer surface temperatures in summer (1–10 °C versus –1 to 4 °C), sea-ice formation is heavier and more extensive in the Beaufort than in the Laptev Sea because the winds blow predominantly onshore, causing compression ice to form and build-up thick ridges that ground on the central shelf in winter. Therefore, the Bathurst flaw polynya is very small compared with that of the inner Laptev Sea. Nonetheless, overall cyst production is approximately the same (100 to >3000 cysts g<sup>-1</sup>) in the two Arctic estuarine seas, and it appears that upwelling of Atlantic and Pacific water via the Mackenzie Trough and at the shelf edge may account for the greater prevalence of Gonyaulacoids on the Beaufort Shelf. It also is interesting that although the Beaufort assemblage I resembles the *O. centrocarpum*-dominated Bering Strait and Chukchi Sea assemblages (Radi *et al.*, this issue), the lower abundance of cysts of *Pentapharsodinium dalei*, and absence of *Lejeunecysta oliva*, *Quinquecuspis concreta* and *Selenopemphix nephroides* clearly distinguishes the Beaufort assemblage from the Bering and Chukchi Sea assemblages, which are influenced more strongly by Pacific water.

## Comparison with Antarctica

There are two major western Antarctic dinocyst assemblages coinciding with the maximum sea-ice in winter at 60°S Latitude (Harland *et al.*, 1998). The southern assemblage, with low cyst concentrations and  $N < 6$ , is dominated by either *Impagidinium pallidum*, *Algidasphaeridium? minutum* s.l. or *Protoperidinium* spp. (mostly *Brigantedinium* cysts), with significant percentages of cysts of *Pentapharsodinium dalei* and *Selenopemphix antarctica* near the northern ice-margin. This assemblage is associated with SSTs ranging from -1.9 to 1.0°C, and SIC of 9 months yr<sup>-1</sup>. The northern sub-Antarctic and Polar Front assemblage is associated with SSTs of 0–4°C and less than four-tenths SIC in winter. This sub-Antarctic assemblage has higher cyst numbers and greater species diversity ( $N = 9–11$ ). *Selenopemphix antarctica* and *Brigantedinium* cysts are co-dominant, but Gonyaulacoids also are present, including *O. centrocarpum* s.l., *Impagidinium* spp., low percentages of *Nematosphaeropsis labyrinthus* and *Spiniferites* spp. and an endemic species, *Dallella chathamense*. Similar assemblages occur in subarctic waters off eastern Antarctica (Marret and de Vernal, 1997).

Clearly, there is a much greater diversity of dinocyst assemblages in the Arctic Ocean than in the Antarctic, presumably because of the wider regional variation in temperature, salinity and sea-ice cover, and the greater diversity of polar shelf environments in the Arctic. It therefore is remarkable that there are more endemic dinocysts (both autotrophs and heterotrophs) in the Antarctic, reflecting a more diverse dinoflagellate flora, whereas there are no endemic cyst-producing species in the circum-Arctic region. Only two species (*Peridiniella catenata* and *Gymnodinium* cf. *punctatum*) are associated consistently with sea-ice and there are no known dinoflagellate species restricted to the Arctic Ocean (Okolodkov and Dodge, 1996). However, the ice-covered regions of both polar oceans share the characteristic of being largely dominated by heterotrophic dinocyst assemblages whereas the subarctic regions have a higher G : P ratio, indicating a greater prevalence of autotrophs.

## Comparison of Arctic marine phytoplankton and cyst G : P ratios

Comparison of the composition of plankton-stage populations and the dinocyst thanatocoenoses provides important information for evaluating the likelihood that some cysts are present in the Arctic only as allochthonous particles transported by the Atlantic and Pacific Current systems (e.g. Kunz-Pirring, this issue). Plankton–cyst correlations also assist in (i) determining the taxonomic relationships of Arctic cysts; (ii) understanding of the relationship between plankton population size and cyst production; and (iii) in assessing the likelihood that post-depositional oxidation of thin-walled protoperidinioid cysts has shifted the cyst G : P ratio towards higher values of the more resistant gonyaulacoids.

Knowledge of Arctic dinoflagellates is still in the exploration stage (Okolodkov, 1998), and nothing is known presently about psammophytic (sand dwelling) dinoflagellates. However, there are three sources of data that can be used for initial studies.

1 Okolodkov (1998) reviewed all literature for the Russian Arctic and grouped the number of species into orders (see Table 4) for each major subregion of the Russian Arctic.

2 We (PJM) made a comparable survey of the literature for the Canadian Arctic (Table 4), using the following data sources: Baffin Bay (Grontved and Seidenfaden, 1938; Hsaio, 1980, 1983); Hudson Bay (Bursa, 1961a); Frobisher Bay (Hsaio, 1979b); Northwest Passage (Bursa, 1961b; Hsaio, 1980); Beaufort Sea (Foy and Hsaio, 1976; Hsaio, 1979a); and Canada Basin (Tibbs, 1967).

3 Connie Lovejoy of Laval University kindly made available her list of dinoflagellates collected in the NOW polynya from ca. 1997–1999.

The results of this rough survey show that when the sub-regions of the Russian and Canadian Arctic are arranged in sequence from the Atlantic entrances to the seas closest to the Pacific entrances, there is a general decrease in species diversity from maxima of 140 and 70 in the Atlantic entrances, to minima of 11–13 and 4–16 in the most distant shelves and the ocean basins, and a slight recovery ( $N = 79$ ) at the Siberian Pacific entrance (unfortunately, no summer data are available presently for the Alaskan Shelf to balance the North American perspective). Anomalously low values for the Greenland–Iceland–Norwegian sea (GIN) appear to be related to the deep-water location of the plankton survey area. The low Frobisher Bay values probably reflect its relatively small size and location on the margin of the polar Baffinland Current in contrast to the high values for the larger White Sea on the edge of the North Atlantic inflow to Barents Sea.

Table 4 also shows the ratios of Gonyaulacales:Peridinales compiled from these phytoplankton data. Although these G : P values are not exactly the same as the dinocyst G : P values, it is notable that within the Russian Arctic, they show the same general trend from high values (0.33–0.52) near the Atlantic entrances to lows of 0.12 and 0.22 in the most central regions. In contrast, although the average value for the Canadian Arctic (0.32) is almost the same as for the Russian Arctic (0.38), there is not such a clear trend within the Canadian region. This particularly is notable in the very high value of 1.27 for the NOW polynya and values of 0.5 for the Northwest Passage, in contrast to the cyst G : P values of <0.1 for these subregions.

The reason for these discrepancies partly lies in the fact that some dinoflagellates produce abundant cysts (e.g. *Protoceratium reticulatum*, the thecate-stage of *O. centrocarpum* cysts) whereas others (e.g. *Protoperidinium conicum*, the thecate stage of *Selenopemphix quanta* cysts) are cyst under-producers (Dale, 1976). Furthermore, the cyst production potential of many Arctic dinoflagellates is still unknown. For example, initial studies of dinocysts in suspended sediments from sediment traps moored for 3 yr in the NOW polynya (Mudie and Rochon, unpublished) show the presence of common *Brigantedinium* cysts, although Lovejoy did not find a known thecate stage. Sample patchiness and interannual variations are also problematic. For example, Mudie (1992) found abundant *Peridiniella catenata* beneath the pack-ice on the Canadian polar margin in 1986, but it was not found in 1985 or 1987–1988.

At present, therefore, it is not possible to determine any quantitative relationships regarding Arctic cyst concentrations and plankton production. Harland and Pudsey (1999) reached a similar conclusion based on sediment trap and cyst core-top data from the Antarctic.

## Conclusions

1 Despite the extreme conditions of temperature, salinity and sea-ice, most parts of the Canadian Arctic have relatively



abundant and diverse dinocyst assemblages, and four assemblages occur that reflect major regional variations in sea-surface conditions.

- 2 The new dinocyst core-top data, which covers 25% of the circum-Arctic shelf region, has the potential for increasing the precision of sea-surface reconstructions for Arctic environments when the taxonomy of endemic Arctic morphotypes is stabilised. However, precision of the transfer functions will remain inadequate for global circulation models until more data are available for surface salinity and SIC, which are more important variables than temperature in the Arctic marine domain.
- 3 The heterotrophic *Algidasphaeridium*–*Brigantedinium*–*Polykrikos* assemblage of the CAA is very similar to that in the estuarine Laptev Sea of the Siberian Arctic, which is the 'locus typus' for the Arctic shelf region. The similarity of the dinocyst floras from these high Arctic shelves with different salinity and SIC regimes points towards the importance of deep Atlantic or Pacific water masses in transporting variable amounts of autotrophic cysts into the other 'mixed' Arctic environments.
- 4 Comparison of the three main circum-Arctic estuarine seas (Beaufort and Laptev seas and Hudson Bay) shows that the Arctic has a very low diversity inshore dinocyst flora dominated by *Brigantedinium* spp., whereas the sub-Arctic estuarine system is dominated by *Pentaparsodinium dalei*. Assemblages in the outer parts of the circum-Arctic estuarine seas differ among regions, but the Atlantic-influenced Hudson Bay and Laptev Sea are more similar than the Beaufort Sea, where a Pacific influence may be present.
- 5 Examination of G:P ratios of subregional cyst assemblages relative to that obtained from the CAA phytoplankton records shows that generally there is an inverse correlation between duration of sea-ice cover and G:P in both cyst and plankton populations. The same trend is found in the Siberian plankton data of Okolodkov (1998). In the Canadian Arctic, large anomalies in dinocyst G:P values are associated with the presence of Atlantic water in Baffin Bay; here, the plankton data also show higher G:P values, suggesting that the cysts are in place and neither entirely transported nor an artefact of oxidation. In the NOW polynya, however, the plankton and G:P values are very different. There are also no reports of *Polykrikos* or a possible thecate stage for *Algidasphaeridium*? in the plankton despite their prominence in the cyst assemblages.
- 6 At present, species diversity is the most consistent index of sea-ice cover, with  $N < 6$  characterising areas with  $>9$  months of multiyear or pack-ice and diversities of  $N > 10$  marking areas with more than 3 months summer open water. The same pattern appears to be true for the Antarctic region, where high percentages of *Impagidinium pallidum* may result in high G:P values, but diversity is consistently low.

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