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Sea ice in the paleoclimate system: the challenge of reconstructing sea ice from proxies – an introduction

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ABSTRACT

Sea ice is an important component of the Earth system with complex dynamics imperfectly documented from direct observations, which are primarily limited to the last 40 years. Whereas large amplitude variations of sea ice have been recorded, especially in the Arctic, with a strikingly fast decrease in recent years partly attributed to the impact of anthropogenic climate changes, little is known about the natural variability of the sea ice cover at multi-decadal to multi-millennial time scales. Hence, there is a need to establish longer sea ice time series to document the full range of sea ice variations under natural forcings. To do this, several approaches based on biogenic or geochemical proxies have been developed from marine, ice core and coastal records. The status of the sea ice proxies has been discussed by the Sea Ice Proxy (SIP) working group endorsed by PAGES during a first workshop held at GEOTOP in Montréal. The present volume contains a set of papers addressing various sea ice proxies and their application to large scale sea ice reconstruction. Here we summarize the contents of the volume, including a table of various proxies available in marine sediments and ice cores, with their possibilities and limitations.

1. The importance of sea ice in the Earth's system

Sea ice is a critical component of the Earth's system with regard to global climate, physical environment and biosphere. In the climate system, sea ice cover generally acts as an amplifier: it influences the energy budget at the surface of the Earth because it reflects a significant part of the incoming solar radiation (corresponding thus to a high albedo) and because it limits the heat exchange between the ocean and the atmosphere (see Fig. 1). Hence sea ice directly and indirectly accounts for feedbacks responsible for particularly large climate variations at high latitudes, often referred to as polar amplification (e.g. Serreze and Barry, 2011). Sea ice also plays an important role for physical oceanography as sea-ice formation is accompanied by brine release and convection, thus influencing the entrainment of water in the mixed layer and deep ocean ventilation (e.g. Killworth, 1983). Moreover, sea ice constitutes a large freshwater reservoir. In the Northern Hemisphere, Artic sea ice is eventually exported towards the North Atlantic, where it induces a decrease in surface salinity and an increase in stratification when melting, thus potentially playing a role in the thermohaline circulation (e.g. Dickson et al., 2007). Finally, sea ice has a profound effect on the biota as it controls light and the distribution of phototrophic organisms and also determines the timing of nutrient release to surface water when sea ice melts (e.g., Meir et al., 2011). Under perennial sea ice there is generally little primary production apart from under special conditions related to meltwater ponds on top of the ice (Lee et al., 2012). In contrast, very high biogenic productivity occurs along the seasonal sea ice

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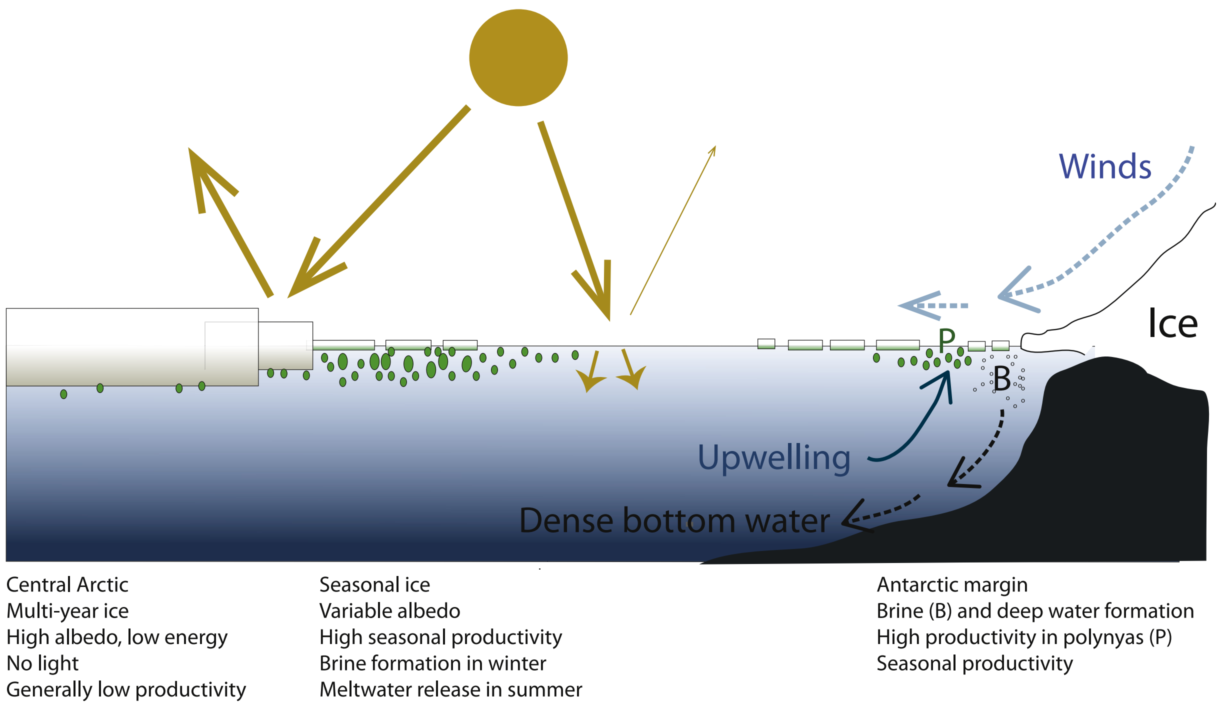

Fig. 1. Simplified scheme of the role of sea ice in the climate and ocean system, including Arctic (left) and circum-Antarctic (right) areas, showing solar energy (yellow arrows), katabatic winds (light blue arrow), ocean processes such as upwelling and brine (B) formation, polynyas (P) and primary production (little green circles).

margins, -under the sea ice (Arrigo et al., 2012) and in polynyas (e.g., Tremblay and Smith, 2007) (Fig. 1). The high carbon fluxes are eventually exported to the deep ocean.

It is thus clear that a full understanding of climate and ocean processes as well as global biochemical cycles cannot be achieved without taking into account the sea ice dynamics.

2. Arctic and Antarctic sea ice dynamics

Sea ice is a highly dynamical component of the climate–ocean system. It is marked by very large amplitude variations in extent throughout the year and from one year to another (see Fig. 2). Not only the extent of sea ice cover varies, but also its thickness and thus its volume. Therefore, the size of the sea ice reservoir and its contribution to the freshwater budget may fluctuate considerably. The development of first year ice and the accumulation of multi-year ice that regulates the thickness, the drift pattern and the export of sea ice towards low latitudes are important processes. From these points of view, the polar configuration of land and ocean in the Northern and Southern Hemispheres are important as they account for very different sea ice dynamics.

In the Southern Hemisphere, the atmospheric and ocean circulations around Antarctica result in a relatively symmetric circumpolar distribution of sea ice (Fig. 3), acting as the thermal barrier between the continent and the ocean. In the Southern Hemisphere, the maximum extent in winter reaches about 18,000,000 km^2 with an average thickness of about 1 m. During summer, almost all sea ice melts and the ice cover records a minimum extent of 3,000,000 km^2 around Antarctica (cf. National Snow and Ice Data Center – NSIDC; Fig. 2). Large variations from year to year were observed from satellite measurements, with small but significant trends, both positive and negative depending on the longitudinal sector, recognized for recent decades (e.g. Comiso and Nishio, 2008; Parkinson and Cavalieri, 2012).

In the Arctic the atmospheric and ocean circulation are characterized by variable patterns. On the one hand, the cyclonic Beaufort Gyre recirculates sea ice within the Arctic and contributes to the development of multi-year ice that is 2 m thick on average and reaches up to 4–5 m. On the other hand, the Trans Polar Drift (TPD) contributes to the export of sea ice through the Fram Strait. Hence the relative strength of the Beaufort Gyre and TPD, which is influenced by atmospheric circulation patterns (e.g. Rigor et al., 2002; Wang et al., 2009; Stroeve et al., 2011), accounts for variations in the residence time of sea ice in the Arctic Ocean and in the freshwater budget of the Arctic and Nordic Seas. It also results in asymmetrical distributions of seasonal sea-ice cover. Through the annual cycle, from winter to summer, Arctic sea ice cover ranges from a maximum of 15,000,000 km^2 to a minimum of about 7,000,000 km^2 (cf. NSIDC; Fig. 2). Whereas the seasonal amplitude in sea ice extent is less than that of the Southern Hemisphere, the magnitude of the recent trend is significant. Observations of sea ice through satellite measurements indicate that sea ice cover in the Arctic Ocean has declined by more than 12% over the last three decades (e.g., Comiso, 2012). The amount of multi-year sea ice and the sea-ice thickness have also recorded a significant decrease (Kwok and Rothrock, 2009), which resulted in volume loss estimates of close to 50% in less than thirty years (Schweiger et al., 2011). Some projections based on the ongoing trends suggest that Arctic summer sea ice may disappear within the course of the next fifty or even thirty years (e.g. Holland et al., 2006; Wang and Overland, 2009). However, the uncertainties in sea ice modeling are large as most coupled models have biases in their simulations of the mean state of the system and of its variations over the last decades (e.g. Rampal et al., 2011). A critical question is thus to evaluate to what extent the ongoing trend is related to natural variations and how much is due to anthropogenic forcing. To address this issue, the variability of sea ice needs to be documented further back in time, i.e. prior to the satellite observations. One must admit,

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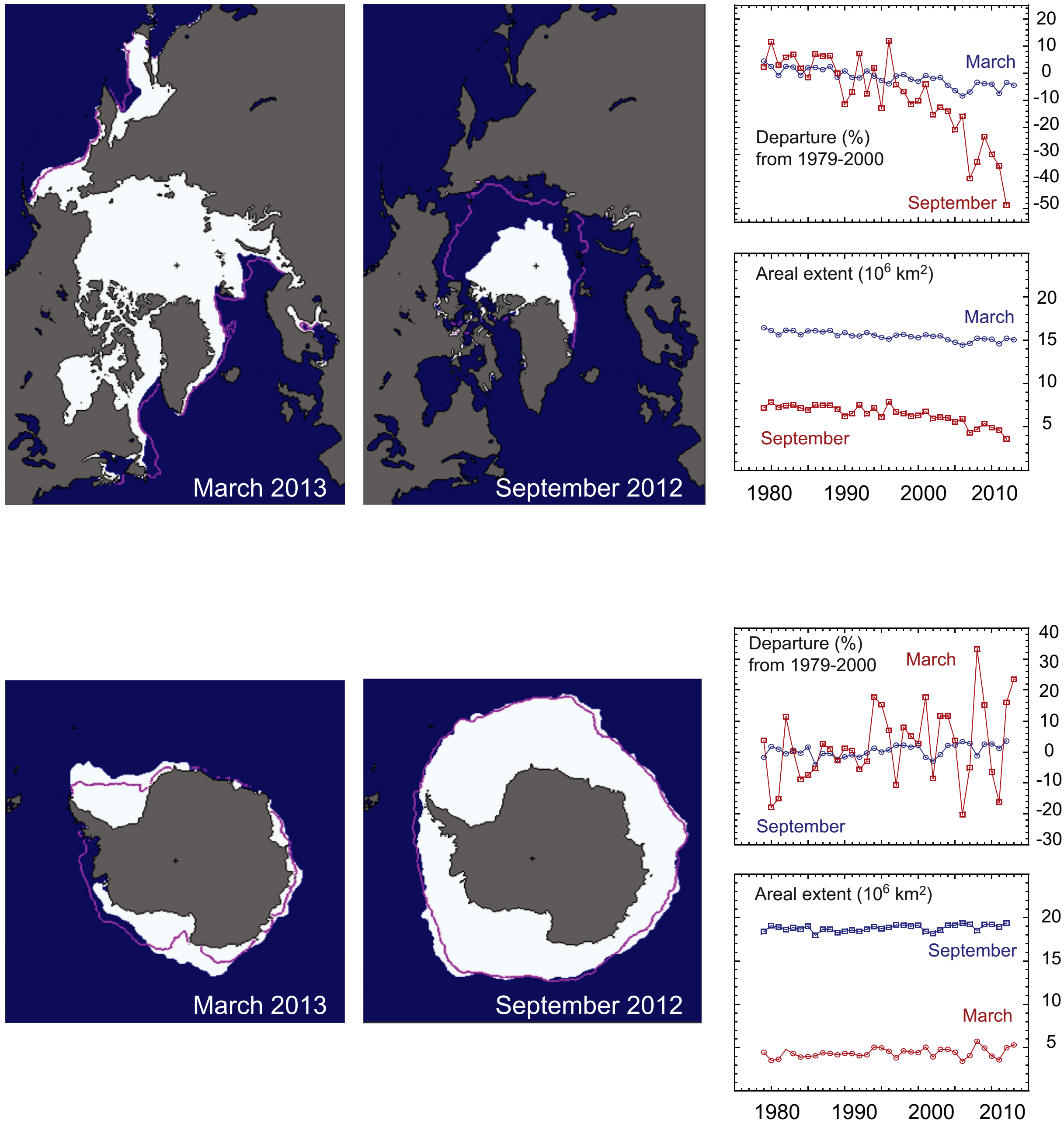

Fig. 2. Sea ice cover extent in March 2013 and September 2012 in the Northern and Southern Hemispheres. The median of the 1979–2000 sea ice limits in March and September is illustrated by the pink line. It roughly corresponds to the maximum (March in the North; September in the South) and minimum (March in the South and September in the North) extent of sea ice. On the right hand side, the time series derived from satellite observations (1978–2013) show the areal extent of sea ice cover in March and September, in the Northern and Southern Hemisphere. In the Southern Ocean, the mean areal extent of sea ice cover from 1979 to 2000 was 18.73 and 4.31 million of km^2 in September and March, respectively. In the Northern Hemisphere, the mean areal extent of sea ice cover from 1979 to 2000 was 15.75 and 7.04 million of km^2 in March and September, respectively. The trends of decreasing sea ice cover are significant in the Arctic, where they are 2.5 ± 0.6% and 13.0 ± 2.9% per decade in March and September respectively. Redrawn from data archived at the National Snow and Ice Data Center in Boulder (http://nsidc.org/data/seaice_index/).

however, that very little is known about the natural variability of Arctic sea ice on long time scales (e.g., Polyak et al., 2010), i.e. from the pre-satellite period (see Fig. 4). This is particularly critical since the few available historical time series and reconstructions of Arctic sea ice (cf. Kinnard et al., 2011), suggest that the recent observational state of Arctic sea ice cover is far below the centennial to millennial averages although large variations may have occurred on longer time scales (e.g., Jakobosson et al., 2010; Funder et al., 2011).

3. The challenge of reconstructing sea ice from indirect observations

The state of the sea ice cover cannot be described by one single variable or a simple parameter. It can be expressed in terms of concentration, extent or thickness in time (from days to decades) and space (local to hemispheric), drift pattern or formation rate. Many of these variables are difficult to measure using modern instruments and *a fortiori* to reconstruct from indirect observations.

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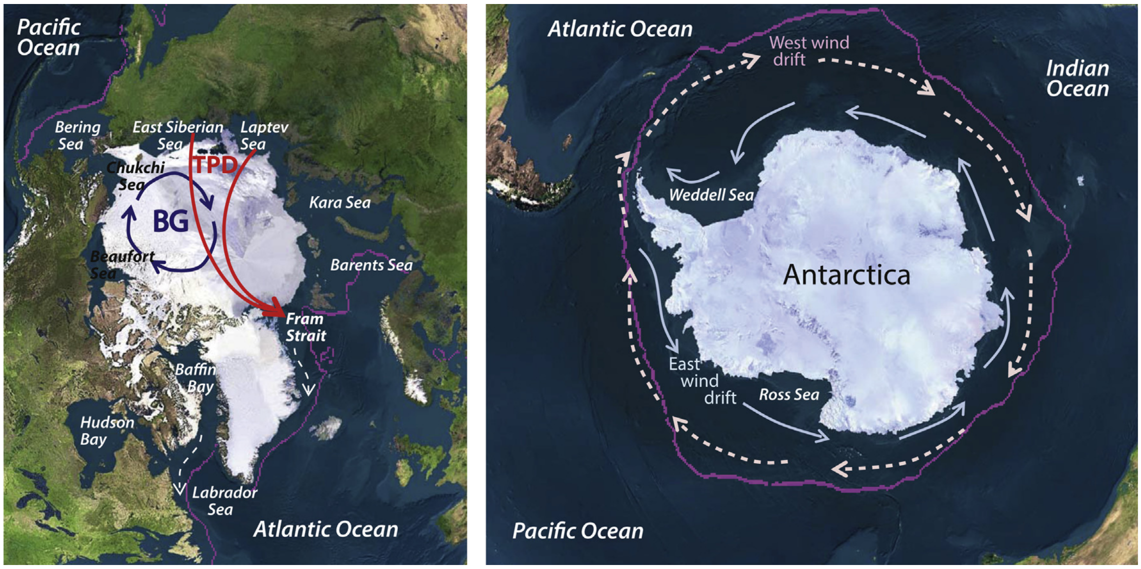

Fig. 3. Polar maps of the Northern and Southern Hemisphere. The arrows illustrate the main drift patterns, which are also responsible for sea ice dispersal and melt towards low latitudes. In the Arctic map BG and TPD stand for Beaufort Gyre and Trans Polar Drift, respectively. The pink line corresponds to the 1979–2000 median of the maximum sea ice cover extent in March (Northern Hemisphere) and September (Southern Hemisphere) as illustrated in Fig. 2.

Moreover, the representation of sea ice differs depending upon disciplines. Climate scientists often refer to sea ice as a purely physical media, while geoscientists reconstruct past sea ice using indicators or proxies that often rely on biogenic fluxes, considering that sea ice exerts a role on the biogeochemistry of sea water, thus on primary productivity and trophic structure of the populations, both qualitatively and quantitatively (e.g. Meir et al., 2011). Moreover, climate scientists and modelers need to examine sea ice at

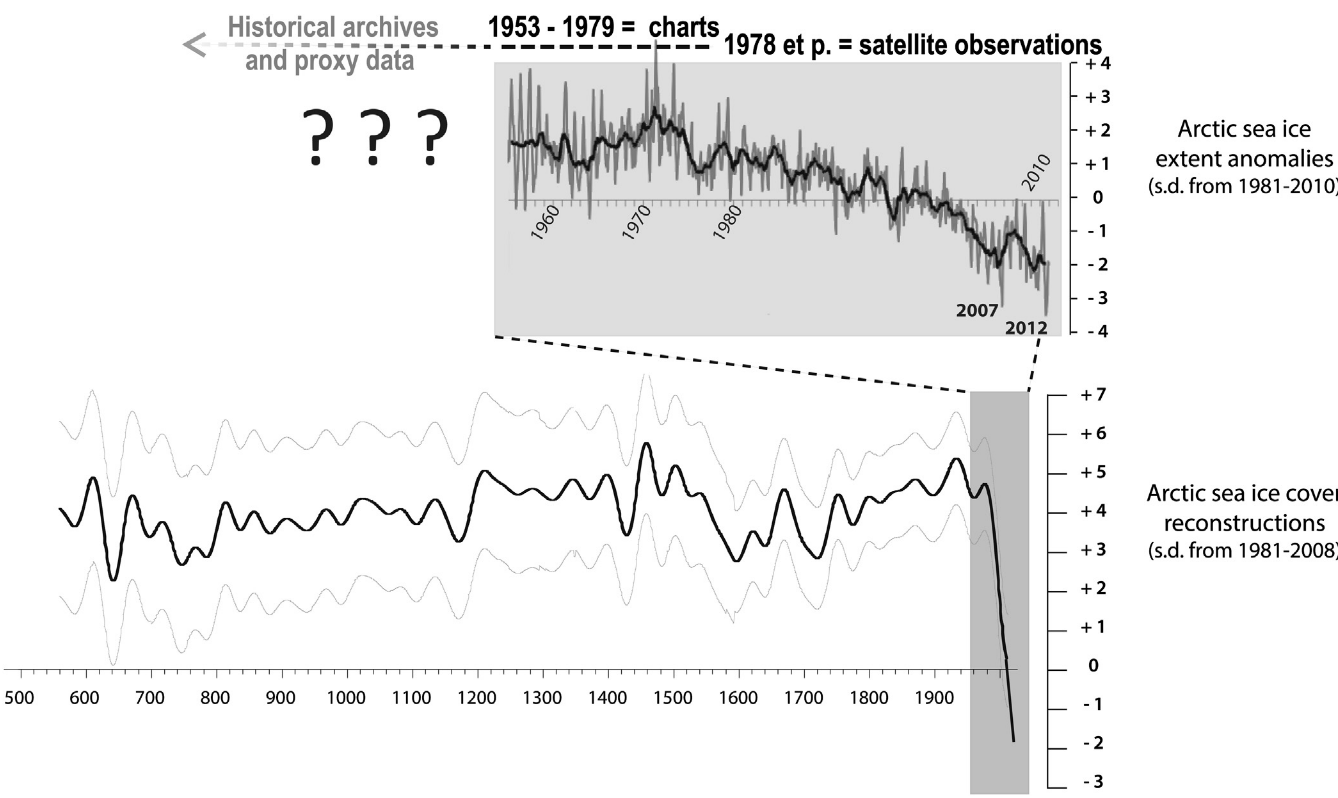

Fig. 4. Arctic sea ice cover time series from observation (upper panel) and reconstructions (lower panel). The upper panel represents the 1953–2012 sea ice anomalies of monthly means (grey line) and 12 months running means (black line) as expressed in terms of standard deviations relative to the 1981–2010 mean (figure from W. Meier and J. Stroeve, National Snow and Ice Data Center, University of Colorado, Boulder; http://nsidc.org/sotc/sea_ice.html). The lower panel shows reconstructions from a network of terrestrial proxies (tree rings and ice cores) from the circum-Arctic region that have been used to extend the record from 563 to 2008 (cf. Kinnard et al., 2011). Sea ice data consists of multi-decadal (40 years) means and are expressed here in terms of standard deviation relative to the 1981–2008 mean for comparison with the upper panel. The black line is the mean values and the grey lines delimitate maximum and minimum 95% confidence intervals (from Kinnard et al., 2011).

Table 1
Summarized status of biogenic and ice core sea ice proxies.

Proxy	Type	Advantages	Disadvantages and limitations	Selected references
Diatoms	Phototroph protists; Microfossils (frustules) composed of opal silica.	Specific species directly related to sea ice (some living in or attached to sea ice); Can be very abundant; Quantitative reconstructions available for the Southern Ocean and North Atlantic.	Sedimentary signal may be biased by opal dissolution related to changing opal export rates and species related preservation efficiency (especially in the North Atlantic, Arctic areas).	Crosta et al., 1998, 2004 Gersonde and Zielinski, 2000 Gersonde et al., 2005, Justwan and Koc, 2008, Armand and Leventer, 2010, Weckström et al., 2013, Barbara et al., 2013
Dinoflagellate cysts	Protists (both phototroph and heterotroph taxa); Microfossils (cysts) composed of refractory organic matter.	Good preservation; Several species occur in seasonal sea ice environments; Large database available for quantitative reconstruction in the Northern Hemisphere; One species related to sea ice in the Southern Ocean.	Indirectly related to sea ice; Low numbers of specimens in distal offshore setting; No occurrence under perennial sea ice; Possibility of cryptic species Database to develop in the Southern Ocean.	de Vernal et al., 1994, 2001, 2005, 2008, 2013a,b Rochon et al., 1999 de Vernal and Hillaire-Marcel, 2000 Matthiessen et al., 2005 Marret and de Vernal, 1997
Ostracods	Arthropods; Microfossils (valves) composed of calcium carbonate.	One taxon indicator of multi-year sea ice cover; Large database available, mostly from the Northern Hemisphere.	Rarely abundant in sediment; Poor preservation under the lysocline.	Cronin et al., 2010, 2013
Foraminifers	Heterotrophic protists; Microfossils (tests) mostly composed of calcium carbonate but also some species with agglutinated tests of aggregated sediment grains and very rarely aragonite.	Easy to observe under binocular microscope; Geochemical carriers; Permit qualitative inference about the occurrence of sea ice and productivity.	Indirect indicator of sea ice; Preservation of calcareous tests is problematic under the lysocline.	Jennings et al., 2002 Kuçera et al., 2005 Scott et al., 2009 Polyak et al., 2013 Seidenkrantz, 2013
$\delta^{18}O$ in foraminiferal tests	Isotopic composition of foraminifers (see above).	Provides indication on brine formation and rate of sea ice formation.	Not unequivocal; Require complementary information for assessing ocean conditions.	Hillaire-Marcel and de Vernal, 2008
IP25 biomarkers	Biomarkers produced by some sea ice diatoms.	Provide indication on seasonal (spring) sea ice occurrence; Rapidity of measurements; can be used with other biomarkers to develop quantitative sea ice productivity index (e.g., PIP_{25}).	Preservation and storage of sediment is problematic; Relationship to sea ice is regional; Calibration is needed for quantitative estimates; Applicable to the Northern Hemisphere only.	Belt et al., 2007 Belt and Müller, 2013 Müller et al., 2009, 2011 Weckström et al., 2013 Xiao et al., 2013 Navarro-Rodriguez et al., 2013 Cabedo-Sanz et al., 2013 Stoynova et al., 2013
Highly branched isoprenoids (HBIs)	Marine productivity in sea ice environments.	Promising approach for reconstruction of ice marginal zone in the Southern Ocean.	Calibration and evaluation still needed.	Massé et al., 2011 Collins et al., 2013
Methanesulfonic acid in ice from glaciers and ice sheets	Oxidation product of dimethylsulfide, emitted to air from certain marine phytoplankton associated with sea ice.	No other sources. Gives view of ice cover over region of ocean rather than at single point.	Flux to ice core also influenced by phytoplankton species present, atmospheric oxidation and transport, requiring careful assessment and calibration at each site. Poor preservation in ice at sites with low snow accumulation rates, probably limiting its use to coastal sites and Holocene period. Good calibration achieved for Antarctic sites only so far.	Curran et al., 2003; Abram et al., 2007, 2010, 2013
Sea salt in ice from glaciers and ice sheets	Sea salt, generally measured as sodium, produced strongly over sea ice.	Gives view of ice cover over region of ocean rather than at single point. Well-preserved in ice over long periods, giving potential for ice cover over glacial cycles.	Flux to ice depends on atmospheric transport and deposition as well as ice extent. Relative role of open ocean and sea ice sea salt as well as exact mechanism by which sea ice produces sea salt aerosol not yet clear.	Wolff et al., 2003, 2010; Fischer et al., 2007; Criscitiello et al., 2013

regional to hemispheric scales, while paleoclimatologists and paleoceanographers make reconstructions from coring sites, where small scale processes may obscure the overall picture relevant for the understanding of the global climate system. Furthermore, paleo-records often provide estimates at a relatively low temporal resolution (at scales of 10^2–10^3 years) and could be influenced by extremes conditions more than by small shifts in the mean state. Nevertheless, in spite of these difficulties, the contribution of geoscientists is indispensable for the understanding of long term sea ice dynamics extending the records back to climate states not covered by instrumental data using information captured through isotopic, geochemical, biochemical, sedimentological and microfossil remains.

4. The sea ice proxy (SIP) working group

The reconstruction of sea ice cover in time and space in order to document its natural variability at time scales ranging from decades to millennia is the overarching goal of the Sea Ice Proxies (SIP) working group, which was formally endorsed by PAGES in 2011. A first milestone identified by the group was a proper assessment of the sea ice proxies by addressing a few fundamental questions: What are the links between proxies and the sea ice related parameters? What are the strength and weaknesses of each proxy for reconstructing sea ice? What is the robustness of the relevant calibrations? What are the geographical and temporal ranges of application of the respective proxies? These questions were discussed during the first SIP workshop that was held at GEOTOP, Montreal, in March 2012. The various sea ice proxies in marine sediments and their respective strengths and limitations are briefly summarized in Table 1 and addressed thoroughly in manuscripts of the present volume, which contains a series of methodological papers in addition to examples of application and regional syntheses.

Several manuscripts of the present volume deal with organic biomarkers, notably with IP25, which is a novel approach based on long carbon chains produced by diatoms living in association with seasonal sea ice (cf. Belt et al., 2007). The manuscripts include a review of current understanding of the Arctic sea ice biomarker IP25 and of the related sea ice index called PIP_{25} (Belt and Müller, 2013), regional analyses of surface sediment data from the Barents Sea (Navarro-Rodriguez et al., 2013), the Laptev and Kara seas (Xiao et al., 2013), the Labrador Sea (Weckström et al., 2013) and other circum-Arctic areas (Stoynova et al., 2013), in addition to examples of application to document sea ice changes during the Younger Dryas (Cabedo-Sanz et al., 2013). Although IP25 cannot be used in the circum-Antarctic Ocean as diatom taxa occurrence differs in the Northern and Southern Hemispheres and IP25 does not seem to be produced in the Southern Ocean, there are other biomarkers that may serve as proxies for Antarctic sea ice cover as first proposed by Massé et al. (2011). The status of these new biomarkers, which permit applications in the Southern Hemisphere, is discussed in details by Collins et al. (2013) in the present volume. A case study based on both biomarkers and diatoms from the sediment core off the Antarctic Peninsula provide evidence for major changes in sea ice conditions prior to the instrumental period (Barbara et al., 2013).

The present volume also contains synthesis papers dealing with the use of microfossils as sea ice proxies. These include papers about the organic walled cyst of dinoflagellates (de Vernal et al., 2013a) and benthic foraminifers (Seidenkrantz, 2013). A comprehensive reconstruction of Holocene sea ice variations in the subpolar North Atlantic and Arctic seas is presented based on dinoflagellate cyst data, which suggests contrasted changes in the eastern and western Arctic (de Vernal et al., 2013b). Sea ice cover variations over the Arctic Ocean during the Quaternary are also proposed based on ostracods (Cronin et al., 2013) and foraminifers (Polyak et al., 2013). In both cases, results illustrate that sea ice has been a persistent feature in the Arctic Ocean through the Quaternary despite some fluctuations in the distribution, which still need to be documented on regional scale.

The present volume also discusses non biogenic proxies. One manuscript reviews the use of geochemical proxies from ice cores to document the extent of sea ice around ice caps (Abram et al., 2013). Another deals with geochemical proxies in marine sediments as a means to identify the source of particles carried by sea ice, thus to reconstruct the sea ice drift patterns and the variation in sea ice export towards the Atlantic Ocean (Hillaire-Marcel et al., 2013).

The set of manuscripts presented in this volume clearly demonstrate that sea ice can be reconstructed from various proxies and that geoscientists have the tools to make important contributions for addressing the critical issue of sea ice variations through time, at least during the Quaternary.

5. Sea ice in the global system: modeling challenges

Modeling sea ice in the Earth's system is an important challenge that has to be approached from both physical and biochemical points of views. As presented by Goosse et al. (2013) in the present issue, the models, on average, simulate a sea ice extent in reasonably good agreement with modern observations, at least for the Arctic, although some models have large biases. However, the ability of models to reproduce the mean present state does not guarantee adequate prediction under different forcing as shown both by the simulation of the ongoing sea ice decrease (e.g. Massonnet et al., 2012; Stroeve et al., 2012a,b) and that of past intervals, such as the Last Glacial Maximum and the mid Holocene as shown by Goosse et al. (2013) in this volume. Hence, testing sea ice modeling by comparison with proxy data for past intervals is a very valuable tool for examining processes and gaining confidence with the physical representation of sea ice in the models under different conditions.

In a global biochemical perspective, sea ice is a medium that also deserves special attention. As presented by Vancoppenolle and colleagues in the present volume, the biological activities related to sea ice can be very important and needs to be taken into account in the global carbon budget (Vancoppenolle et al., 2013). Moreover, among many processes, the export of inorganic carbon to the deep ocean by brine formation possibly plays a key role in the carbon global carbon cycle, thus potentially influencing atmospheric CO_2 concentrations.

6. The next step: towards multiproxy reconstruction of sea ice cover

The reconstruction of past sea ice is relevant for testing and evaluating climate and Earth System models as done within the framework of international program such as the Paleoclimate Model Intercomparison Project (PMIP) or Past4Future (cf. Dahl-Jensen et al., 2013). However, while testing models requires a global view of past conditions, most proxies have a regional significance. This is especially true for biogenic proxies because of the differential evolution of biocenoses in the Arctic and circum-Antarctic realms during the Cenozoic that results in distinct assemblages of boreal and austral species. Even at the scale of the Northern Hemisphere, taxonomic departures between the subpolar North Pacific and subpolar North Atlantic are observed for most biological proxies (e.g. Bonnet et al., 2012) probably because of the Bering Strait that acted as a physiographical barrier. Moreover, the habitat adaptability of organisms and their dependence on several environmental parameters means that few taxa may be considered as sea ice markers. Hence, approaches based on biogenic proxies, including microfossils and organic biomarkers, cannot be used unequivocally at global or hemispheric scales and regional calibrations are often required (cf. Stoynova et al., 2013).

Each proxy for reconstructing sea ice offers advantages and disadvantages due to its respective distribution and its preservation through time. The strength and usefulness of each proxy as a sea ice indicator may also differ in time and space and depending on the sea ice parameter considered. From this point of view, sea ice proxies are complementary. In order to reconstruct past sea ice cover with confidence and the best possible data coverage at hemispheric scales, a multiproxy strategy should be developed. This will be the focus of the SIP working group in the forthcoming years.

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