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New tools for the reconstruction of Pleistocene Antarctic sea ice

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ABSTRACT

Based on the quantitative analysis of diatom assemblages preserved in 274 surface sediment samples recovered in the Pacific, Atlantic and western Indian sectors of the Southern Ocean we have defined a new reference database for quantitative estimation of late-middle Pleistocene Antarctic sea ice fields using the transfer function technique. The Detrended Canonical Analysis (DCA) of the diatom data set points to a unimodal distribution of the diatom assemblages. Canonical Correspondence Analysis (CCA) indicates that not only winter sea ice (WSI) but also summer sea surface temperature (SSST) represent the most prominent environmental variables that control the spatial species distribution. To test the applicability of transfer functions for sea ice reconstruction in terms of concentration and occurrence probability we applied four different methods, the Imbrie and Kipp Method (IKM), the Modern Analog Technique (MAT), Weighted Averaging (WA), and Weighted Averaging Partial Least Squares (WAPLS), using logarithm-transformed diatom data and satellite-derived (1981–2010) sea ice data as a reference. The best performance for IKM results was obtained using a subset of 172 samples with 28 diatom taxa/taxa groups, quadratic regression and a three-factor model (IKM-D172/28/3q) resulting in root mean square errors of prediction (RMSEP) of 7.27% and 11.4% for WSI and summer sea ice (SSI) concentration, respectively. MAT estimates were calculated with different numbers of analogs (4, 6) using a 274-sample/28-taxa reference data set (MAT-D274/28/4an, -6an) resulting in RMSEP ranging from 5.52% (4an) to 5.91% (6an) for WSI as well as 8.93% (4an) to 9.05% (6an) for SSI. WA and WAPLS performed less well with the D274 data set, compared to MAT, achieving WSI concentration RMSEP of 9.91% with WA and 11.29% with WAPLS, recommending the use of IKM and MAT. The application of IKM and MAT to surface sediment data revealed strong relations to the satellite-derived winter and summer sea ice field. Sea ice reconstructions performed on an Atlantic- and a Pacific Southern Ocean sediment core, both documenting sea ice variability over the past 150,000 yr (MIS 1–MIS 6), resulted in similar glacial/interglacial trends of IKM and MAT-based sea-ice estimates. On the average, however, IKM estimates display smaller WSI and slightly higher SSI concentration and probability at lower variability in comparison with MAT. This pattern is a result of different estimation techniques with integration of WSI and SSI signals in one single factor assemblage by applying IKM and selecting specific single samples, thus keeping close to the original diatom database and included variability, by MAT. In contrast to the estimation of WSI, reconstructions of past SSI variability remain weaker. Combined with diatom-based estimates, the abundance and flux pattern of biogenic opal represents an additional indication for the WSI and SSI extent.

1. Introduction

Although restricted to polar regions, sea ice represents a critical component of global climate and ocean dynamics. Sea ice is a fast changing variable, displaying strong seasonal oscillation. It modulates the energy budget and the exchange of vapor and trace gases at the surface of the ocean. Sea ice contributes to the formation of water masses by injecting salt into the underlying ocean, thus affecting the ocean stratification via freshwater deposition at the ocean's surface. Sea ice also represents a habitat and environment for specifically adapted organisms and has an impact on primary and export productivity. Major factors controlling the seasonality and extent of Antarctic sea ice include surface air temperature, wind, ocean currents and sea surface temperature. Interactions between the seasonal cycle of solar insolation, temperatures that drive the freezing and melting of ice, and shifts in the large-scale atmospheric circulation lead to non-linear sea ice dynamics (Zwally et al., 2002).

The unexpected magnitude of summer sea ice reduction in the Arctic Ocean observed during the last decade via satellite observations (Comiso et al., 2008), which culminated in August–September 2012 (Showstack, 2012), has strongly increased the scientific interest in sea ice observation and research, as well as alerting the media, policy makers and economists. The fast loss in sea ice is greater than anticipated in the IPCC 2007 forecasts (Stroeve et al., 2007). The reduction is commonly seen as a result of anthropogenic warming, and affects recent weather and climate trends through retroactive feedbacks (Dethloff et al., 2006). Hemispheric-scale sea ice reconstructions for historical periods predating satellite surveys are hampered by the broad lack of observation data. Rayner et al. (2003) have estimated

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Arctic and Antarctic sea ice and its seasonal variability by considering historical observations and modern climatologies back to 1856 AD. The analysis suggests distinct reductions in the Antarctic sea ice extent mid of the past century, a result that is also supported by studies of whaling positions (Cotté and Guinet, 2007; de la Mare, 2009) and ice core proxy records (Curran et al., 2003; Abram et al., 2010). Such findings are rather puzzling, since satellite derived information indicates an increase of approximately 1% per decade during the past 40 yr (Parkinson and Cavalieri, 2012). The latter pattern has been related to anthropogenic effects leading to stratospheric ozone depletion (Turner et al., 2009) and global warming, which in turn affects the Southern Hemisphere wind field pattern (Holland and Kwok, 2012) as well as the surface water salinity (Bintanja et al., 2013). In most numerical models trends in the historical sea ice extent are mainly driven by greenhouse gas forcing rather than ozone forcing (Sigmond and Fyfe, 2014). Since comprehensive data on annual and seasonal sea ice variability and related trends have been restricted to systematic satellite observations since 1978, it remains difficult to generate a full understanding of sea ice dynamics at various climate states. As such, efforts to further enhance our knowledge about sea ice development on historical and geological time scales are highly relevant.

Here we focus on the reconstruction of past Antarctic sea ice. Previous studies on this topic have emphasized the abundance pattern of diatoms, specific diatom species or diatom assemblages as representing a powerful tool for past sea ice reconstruction in the sediments of the Southern Ocean. Early works (e.g. Hays et al., 1976; DeFelice, 1979; Burckle et al., 1982; Cooke and Hays, 1982; Burckle, 1983) used the boundary of diatom-rich and diatom-poor sediments for mapping the sea ice extent. A close relationship between the southern extent of the diatom ooze belt (Burckle, 1984a) and the maximum WSI is questioned, however, by Armand and Leventer (2010). Burckle (1984a) and Burckle et al. (1990) proposed the abundance pattern of the diatom species *Eucampia antarctica* as a sea ice indicator, while Kaczmarska et al. (1993) defined a *Eucampia*-index calculated as the ratio of winter terminal to intercalary valves to trace the winter sea-ice field. Whitehead et al. (2005) enhanced the latter approach by calibrating the index with satellite-derived sea ice data. Leventer (1992) and Leventer et al. (1993) suggested the relative abundance of *Chaetoceros* and the ratio of *Chaetoceros* resting spores to vegetative cells to be a potential tool for sea ice reconstruction. Pike et al. (2009) suggested that the relationship between resting spores of *Porosira glacialis* and *Thalassiosira antarctica* has a potential as a semi-quantitative sea ice proxy. Crosta et al. (1998a, b) accomplished major progress in Antarctic sea ice reconstruction with the establishment of a diatom assemblage-based transfer function using the Modern Analog Technique (MAT). For the first time, this allowed a quantitative reconstruction of sea ice duration in terms of months per year coverage. Whitehead and McMinn (2002) proposed another statistical approach to determine diatom assemblages for sea ice reconstruction using the Bray–Curtis Cluster Analysis. Gersonde and Zielinski (2000) presented data on the timing and magnitude of diatom sea ice signal transfer through the water column, as well as its distribution in the surface sediment record. This was used to define indices for a qualitative estimation of past winter and summer sea ice extent while also considering preservation and biogenic sediment accumulation. The data obtained for the sea ice signal transfer suggest that the signal preserved in the sediment record is not directly related to the annual duration of sea ice coverage but rather to the presence/absence pattern of sea ice at a given site. This observation implies that the first-order relationship between sea ice and diatom signals preserved in the sediment record is more likely represented by the probability of sea ice occurrence rather than by sea ice duration (e.g. month per year). A comprehensive summary of the reconstruction methods and their application is presented by Armand and Leventer (2010). All these reconstruction methods rely on the fact that specific diatom species are adapted to use sea ice as a habitat (e.g. Arrigo et al., 2010) and that some of them produce valves that are well enough silicified to be preserved in the sediment record. As such, diatoms represent the only microorganisms directly related to Antarctic sea ice as a habitat that are preservable in marine sediments, with the exception of the foraminifer *Neogloboquadrina pachyderma* (e.g. Spindler and Dieckmann, 1986) and the cyst of the dinoflagellate *Islandinium minutum* (Zonneveld et al., 2013).

We present new diatom calibration sets of surface sediment samples recovered from the Indian, Atlantic and Pacific sectors of the Southern Ocean (SO) (Fig. 1), representing the base for quantitative reconstructions of past winter and summer sea ice occurrence probability and concentration by applying transfer function (TF) techniques. We have selected two techniques, (1) the classical Imbrie and Kipp Method (IKM; Imbrie and Kipp, 1971), which generates a single calibration formula between the diatom counts and the environmental parameters and (2) the Modern Analog Technique (MAT; Hutson, 1980), which searches for best analogs between the surface sediment reference and the down-core assemblage for calculating past environmental conditions. In addition, we tested the diatom reference data with two alternative statistical methods, which are based on the assumption of a unimodal species–environment response model: Weighted Averaging (WA; Birks et al., 1990) and Weighted Averaging Partial Least Squares (WAPLS; ter Braak and Juggins, 1993). The applicability and limitations of the new data sets and the different TF techniques for winter and summer sea ice reconstruction were tested on surface sediment sample sets and two down-core records retrieved from the Atlantic and the Pacific sectors of the SO, respectively, both documenting the past approx. 150 ka (ka = 10^3 yr). This was combined with observations on the relationship between sea ice occurrence and biogenic opal sedimentation pattern to further constrain the significance of sediment deposition signals for sea ice reconstruction purposes. With our approach, we aimed to greatly enhance the capability of reconstructing quantitative Antarctic sea ice using the diatom signal recorded in late-middle Pleistocene sediments.

2. Material and methods

2.1. Samples, preparation and counting

To generate a new diatom calibration set for sea ice reconstruction the diatom assemblage data from 315 surface samples recovered in the Atlantic, the western Indian, and the Pacific sectors of the SO were examined and tested for their applicability to TF-based sea ice estimates. This includes data sets obtained from 133 sites in the Atlantic and western Indian sectors from Zielinski and Gersonde (1997), 39 sites in the southeastern Pacific sector (Esper et al., 2010), 40 sites in the Ross Sea (Cunningham and Leventer, 1998), 38 sites off the Georg V Coast (Leventer, 1992), together with data established within this study from 65 sites in the Atlantic and Pacific sectors. The majority of the surface sediment samples were recovered with a large box corer, a multiple corer, and a mini corer (Zielinski and Gersonde, 1997; Esper et al., 2010; Gersonde, 2011). Samples added from the Ross Sea and the George V Coast represent trigger-, box-, and kasten corer tops (Cunningham and Leventer, 1998) or were grab samples (Leventer, 1992) (for more detailed information on the samples see Appendix A). All samples represent the upper 0.5 to 1 cm of surface sediment.

For our down-core testing of the TFs we selected Core PS1768-8 recovered in the Antarctic Zone of the eastern Atlantic sector of the SO (52°35.6′S, 4°28.6′E; water depth 3270 m) and Core PS58/271-1 from the southern Polar Front Zone in the eastern Pacific sector (60°62.0′S, 115°87.0′W; water depth 5139 m). Both core sites are located north of the present winter sea ice edge (Fig. 1). The diatom counts and the age model of the 9.03 m long piston core PS1768-8 are taken from Zielinski et al. (1998) and Frank et al. (1996), respectively. The diatom assemblage composition of the 24.5 m long piston core PS58/271-1 has been established as being part of the present study at a sample