

Chapitre 2. Modern dinoflagellate cyst assemblages in surface sediments of Nunatsiavut fjords (Labrador, Canada).

Résumé

Dans le but de documenter les cycles climatiques à long terme et de prévoir les tendances climatiques futures pour l'Arctique, les enregistrements géologiques archivés dans les sédiments océaniques peuvent aider à établir le lien entre les paramètres modernes et passés de la surface de l'océan. Les kystes de dinoflagellés (dinokystes) sont employés comme bioindicateurs de ces paramètres (température, salinité, couvert de glace de mer, productivité primaire). Conjointement avec l'utilisation de fonctions de transfert et une base de donnée des assemblages modernes de dinokystes, ils permettent de reconstituer l'évolution des conditions de surface de l'océan à des échelles de temps décennales et millénaires. Nous présentons ici la distribution de surface des assemblages modernes de dinokystes pour 13 échantillons de prélevés dans quatre fjords du Nunatsiavut (Nord du Labrador, Canada). Les concentrations de dinokystes dans les sédiments de surface augmentent de la tête vers l'embouchure de chaque fjord, ainsi que du Nord au Sud. On observe également au Sud une augmentation de la biodiversité des espèces dont l'apparition et la dominance des kystes de dinoflagellés autotrophes. La présence de kystes calcaire de dinoflagellés de l'espèce *Scrippsiella* cf. *S. crystallina* dans le fjord d'Anaktalak, où des opérations minières sont en cours, semble être un indicateur d'une pollution causée par l'homme dans le fjord.

Abstract

In order to document long-term climate cycles and predict future climate trends for the Arctic, geological records archived in ocean sediments can help 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 in 13 surface samples collected in four Nunatsiavut fjords (northern Labrador, Canada) along a latitudinal gradient, and their relationship with various environmental and biological parameters. Dinocyst concentrations in surface sediments increased from the inner to the outer part of each fjord and also from the northernmost to the southernmost fjords. There was also a southward increase in the species diversity with an occurrence and a dominance of cysts from autotrophic dinoflagellates. The presence of cysts of the calcareous dinoflagellate species *Scrippsiella* cf. *S. crystallina* in Anaktalak Fjord, where mining activities are underway, appears to be an indicator of human-related pollution within the fjord.

2.1. Introduction

Labrador Inuit depend on the ocean and sea ice for their hunting and harvesting activities. They are concerned about the ecological integrity of the marine environment of northern Labrador, especially with respect to the impacts of climate change, industrialization (maritime navigation, mining) and contamination of their traditional foods. These natural resources are very important to native cultures and peoples. The peculiarities of Arctic ecosystem conditions (ice cover, photoperiod etc.) have determined their way of life for millennia. However, rapid changes with numerous ecosystem disruptions that are of natural or anthropogenic origin will result in significant disturbances in these fragile northern communities. As part of the Network of Centres of Excellence ArcticNet project “Nunatsiavut Nuluak: Understanding the effects of climate change and modernization in a northern marine environment” addresses these concerns. Since then, several oceanographic campaigns aboard the Canadian Coast Guard Ship (CCGS) Amundsen have been conducted along the Labrador coast, specifically inside four fjords, some with environmental disturbances and stresses caused by human activities (Figure 2.1).

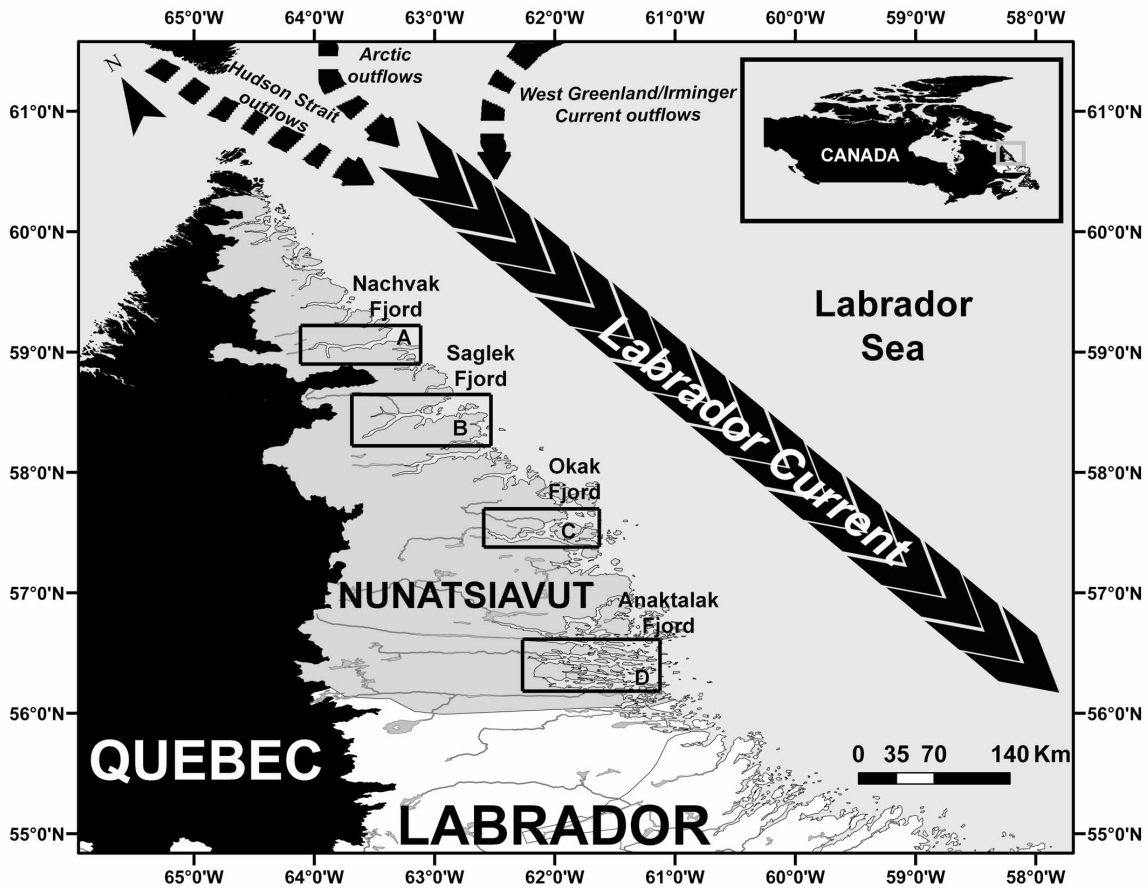


Figure 2.1: Map of the Nunatsiavut (North Labrador, Canada) illustrating the location of the four fjords involved in this study: A. Nachvak Fjord; B. Saglek Fjord; C. Okak Fjord and D. Anaktalak Fjord.

Dinoflagellates are microscopic unicellular biflagellate protists (Taylor et al., 2008), that occasionally form massive bloom events known as red tides. Some dinoflagellate species can be toxic. The life cycle of some species comprises a dormancy phase during which the vegetative stages form cysts. The cyst's membrane is composed of a highly resistant polymer called dinosporin, allowing the cyst to be preserved in sediments (Richerol et al., 2008b). Dinocysts have been used as proxy indicators to compare past and modern assemblages and link them with environmental parameters (sea-surface temperature and salinity, sea-ice

cover duration, productivity) through the use of transfer functions (Rochon et al., 1999; Devillers and de Vernal, 2000; Boessenkool et al., 2001; de Vernal et al., 2001, 2006; Grøsfjeld and Harland, 2001; Kunz-Pirrung, 2001; Mudie and Rochon, 2001; Radi et al., 2001; Voronina et al., 2001; Richerol et al., 2008a,b). In November 2009 and October 2010, the Nunatsiavut fjords were sampled to document modern assemblages of dinoflagellate cysts (dinocysts) and their relationship with several environmental parameters including summer sea-surface temperature and salinity, sea-ice cover duration, photosynthetically available radiation (PAR), nutrients (nitrites, nitrates, silicates and phosphates) and diatom abundance.

Dinocysts in fjords from arctic and subarctic regions have already been the subject of previous studies. In Norwegian fjords, the dynamics of the formation, sedimentation and preservation of dinocysts have been studied in Trondheimsfjord (Dale, 1976), whereas they served as pollution and past climate indicators in Nordåsvannet and Grimstadfjord (Thorsen and Dale, 1997) and as indicators of cultural eutrophication in Oslofjord (Dale et al., 1999). Dinocysts were also part of a multi-proxy study on Holocene climate in the subarctic fjord Malangen (Hald et al., 2003). In Gullmar Fjord (Sweden) the relationship between the abundance of planktonic dinoflagellates, the abundance of dinocysts recovered from sediment traps and environmental factors have been studied (Godhe et al., 2001). In Igaliku Fjord (southern Greenland) dinocysts have been used to document the palynofacies of the late Holocene in relation to the paleohydrography of the fjord (Roncaglia and Kuijpers, 2004). The assemblages of dinocysts from Svalbard fjords have been documented in relation to the modern oceanographic conditions (Kongsfjorden, Krossfjorden, Sassenfjorden, Van Mijenfjorden and Storfjorden) (Grøsfjeld et al., 2009) and the influence of Atlantic water circulation (Kongsfjorden and Rijpfjorden) (Howe et al., 2010). On the Canadian west coast, the anoxic fjord Effingham Inlet (Vancouver Island, BC) has been studied for the modern assemblages of dinocysts (Kumar and Patterson, 2002) and paleoceanographic conditions (Patterson et al., 2011).

This study is the first to document the modern dinocyst assemblages in the fjords of Nunatsiavut (northern Labrador, Canada) with the aim of providing a better understanding of the ecological status of these fjord ecosystems, thereby allowing us to predict their response to future anthropogenic changes. A better knowledge of the natural background conditions will help develop appropriate mitigation measures for the effective management and sustainable development and preservation of the ecological and cultural integrity and diversity of the North. The dinocyst assemblages from this study (n=12 sites; Figure 2.2) will be integrated into the regularly updated reference database of modern dinocyst assemblages from the Northern Hemisphere (n=1,429 sites), managed by GEOTOP (de Vernal et al., 2001; Radi and de Vernal, 2008), for subsequent use in paleoceanographic reconstructions. This is a prerequisite for a better understanding of the impacts of present-day and future changes on these fjord ecosystems.

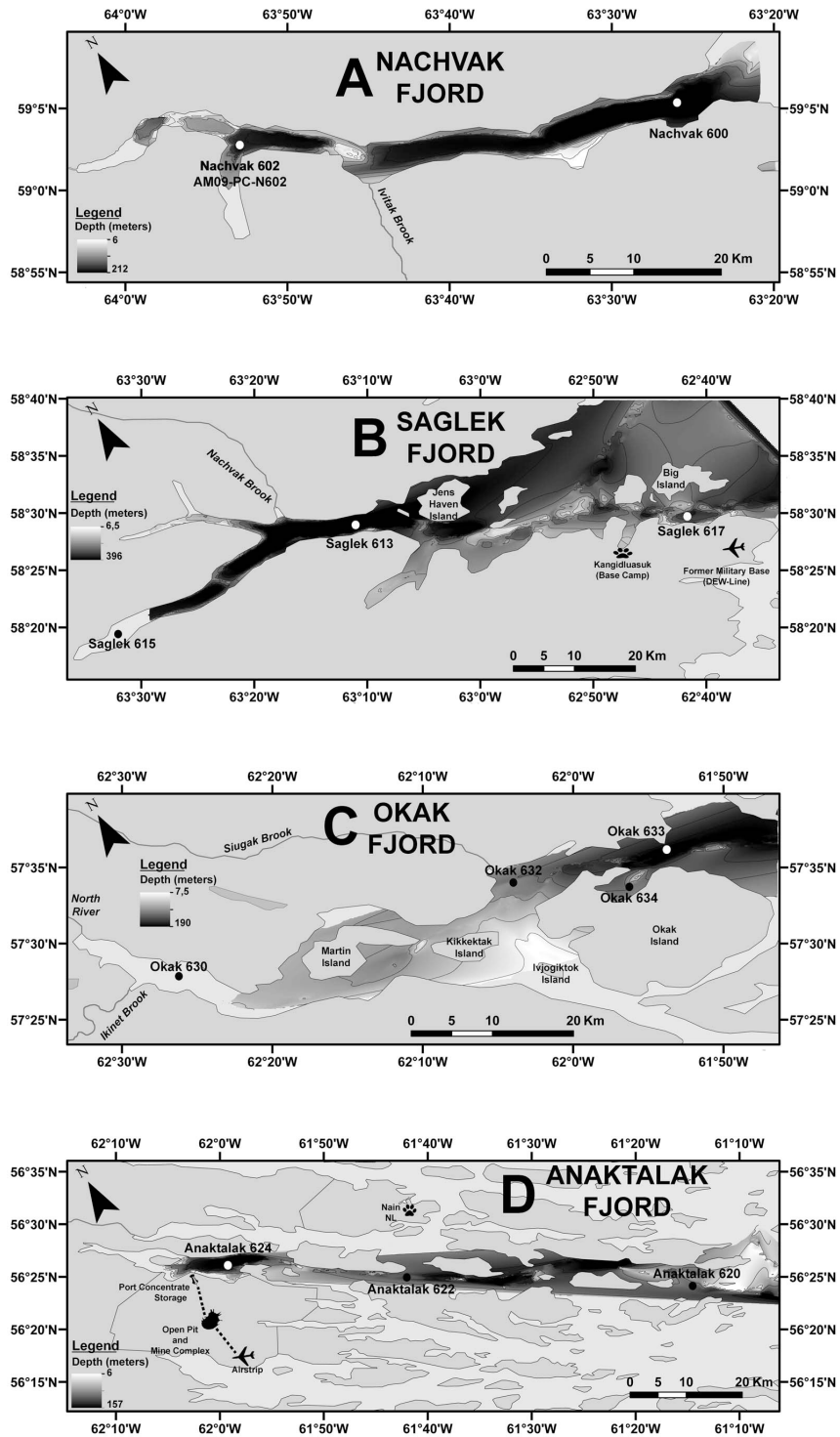


Figure 2.2: Maps of the four fjords showing the location of the surface sediment samples used in our study.

2.2. Environmental Settings

Labrador is a region located on the eastern seaboard of Canada and extends between 46-60°N, along the Labrador Sea (Figure 2.1). It is underlain mostly by granitic-gneissic Precambrian rocks of the Canadian Shield (De Blij, 2005). Our study region is located in the northern part of the province called Nunatsiavut (“Our Beautiful Land”) that belongs to the Inuits.

During the last glaciation (between 110,000 and 10,000 kBP), the Laurentide Ice Sheet covered the entire region, except for some nunataks (high ice-free peaks extending above the ice dome of the ice sheet) in the Torngat Mountains. The southeastern part of Labrador was free of ice ca. 11,000 BP (Dyke and Prest, 1987; Dyke et al., 2002). Between 11,000 and 6,000 BP, the retreat of the ice sheet exposed the northern part of Labrador while wasting ice persisted in the central high plateau area of Labrador-Ungava until about 6,000 BP (Lamb, 1980; Engstrom and Hansen, 1985). Large parts of Labrador are located between 450 m and 750 m above sea level. However, in the northeastern part there are mountain ranges (Torngat, Kaumajet) that rise to 1,600 m and 1,800 m above present-day sea level (Short and Nichols, 1977). The western and central regions of Labrador are characterized by broad flat till plains that are covered with lakes and peatlands. Closer to the coast, bedrock-controlled hills dissected by large rivers dominate the landscape (Engstrom and Hansen, 1985).

The climate of Labrador is characterized by long cold winters and short cool and moist summers. The temperature and moisture regimes are dominated by north-south transgressions of cold dry Arctic air and warm moist Atlantic air masses (Hare and Hay, 1974). There is a strong climatic contrast between the coastal and the interior Labrador. The cold Labrador Current (Figure 2.1), which flows southward from the Arctic through Nares Strait and Baffin Bay, has a significant influence on the local climate (Engstrom and Hansen, 1985). In July and August, the mean temperature along the coast is around 10°C, while inland the mean temperature can reach 16°C, with occasional peaks as high as 38°C. These conditions are reversed during the winter when mean temperatures are around 3°C

along the coast and warmer than inland temperatures (Short and Nichols, 1977; Ullah et al., 1992). The mean annual precipitation in Labrador varies from 750 mm in the North to 960 mm in the South. Precipitation is fairly evenly distributed throughout the year with slightly higher values occurring during the summer and early autumn. Snowfall is relatively heavy with annual amounts ranging from 390 cm to 480 cm (Ullah et al., 1992). Over the last ten years, the melting of the sea-ice cover in the fjords occurred in the first half of July, and the freezing in the second half of December (NCDC).

Nachvak is the northernmost fjord in this study (Figures 2.1, 2.2A), located in the Torngat Mountains National Park Reserve, hence it is the most remote and pristine system. This fjord serves as a reference or control site to assess the natural climatic and environmental variability of the Labrador fjord ecosystems. Nachvak Fjord is glaciated, 45 km long and 2 to 4 km wide, gradually increasing in width eastward to Nachvak Bay, which opens to the Labrador Sea (Bell and Josenhans, 1997). Local elevations extend up to 1,000 m above sea level (Bell and Josenhans, 1997). There is a succession of basins with maximum water depths of 90, 160, 170, and 210 m from West to East. The four basins are separated by sills between 10 and 180 m below sea level. Nachvak Fjord receives most of its sediment from Ivitak Brook, a glaciated catchment. The average annual sediment load for the basins ranges between 1.1 to 3.2 kg s⁻¹ (Kahlmeyer, 2009).

Saglek Bay (Figures 2.1, 2.2B) has been the site of a military radar station since 1953 as part of the DEW (Distant Early Warning) Line. Because of poor disposal of wastes from processed oils (e.g. liquid lubricants) after its abandonment in 1971, soils were contaminated with PCBs (PolyChloroBiphenyls) in three separate areas around Saglek Bay, at concentrations as high as 250 µg of PCB per gram of soil (Pier et al., 2003). Before the decontamination of the soils, at the return of military activities in 1997-1999, PCB-contaminated soils at the site were a source of pollution to the surrounding landscapes, lake sediments and marine coastal environments. Previous studies on PCB contamination in the marine and lake sediments from this region focused on freshwater microalgae

(chrysophytes) (Paterson et al., 2003). Other studies have examined the impact on animals that are of commercial and dietary interest to Labrador Inuit (arctic char, salmon, seals and whales) or of diagnostic interest, such as seabirds or the shorthorn sculpin, a fish that feeds near and on the seafloor (Kuzyk et al., 2003, 2005a). These studies have provided evidence for the bioaccumulation and biomagnification of contaminants through the marine food chain (Kuzyk et al., 2005b). Saglek Fjord is unglaciated, 55 km long and 2 to 14 km wide, increasing in width eastward to Saglek Bay, which opens to the Labrador Sea. The sidewalls are generally steep, extending to more than 800 m above sea level. There is a succession of seven basins with maximum water depths of 170, 256, 190, 117, 112, 149, and 160 m from West to East. The basins are separated by sills between 45 and 96 m below sea level. Saglek Fjord receives the greatest amount of its sediment from Nachvak Brook, an unglaciated catchment. The average annual sediment load for the basins ranges between 0.5 to 12 kg s⁻¹ (Kahlmeyer, 2009).

Okak Fjord (Figures 2.1, 2.2C), the “ghost fjord”, was the site of a Moravian settlement in 1775. The pandemic “Spanish flu” in 1918 devastated its population, wiping out the entire community. Since then the fjord has remained “unoccupied” (Rompkey, 2003) except for occasional harvesting and travel by the Inuit from the Nain community (Brown and Gratton, pers. comm.). Okak Fjord is approximately 51 km long and has a North and South entrance. The head of the fjord is a narrow, flat channel running northwest, with a sharp turn midway towards the northeast and is approximately 21 km in length. The depth is fairly shallow, averaging 45-50 m throughout the region, with shallower areas (16-20 m) closer to the head and the margins of the channel. The deepest point is found at the end of the channel (75 m) where it is separated from the adjoining region by a small, deep sill. There are two sources of freshwater input near the head, Ikinet Brook and the North River, which enter the fjord from the southern and eastern sides of the head respectively. The central fjord encompasses the region around the inner islands and is characterized by basins of medium depth, shallow sills and steep sidewalls. Average depth is 70-80 m, with several shallow sills of less than 20 m. The central fjord region is separated from the fjord head by a deep sill. The northern entrance

to the fjord consists of the deepest areas of Okak Bay, characterized by deep basins and sills with steep sidewalls. The average depth of the basins is 200 m, whereas the sills separating the basins range between 100-120 m. The coastal areas consist of a series of small islands, and the northern shore of Okak Islands. In these areas the seabed is shallow (40 m or less), before dramatically dropping to the basin depth. The southern entrance to the fjord is 30 km in length, and consists of a narrow, shallow channel bordered by the Ubilik Peninsula to the south, and the southern coast of the Okak Islands to the north (Brown and Gratton, pers. comm.).

The southernmost site Anaktalak Fjord (Figures 2.1, 2.2D) is 66 km long and 1 to 5 km wide, gradually increasing in width eastward to the Labrador Sea. Within the fjord there are numerous islands of varying size. Much of the bay forms a large basin 100-120 m in depth. The depth rises to 85 m to form a sill at the outer part of the bay. The average sediment load entering the Anaktalak Bay marine basin range between 0.04 to 0.45 kg s⁻¹ (Kahlmeyer, 2009). The fjord is extensively used by Inuit for harvesting and traveling. Between 1997 and 2002, a nickel mine operation was established in Voisey's Bay (Hulett and Dwyer, 2003; Noble and Bronson, 2005). Since the beginning of the Vale Inco Nickel Mine (formerly Voisey's Bay Nickel Company) operations, the fjord and marine environment have received treated effluents from the mine. Nunatsiavut communities have expressed concerns about the effects of mining and associated shipping operations on the ecosystem's integrity in Anaktalak Bay. Part of our research aims at determining the impacts of these activities, as well as developing appropriate indicators for the long-term monitoring of the environmental and ecological conditions within this fjord ecosystem.

The surface stratification in the fjords is controlled by both runoff and ice melt. During summer, a strong pycnocline with fresh surface waters overlies more saline intermediate waters, and is more pronounced in the northern fjords, whereas during the fall the water column is more homogeneous (non-stratified). Anaktalak Bay, Nachvak Fjord and Saglek Fjord had the lowest salinity values recorded in

summer (27.9, 29.0 and 30.4 respectively). Circulation appears to occur at all depths, as the waters in the fjords are oxygen-rich. Nutrient distributions in the fall (surface and bottom) reveal a pattern of nitrate and phosphate depletion from the northernmost to the southernmost fjord (Brown and Gratton, pers. comm.).

2.3. Methodology

2.3.1. Sampling

Sampling in the Labrador fjords (Nachvak, Saglek, Okak and Anaktalak) was carried out in November 2009 and October 2010. A total of 13 surface samples were collected using a boxcorer, and the uppermost 5 mm of the sediment surface were collected using a microscope slide (Table 2.1). Each sample was then processed according to the standard palynological method described by Rochon et al., (1999) and adapted by Richerol et al. (2008a, b). Station 632 in Okak Fjord has been sampled twice (in 2009 and 2010), however only one sample (2009) was included in the database for the statistical analyses of the species-environment relationships.

Table 2.1 : Geographical coordinates, water depth (in meters), number of cyst counted, cyst concentration (cyst g⁻¹) and hydrographic data for samples shown in Fig. 2A/B/C/D : S-SST=summer sea surface temperature (°C); S-SSS=summer sea surface salinity; ICE=sea-ice cover duration (months year⁻¹); PAR=photosynthetically available radiation (Einstein m⁻² day⁻¹); NUTRIENTS=average concentration of nitrates, nitrites, silicates and phosphates in the water column for 2006/2007/2009/2010 (µmol L⁻¹); DIATOMS=average concentration of diatoms in the water column for 2006/2009/2010 (number of cells cm⁻³).

Station number	Year	Latitude	Longitude	Water Depth	Count	Concentration	S-SST	S-SSS	Ice	PAR	NUTRIENTS	DIATOM
N602	2009	59.52 N	63.87 W	151	328	1763	2.0	30.9	6.6	29.4	19.0	5.9E+08
N600	2009	59.09 N	63.43 W	204	309	2448	2.4	31.6	6.6	32.0	15.6	2.9E+08
S615	2009	58.32 N	63.54 W	138	303	1258	1.2	24.9	6.3	31.8	14.8	5.5E+08
S613	2010	58.48 N	63.22 W	255	305	7213	2.3	24.9	6.3	34.5	16.6	5.5E+08
S617	2009	58.50 N	62.69 W	134	342	3639	4.1	28.2	6.3	32.7	10.1	4.5E+08
O630	2009	59.47 N	62.44 W	50	356	1938	2.6	28.3	6.3	NA	11.2	1.2E+08
O632	2009	57.57 N	62.55 W	83	328	5939	3.0	30.7	6.3	35.0	11.5	2.2E+08
O632	2010	57.57 N	62.05 W	83	508	8047	3.0	30.7	6.3	35.0	11.5	2.2E+08
O634	2009	57.57 N	61.94 W	101	313	5666	3.1	30.7	6.3	34.1	9.7	2.2E+08
O633	2009	57.61 N	61.90 W	182	307	4649	3.7	30.7	6.3	33.2	9.7	2.2E+08
A624	2009	56.44 N	61.99 W	115	307	4981	3.2	27.3	6.4	33.6	9.8	9.8E+07
A622	2010	56.42 N	61.74 W	81	623	13805	3.4	27.3	6.4	34.3	6.9	1.2E+08
A620	2009	56.40 N	61.22 W	93	315	5465	4.4	30.0	6.4	33.6	5.4	1.2E+08

2.3.2. Sieving

Preparation of palynological samples followed standard procedures as outlined in Richerol et al. (2008a,b). Approximately 5 cm³ was taken from each sample and the volume measured in a graduated cylinder by water displacement. A tablet of *Lycopodium clavatum* spores of known concentration (12,100 ± 1,892 spores tablet⁻¹; batch #414831) was added to each sample, which serve as palynological markers to facilitate the calculation of the concentration of palynomorphs in each sample (Mertens et al., 2009). Sieving was performed using Nytex® sieves of 100 µm and 10 µm mesh, to eliminate coarse sands, fine silts and clays. The fraction between 10 µm and 100 µm was preserved in a conical tube with a few drops of phenol for subsequent chemical processing.

2.3.3. Chemical processing

The 10 µm to 100 µm fraction was later treated with hydrochloric acid (4 treatments with 10% HCl) and hydrofluoric acid (3 treatments, one of which was performed overnight, with 49% HF) in alternation in order to dissolve carbonates and silicates, respectively. These acid treatments were performed with heat in order to accelerate the reaction. The remaining fraction was rinsed with distilled water to eliminate traces of acid before a final sieving at 10 µm was performed to remove fluorosilicates and fine particles. The samples were mixed in a Vortimixer, and a few drops of the supernatant were drawn off and added to glycerin jelly to be mounted between microscope slides and cover slips.

2.3.4. Palynomorph counts

Palynomorphs (pollen, spores, dinoflagellate cysts, acritarchs, freshwater palynomorphs) were counted using a transmitted-light microscope (Leica

DM5500B) at a magnification factor of 400×. A minimum of 300 dinocysts were counted in each sample. This method yields the best statistical representation of all the taxa present in the samples. Using these counts, the concentration of dinocysts per unit of dry weight (g) and the relative abundance of each species in each sample were determined (Tables 2.2 and 2.3). The nomenclature used for the identification of the dinocysts corresponds to the index of Lentin and Williams (Fensome and Williams 2004), Head et al. (2001), and Rochon et al. (1999).

Table 2.2 : List of dinoflagellate taxa present in our samples and their code names.

Dinocyst name	Code name
<i>Brigantedinium spp.</i>	Bspp
<i>Brigantedinium cariaeoense</i>	Bspp
<i>Brigantedinium simplex</i>	Bspp
<i>Echinidinium karaense</i>	Ekar
<i>Islandinium brevispinosum</i>	Iminsl
<i>Islandinium minutum</i>	Iminsl
<i>Islandinium minutum var. cezare</i>	Iminsl
<i>Pentapharsodinium dalei</i>	Pdal
<i>Polykrikos Arctic Morphotype I</i>	Parcsl
<i>Polykrikos Arctic Morphotype II</i>	Parcsl
<i>Protoperidinium americanum</i>	Pame
<i>Scrippsiella cf. S. crystallina</i>	Scrycf
<i>Selenopemphix quanta</i>	Squa
<i>Spiniferites elongatus</i>	Selofri
<i>Spiniferites frigidus</i>	Selofri
<i>Spiniferites ramosus</i>	Sram

Table 2.3: Relative abundance (%) of dinoflagellate cyst taxa in our samples. See Table 2 for the codenames of the dinocyst species and also : Selo=*Spiniferites elongatus*; Sfri=*Spiniferites frigidus*; lmin=*Islandinium minutum*; lmic=*Islandinium minutum* var. *cezare*; lbre=*Islandinium brevispinosum*; Bcar=*Brigantedinium cariacense*, Bsim=*Brigantedinium simplex*; Parc=*Polykrikos* Arctic Morphotype I; Pqua=*Polykrikos* Arctic Morphotype II (*quadratus*).

Station number	Pdal	Sram	Selo	Sfri	Scrycf	lmin	lmic	lbre	Bspp	Bcar	Bsim	Ekar	Pame	Squa	Parc	Pqua
N602	0	0	0	0	0	50	8	4	33	0	2	0	0	0	2	1
N600	0	0	0	0	0	40	8	5	41	2	3	1	0	0	0	0
S615	0	0	0	0	0	39	11	18	25	0	0	1	0	1	3	2
S613	0	0	0	0	0	34	6	10	45	0	0	3	0	0	2	0
S617	0	0	0	0	0	58	5	11	23	0	2	0	0	1	1	0
O630	63	9	0	3	0	3	0	0	17	0	0	0	0	4	1	0
O632	56	3	0	0	0	19	3	3	12	0	0	1	0	2	1	0
O632	67	2	0	0	0	8	1	1	15	0	0	1	0	3	0	0
O634	52	2	0	1	4	11	3	4	15	0	0	1	1	4	0	1
O633	25	0	0	0	0	34	4	10	19	0	1	2	1	2	1	0
A624	71	5	0	0	2	3	2	1	13	0	0	1	1	0	1	0
A622	68	2	0	0	0	4	3	1	16	0	0	1	0	4	0	0
A620	58	6	0	0	1	6	4	2	16	0	0	1	0	6	0	0

2.3.5. Statistics

The software CANOCO version 4.5 (Ter Braak and Šmilauer, 2002) was used to determine which environmental parameter explained most of the variance in the distribution of each principal dinocyst species, using Canonical Correspondence Analysis (CCA). Analyses were based on the natural logarithm (Ln) of the relative abundances of dinocyst taxa. Morphologically similar species were grouped together (Table 2.2). *Scrippsiella* cf. *S. crystallina* was not taken into account, given that this dinocyst is not included in the GEOTOP database used for paleoceanographic reconstructions.

The free software ZONE, created by Stephen Juggins (<http://www.staff.ncl.ac.uk/staff/stephen.juggins/software.htm>), was used to statistically determine the dinoflagellate cyst assemblages in the surface sediments from the fjords. The method of Unweighted Least Squares Analysis (SPLITLISQ) with the calculation of a Euclidian distance was performed to identify assemblages, based on the relative abundance of the species (excluding *Scrippsiella* cf. *S. crystallina* from the sum) (Richerol et al., 2008b).

2.3.6. Environmental data

The hydrological data collected during the ArcticNet campaign represent a snapshot of the environmental conditions in the fjords that is limited in time. In order to obtain a multi-year representation of conditions, we used data available from the National Oceanic and Atmospheric Administration (NOAA) for summer sea-surface salinity and temperature from 1900 to 2001, as well as data on the summer sea-surface temperature 2000-2010 from the National Aeronautics and Space Administration (NASA) using the Moderate Resolution Imaging Spectroradiometer (MODIS) and the Sea-viewing Wide Field-of-view Sensor (SeaWiFS). Data on the ice cover duration 2000-2007 were retrieved from the

National Climate Data Center in Boulder (NCDC). We also used MODIS and SeaWiFS to obtain data on the annual PAR 2000-2010. Data about the nutrients (nitrates, nitrites, silicates, phosphates: 2006, 2007, 2009, 2010) in the water column and the concentration of diatoms (2006, 2009, 2010) were acquired during the corresponding CCGS Amundsen cruises (Brown, pers. comm.). These data provide annual averages of environmental conditions, thus the impact of the interannual variability in the area is reduced (de Vernal et al. 2001, 2005) (Table 2.1).

2.4. Results and Discussion

In 2009, the concentration of dinocysts in the sediments varied between 1,000 and 6,000 cysts g^{-1} in the Nunatsiavut fjords. We observed two trends in these concentrations: a local trend with an increase from the inner toward the outer part of the fjords, and a regional trend showing an increase from north to south (Figure 2.3). In 2010, we observed the same regional trend with an important overall increase of productivity by ~ 2 orders of magnitude between 2009 and 2010. This increase could be the result of the integration of several years of productivity in the surface sediments (Howe et al., 2010). However, an increase in productivity has been confirmed by the analyses of the phytoplankton community in the water column of the fjords in 2006, 2009 and 2010 (Brown, pers. comm.).

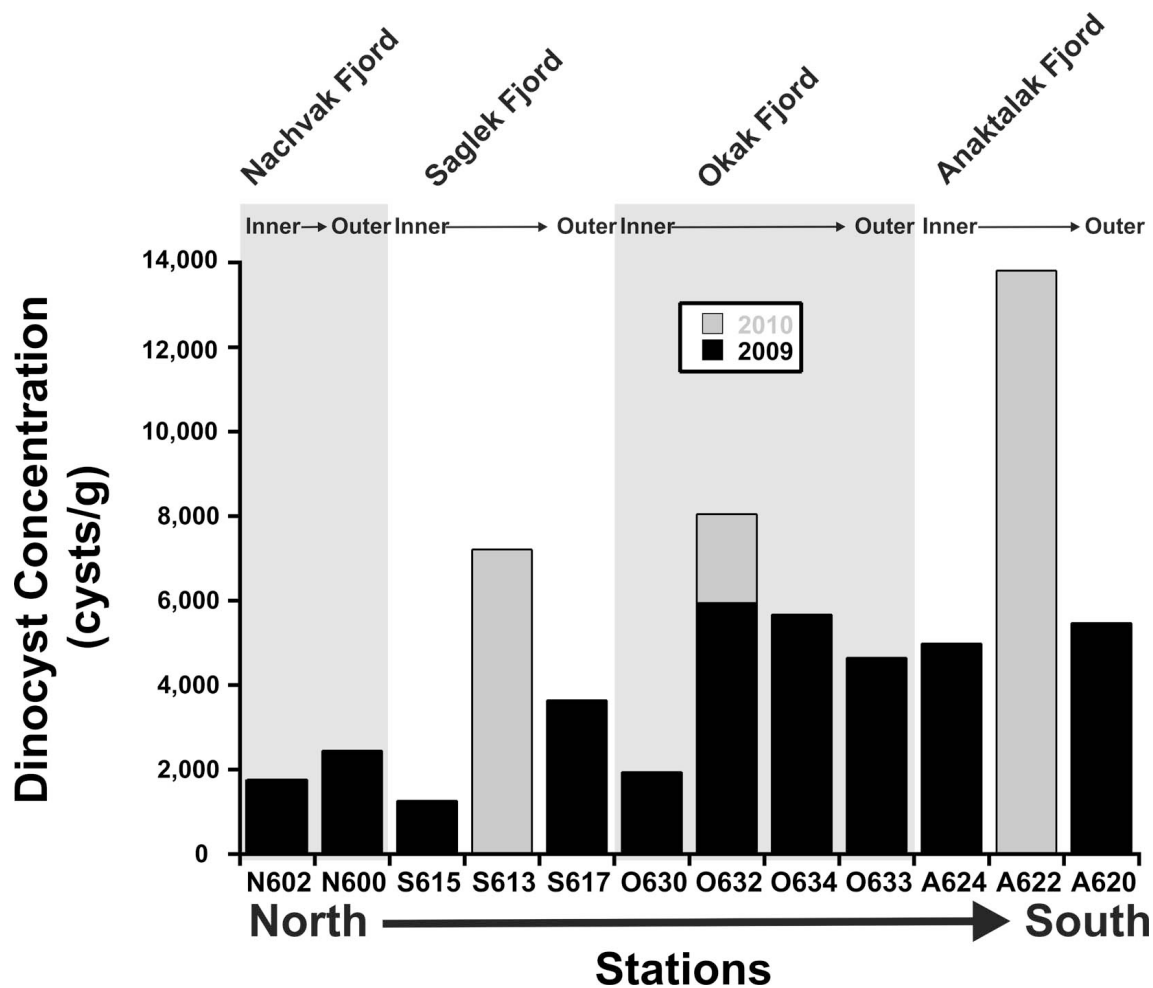


Figure 2.3: Latitudinal distribution of the total concentration of dinocysts (cysts g^{-1}) in the fjords.

A total of 16 different dinocyst taxa were identified in the samples (Table 2.2). These taxa can be divided into three categories: cysts from heterotrophic dinoflagellates, cysts from autotrophic dinoflagellates and cysts of the calcareous dinoflagellate species *Scrippsiella* cf. *S. crystallina*. Recent studies have shown that some autotrophic dinoflagellates are also able to feed on other microorganisms (diatoms, ciliates, cyanobacteria, bacteria, other dinoflagellates) and are in fact mixotrophs (Jacobson and Anderson, 1996; Jeong et al., 2005a, 2008, 2010a,b; Burkholder et al., 2008; Hansen, 2011). The feeding behavior of the autotrophic species depends on their response to the underwater light conditions in the ecosystem. For example some species switch to a heterotrophic feeding mode to supply their growth in case there is not enough or too much irradiance (Hansen, 2011). Several heterotrophic dinoflagellates have been reported to feed on the blood, flesh, eggs, or early naupliar stages and adult forms of metazoans (Jeong, 1994; Jeong et al., 2007). Other mixotrophic and heterotrophic dinoflagellates are able to feed on toxic algae, which could be beneficial in the eco-management of harmful algal blooms (Jeong et al., 2003, 2005b). Due to their high abundance, both mixotrophic and heterotrophic dinoflagellates, have been shown to play an important role in the trophic chain of marine environments (Lessard and Swift, 1985; Jeong, 1999; Jeong et al., 2010b).

Within the heterotrophic taxa category, we found species belonging to 6 different genera. *Islandinium minutum* s.l. (*Islandinium minutum*, *I. minutum* var. *cezare*, *I. brevispinosum*) and *Echinidinium karaense* are taxa characteristic of polar/subpolar regions, associated with cold to subarctic waters seasonally covered with sea-ice. Their maximum abundance is found in waters covered by sea-ice 8-12 months year⁻¹ (Rochon et al., 1999; Head et al., 2001; Marret and Zonneveld, 2003). *Brigantedinium* spp. (*Brigantedinium* sp., *B. cariacense*, *B. simplex*) is a cosmopolitan and opportunistic group of taxa whose distribution is largely controlled by nutrients (i.e. : nitrates, nitrites, silicates, phosphates) and prey availability (i.e.: small diatoms, ice algae, dinoflagellates and ciliates) (Rochon et al., 1999; Marret and Zonneveld, 2003). *Brigantedinium* spp. are often

associated with *I. minutum* s.l. and *E. karaense* in polar regions, and their distribution seems to be driven more by prey or nutrient availability than physical parameters like temperature, salinity or sea-ice cover (Head et al., 2001). In polynyas (seasonally fixed ice-free areas of the Arctic during winter and spring) an increase in the abundance of *Brigantedinium* spp. relative to a decrease of the abundance of *I. minutum* s.l. has been observed (Rochon et al., 1999; Richerol et al., 2008a; Grøsfjeld et al., 2009). *Protoperidinium americanum* is a taxon distributed within a broad temperature range and with high relative abundance in regions where mesotrophic to eutrophic, fully marine conditions prevail in the water column. It can also be characteristic of upwelling areas (Rochon et al., 1999). *Selenopemphix quanta*, although quite scarce in arctic regions, has a wide range of temperature and salinity tolerance, but tends to indicate warmer rather than colder conditions (Rochon et al., 1999; Marret and Zonneveld, 2003). However, *S. quanta* also shows a preference for the temperate to subpolar domain (de Vernal et al., 2001). It can also be an indicator for highly productive areas (Dale and Fjellså, 1994; Devillers and de Vernal, 2000). *Polykrikos* Arctic Morphotypes I and II were observed almost exclusively in shelf environments of the Canadian Arctic and Laptev and Kara seas (de Vernal et al., 2001), but they can also be found in subarctic regions like Hudson Bay (Marret and Zonneveld, 2003).

Within the autotrophic taxa category we found species belonging to 3 genera. *Pentapharsodinium dalei* can be considered a cosmopolitan species forming a prominent part of the dinoflagellate cyst associations in the Northern Hemisphere (Rochon et al., 1999; Marret and Zonneveld, 2003). It occurs in a wide range of conditions with respect to temperature, salinity and sea-ice (de Vernal et al., 2001), and has been reported to occur in high amounts in fjords and embayments of the western and eastern North Atlantic and adjacent seas (Marret and Zonneveld, 2003; Howe et al., 2010). *Spiniferites ramosus* is associated with temperate to subarctic water masses of both neritic and oceanic domains (Rochon et al., 1999; Marret and Zonneveld, 2003). The distribution of this taxon appears to have its northernmost limit occurring around latitude 70°N. The light intensity rather than the temperature could be a limiting factor for *S. ramosus* (Rochon et al.,

1999), as well as the nitrate concentration (Devillers and de Vernal, 2000). *Spiniferites elongatus/frigidus* (*Spiniferites elongatus* and *Spiniferites frigidus*) are ubiquitous in middle to high latitudes, but shows some preference for open oceanic environments in the temperate to subpolar domains (Rochon et al., 1999; de Vernal et al., 2001). They show great abundance in dinocyst assemblages of areas characterized by eutrophic surface water conditions (Marret and Zonneveld, 2003). The morphological gradient between *S. frigidus* and *S. elongatus* (the development of the septae) seems to reflect a gradient of temperature tolerance: *S. frigidus* can be associated with cold temperatures ranging from -1°C to 4°C and salinity ~29, whereas *S. elongatus* can be associated with cool to temperate conditions (Rochon et al., 1999).

In four stations from Okak Fjord (O632 and O634) and from Anaktalak Fjord (A620 and A624), the cyst of the calcareous dinoflagellate species *Scrippsiella* cf. *S. crystallina* appeared in high numbers in the surface sediments. This species was first described in 1991 from the sediments of a sea-loch in Scotland (Kapraun and Dutcher, 1991). It belongs to the family Peridiniaceae, and the subfamily Calciodinelloideae. The dinoflagellates of this subfamily are commonly found in tropical to temperate coastal and oceanic waters, whereas their presence is rather scarce in the sediments of arctic and subarctic marine waters (Head et al., 2006). The cyst has a granular content and a red accumulation body (Plate 2.1). So far, all living specimens examined are marine and presumably autotrophic (Montresor et al., 1993, 1997, 1998). A characteristic feature of this subfamily is the production of a calcareous cyst within its life cycle (Head et al., 2006), except for *P. dalei*, which produces an organic-walled cyst (Indelicato and Loeblich, 1986; Montresor et al., 1993). The *Scrippsiella* species are known to be associated with *Alexandrium* species, which can be responsible for toxic blooms (Vila and Masó, 2005 ; Vila et al., 2005). Although we did not find any *Alexandrium* cysts in our samples, the presence of *Scrippsiella* cysts north of their usual geographic distribution, in semi-enclosed areas like Okak Bay or Anaktalak Fjord, could be related to anoxia in the sediments or to human-related pollution (Satta et al., 2010). The analyses of the phytoplankton samples collected in the water column of the fjords in 2006, 2009

and 2010 never revealed any sign of *Alexandrium* spp. However in 2009 a large amount of *Scrippsiella* spp. was observed in Anaktalak Fjord (A624) (Brown, pers. comm.).

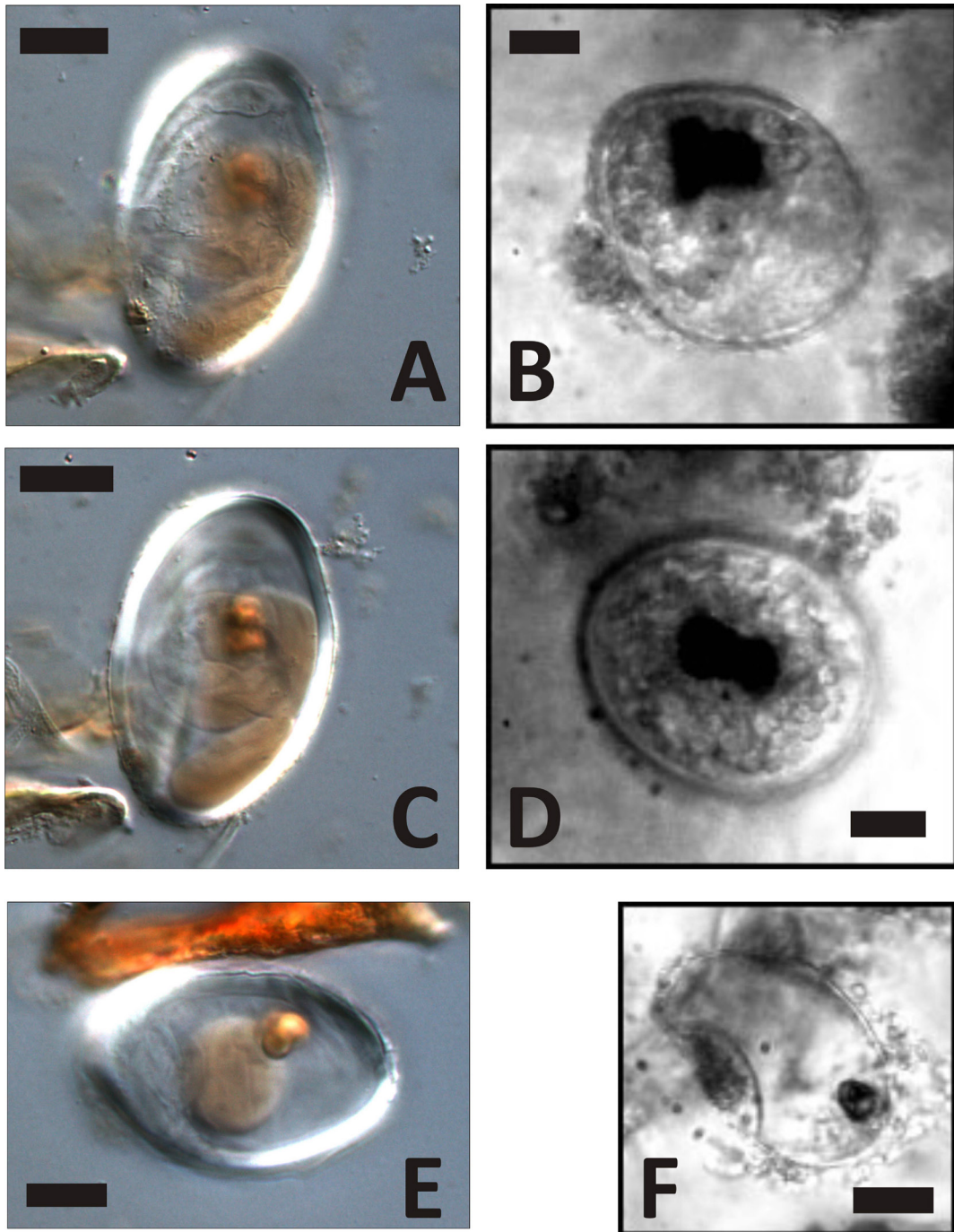


Plate 2.1: Each scale bar represents 10 μm . A/C. *Scrippsiella* cf. *S. crystallina* station Okak-634, observed after chemical treatment using transmitted-light microscopy at 100x. B/D. *Scrippsiella* cf. *S. crystallina* station Okak-634, observed before chemical treatment with an inverse microscope at 40x. E. *Scrippsiella* cf. *S. crystallina* station Anaktalak-624, observed after chemical treatment using transmitted-light microscopy at 100x. F. *Scrippsiella* cf. *S. crystallina* station Anaktalak-624, observed before chemical treatment with an inverse microscope at 40x.

A clear difference in assemblage composition is observed between the northernmost (Nachvak and Saglek) and the southernmost (Okak and Anaktalak) fjords. In Nachvak and Saglek fjords, more than 95% of the total dinocyst assemblage (Table 2.3 and Figures 2.4, 2.5) was composed of four heterotrophic dinocyst taxa, including *I. minutum*, *I. minutum* var. *cezare*, *I. brevispinosum* and *Brigantedinium* spp. In Okak and Anaktalak fjords, cysts from autotrophic dinoflagellates are dominant (Table 2.3 and Figures 2.4, 2.5). Mostly seven taxa made up more than 95% of the total dinocyst counts in these fjords: *P. dalei*, *S. ramosus*, *I. minutum*, *I. minutum* var. *cezare*, *I. brevispinosum*, *Brigantedinium* spp. and *S. quanta*.

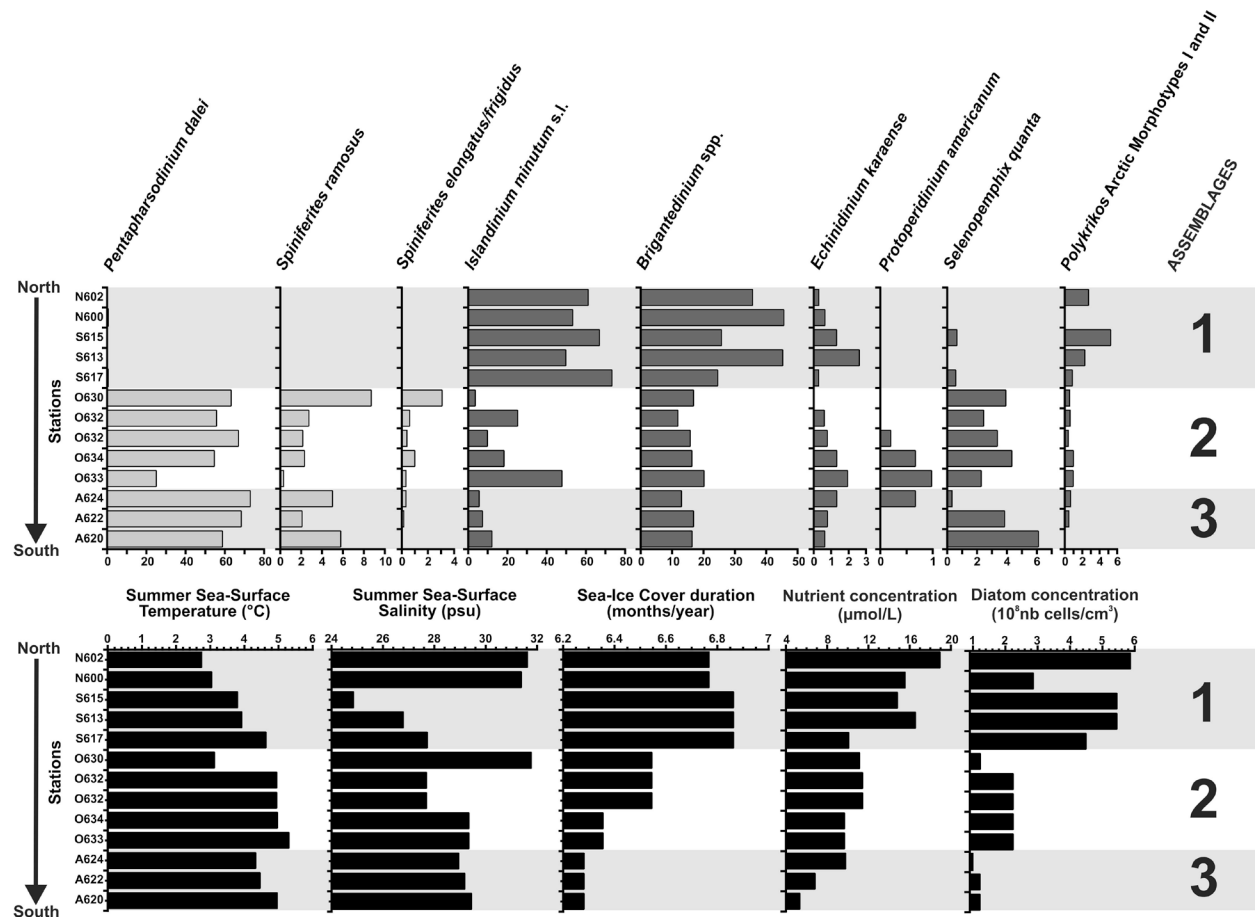


Figure 2.4: Relative abundance of major dinocyst taxa, hydrographic parameters (temperature, salinity, sea-ice cover, nutrients and diatoms) and statistical assemblages of dinocysts.

Statistically we were able to distinguish three assemblages in the fjords, from north to south (Figure 2.4). The first assemblage regroups the two northernmost fjords Nachvak and Saglek and is characterized by a dominance of *I. minutum* s.l. and *Brigantedinium* spp., and the maximum abundance of *Polykrikos* Arctic Morphotypes I and II. The second assemblage comprises samples from Okak Fjord and seems to be transitional between the northern and the southern fjords. Assemblage 2 is dominated by autotrophic dinoflagellate species (*P. dalei* and *S. ramosus*) but also has a relatively high abundance of the cysts belonging to heterotrophic species *P. americanum* and *S. quanta*. The third assemblage comprises samples from Anaktalak Fjord and is characterized by the dominance of cysts from autotrophic dinoflagellate species (*P. dalei* and *S. ramosus*) and the lower abundance of *I. minutum* s.l.

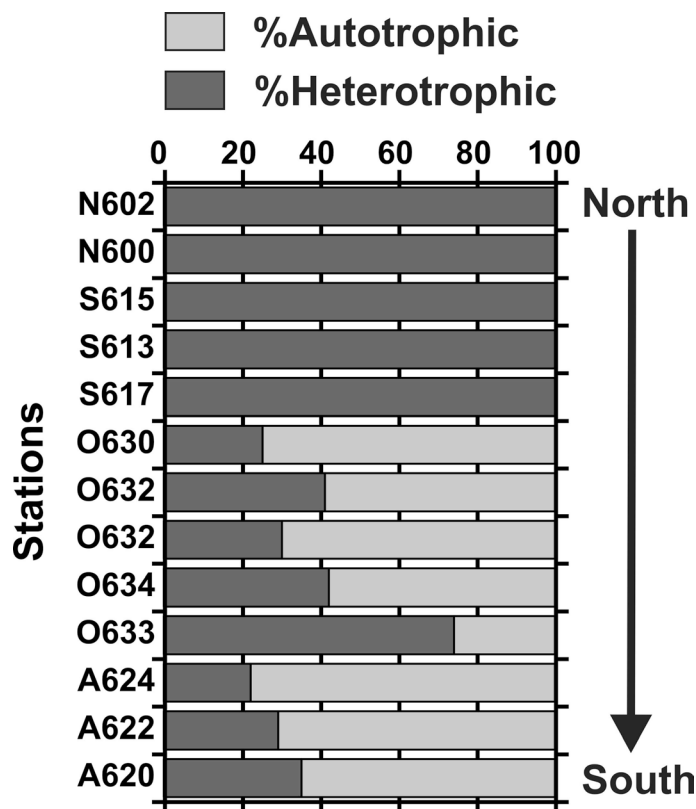


Figure 2.5: Latitudinal distribution of the relative abundance (%) of cysts from autotrophic and heterotrophic dinoflagellates in our samples.

The CCA analysis revealed that six environmental parameters, notably summer sea-surface temperature and salinity, sea-ice cover duration, PAR and food availability (nutrients and diatoms) play an important role in the distribution of most taxa (Figure 2.6). Most of the cysts from heterotrophic dinoflagellate taxa, such as *Brigantedinium* spp., *E. karaense* and *I. minutum* s.l. vary strongly in accordance with increases in the abundance of diatoms (abundance of prey for the motile form) and to a lesser extent with increases in sea-ice and nutrient contents. *Polykrikos* Arctic Morphotypes I and II are strongly linked to the variations in nutrients in the water column. *Selenopemphix quanta* seems to be driven essentially by the increase of temperature and salinity, with a slightest component of decreasing sea-ice, diatoms concentration and nutrients content. The cysts of autotrophic dinoflagellate taxa can be divided into two distinct groups. First, *P. dalei* seems to vary according to an increase in temperature and salinity and a decrease in sea-ice. Second, the *Spiniferites* species (*S. ramosus* and *Spiniferites elongatus/frigidus*) display distribution patterns that reflect controls by decreasing PAR, and a component of decreasing nutrients for *S. ramosus* (Devillers and de Vernal, 2000).

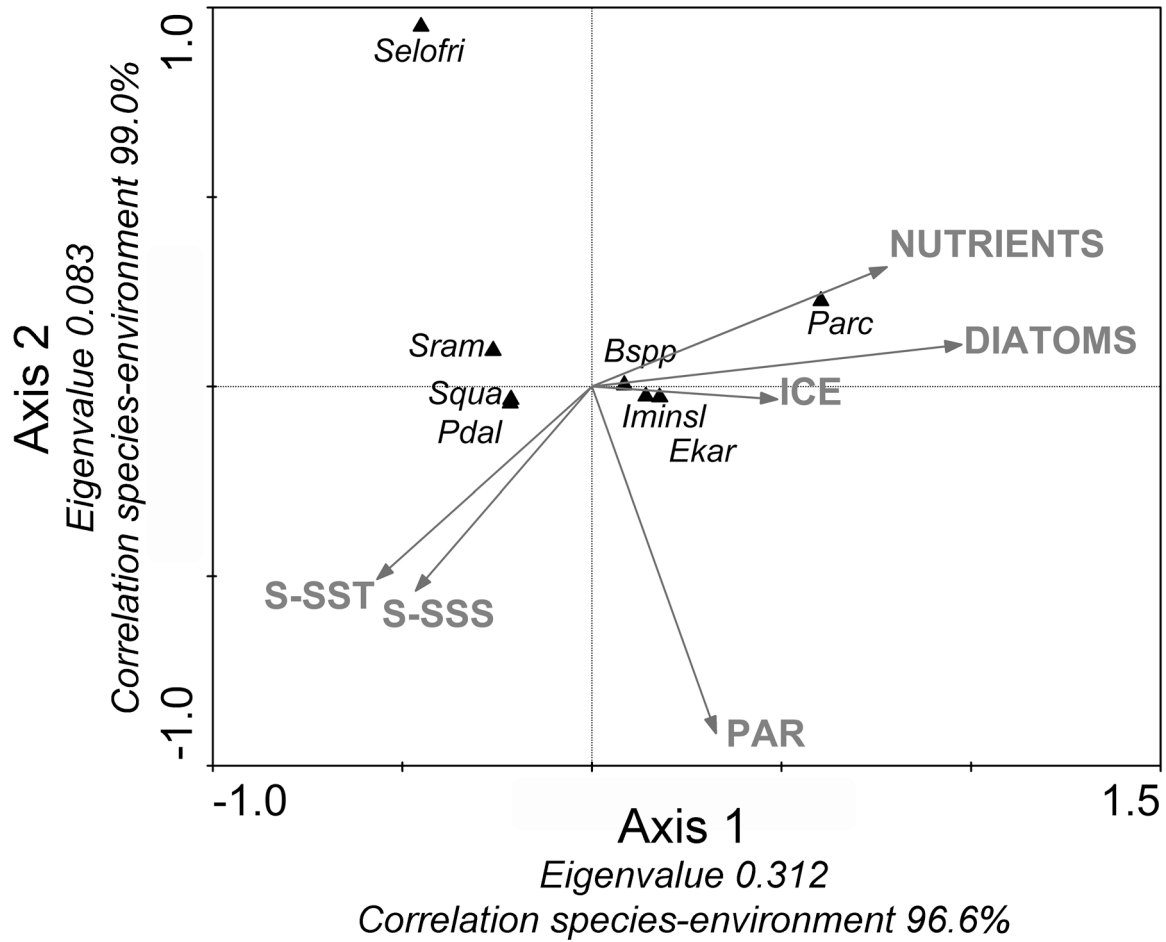


Figure 2.6: Graph of the Canonical Correspondence Analysis (CCA) between the dinocyst species and six parameters : S-SST=summer sea-surface temperature; S-SSS=summer sea-surface salinity; ICE=sea-ice cover duration; PAR=photosynthetically available radiation; NUTRIENTS=average concentration of nitrates, nitrites, silicates and phosphates in the water column; DIATOMS=average concentration of diatoms in the water column. See Table 2 for the codenames of the dinocysts species.

The only fjords from the Canadian west coast where assemblages of dinocysts were studied show significant differences in composition and diversity (Kumar and Patterson, 2002). Many fjords from the west coast of Canada do not undergo any renewal of water and are therefore anoxic like Effingham Inlet (Kumar and Patterson, 2002; Hay et al., 2003; Patterson et al., 2011). Indeed, all fjords of eastern Canada share a common characteristic, such as the complete water renewal below the sill, with a frequency specific to each fjord and depending on the depth of the sill and the currents (Gilbert, 1983). Assemblages of dinocysts similar to those found in our Nunatsiavut fjord sites can be found in sediments from arctic fjords in Svalbard (Grøsfjeld et al., 2009; Howe et al., 2010). According to these studies, a strong dominance of *I. minutum* seems to be characteristic of arctic assemblages (Matthiessen et al., 2005) and associated with cold polar waters. The significant abundance of *S. quanta* is interpreted as a flow of warmer Atlantic water, but can also indicate the availability of a particular food source (Howe et al., 2010) or a high productivity (Dale and Fjellså, 1994; Devillers and de Vernal, 2000). Furthermore, a high abundance of *P. dalei* can be related to a fjord being dominated by fully arctic conditions with water column stratification and high productivity (Howe et al., 2010) or to locations with large seasonal temperature gradients (Rochon et al., 1999).

In the case of the Labrador fjords, it seems unlikely that *S. quanta* is related to Atlantic water advection into the fjords, given that the Labrador Current maintains an effective barrier along the continental shelf (Iselin, 1930; Nutt, 1953; Nutt and Coachman, 1956, Yashayaev, 2007). However, according to Nutt (1953) and Yashayaev (2007) the Labrador Current is divided into two bands: the inner shelf band composed of arctic waters from Baffin Bay and Hudson Strait and the outer/slope band originating from the West Greenland/Irminger Current that is characterized by higher temperature and salinity. The bottom water (generally below 50 m) of the Labrador fjords is clearly identified as Labrador Current water of Arctic origin, and between 1953 and 2007 no West Greenland influence was noted in the inlets and fjords. Therefore, the presence of *S. quanta* may be interpreted as

related to the advection of water from Baffin Bay in the southern fjords, if not a particular food source. Paleoceanographic reconstructions in Okak Fjord should help confirm this hypothesis based on how long this species has been present in the fjord.

2.5. Conclusions

This study provides the first description of dinocyst assemblages in surface sediments in the Nunatsiavut fjords. With respect to the dinocyst concentrations, that likely reflect variations in productivity, two major trends can be observed. First, an increase in the concentration from the inner to the outer part of each fjord. Secondly, an increase in the concentration from the northern to the southern fjords. The dinocyst biodiversity also increases southward, with the occurrence and dominance of dinocyst of autotrophic dinoflagellate species in the two southernmost fjords.

The presence of the calcareous dinoflagellate species *Scrippsiella* cf. *S. crystallina* in the Anaktalak Bay, in proximity to the Vale Inco Nickel Mine, could be an indication of the pollution of fjord waters by the mine's effluents and/or a transport by ballast waters released from the ships that navigate the waters leading to the mine. Additional data are required to confirm these hypotheses.

We have determined the presence of three distinct dinocyst assemblages within the surface sediments of the Labrador fjords, that vary from north to south.

Assemblage 1 (Nachvak and Saglek fjords) is dominated by cysts of heterotrophic dinoflagellates strongly dependent on nutrient and prey availability. It seems to be characteristic of sea-ice driven fjords and arctic water conditions. Assemblage 2 (Okak Fjord) comprises cysts from autotrophic dinoflagellate taxa and has a comparatively greater abundance of protoperidinioid cysts such as *Protoperidinium americanum* and *Selenopemphix quanta*. This transitional assemblage is characteristic of a fjord less driven by the sea-ice conditions and more by the sea-surface salinity and temperature and following the latitudinal gradient of the nutrients. Assemblage 3 (Anaktalak Fjord) is composed exclusively of dinocysts belonging to autotrophic species. It appears to be controlled by sea-surface salinity, temperature and the irradiance. This fjord, which is the less arctic of the investigated fjords, shows the lowest abundance of *I. minutum* s.l.

Based on the analysis of 13 surface sediment samples, this study draws a first sketch of the linkages between the recorded dinocyst assemblages and the modern oceanographic conditions in the Nunatsiavut fjords, illustrating some interesting trends. Additional sampling from the inner parts of the fjords and along the coast of Nunatsiavut in the Labrador Sea is necessary to improve our understanding of these fragile and remote coastal ecosystems that are increasingly under pressure from human activities. The study has generated data on species-environment relationships that will be useful for future paleoceanographic investigations in the Labrador fjords.

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References

- Bell, T., Josenhans, H., 1997. The seismic record of glaciation in Nachvak Fiord, Northern Labrador. In: Davies, T. A., Bell, T., Cooper, A. K., Josenhans, H., Polyak, L., Solheim, A., Stoker, M. S., Stravers, J. A. (Eds.), *Glaciated Continental Margins: An Atlas of Acoustic Images*. Chapman & Hall, London UK, pp.190-193.
- Boessenkool, K.P., van Gelder, M.J., Brinkhuis, H., Troelstra, S.R., 2001. Distribution of organic-walled dinoflagellate cysts in surface sediments from transects across the Polar Front offshore southeast Greenland. *Journal of Quaternary Science* 16(7), 661-666.
- Burkholder, J. M., Glibert, P. M., Skelton, H. M., 2008. Mixotrophy, a major mode of nutrition for harmful algal species in eutrophic waters. *Harmful Algae* 8, 77-93.
- Dale, B., 1976. Cyst formation, sedimentation, and preservation: factors affecting dinoflagellate assemblages in recent sediments from Trondheimsfjord, Norway. *Review of Palaeobotany and Palynology* 22, 39-60.
- Dale, B., Fjellså, A., 1994. Dinoflagellate cysts as productivity indicators: state of the art, potential and limits. In: Zahn, R. (Ed.), *Carbon Cycling in the Glacial Ocean: Constraints in the Ocean's Role in Global Change*. Springer, Berlin, pp. 521–537.
- Dale, B., Thorsen, T. A., Fjellså, A., 1999. Dinoflagellate cysts as indicators of cultural eutrophication in the Oslofjord, Norway. *Estuarine, Coastal and Shelf Science* 48, 371-382.
- De Blij, H. J. (Ed.) 2005. *Atlas of North America*. Oxford University Press.
- de Vernal, A., Rosell-Melé, A., Kucera, M., Hillaire-Marcel, C., Eynaud, F., Weinelt, M., Dokken, T., Kageyama, M., 2006. Comparing proxies for the reconstruction of LGM sea-surface conditions in the northern North Atlantic. *Quaternary Science Reviews* 25, 2820-2834.
- de Vernal, A., Eynaud, F., Henry, M., Hillaire-Marcel, C., Londeix, L., Mangin, S., Matthiessen, J., Marret, F., Radi, T., Rochon, A., Solignac, S., Turon, J.-L., 2005. Reconstruction of sea-surface conditions at middle to high latitudes of the Northern Hemisphere during the Last Glacial Maximum (LGM) based on dinoflagellate cyst assemblages. *Quaternary Science Reviews* 24, 897-924.
- de Vernal, A., Henry, M., Matthiessen, J., Mudie, P.J., Rochon, A., Boessenkool, K.P., Eynaud, F., Grøsfjeld, K., Guiot, J., Hamel, D., Harland, R., Head, M.J., Kunz-Pirrung, M., Levac, E., Loucheur, V., Peyron, O., Pospelova, V., Radi, T., Turon, J.-L., Voronina, E., 2001. Dinoflagellate cyst assemblages as tracers of sea-surface conditions in the northern North Atlantic, Arctic and sub-Arctic seas : the new 'n=677' data base and its application for quantitative palaeoceanographic reconstruction. *Journal of Quaternary Science* 16(7), 681-698.
- Devillers, R., de Vernal, A., 2000. Distribution of dinoflagellate cysts in surface sediments of the northern North Atlantic in relation to nutrient content and productivity in surface waters. *Marine Geology* 166(1-4), 103-124.
- Dyke, A. S., Prest, V. K., 1987. Late Wisconsinan and Holocene history of the Laurentide Ice Sheet. *Geographie Physique et Quaternaire* 41(2), 237–263.
- Dyke, A. S., Andrews, J. T., Clark, P. U., England, J. H., Miller, G. H., Shaw, J., Veillette, J. J., 2002. The Laurentide and Inuitian ice sheets during the Last Glacial Maximum. *Quaternary Science Reviews* 21(1-3), 9-31.
- Engstrom, D. R., Hansen, B. C. S., 1985. Postglacial vegetational change and soil development in southeastern Labrador as inferred from pollen and chemical stratigraphy. *Canadian Journal of Botany* 63, 543-561.

- Fensome, R. A., Williams, G. L., 2004. The Lentin and Williams Index of Fossil Dinoflagellates. Contribution Series Number 42, American Association of Stratigraphic Palynologists Foundation, Dallas, TX.
- Gilbert, R., 1983. Sedimentary processes of Canadian Arctic fjords. *Sedimentary Geology* 36(2-4), 147-175.
- Godhe, A., Norén, F., Kuylenstierna, M., Ekberg, C., Karlson, B., 2001. Relationship between planktonic dinoflagellate abundance, cysts recovered in sediment traps and environmental factors in the Gullmar Fjord, Sweden. *Journal of Plankton Research* 23(9), 923-938.
- Grøsfjeld, K., Harland, R., 2001. Distribution of modern dinoflagellate cysts from inshore areas along the coast of southern Norway. *Journal of Quaternary Science* 16(7), 651-659.
- Grøsfjeld, K., Harland, R., Howe, J., 2009. Dinoflagellate cyst assemblages inshore and offshore Svalbard reflecting their modern hydrography and climate. *Norwegian Journal of Geology* 89, 121-134.
- Hald, M., Husum, K., Vorren, T. O., Grøsfjeld, K., Jensen, H. B., Sharapova, A., 2003. Holocene climate in the subarctic fjord Malangen, northern Norway: a multi-proxy study. *Boreas* 32(4), 543-559.
- Hansen, P. J., 2011. The role of photosynthesis and food uptake for the growth of marine mixotrophic dinoflagellates. *The Journal of Eukaryotic Microbiology* 58(3), 203-214.
- Hare, F. K., Hay, J. E., 1974. The climate of Canada and Alaska. In: Bryson, R. A., Hare, F. K. (Eds.), *World survey of climatology*, Vol. II. Elsevier Scientific Publishing Co., Amsterdam, pp. 49-192.
- Hay, M.B., Pienitz, R., Thomson, R. 2003. Distribution of diatom surface sediment assemblages within Effingham Inlet, a temperate fjord on the west coast of Vancouver Island (Canada). *Marine Micropaleontology* 48, 291-320.
- Head, M. J., Lewis, J., de Vernal, A., 2006. The cyst of the calcareous dinoflagellate *Scrippsiella trifida*: resolving the fossil record of its organic wall with that of *Alexandrium tamarense*. *Journal of Paleontology* 80(1), 1-18.
- Head, M. J., Harland, R., Matthiessen, J., 2001. Cold marine indicators of the late Quaternary: the new dinoflagellate cyst genus *Islandinium* and related morphotypes. *Journal of Quaternary Science* 16(7), 621-636.
- Howe, J. A., Harland, R., Cottier, F. R., Brand, T., Willis, K. J., Berge, J. R., Grøsfjeld, K., Eriksson, A., 2010. Dinoflagellate cysts as proxies for palaeoceanographic conditions in Arctic fjords. *Geological Society, London, Special Publication* 344, 61-74.
- Hulett, L., Dwyer, E., 2003. Voisey's Bay Environmental Assessment Challenges and Successes. PDAC Convention, Toronto, March 2003.
- Indelicato, S. R., Loeblich III, A. R., 1986. A revision of the marine peridinoid genera (*Pyrrhophyta*) utilizing hypothecal-cingular plate relationship as a taxonomic guideline. *Japanese Journal of Phycology* 34, 153-162.
- Iselin, C., 1930. A report on the coastal waters of Labrador, based on explorations of the «Chance» during the Summer of 1926. *Proceedings of the American Academy of Arts and Sciences* 66(1), 1-37.
- Jacobson, D. M., Anderson, D. M., 1996. Widespread phagocytosis of ciliates and other protists by marine mixotrophic and heterotrophic thecate dinoflagellates. *Journal of Phycology* 32, 279-285.
- Jeong, H. J., 1994. Predation by the heterotrophic dinoflagellate *Protoberidinium* cf. *divergens* on copepod eggs and early naupliar stages. *Marine Ecology Progress Series* 114, 203-208.

- Jeong, H. J., 1999. The ecological roles of heterotrophic dinoflagellates in marine planktonic community. *Journal of Eukaryotic Microbiology* 46(4), 390-396.
- Jeong, H. J., Park, K. H., Kim, J. S., Kang, H. J., Kim, C. H., Choi, H. J., Kim Y. S., Park, J. Y., Park, M. G., 2003. Reduction in the toxicity of the dinoflagellate *Gymnodinium catenatum* when fed on by the heterotrophic dinoflagellate *Polykrikos kofoidii*. *Aquatic Microbial Ecology* 31, 307-312.
- Jeong, H. J., Yoo, Y. D., Park, J. Y., Song, J. Y., Kim, S. T., Lee, S. H., Kim, K. Y., Yih, W. H., 2005a. Feeding by phototrophic red-tide dinoflagellates: five species newly revealed and six species previously known to be mixotrophic. *Aquatic Microbial Ecology* 40, 133-150.
- Jeong, H. J., Kim, J. S., Kim, J. H., Kim, S. T., Seong, K. A., Kim, T. H., Song, J. Y., Kim, S. K., 2005b. Feeding and grazing impact of the newly described heterotrophic dinoflagellate *Stoeckeria algicida* on the harmful alga *Heterosigma akashiwo*. *Marine Ecology Progress Series* 295, 69-78.
- Jeong, H. J., Ha, J. H., Yoo, Y. D. U., Park, J. Y., Kim, J. H., Kang, N. S., Kim, T. H., Kim, H. S., Yih, W. H., 2007. Feeding by the *Pfiesteria*-like heterotrophic dinoflagellate *Luciella masanensis*. *Journal of Eukaryotic Microbiology* 54(3), 231-241.
- Jeong, H. J., Seong, K. A., Yoo, Y. D., Kim, T. H., Kang, N. S., Kim, S., Park, J. Y., Kim, J. S., Kim, G. H., Song, J. Y., 2008. Feeding and grazing impact by small marine heterotrophic dinoflagellates on heterotrophic bacteria. *Journal of Eukaryotic Microbiology* 55(4), 271-288.
- Jeong, H. J., Yoo, Y. D., Kang, N. S., Rho, J. R., Seong, K. A., Park, J. W., Nam, G. S., Yih, W., 2010a. Ecology of *Gymnodinium aureolum* - I. Feeding in western Korean waters. *Aquatic Microbial Ecology* 59, 239-255.
- Jeong, H. J., Yoo, Y. D., Kim, J. S., Seong, K. A., Kang, N. S., Kim, T. H., 2010b. Growth, feeding and ecological roles of the mixotrophic and heterotrophic dinoflagellates in marine planktonic food webs. *Ocean Science Journal* 45(2), 65-91.
- Kahlmeyer, E., 2009. Comparisons of the sedimentary record in three sub-arctic fjord systems in Northern Labrador. Hons. Diss. (B.Sc.), Memorial University of Newfoundland, St. Johns.
- Kapraun, D. F., Dutcher, J. A., 1991. Cytophotometric estimation of inter- and intraspecific nuclear DNA content variation in *Gracilaria* and *Gracilariopsis* (Gracilariales, Rhodophyta). *Botanica Marina* 34, 139-144.
- Kumar, A., Patterson, R. T., 2002. Dinoflagellate cyst assemblages from Effingham Inlet, Vancouver Island, British Columbia, Canada. *Palaeogeography, Palaeoclimatology, Palaeoecology* 180, 187-206.
- Kunz-Pirrung, M., 2001. Dinoflagellate cyst assemblages in surface sediments of the Laptev Sea region (Arctic Ocean) and their relationship to hydrographic conditions. *Journal of Quaternary Science* 16(7), 637-649.
- Kuzyk, Z. A., Burgess, N. M., Stow, J. P., Fox, G. A., 2003. Biological effects of marine PCB contamination on Black Guillemot Nestlings at Saglek, Labrador : Liver Biomarkers. *Ecotoxicology* 12, 183-197.
- Kuzyk, Z. A., Hodson, P. V., Solomon, S. M., Reimer, K. J., 2005a. Biological responses to PCB exposure in shorthorn sculpin from Saglek Bay, Labrador. *Science of the Total Environment* 351-352, 285-300.
- Kuzyk, Z. A., Stow, J. P., Burgess, N. M., Solomon, S. M., Reimer, K. J., 2005b. PCBs in sediments and the coastal food web near a local contaminant source in Saglek Bay, Labrador. *Science of the Total Environment* 351-352, 264-284.
- Lamb, H. F., 1980. Late Quaternary vegetational history of southeastern Labrador. *Arctic and Alpine Research* 12, 117-135.

- Lessard, E. J., Swift, E., 1985. Species-specific grazing rates of heterotrophic dinoflagellates in oceanic waters, measured with a dual-label radioisotope technique. *Marine Biology* 87, 289-296.
- Marret, F., Zonneveld, K. A. F., 2003. Atlas of modern organic-walled dinoflagellate cyst distribution. *Review of Palaeobotany and Palynology* 125, 1-200.
- Matthiessen, J., de Vernal, A., Head, M., Okolodkov, Y., Zonneveld, K., Harland, R., 2005. Modern organic-walled dinoflagellate cysts in Arctic marine environments and their (paleo-) environmental significance. *Paläontologische Zeitschrift* 79(1), 3-51.
- Mertens, K. N., Verhoeven, K., Verleye, T., Louwe, S., Amorim, A., Ribeiro, S., Deaf, A. S., Harding, I. C., De Schepper, S., González, C., Kodrans-Nsiah, M., de Vernal, A., Henry, M., Radi, T., Dybkjaer, K., Poulsen, N. E., Feist-Burkhardt, S., Chitolie, J., Heilmann-Clausen, C., Londeix, L., Turon, J.-L., Marret, F., Matthiessen, J., McCarthy, F. M. G., Prasad, V., Pospelova, V., Kyffin Hughes, J. E., Riding, J. B., Rochon, A., Sangiorgi, F., Welters, N., Sinclair, N., Thun, C., Soliman, A., Van Nieuwenhove, N., Vink, A., Young, M., 2009. Determining the absolute abundance of dinoflagellate cysts in recent marine sediments : The *Lycopodium* marker-grain method put to the test. *Review of Palaeobotany and Palynology* 157, 238-252.
- Montresor, M., Zingone, A., Marino, D., 1993. The calcareous resting cyst of *Pentapharsodinium tyrrhenicum* comb. nov. (Dinophyceae). *Journal of Phycology* 29, 223-230.
- Montresor, M., Janofske, D., Willems, H., 1997. The cyst-theca relationship in *Calciodinellum operosum* emend. (Peridinales, Dinophyceae) and a new approach for the study of calcareous cysts. *Journal of Phycology* 33, 122-131.
- Montresor, M., Zingone, A., Sarno, D., 1998. Dinoflagellate cyst production at a coastal Mediterranean site. *Journal of Plankton Research* 20(12), 2291-2312.
- Mudie, P.J., Rochon, A., 2001. Distribution of dinoflagellate cysts in the Canadian Arctic marine region. *Journal of Quaternary Science* 16(7), 603-620.
- Noble, B. F., Bronson, J. E., 2005. Integrating human health into environmental impact assessment : case studies of Canada's Northern Mining Resource Sector. *Arctic* 58(4), 395-405.
- Nutt, D. C., 1953. Certain aspects of oceanography in the coastal waters of Labrador. *Journal of the Fisheries Research Board of Canada* 10(4), 177-186.
- Nutt, D. C., Coachman, L. K., 1956. The oceanography of Hebron Fjord, Labrador. *Journal of the Fisheries Research Board of Canada* 13(5), 709-758.
- Paterson, A. M., Betts-Piper, A. A., Smol, J. P., Zeeb, B. A., 2003. Diatom and chrysophyte algal response to long-term PCB contamination from a point-source in northern Labrador, Canada. *Water, Air, and Soil Pollution* 145, 377-393.
- Patterson, R. T., Swindles, G. T., Roe, H. M., Kumar, A., Prokoph, A., 2011. Dinoflagellate cyst-based reconstructions of mid to late-Holocene winter sea-surface temperature and productivity from an anoxic fjord in the NE Pacific Ocean. *Quaternary International* 235, 13-25.
- Pier, M. D., Betts-Piper, A. A., Knowlton, C. C., Zeeb, B. A. and Reimer, K. J., 2003. Redistribution of Polychlorinated Biphenyls from a local point source: terrestrial soil, freshwater sediment and vascular plants as indicators of the Halo Effect. *Arctic, Antarctic, and Alpine Research*, 35(3), 349-360.
- Radi, T. and de Vernal, A., 2008. Dinocysts as proxy of primary productivity in mid-high latitudes of the Northern Hemisphere. *Marine Micropaleontology*, 68, 84-114.
- Radi, T., de Vernal, A. and Peyron, O., 2001. Relationships between dinoflagellate cyst assemblages in surface sediment and hydrographic conditions in the Bering and Chukchi seas. *Journal of Quaternary Science*, 16(7), 667-680.

- Richerol, T., Rochon, A., Blasco, S., Scott, D. B., Schell, T. M. and Bennett, R. J., 2008a. Distribution of dinoflagellate cysts in surface sediments of the Mackenzie Shelf and Amundsen Gulf, Beaufort Sea (Canada). *Journal of Marine Systems*, 74, 825-839.
- Richerol, T., Rochon, A., Blasco, S., Scott, D. B., Schell, T. M. and Bennett, R. J., 2008b. Evolution of paleo sea-surface conditions over the last 600 years in the Mackenzie Trough, Beaufort Sea (Canada). *Marine Micropaleontology*, 68, 6-20.
- Rochon, A., de Vernal, A., Turon, J.-L., Matthiessen, J. and Head, M.J., 1999. Distribution of recent dinoflagellate cysts in surface sediments from the North Atlantic Ocean and adjacent seas in relation to sea-surface parameters. Contribution Series Number 35, American Association of Stratigraphic Palynologists Foundation: Dallas, TX; 152pp.
- Rompkey, B., 2003. *The Story of Labrador*. McGill-Queen's University Press, Montréal-Kingston, QC-ON; 195pp.
- Roncaglia, L. and Kuijpers, A., 2004. Palynofacies analysis and organic-walled dinoflagellate cysts in late-Holocene sediments from Igaliku Fjord, South Greenland. *The Holocene*, 14(2), 172-184.
- Satta, C. T., Anglès, S., Garcés, E., Lugliè, A., Padedda, B. M. and Sechi, N., 2010. Dinoflagellate cysts in recent sediments from two semi-enclosed areas of the Western Mediterranean Sea subject to high human impact. *Deep-Sea Research II: Topical Studies in Oceanography*, 57(3-4), 256-267.
- Short, S. K. and Nichols, H., 1977. Holocene pollen diagrams from subarctic Labrador-Ungava : Vegetational history and climatic change. *Arctic and Alpine Research*, 9, 265-290.
- Taylor, F. J. R., Hoppenrath, M. and Saldarriaga, J. F., 2008. Dinoflagellate diversity and distribution. *Biodiversity and Conservation*, 17(2), 407-418.
- Ter Braak, C. J. F. and Šmilauer, P., 2002. *CANOCO Reference Manual and CanoDraw for Windows Users's Guide: Software for Canonical Community Ordination (version 4.5)*. Wageningen University and Research Center Publication, Netherlands, ER.
- Thorsen, T. A. and Dale, B., 1997. Dinoflagellate cysts as indicators of pollution and past climate in a Norwegian fjord. *The Holocene*, 7(4), 433-446.
- Ullah, W., Beersing, A., Blouin, A., Wood, C. H. and Rodgers, A., 1992. *Water Resources Atlas of Newfoundland*. Water Resources Division - Department of Environment and Lands - Government of Newfoundland and Labrador, pages ii-80.
- Vila, M. and Masó, M., 2005. Phytoplankton functional groups and harmful algal species in anthropogenically impacted waters of the NW Mediterranean Sea. *Scientia Marina*, 69(1), 31-45.
- Vila, M., Giacobbe, M. G., Masó, M., Gangemi, E., Penna, A., Sampedro, N., Azzaro, F., Camp, J. and Galluzzi, L., 2005. A comparative study on recurrent blooms of *Alexandrium minutum* in two Mediterranean coastal areas. *Harmful Algae*, 4, 673-695.
- Voronina, E., Polyak, L., de Vernal, A. and Peyron, O., 2001. Holocene variations of sea-surface conditions in the southeastern Barents Sea, reconstructed from dinoflagellate cyst assemblages. *Journal of Quaternary Science*, 16(7), 717-726.
- Yashayaev, I., 2007. Hydrographic changes in the Labrador Sea, 1960-2005. *Progress in Oceanography*, 73(3-4), 242-276.