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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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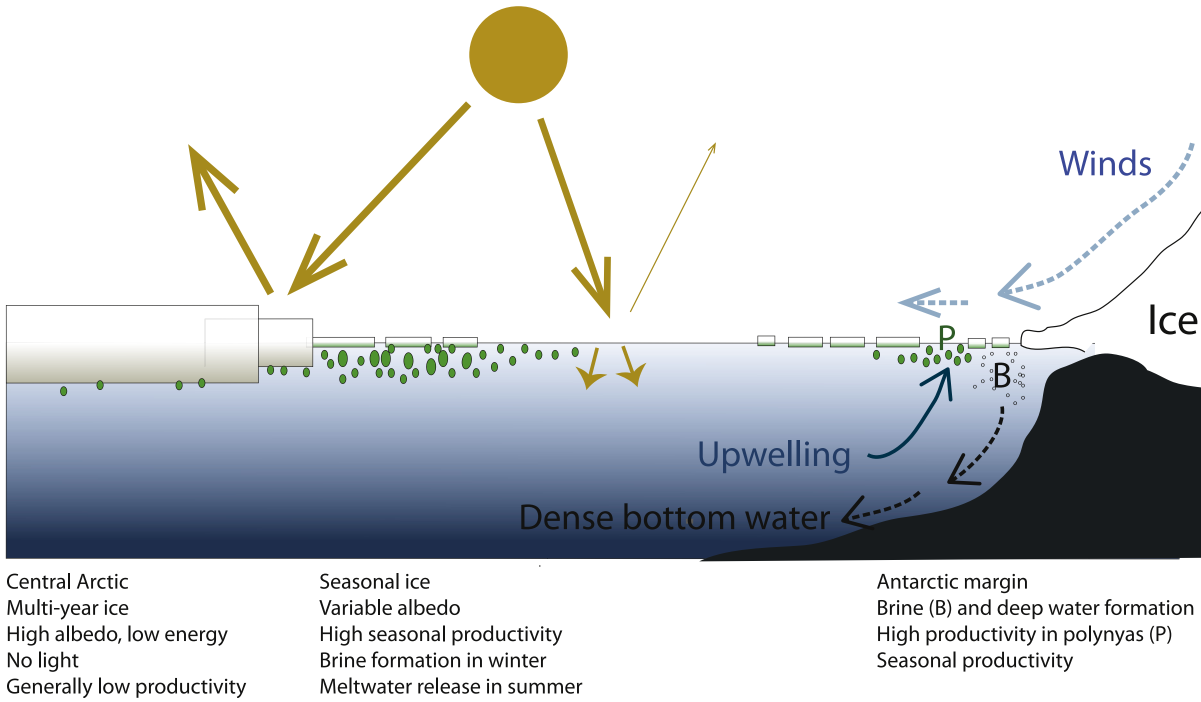

Fig. 1. Simplified scheme of the role of sea ice in the climate and ocean system, including Arctic (left) and circum-Antarctic (right) areas, showing solar energy (yellow arrows), katabatic winds (light blue arrow), ocean processes such as upwelling and brine (B) formation, polynyas (P) and primary production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