Reconstruction of past sea ice extent

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Past sea ice extension is a critical component of the Earth's climate system. Reconstructions relying on geochemical, sedimentological and microfossil-based proxy records in ice and sediment climate archives are presented here.

On August 27, 2012 the US National Snow & Ice Data Center (NSIDC, http://nsidc.org/arcticseaicenews/) and the National Aeronautics and Space Administration (NASA, http://www.nasa.gov/topics/earth/features/arctic-seaice-2012.html) alerted the public about the lowest Arctic summertime sea ice extent measured since the satellite-based sea ice survey was started in the late 1970s. The observed August 2012 minimum sea ice extent of 4.1×10^6 km^2 confirms the ongoing decline of perennial Arctic sea ice, which potentially began in the middle of the last century (Kinnard et al. 2008). The decline reached 2 to 3% per decade between 1979 and 1996 and accelerated to 12 to 13% per decade since then (Comiso 2012). This rapid loss of sea ice, higher than anticipated by the forecasts of the IPCC 2007 report (Stroeve et al. 2007), may lead to the disappearance of summer Arctic sea ice by 2050 if not earlier, according to several model simulations (Wang and Overland 2009). Arctic sea ice decline, which is related to Arctic surface water temperature increase (Comiso 2012), represents a striking example of current climate change related to anthropogenic global warming (Spielhagen et al. 2011; Kinnard et al. 2011).

Although sea ice is generally restricted to high latitudes, its formation, extent and seasonal variability play a critical role in the Earth´s climate and ocean dynamics at global and regional scales, affecting surface albedo, the exchange of energy fluxes between ocean and atmosphere, thermohaline ocean circulation and formation of deep water masses, primary and export productivity, and weather system formation (e.g. Budikova 2009) (Fig. 1A). Sea ice is a fast changing environmental component of the Earth system (Fig. 1B) and effectively amplifies climate and environmental change due to positive feedback mechanisms. The recent changes in Arctic sea ice extent are of concern to scientists and policy-makers, and this topic is regularly reported in the media. Thus we need to further extend sea ice records into the past to document the natural variability of sea ice beyond short term satellite measurements to better understand the recently observed changes and enhance our ability to perform projections of future sea ice extent.

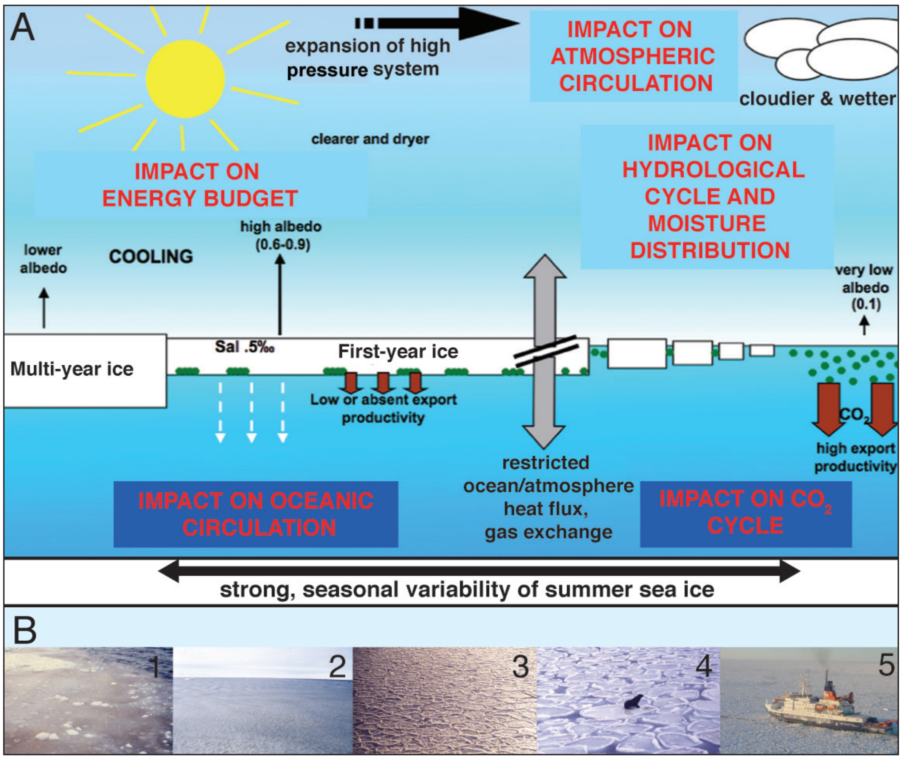

Figure 1: ***A)*** *Schematic representation of major sea ice related environmental and climatic parameters (adapted from Gersonde and Zielinski 2000).* ***B)*** *Photo gallery showing the development of Antarctic sea ice (a fast changing environmental factor) from frazil ice (1) to aggregation of ice crystals (2) to form pancake ice (3), freezing and rafting of pancake ice (4, see fur seal for comparison) to form a close ice cover (5, crossed by the German research vessel ice breaker Polarstern). The different steps of this process take only a few days to weeks. Photos: R. Gersonde.*

Historical sea ice records

At the hemispheric scale, sea ice reconstructions for historical periods predating the start of satellite surveys are hampered by the lack of observational datasets. Nevertheless, Kinnard et al. (2008) extended the observation-based record of Arctic sea ice back to 1870 AD. This was mainly based on statistical analysis of ice edge position data. The record was then extended to 560 AD based on a high-resolution multi-proxy approach using ice, terrestrial, and marine records. This historical record demonstrates that the observed modern decline of sea ice has been unprecedented for the past 1,450 years (Kinnard et al. 2011). Rayner et al. (2003) simulated Arctic and Antarctic sea ice and their seasonal variability back to 1856 AD, taking into account historical observations and modern climatologies. Their analysis indicates reductions in Antarctic sea ice extent by the middle of the last century; a result supported by a comprehensive study of whaling positions (de la Mare 2009) and ice core proxy records (Abram et al. 2010). Such a finding is puzzling, since satellite-derived information indicates a slight increase in Antarctic sea ice (about 1% per decade) during the past 40 years (Turner et al. 2009).

Sea ice on geological time scales

Sea ice reconstructions on geological timescales rely on indirect observations obtained from marine and ice core records. Various proxies have been developed to estimate sea ice extent, concentration, annual occurrence, and seasonal pattern. However, each proxy has its own limitations. While winter sea ice extent can be reconstructed somewhat accurately with a number of proxies, estimating the extent of the perennial sea ice field remains challenging. Moreover, while the analyses of cores may yield time series at given locations, the reconstruction of sea ice extent in space with the position of maximum and minimum limits requires densely distributed data. Consequently, comprehensive glacial/interglacial reconstructions require combining different proxy records and consideration of sedimentation patterns to map sea ice extent and its variability.

Sea ice proxies include chemical tracers in ice cores and biogenic remains of microorganisms as well as non-biogenic particles in marine records. Flux rates of methanesulfonic acid (MSA) and sea salt sodium in ice cores are used to reconstruct past sea ice extent (e.g. Becagli et al. 2009; Wolff et al. 2006) but their interpretation is equivocal and more studies are needed to understand and calibrate these proxies (Abram et al. 2010). Marine reconstruction methods include the use of microfossil marker species, transfer functions based on microfossil assemblages, stable isotope signals, biomarker and terrigenic particles. Specific diatom species are able to dwell in sea ice, attached to it or within sea ice governed cold-water environments (less than -1.5°C). Some of these species produce biomarkers or secrete siliceous valves that can be preserved in the sediment record. For example, a proxy to reconstruct past Arctic sea ice is the IP25 biomarker (a C25 mono-unsaturated highly branched isoprenoid lipid) (Belt et al. 2007). IP25 is produced by a sea ice-related diatom, which secretes thinly walled siliceous valves generally not preserved in the sedimentary record. To better quantify sea ice occurrence, Müller et al. (2011) have proposed using a combination of IP25 and a phytoplankton productivity proxy. The occurrence of IP25 is restricted to the polar North (e.g. Müller et al. 2009). A similar biomarker has recently been proposed for reconstruction of Antarctic sea ice (Massé et al. 2011).

The abundance pattern of sea ice related diatom species preserved in the sediment record represents a powerful tool for Southern Ocean sea ice reconstruction. While early work (Hays et al. 1976) simply used the boundary of diatom-rich and diatom-poor sediments for the mapping of the sea ice extent at the Last Glacial Maximum (LGM), later studies considered the composition of diatom assemblages and reconstructed sea ice quantitatively as expressed by the annual duration (month per year) of sea ice occurrence using a diatom transfer function (Crosta et al. 1998). A combination of different diatom-based methods allowed the first comprehensive circum-Antarctic reconstruction of the LGM winter and summer sea ice distribution as part of the MARGO project to be realized (Gersonde et al. 2005; Fig. 2A).

In Northern Hemisphere high latitudes, the use of diatoms, however, is often restricted by silica dissolution. Some reconstructions from Quaternary sediments are nevertheless available for the North Atlantic (e.g. Justwan and Koç 2008), the Labrador Sea and the polar North Pacific. In contrast, organic-walled dinoflagellate cysts display a broad distribution pattern and are usually well-preserved in sediment. They have successfully been used for past sea ice reconstructions (e.g. de Vernal et al. 2005, 2008) documenting the LGM sea ice distribution in the North Atlantic (Fig. 2B). Other potentially useful proxies include ostracode species that live parasitically on sea ice-related amphipods (Cronin et al. 2010), the isotopic signature of a sea ice-related planktic foraminifer species (Hillaire-Marcel and de Vernal 2008), and the relationship between sea surface temperatures derived from the planktic foraminiferal assemblage record and sea ice occurrence (Sarnthein et al. 2003). Finally, the application of different sedimentological proxies for reconstruction of Arctic sea ice and its transport pathways has been attempted (Stein 2008). An interesting combination of terrigenic components (ice-rafted debris) and the occurrence of an extinct diatom species, which may be related to an extant sea ice-related diatom genus, has been used for the establishment of a two-million-year sea ice record which occurred in the middle Eocene Arctic Ocean (Stickley et al. 2009).

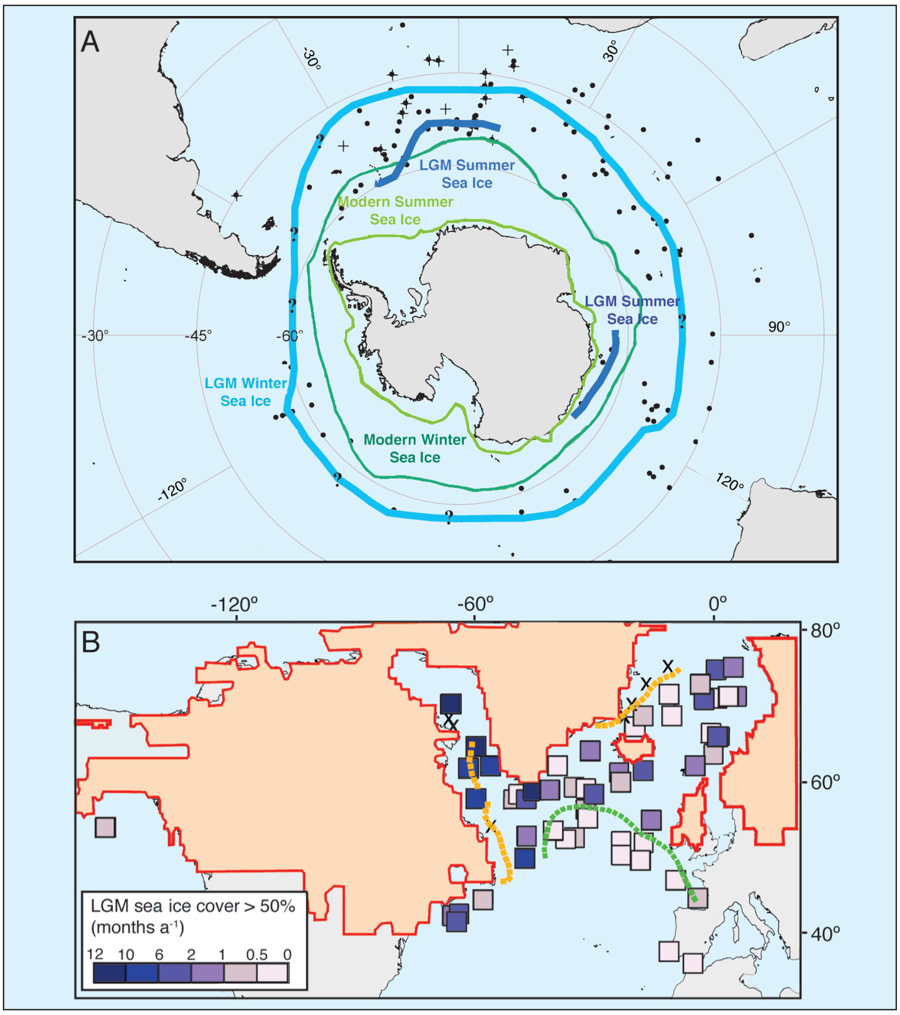

*Figure 2: **A)** Reconstruction of Antarctic winter and summer sea ice extents during the Last Glacial Maximum based on diatom proxies (blue lines). For comparison modern winter and summer sea ice extents are indicated (green lines). The LGM reconstruction in the Pacific sector and the Drake Passage are weak because of the small number of available cores at the time of data compilation. Dots indicate locations with diatom-based reconstruction, crosses indicate locations with radiolarian-based reconstruction (modified from Gersonde et al. 2005). **B)** Reconstruction of sea ice cover in the North Atlantic during the Last Glacial Maximum based on organic walled dinoflagellates. The orange and green dashed lines correspond to the probable limits of summer (perennial) and winter sea ice limits, respectively (modified from de Vernal et al. 2005).*

Outlook

In the framework of the Past4Future project, bipolar reconstructions, derived from several of the proxies described above, are generated to enhance our knowledge of sea ice variability during the present and last interglacial stages and the preceding glacial/interglacial transitions. The challenge to produce time series of sea ice extent into past warmer than present climates and to study natural sea ice variability under such conditions is central to the Sea Ice Proxy (SIP) working group supported by PAGES (de Vernal et al. 2012).

Selected references

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http://www.pages-igbp.org/products/newsletters/ref2012_3pdf

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