**Biogeosciences Discussions**

# Quantitative reconstruction of sea-surface conditions over the last ~150 yr in the Beaufort Sea based on dinoflagellate cyst assemblages: the role of large-scale atmospheric circulation patterns

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# Abstract

Dinoflagellate cyst (dinocyst) assemblages have been widely used over the Arctic Ocean to reconstruct sea-surface parameters on a quantitative basis. Such reconstructions provide insights into the role of anthropogenic vs natural forcings in the actual climatic trend. Here, we present the palynological analysis of a 36 cm-long core collected from the Mackenzie Through in the Canadian Beaufort Sea. Dinocyst assemblages were used to quantitatively reconstruct the evolution of sea surface conditions (temperature, salinity, sea ice) and freshwater palynomorphs influxes were used as local paleo-river discharge indicators over the last ∼ 150 yr. Dinocyst assemblages are dominated by autotrophic taxa (68 to 96 %). *Pentapharsodinium dalei* is the dominant specie throughout most of the core, except at the top where the assemblages are dominated by *Operculodinium centrocarpum*. Quantitative reconstructions of sea surface parameters display a serie of relatively warm, lower sea ice and saline episodes in surface waters, alternately with relatively cool and low salinity episodes. The warm episodes are characterized with high dinocyst productivity. Variations of dinocyst influxes and reconstructed sea surface conditions are closely linked to large scale atmospheric circulation patterns such as the Pacific Decadal Oscillation (PDO) and to a lesser degree, the Arctic Oscillation (AO). Positive phases of the PDO correspond to increases of dinocyst influxes, warmer and saltier surface waters, which we associate with upwelling events of warm and relatively saline water from Pacific origin. Freshwater palynomorph influxes increased in three phases from AD 1857 until reaching maximum values in AD 1991, suggesting that the Mackenzie River discharge followed the same trend when its discharge peaked between AD 1989 and AD 1992. The PDO mode seems to dominate the climatic variations at multi-annual to decadal timescales in the Western Canadian Arctic and Beaufort Sea areas.

## 1 Introduction

Recent observations revealed that the Arctic is experiencing a climatic warming at a rate nearly twice of the global average during the past decades (e.g., IPCC, 2001, 2007; McBean, 2005; Hassol, 2004). Most of the climate variability over the Arctic has been associated with change in the phase of large scale atmospheric patterns such as the Arctic Oscillation (AO) or the Pacific Decadal Oscillation (PDO) (Niebauer and Day 1989; Macdonald et al., 2005; Overland et al., 1999; Thompson and Wallace, 1998), which are both important natural patterns in global climate variability. Unfortunately, the lack of long-term observations in the Arctic makes it impossible to reach any definitive conclusion concerning the impacts climatic oscillations in Arctic regions (e.g., Polyakov et al., 2002). In this context, paleoceanographic studies at high temporal resolution (i.e. multi-annual to decadal scales) were recently solicited in order to acquire a better knowledge about past and actual climate affecting high latitudes. Previous paleoceanographic studies have actually shown a relative importance of the Arctic Oscillation in the Southern Beaufort Sea during the Holocene (e.g., Bringué et al., 2012; Ledu et al., 2010). The Arctic Oscillation is a multi-year run of positive and negative values index reflecting anomalies in the strength of the circumpolar vortex, which is well-correlated with the interannual and decadal time scale variability in the Arctic (Thompson and Wallace, 1998). However, the actual understanding of natural variability versus the anthropogenic warming contribution, essentially based on past observations with both proxy and instrumental records still needs to be better documented at accurate temporal scales. In this paper, we present quantitative multi-year resolution (3–5 yr) reconstructions of sea-surface conditions based on dinocyst assemblages preserved in the Beaufort Sea sediments. The sediment core was collected as part of the Malina Program (http://www.obs-vlfr.fr/Malina) in an attempt to provide a paleoenvironmental perspective on the recent climatic evolution in the Beaufort Sea coastal region, which has experienced a drastic reduction of both area and thickness of sea-ice cover (SIC) over the last few decades (Baber and Hanesiak, 2004).

Dinoflagellate cyst (dinocyst) assemblages were used as proxy indicators to document the quantitative evolution of sea-surface conditions. Dinoflagellates are unicellular protists, some of which will produce a cyst as part of their life cycle to avoid adverse conditions (e.g. winter), and will return to their planktonic form the following season.

⁵ They can be found in most marine sediments because of the composition of their highly resistant organic membrane, and despite extremely cold conditions (e.g., Harland and Pudsey, 1999; de Vernal et al., 2001). Dinocysts are particularly useful microfossils in high latitudes because they are especially sensitive to sea-surface conditions in Arctic and sub-Arctic areas (e.g., Kunz-Pirrung, 2001; Matthiessen et al., 2005; Mudie and

¹⁰ Rochon 2001; Radi et al., 2001; de Vernal et al., 2001, 2005). Furthermore, dinocysts are well preserved, especially in environments like the Mackenzie Trough where sediment accumulation rates are high, which prevent oxidation.

## 2 Study area

The Mackenzie Shelf is a 120 km wide and 530 km length area, representing approxi-
¹⁵ mately $6.0 \times 10^4$ km$^2$ (Carmack et al., 2004). It is located between the Mackenzie Trough to the west and the Amundsen Gulf to the East (Fig. 1), and the water column is characterized by local water masses, as well as from Pacific origin. Atlantic water is also present at depth below 200 m. Sea-ice is generally present between mid-October and the end of May (Wang et al., 2005; O'Brien et al., 2006). Among others, the Beau-
²⁰ fort Shelf surface circulation is strongly influenced by ice, winds and freshwater input resulting from river discharge and sea-ice melt.The water column at the core location is composed of 3 layers: the upper polar mixed layer (salinity < 28), the relatively cold lower Polar Mixed Layer (20–50 m, salinity of 28 to 30.7) (Matsuoka et al., 2011) and the nutrient-rich relatively warm and salty Bering Summer Water below 50 m (with
²⁵ a salinity of ∼ 31) (Carmack et al., 1989; Carmack and Macdonald, 2002; Macdonald et al., 1987) composed in part by the Alaskan Coastal Water (Steele et al., 2004). The upper polar mixed layer is a combination of surrounding sea ice melt, Mackenzie

River discharge, but also other processed waters (from Pacific and/or Atlantic). In this layer, primary production usually responds to nutrient inputs. Intense turbidity due to the Mackenzie plume between May and September and the absence of nutrients limit primary production, but a chlorophyll *a* maximum is found near 20–60 m depth (Martin
5   et al., 2010). Offshore, the Beaufort Gyre flows clockwise while, closer to shore, the relatively warm Alaskan Coastal Current (Fig. 1) (Aagaard, 1984; Coachman et al., 1975) flows eastward throughout the year (Nickolopoulos et al., 2009) transporting the Alaskan Coastal Waters, which composed a part of the halocline of the water column in the study area (Aaagard, 1984; Melling, 1998).
10   The Mackenzie River is the fourth largest Arctic river in term of freshwater discharge but the first in term of sediment discharge, which represents annually 127 Mt of sediments, and largely influenced by an ice cover, winds and currents (Macdonald et al., 1998). Closer to shore, the Mackenzie River freshwater inputs form a large plume (Fig. 1), dominant at the surface during summer time, which distributes water prop-
15   erties of the river over the Beaufort Sea surface layer (Macdonnald et al., 2002). The Mackenzie River plume is typically 2–3 m thick and there is a strong vertical structure and horizontal currents in surface waters. It follows westward coastal winds toward the Mackenzie Trough and eastward surface current to the Canadian Archipelago (Carmack and Macdonald, 2002). The Mackenzie shelf receives 249–333 km$^3$ of freshwater
20   annually (Dittmar and Kattner, 2003), usually during May–September period (Macdonald et al., 1998). It is generally accompanied by an important terrigenous sediment discharge (O'Brien et al., 2006), but reduced in winter near the coast, underneath the land fast ice (Macdonald et al.,1995). Coastal erosion represents around 7 Mt yr$^{-1}$ over the shelf (Macdonald et al., 2002.) depending on Mackenzie River flow intensity and
25   storms.
   The Mackenzie River drainage basin covers a large part of Western Canada, around 1.8 × 10$^6$ km$^2$ (Abdul Aziz and Burn, 2006; Hill et al., 2001; Wang et al., 2005), delimited by the west flank of the Rocky and Mackenzie Mountains. Highest sediment accumulation rates are found in the Mackenzie Trough and the nearby continental slope (Hill

et al., 1991; Macdonald et al., 1998). The main part of the Mackenzie Trough is composed of silty sediments, while the nearby shelf is mostly characterized by silt and sand (Blasco et al., 1990; Hill 1996). The morphology of the Mackenzie Trough, together with strong winds and ice dynamics, can cause upwelling of the warmer and
5  saltier Pacific halocline (Aagaard, 1984). These conditions occur over the trough, shelf areas, along the slope, and many were observed over the last 4 decades (Carmack et al., 1989, 2004; Iseki et al., 1987; Kulikov et al., 1998; Macdonnald et al., 1987; Williams et al., 2006). Periods with no upwelling conditions are characterized by relatively lower sea-surface primary production (Macdonald et al., 2002). Both ice-motion
10 and ice-free conditions allow the development of upwelling events, which are observed in both winter and summer seasons.

## 3  Material and methods

### 3.1  Sampling and preparations

The 36 cm-long core MA680BC (69°36′15″ N, 138°13′34″ W) studied here was col-
15 lected during the 2009 Malina sampling campaign onboard the *CCGS Amundsen* with a Box Corer at 56 m water depth (Fig. 1). The core was sub-sampled at 1 cm intervals and treated using standardized palynological procedures (e.g., Rochon et al., 1999) involving chemical treatments. To that end, 5 cm$^3$ of sediments were collected by water displacement and a tablet of makers grains (*Lycopodium clavatum*, University of
20 Lund, Sweden) with known concentration (12 100 spores ± 1892 spores/tablet, Batch no. 414831) were added to the sediments, allowing calculation of palynomorphs concentrations (Matthews, 1969). Sieving at 10 and 100 μm was performed in order to eliminate fine and coarse particles (< 10 μm and > 100 μm). This was followed by warm acid treatments using hydrochloric acid (HCl-10 %, 4 treatments) to dissolve the car-
25 bonated fraction alternating with hydrofluoric acid to dissolve the silicate fraction (HF-49 %, 3 treatments). A final sieving was realized (10 μm) to eliminate fine particles and

fluorosilicates formed during the chemical treatments. Finally, a drop of the remaining fraction was mounted on slides using glycerin gel.

## 3.2 Dinocysts counts

Slides were observed in transmitted-light microscopy (Leika, DM5500B) at 40× magnification. All palynomorphs (pollen, spores, dinoflagellate cysts, freshwater palynomorphs, organic foraminifera linings, acritarchs and pre-Quaternary palynomorphs) were counted systematically in each sample. A minimum of 300 dinocysts were counted to obtain a useful statistical representation of the dinoflagellate cyst populations. Relative abundances, calculated from the total dinocysts sum, were used to present dinocyst assemblages, and influxes were calculated using concentrations (cysts cm$^{-3}$) and the calculated sediment accumulation rates (specimens cm$^{-2}$ yr$^{-1}$). High sediment accumulation rates (0.23 to 0.32 cm yr$^{-1}$; Richerol et al., 2008) in the study area prevented oxidation of organic material within the core, including dinoflagellate cyst assemblages. The low oxidation level was evidenced by the excellent preservation of the most oxidation-sensitive taxa, such as those of the genus *Brigantedinium*.

## 3.3 MAT method – estimation of past sea surface conditions and taxonomy considerations

The reconstruction of past sea-surface conditions was done using the Modern Analogue Technique (MAT) (Guiot et al., 1990; Prell, 1985; de Vernal et al., 2001, 2005) with the statistical software R version 2.13.0 MAT is routinely used and particularly well-suited for the reconstruction of past sea-surface conditions in high-latitude environments (Guiot and de Vernal, 2007, 2011; Bonnet et al., 2010; Ledu et al., 2010). The MAT method is based on similarity between fossil dinocyst spectra and modern analogs from a large reference database (1429 sites). Modern sea-surface temperature (SST) and salinity (SSS) (at 10 m depth) are respectively from the World Ocean Atlas (NODC, 2001) and Arctinet 2009 data. Sea ice cover (SIC) data (number of months per year

with > 50 % of sea-ice coverage) are from the National Snow and Ice Data Center. Data of Mackenzie River discharge are from the Environment Canada website, and viewed with HYDAT software (ftp://arccf10.tor.ec.gc.ca/wsc/software/HYDAT/). Data of the AO and the PDO are from the National Oceanic and Atmospheric Administration (NOAA).

Dinocyst nomenclature follows that of Rochon et al. (1999), de Vernal et al. (2001), Head et al. (2001), Radi et al. (2001), Fensome and Williams (2004) and Radi et al. (2012). The following taxa are grouped together with *Islandinium minutum* because they often co-occur in samples and their individual ecologies are still unknown: *Islandinium brevispinosum* (Fig. 5i), *Echinidinium karaense* (Fig. 5k), *Echinidinium zonneveldiae*, *Echinidinium granulatum* and *Echinidinium*? sp. Z. *Spiniferites elongatus*, *S. frigidus* and intergraded morphotypes are also grouped together (cf. Rochon et al., 1999).

## 3.4 Palynomorphs counts

Other palynomorphs include pollen and spores, freshwater palynomorphs, which include *Pediastrum* (Fig. 5a), *Halodinium* (Fig. 5b) and spores of *Zygnema* (Fig. 5c), acritarchs and pre-Quaternary palynomorphs. All these palynomorphs were expressed with influxes (specimens $cm^{-2} yr^{-1}$). Freshwater palynomorphs are identified at the genus level and are used as indicators of freshwater input from the Mackenzie River. Acritarchs and pre-Quaternary palynomorphs, which include dinocysts, pollens grains and spores, are used as sediment reworking indicators.

## 3.5 Chronology

The chronological framework of core MA680BC was determined by ^{210}Pb and [226]Ra activities. The measurements of ^{210}Pb excess were made in the UMR5805 EPOC-OASU laboratory using the constant rate supply model (Appleby and Oldfield, 1978) in order to obtain sediment accumulation rates. The activity of ^{137}Cs was also used to validate the ^{210}Pb-based chronology, based on two markers (the Chernobyl accident

of 1986 and the maximum of thermonuclear weapon testing in 1963) showed by two peaks of $^{137}$Cs activity.

## 4 Results

### 4.1 Chronology

The 36-cm long core encompasses the last 154 yr and the age-depth model is based on a second order polynomial regression (Ledu et al., 2012). The calculated sediment accumulation rates range from 0.22 cm yr$^{-1}$ at the base of the core to 0.32 cm yr$^{-1}$ in the upper part of the sequence allowing for a multi-annual resolution of 3–4 yr throughout the record.

### 4.2 Palynomorphs influxes

Dinocysts concentrations varied between 700 and 2400 cysts cm$^{-3}$ (average 1500 cysts cm$^{-3}$) and are similar to those previously found in surface sediments from the Beaufort Shelf area (200–3100 cysts cm$^{-3}$) (Geotop dinocysts database, http://www.geotop.ca/). In the present study we are presenting dinocyst results as influx to better reflect changes in dinoflagellate primary productivity throughout the time period covered by our core. Dinocyst fluxes (Fig. 2a) vary between 200 and 1400 cysts cm$^{-2}$ yr$^{-1}$ (average 500 cysts cm$^{-2}$ yr$^{-1}$). From ~AD 1865–1930, fluxes increase gradually from 300 to 1000 cysts cm$^{-2}$ yr$^{-1}$). Between ~AD 1930–1970, dinocysts influxes are decreasing, with a minimum value reached around AD 1950 (200 cysts cm$^{-2}$ yr$^{-1}$ at 14 cm downcore) and increase again from AD 1970–1980 to reach a maximum value of 1400 cysts cm$^{-2}$ yr$^{-1}$ at 8 cm downcore. Dinocyst influxes then steadily decrease from ~AD 1980 to their modern value of 500 cysts cm$^{-2}$ yr$^{-1}$ at the top of the core.

Freshwater palynomorphs, pollen grains and spores, and pre-Quaternary paly-nomorphs influxes are all characterized by an increase from minimum values around ∼AD 1885 to maximum values during ∼AD 1992–1997 (Fig. 2f–h, respectively).

Pollen and spores influxes (Fig. 2g) remain relatively stable during ∼AD 1855–1950 with a mean value of 267 grains $cm^{-2}$ $yr^{-1}$, despite a peak centered ∼AD 1900. From AD 1950, influxes progressively increase to reach a maximum value of 660 grains $cm^{-2}$ $yr^{-1}$ during ∼AD 1980–2000, with a mean value of 580 grains $cm^{-2}$ $yr^{-1}$. Only 5 genus composed the pollen assemblages: *Picea*, *Pinus, Betula, Alnus* and *Salix*. *Pinus* dominated the assemblages and it is generally over-represented in ocean basins due to its morphology and density, which allow transport over long distances (e.g., Heusser, 1983; Mudie, 1982; Rochon and de Vernal, 1994). Influxes of pollen and spores and pre-Quaternary palynomorphs (pollen grains, spores, acritarchs and dinocysts) present similar distribution patterns. Influxes are minimum ∼AD 1880 (210 and 190 $cm^{-2}$ $yr^{-1}$, respectively) and gradually increase until ∼AD 1980. They are then characterized by an important increase between ∼AD 1980–2000 and reach maximum values of 660 and 915 specimens $cm^{-2}$ $yr^{-1}$, respectively (Fig. 2h).

Freshwater palynomorphs were used as tracers for the variations of the Mackenzie River discharge (Fig. 2f). Their influxes gradually increase from minimum values of ∼30 specimens $cm^{-2}$ $yr^{-1}$ around AD 1880 to maximum values of 200 specimens $cm^{-2}$ $yr^{-1}$ in the period ∼AD 1980–2000.

## 4.3 Dinocyst assemblages

A total of 24 dinocyst taxa were observed in all the samples, but 7 taxa comprised more than 95 % of the assemblages (Fig. 3). The assemblages are dominated by the autotrophic taxa *Pentapharsodinium dalei* (Fig. 5e) and *Operculodinium centrocarpum sensu lato*, which includes the arctic and short spines morphotypes (Fig. 3). Both taxa are common in Arctic and sub-Arctic regions (Mudie and Rochon, 2001; Kunz-Pirrung et al., 2001) and were recorded in estuarine environments (Dale, 1976; Persson et al., 2000). *Pentapharsodinium dalei*, which represents 68 to 96 % of the assemblages, is

generally associated with low salinity environments and stratified waters in summer. The second most abundant taxa, *O. centrocarpum sensu lato*, represents 9–66 % of the assemblages (average 31 %). The accompanying taxa include *Spiniferites elongatus/frigidus* and a series of heterotrophic taxa: *Islandinium minutum* sensu lato (2–18 %), *Brigantedinium simplex* (1–30 %), the cyst of *Protoperidinium americanum* (≤ 2 %) and the cyst of *Polykrikos* var. Arctic (≤ 3 %).

The software zone allowed to differentiate three dinocyst assemblage zones, which can also be distinguished on the basis of the relative abundance of all taxa: Dinocyst assemblage 1 encompasses the period ∼AD 1855–1880 (Fig. 3), and is characterized by the co-dominance of *P. Dalei* (34–56 %) and *O. centrocarpum sensu lato* (28–46 %), accompanied by *S. elongatus/frigidus* (2–4 %) (Fig. 5h), *I. minutum* sensu lato (5–17 %) and *B. simplex* (3–10 %). Dinocyst assemblage 2 encompasses the period ∼AD 1880–1987 and is dominated by the autotrophic taxa *P. dalei* (24–73 %), *O. centrocarpum* sensu lato (9–46 %), while *S. elongatus/S. frigidus* (0.3–3 %) show their minimum relative abundances in this zone. Conversely, the assemblage is characterized by the maximum abundance of heterotrophic taxa, such as *I. minutum* sensu lato (up to 24 %) and *B. simplex* (up to 20 %), and by the appearance of cysts of *P. americanum* (0.3–2 %) and cysts of *Polykrikos* var. Arctic (0.3–3 %); Dinocyst assemblage 3, from AD 1987–2009, is characterized by a marked decrease of *P. dalei* abundance (from 46 to 11 %) and dominance of *O. centrocarpum* sensu lato (up to 65 %). This assemblage is also marked by the maximum abundance of *S. elongatus/frigidus* (up to 5 %), the minimum abundance of all heterotrophic taxa and the disappearance of the cysts of *P. americanum*.

## 4.4 Reconstruction of sea-surface conditions

Summer temperature reconstructions are characterized by a decreasing trend between ∼AD 1855–1960. Indeed, reconstructed SST values between ∼AD 1885–1935 are warmer by up to 3 °C with respect to the average modern temperature at the coring site (4.1 °C). During ∼AD 1935–1975 reconstructed SSTs are ∼1 °C below the modern

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value. Within the next 10 yr, the temperature increases up to 5.4 °C (~AD 1987) and gradually decreases towards the modern value of 4.1 °C.

The reconstructed SIC trend mirrors that of reconstructed SSTs (Fig. 4b). Between ~AD 1887–1945, reconstructed SIC values are as low as 3.9 months yr$^{-1}$, which is nearly 6 months yr$^{-1}$ below the modern value (9.8 months yr$^{-1}$). The period AD 1945–1975 is marked by reconstructed SIC values similar to the modern conditions. A sudden decrease in SIC characterizes the period AD 1975–1995, with values as low as 4.6 months yr$^{-1}$, which is 5 months below the modern value. Sea-ice cover duration then gradually increases towards the modern value.

Reconstructions of SSS depict a series of oscillations between minimum and maximum values varying between −7 and +5 salinity units around the modern salinity conditions at the coring site (27) measured at 17 stations in 2009 all located within 30 km of the coring site. The periods AD 1860–1905, 1935–1980 and 1990–2009 are characterized by reconstructed SSSs lower than the modern value, while SSS is similar to modern conditions between AD 1905–1935. The most salient feature of the reconstructions is the sharp peak recorded by all parameters during ~AD 1980–1990.

# 5  Discussion

Instrumental data for the Mackenzie River discharge are only available since 1938, which allow for short time scale observations on the fluctuations of the freshwater discharge. In an attempt to trace the temporal variability of freshwater inputs to the Beaufort Sea area prior to 1938, Richerol et al. (2008) previously showed the similarities between concentrations of the freshwater palynomorph *Halodinium*, a thecamoeban-like palynomorph, and the Mackenzie River discharge in the Beaufort Sea area. Here, we have used the influxes of several freshwater palynomorphs, including *Halodinium*, as well as remains of the freshwater algae *Pediastrum* (Chlorophyceae) and *Zygnema* (Zygnematophyceae). Figure 2d illustrates the influxes of these palynomorphs next to the Mackenzie River discharge (Fig. 2e) data from 1938 to 2005. Because of the

similarity between both profiles, we suggest that the influx of these freshwater paly-nomorphs can be used as tracers of the river discharge prior to instrumental data, which is directly related to precipitations within its catchment area.

The freshwater palynomorph influxes curve (Fig. 4f) displays 3 major phases: from AD 1858–1902 where freshwater palynomorph influxes are minimum ($\sim 50$ specimens cm$^{-2}$ yr$^{-1}$); an intermediate phase from AD 1900–1976 ($\sim 100$ specimens cm$^{-2}$ yr$^{-1}$); and the most recent phase, from AD 1976–2004, where their influxes reach maximum values ($\sim 130$ specimens cm$^{-2}$ yr$^{-1}$). Previous studies of tree ring records from Central Canada (Case and Macdonald 1995; Sauchyn and Beaudoin, 1998; Sauchyn and Skin-ner, 2001), Yellowknife and the Mackenzie delta area (Pisaric et al. 2007, 2009; Porter et al., 2009) going as far back as AD 1505 can be used to infer precipitations and assess the variability of freshwater inputs from the Mackenzie River. Reconstructions of August–July annual precipitations in two regions of the Western Canadian Prairies (Western Saskatchewan) indicate that the period AD 1850–1900 was characterized by drought or low-precipitation episodes lasting several years, the most severe occur-ring between $\sim$AD 1860–1875 (Case and Macdonald, 1995), AD 1880–1900 (Sauchyn and Beaudoin, 1998, Sauchyn and Skinner, 2001), and AD 1942–1877 in the Eastern Rocky Mountains (Saint Georges et al., 2009). For the Yellowknife area, June precipita-tion reconstructions indicate a negative anomaly (low precipitations) during AD 1850–1890, which coincides with a particularly low level stand of lake Athabasca (Stockton and Fritts, 1973) and low river levels in Northern Saskatchewan (Case and Macdon-ald, 1995). For the Mackenzie delta region, the tree-ring width index for the period AD 1850–1900 displays relatively low values (Pisaric et al., 2007), and it also corresponds with the AD 1855–1880 positive Northern Hemisphere summer temperature anomaly (Brohan et al., 2006). The minimum values of freshwater palynomorph influxes in our record during AD 1855–1900 ($\sim 30$ specimens cm$^{-2}$ yr$^{-1}$), coupled with the relatively high sea surface temperature reconstructions during AD 1855–1890 (up to 3°C above the modern value) correlate very well with these records and strongly suggest that the Mackenzie River discharge was at a minimum level during the 150 yr of our record.

The intermediate phase of our freshwater palynomorph record (AD 1902–1976; ~ 100 specimens cm$^{-2}$ yr$^{-1}$) corresponds to a relatively wet period, during which the population census divisions in the Prairies doubled (Government of Canada, 1938), and which was also marked by more favorable climatic conditions for crop production until the 1970s. Indeed, the 20th century began with a wet period (AD 1900–1920) (Sauchyn and Beaudoin, 1998; Watson and Luckman, 2006), as indicated by the Palmer Drought Severity Index (drought index), which was often positive during that period (Sauchyn and Skinner, 2001). The most recent phase during AD 1976–2004 (~130 specimens cm$^{-2}$ yr$^{-1}$) is marked by maximum influxes of freshwater palynomorphs (Fig. 4f). This period is well documented with instrumental data and displays the highest annual Mackenzie River discharge values on record (between 700 and 11900 m$^3$ s$^{-1}$), with a maximum reached in 1990. The Mackenzie Trough area is thus clearly affected by freshwater inputs from the Mackenzie River (Rawlins et al., 2009), which are probably controlled by regional and global oceanic and atmospheric (precipitations) circulation patterns, such as the PDO.

The PDO is a major mode of North Pacific climate variability and is reflected in the evolution of North Pacific monthly surface temperatures (Mantua et al., 1997; Mantua and Hare, 2002; Minobe, 1997). During positive phases, it manifests itself by low sea-level pressure anomalies over the North Pacific and high sea-level pressure anomalies over Western North America. At the same time, the surface air temperatures tend to be anomalously cool in the Central North Pacific and anomalously warm along the west coast of North America. The PDO also affects low pressure centers like the Aleutian Low system, which controls most of the daily precipitations in the Mackenzie and Yukon River basin (Cassano and Cassano, 2010) and the Bering Sea oceanic advection (Danielson et al., 2010). Moreover, the most recent variations of the position and intensity of the Aleutian Low centered above the Gulf of Alaska are linked with the PDO pattern (Moore et al., 2003; Schneider and Cornuelle, 2005). The Aleutian Low has been shown to deepen during positive phases of the PDO (Bjerknes, 1966, 1969, 1972; Overland et al., 1999). These regime shifts have many environmental impacts,

like sea-ice coverage anomaly in the Bering Sea during PDO positive phases (Niebauer 1989, 1998). On the other hand, Aleutian Pacific-born storms (and especially northward tending trajectories storms) have many impacts in oceanic environment along the Beaufort Shelf. They generally induce upwelling events and intrusions of warmer waters through the Alaskan Coastal Current onto the Beaufort Shelf (Okkonen et al., 2009; Pickart et al., 2009). Reconstructions of sea surface parameters for the entire time-period covered by the core indicate SSTs and SSSs above modern values during positive phases of the PDO (Fig. 4). Estimations of SIC indicate a lower duration of sea ice, with respect to modern values, during warm episodes and are consistent with upwelling events of saltier and warmer Pacific water recorded during positives phases of the PDO between AD 1925–1946 and 1979–1996 (e.g., Macdonnald et al., 1987). These events have many impacts in local productivity (e.g., Tremblay et al., 2011), such as the enhancement of local zooplankton density (Suzuki et al., personal communication) affecting the carbon cycle (Mucci et al., 2010). Our data indicate peaks of dinocyst influxes during these two periods, synchronous with higher than normal SST and SSS estimates, decreased SIC duration, which are consistent with an increase of primary productivity caused by upwellings of Pacific-water in the Mackenzie Trough area. Conversely, dinocysts fluxes are minimum during negative phases of the PDO, which are usually characterized by cooler than normal conditions (e.g., Schneider and Cornuelle, 2005). Our temperature and salinity estimates also agree with the sea-surface conditions expected during negative phases of the PDO (cooler temperatures, lower salinities and normal or slightly increased SIC values). A study by Ledu et al. (2012) on the same core based on lipid compounds production ($IP_{25}$) by sea-ice algae indicated a close relationship between PDO index and sea ice productivity. They attributed the enhancement of sea ice primary productivity to the increased frequency of upwelling events of warm and salty Pacific waters along the Beaufort slope events during positive phases of the PDO.

Most authors attributed interannual variability of the Arctic Ocean with fluctuations of the North Atlantic (NAO) and Arctic (AO) Oscillations (e.g., Deser et al., 2000; Morison

et al., 2012). The AO is generally difficult to distinguish from the NAO, which is a major source of low-frequency variability. The AO switched to a positive mode around AD 1970, but showed a maximum around AD 1991 (Dickson et al., 2000; Hurell, 1995; Hurrel and Van Loon, 1997). Our results indicate that freshwater palynomorph influxes increased > fivefold between AD 1972 and 1991, from 37 specimens $cm^{-2} yr^{-1}$ to 202 specimens $cm^{-2} yr^{-1}$. Also, the maximum positive phase of the AO around AD 1991 coincides with a shift from a *P. dalei*-dominated dinocyst assemblage to one dominated by *O. centrocarpum*, which is also marked in our reconstructions by a decrease of SIC duration (from 9 to 5 months $yr^{-1}$) and an increase of ~ 1.5 °C in SST (Fig. 4b, c), that are consistent with satellite data reported by National Snow and Ice Data Center in the same period. In the same way, Radi et al. (2001) noticed a decrease in the relative abundance of *P. dalei* when sea ice cover duration is reduced in the Chukchi Sea and Bering Strait areas. They also noted that this taxa is generally replaced by *O. centrocarpum* and *S. elongatus/frigidus* when ice conditions become important again, which is also depicted by our dinocyst assemblages (Fig. 3).

The positive reconstructed temperature and salinity values and associated decline of reconstructed sea-ice in our results occurred quasi-synchronously with: (1) a positive phase of the PDO during AD 1979–1996; (2) a major shift in the Arctic atmospheric and oceanic circulation associated with a positive phase of the AO that began in the 1970s (Thompson and Wallace, 1998, 2000; Walsh et al., 1996). This atmospheric configuration generated an anomalously low sea level pressure in the Arctic. In the same time, satellite imagery and physico-chemical data (Macdonald et al., 1999; Parkinson et al., 1999) suggest that a strong seasonality prevailed in the marginal seas surrounding Canada Basin during the 1990s with respect to sea ice coverage, with large areas of open water during the summer season and intensification of Pacific water intrusions in the Arctic during positive AO phases (McLaughin et al., 2002). However, the observed seasonality and associated reduction of sea ice extent in summer coincides with the maximum values of the Mackenzie River discharge and the maximum influxes of freshwater palynomorphs (Fig. 4b–f). The similarity between the freshwater palynomorphs

record (Fig. 4f) and the AO index (Fig. 4g) during the most recent phase of our fresh-
water palynomorph record (1976–2004) would suggest a relationship between the AO
and the Mackenzie freshwater discharge, but not appears during the previous phase
(1902–1976). Déry and Wood (2004) have highlighted such teleconnection between
the AO with the recent decline of Hudson Bay river discharge, therefore linking the AO
with the regulation of terrestrial hydrology budgets. However, Burn (2008) compared
the trends in the timing of runoff of three sub-watersheds of the Mackenzie River Basin
with a series of 6 climatic indices. The results showed that the AO had no effect on
the timing of river runoff, suggesting that the AO has little to no effect on the hydrologic
cycle in the Mackenzie Basin. His analysis clearly showed a link between the timing of
runoff within these watersheds and the PDO index. Moreover, the oscillation that has
the greatest impact on the zones located around the AO Core Region is probably the
PDO (Zhao et al., 2006). At a global scale, the PDO pattern seems to show a covari-
ability with AO (Hetzinger et al., 2011). Thus, the series of climatic oscillations affecting
the Northern Hemisphere are linked through a teleconnection sequence between the
oceans and the atmosphere called "stade wave" (Wyatt et al., 2012). This teleconnec-
tion plays a crucial role in climatic changes, notably in exchanges of heat fluxes within
the Arctic thought the Bering Strait (Woodgate et al., 2004). According to our results,
the PDO pattern is closely linked with most of the sea-surface condition variability in
the study area through upwelling events of Pacific origin. However, the effect of the AO
cannot be totally excluded, especially with respect to freshwater inputs.

## 6   Conclusions

The Mackenzie Trough is characterized by a high sedimentation rate suitable for high
resolution studies of paleo-sea surface conditions. The excellent preservation of pa-
lynomorphs allowed the reconstructions of sea-surface parameters. We also demon-
strated that the evolution of temperature, salinity, sea ice cover and dinoflagellate pro-
ductivity of the Mackenzie Trough area are closely linked with the phases of the PDO at

a decadal timescale. Positive phases of the PDO are associated with warm, high salinity, low sea ice and high primary productivity conditions in surface waters. Conversely, negative phases are associated with cool and low salinity conditions. Freshwater palynomorphs were used to infer the evolution of local freshwater inputs, which showed three distinct phases, a dry phase in the late 19th century, and intermediate phase from AD 1900 to ~ 1976 and the maximum Mackenzie River discharge phase which peaked around 1990. The AO does not seem to correlate with any of the parameters considered in the present study, which suggests that the Mackenzie Trough primary productivity and Mackenzie River freshwater discharge may be controlled by other parameters. The PDO may be the dominant climate oscillation mode leading oceanic circulation pattern, sea-surface parameters and productivity in the Western Canadian Arctic, at least at decadal timescales.

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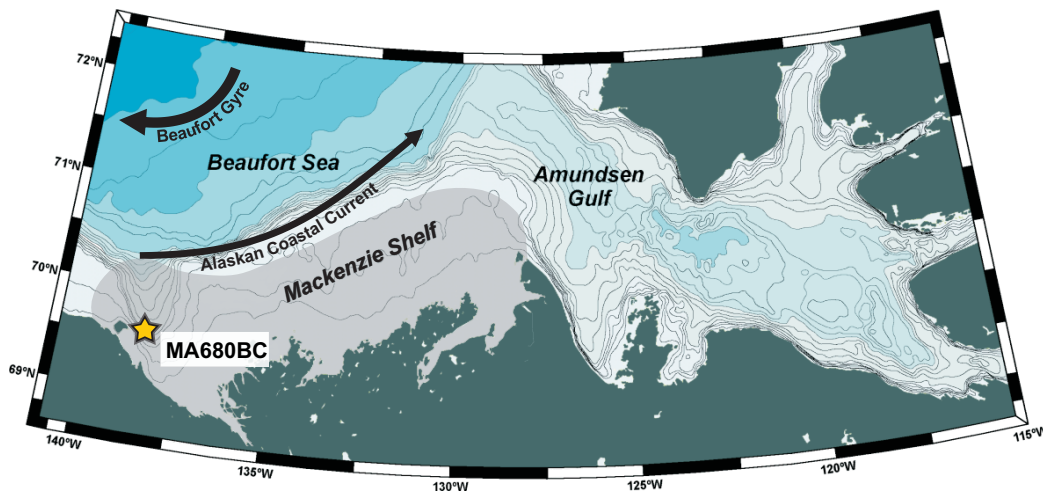


**Fig. 1.** Location map of core MA680BC and oceanic circulation in the study area. The thick arrow represents the clockwise Beaufort Gyre, the thin arrow indicates the Alaska Coastal Current and the grey area represents the Mackenzie River plume.
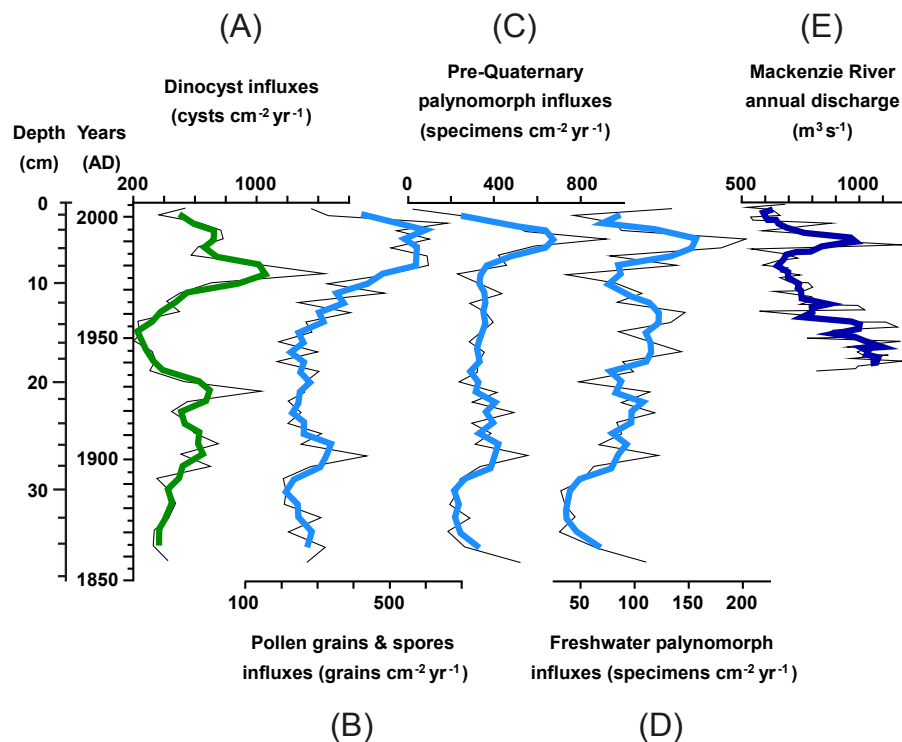
**Fig. 2.** Palynomorph influxes in core MA680BC plotted against depth and age AD. Dinocyst influxes **(A)**; Pollen and spores influxes **(B)**; pre-Quaternary palynomorph influxes **(C)**; freshwater palynomorph influxes **(D)**; Mackenzie River annual discharge from 1938 to 2006 (HYDAT) **(E)**. The thick curves represent a smooth over 3 data points.

**Fig. 3.** Relative abundances of the major dinoflagellate cyst taxa in core MA680BC and dinocyst assemblage zones plotted against depth and age AD. The thick curves represent a smooth over 3 data points.

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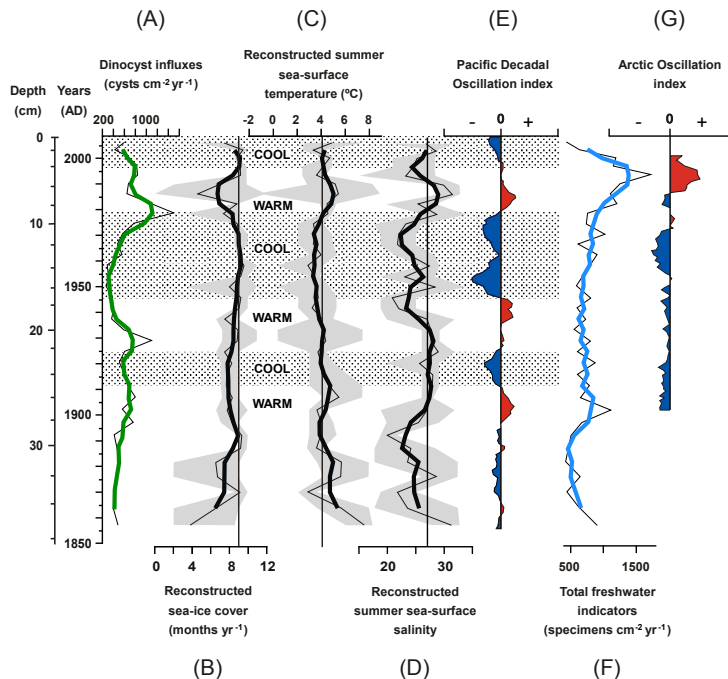Conclusions | References

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**Fig. 4.** Dinocyst influxes and reconstructed sea surface parameters in core MA680 BC, and climate indexes plotted against depth and age AD. Dinocysts influxes **(A)**; reconstructed sea-ice cover **(B)**; reconstructed temperature **(C)**; reconstructed salinity **(D)**; Pacific Decadal Oscillation (PDO) normalized index **(E)**; freshwater palynomorph influxes **(F)**; Arctic Oscillation (AO) normalized index **(G)**. The modern values of sea-surface parameters are represented by the vertical line. The grey areas represent the confidence interval (minimum and maximum possible values) for each reconstructed parameter. The horizontal dotted areas represent warm and cool intervals asociated with positive and negative phases respectively for the PDO index (Mantua and Hare, 2002). The thick curves represent a smooth over 3 data points. Both PDO and AO indexes are smoothed over 5 data points.
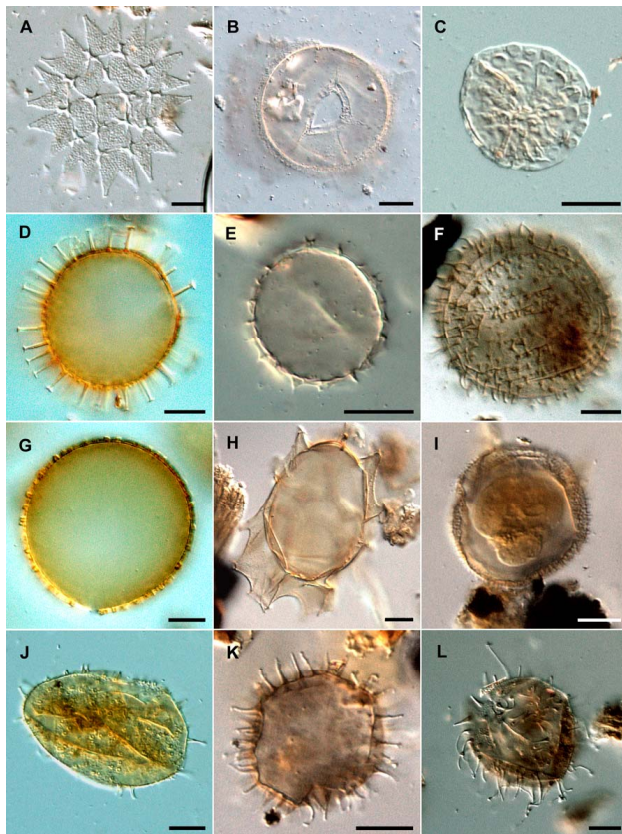
**Fig. 5. (A)** *Pediastrum* sp. **(B)** *Halodinium* sp. **(C)** *Zygnema* sp. **(D)** *Operculodinium centrocarpum* **(E)** Cyst of *Pentapharsodinium dalei* **(F)** *Islandinium minutum* **(G)** *Operculodinium centrocarpum* short spines **(H)** *Spiniferites frigidus* **(I)** *Islandinium brevispinosum* **(J)** *Operculodinium centrocarpum* var. Arctic **(K)** *Echinidinium karaense* **(L)** *Islandinium minutum* var. Cezare.

**Specimens data: MA680BC**

**(A)** *Pediastrum* sp.: 19–20 cm, K14, 3
**(B)** *Halodinium* sp.: 19–20 cm, K26; 4
**(C)** *Zygnema* sp.: 20–21 cm; U15
**(D)** *Operculodinium centrocarpum*: 21–22 cm, O28; 4
**(E)** Cyst of *Pentapharsodinium dalei*: 21–22 cm; E15; 3
**(F)** *Islandinium minutum*: 19–20 cm, M23; 4
**(G)** *Operculodinium centrocarpum* short spines: 25–26 cm; R10; 2
**(H)** *Spiniferites frigidus*: 21–22 cm; E11; 1
**(I)** *Islandinium brevispinosum*: 29–30 cm, V23; 1
**(J)** *Operculodinium centrocarpum* var. Arctic : 19–20 cm; 535; 3
**(K)** *Echinidinium karaense*: 21–22 cm, G4; 3
**(L)** *Islandinium minutum* var. Cezare: 21–22 cm: E38