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Reconstructing past sea ice cover of the Northern Hemisphere from dinocyst assemblages: status of the approach

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A B S T R A C T

Dinocysts occur in a wide range of environmental conditions, including polar areas. We review here their use for the reconstruction of paleo sea ice cover in such environments. In the Arctic Ocean and subarctic seas characterized by dense sea ice cover, *Islandinium minutum*, *Islandinium*? *cezare*, *Echinidinium karaense*, *Polykrikos* sp. var. Arctic, *Spiniferites elongatus–frigidus* and *Impagidinium pallidum* are common and often occur with more cosmopolitan taxa such as *Operculodinium centrocarpum* sensu Wall & Dale, cyst of *Pentapharsodinium dalei* and *Brigantedinium* spp. Canonical correspondence analyses conducted on dinocyst assemblages illustrate relationships with sea surface parameters such as salinity, temperature, and sea ice cover. The application of the modern analogue technique permits quantitative reconstruction of past sea ice cover, which is expressed in terms of seasonal extent of sea ice cover (months per year with more than 50% of sea ice concentration) or mean annual sea ice concentration (in tenths). The accuracy of reconstructions or root mean square error of prediction (RMSEP) is ±1.1 over 10, which corresponds to perennial sea ice. Such an error is close to the interannual variability (standard deviation) of observed sea ice cover. Mismatch between the time interval of instrumental data used as reference (1953–2000) and the time interval represented by dinocyst populations in surface sediment samples, which may cover decades if not centuries, is another source of error. Despite uncertainties, dinocyst assemblages are useful for making quantitative reconstruction of seasonal sea ice cover.

1. Introduction

Sea ice is an important parameter of the climate system, which has recorded significant decrease in the Arctic during the past decades (cf. http://nsidc.org/data/seaice_index/). The recent sea ice cover reduction of the Arctic Ocean may be due to anthropogenic warming (Notz and Marotzke, 2012). However, the assessment of forcing and quantification of feedback mechanisms remain challenging without an adequate knowledge of natural sea ice variability (Holland et al., 2008). The observations of sea ice predating recent "satellite" times are rare and discontinuous, which makes it difficult to document past sea ice variations beyond multidecadal scales. Moreover, modelling sea ice is very challenging (e.g. Stroeve et al., 2007, 2012; Rampal et al., 2011) and the evaluation of climate models is difficult, especially since very little is known about the variability of the sea ice extent prior to observational records through satellite imagery, which started in the 1970s. Hence proxy data are essential for extending sea ice records back in time. This has motivated efforts of the paleoceanographer community toward the development of proxy approaches to reconstruct sea ice from marine sediment cores. To date, most sea ice proxies rely on biogenic fluxes to the sea floor, assuming that sea ice exerts a role on the biogeochemistry of sea water, thus on primary productivity and trophic structure of the populations. Biogenic proxies include microfossils such as diatoms (e.g., Crosta et al., 2004; Gersonde et al., 2005), dinoflagellate cysts (e.g., de Vernal et al., 1994, 2001, 2005, 2008; Rochon et al., 1999; de Vernal and Hillaire-Marcel, 2000), ostracods (Cronin et al., 2010), foraminifers (e.g., Scott et al., 2009; Seidenkrantz, 2013) and their isotopic composition (Hillaire-Marcel and de Vernal et al., 2008) in addition to organic biomarkers (e.g., Belt et al., 2007; Massé et al., 2011; Müller et al., 2011; Belt and Müller, 2013). Among those, organic-walled cysts of dinoflagellates (hereafter, dinocysts) have been used for the reconstruction of sea ice over the northern

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North Atlantic during the Last Glacial Maximum (LGM) and the Holocene (de Vernal and Hillaire-Marcel, 2000, 2006; de Vernal et al., 2005a, 2008).

Proxy-data are useful to reconstruct past sea ice cover on a qualitative or quantitative basis, but none of the approaches are unequivocal. Hence a critical assessment of the reliability of reconstruction is necessary, especially prior to combine data for multi-proxy compilations or for data-model comparisons. In this context, the primary objective of this paper is to provide an assessment of the reliability of the dinocyst transfer functions that are currently used to reconstruct past sea ice cover. The reliability of any transfer function, based on calibration or comparison technique, depends on the quality of the initial data sets. The accuracy and adequacy of sea ice data used for calibration is a first issue, which we examine here. The quality of dinocyst data that relies on laboratory procedures and taxonomical identification in addition to the statistical values of the populations analysed is another issue. It has been addressed in several papers (cf. de Vernal et al., 2001, 2005; Guiot and de Vernal, 2007) and is re-assessed here. The reliability of transfer functions also depends on the strength of the relationship between the determinant and dependent parameters, here sea ice cover and dinocyst assemblages. This can be explored with multivariate analyses, which are briefly presented here. Then, finally, the accuracy of the reconstructions is assessed with reference to the usual procedures of validation that provide the error of prediction (e.g. Guiot and de Vernal, 2007). In this manuscript, we make use of an updated standardized dinocyst database from the Northern Hemisphere that comprises 1492 data points (cf. http://www.geotop.ca; Fig. 1).

2. The status of sea ice cover in the reference database

Sea ice cover is a dynamical parameter that records large amplitude changes throughout the year and that varies from one year to another. Its seasonal occurrence and its spatial concentration are difficult to quantify but observations by satellite imagery since the 1970s have permitted a comprehensive description of the Arctic sea ice cover, especially after the satellite microwave data collection began (e.g. Rayner et al., 2003). Sea ice thickness is another important parameter, which is measured mostly based on radar altimetry and in situ observation from submarines (e.g. Kwok and Rothrock, 2009). Hence, the sea ice thickness data coverage is still fragmentary and sea ice thickness over large areas is generally estimated from modelling (e.g. Maslowski et al., 2012). Ideally, both parameters, the sea ice areal extent and the sea ice thickness, should be reconstructed as they are both required to calculate the volume of the Arctic sea ice that constitutes an important freshwater reservoir. However, the recent sea ice thickness is insufficiently documented to establish a modern reference database. Sea ice cover extent is better documented and the establishment of

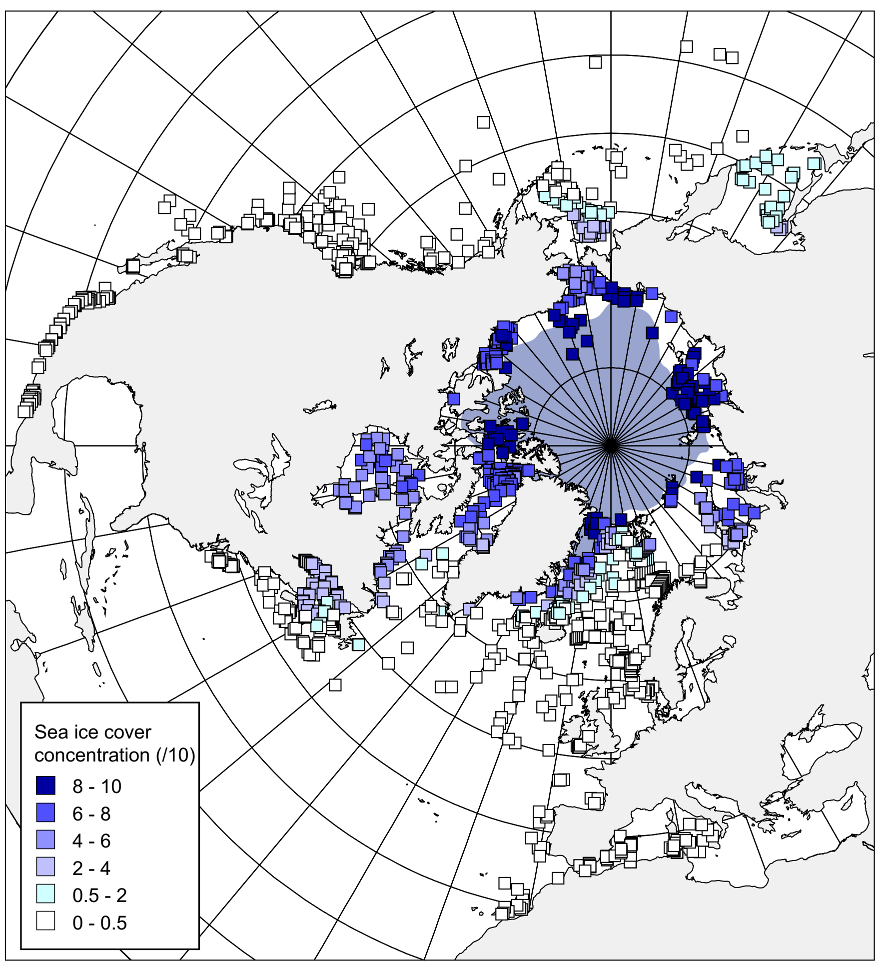

Fig. 1. Map showing the location of surface sediment samples (squares) in the updated "$n = 1492$" dinocyst database. Mean annual concentration of sea ice at site location are reported on a scale from 0 (ice free) to 10 (continuous ice cover). The reference interval is 1953–2003 AD. Sea ice data were compiled from the measurements and estimates provided by the National Snow and Ice Data Center (NSIDC) in Boulder. The median (1979–2000) limits of the minimum (September) extent of sea ice is indicated by the shaded area as defined from NSIDC.