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New Evidence for Abrupt Sea-Ice Fluctuations in the Subpolar North Atlantic at the End of the Last Glacial in Relation with Thermohaline and Atmospheric Circulation

by Juliane Müller*

Abstract: A temporally highly resolved reconstruction of sea-ice conditions in eastern Fram Strait, using the sea-ice proxy IP_{25}, sheds new light on potential feedback mechanisms between sea-ice variability and ocean circulation changes during rapid deglacial climate shifts. While a post-LGM sea-ice maximum probably played an important role for the timing of Heinrich Event 1, distinct sea-ice discharge events seem to be intrinsically tied to perturbations in the oceanic overturning circulation. The herein presented sea-ice record is the hitherto only continuous documentation of sea-ice changes in the subpolar North Atlantic that covers the transition from the last glacial into the Holocene. These data strengthen the need for more studies of high-resolution sediment cores to better assess the short-term palaeoenvironmental development and the feedback mechanisms between sea-ice variability and oceanic/atmospheric circulation fluctuations during this crucial time of climate change.

Zusammenfassung: Eine auf dem Meereisproxy IP_{25} basierende, zeitlich hochauflösende Rekonstruktion der Meereisbedingungen in der östlichen Framstraße wirft ein neues Licht auf mögliche Wechselwirkungen zwischen Meereisschwankungen und Veränderungen der Ozeanzirkulation während schneller deglazialer Klimaänderungen. Während ein post-LGM Meereismaximum wahrscheinlich eine wichtige Rolle für den Beginn von Heinrich-Ereignis 1 gespielt hat, scheinen Intervalle eines verstärkten Meereisexports untrennbar mit der Schwächung der ozeanischen Umwälzzirkulation verbunden zu sein. Der hier präsentierte Datensatz ist die bisher einzige durchgehende Dokumentation der Meereisveränderungen im subpolaren Nordatlantik während des Übergangs vom letzten Glazial in das Holozän. Diese Daten belegen den Bedarf an weiteren Studien an ähnlich zeitlich hochaufgelösten Sedimentkernabfolgen, um die kurzzeitige Entwicklung der Paläoumweltbedingungen und die Wechselwirkungen zwischen Meereisveränderungen und der ozeanisch/atmosphärischen Zirkulation während dieser Zeit häufiger Klimaschwankungen besser abschätzen zu können.

INTRODUCTION

Arctic sea ice is a crucial element within the global climate system. It has a direct influence on thermohaline processes (governing ocean circulation) and the oceanic-atmospheric heat and gas exchange with considerable effects on atmospheric circulation and precipitation patterns (DIECKMANN & HELLMER 2003). Reconstructions of the spatial-temporal variability of sea ice in the geological past provide important information on ocean-atmosphere feedback mechanisms and thus support a more detailed assessment of natural (i.e. non-anthropogenically induced) climate changes. In particular, the transition from the last glacial into the current interglacial was accompanied by significant climate perturbations. Only few studies, however, address the role that sea ice might have played during these (often abrupt) climate shifts. The sea-ice biomarker IP_{25} is an organic molecule exclusively produced by sea-ice diatoms and a robust indicator of previous sea-ice coverage when identified in marine sediments (BELT et al. 2007, BROWN et al. 2014). Several studies from the (sub) Arctic Ocean strengthen the reliability of IP_{25} but also highlight the need for the complementary analysis of phytoplankton-derived biomarkers for an unambiguous and more quantitative reconstruction of the sea-ice conditions by means of the PIP_{25} index (MÜLLER et al. 2011, STEIN et al. 2012, KNIES et al. 2014, XIAO et al. 2015). This index combines the environmental information of the sea-ice proxy IP_{25} and a phytoplankton biomarker – indicative of ice-free conditions – and provides a semi-quantitative estimate of the intensity of a paleo sea-ice cover (see BELT & MÜLLER 2013 for further details). The Fram Strait, the only deep-water passage connecting the Arctic and the Atlantic Ocean and the major outlet for the export of sea ice into the North Atlantic (KWOK et al. 2004), is a strategic study area to identify past changes in sea-ice export associated with climate shifts. Sediment core MSM5/5-712-2 from the western continental margin of Svalbard provides an exceptional high temporal resolution. Organic geochemical analyses of this core hence enabled a detailed reconstruction of the variable sea-ice conditions during the past 30 ka BP (i.e. 30,000 years before present, MÜLLER et al. 2012, MÜLLER & STEIN 2014). Analytical details and the calculation of the P_BIP_{25} index are described in MÜLLER & STEIN (2014).

RESULTS AND DISCUSSION

Distinct short-term fluctuations in the biomarker content of MSM5/5-712-2 reveal that the late glacial period and the Last Glacial Maximum (LGM; 23-19 ka BP) were characterised by recurrent advances and retreats of sea ice at the core site (see Müller & Stein 2014 for further discussion), which is in good agreement with earlier observations of a variable North Atlantic heat flow (WEINELT et al. 2003) and seasonally ice free conditions in the Norwegian Sea (DE VERNAL et al. 2006). These frequent oscillations in sea-ice cover (and associated changes in the heat and moisture flux) might have played an important role for the sustained growth of the Svalbard-Barents Sea Ice Sheet during the LGM.

A sudden rise towards maximum P_BIP_{25} values at 19.2 ka BP points to a significant increase in the sea-ice cover at the end of the LGM (Fig. 1). Probably in direct response to the onset of meltwater discharge from disintegrating ice sheets that covered Eurasia and North America (CLARK et al. 2004) and a significant

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* Alfred Wegener Institute, Helmholtz Centre for Polar and Marine Re-search, Am Alten Hafen 26, 27568 Bremerhaven, Germany, <juliane.mueller@awi.de>

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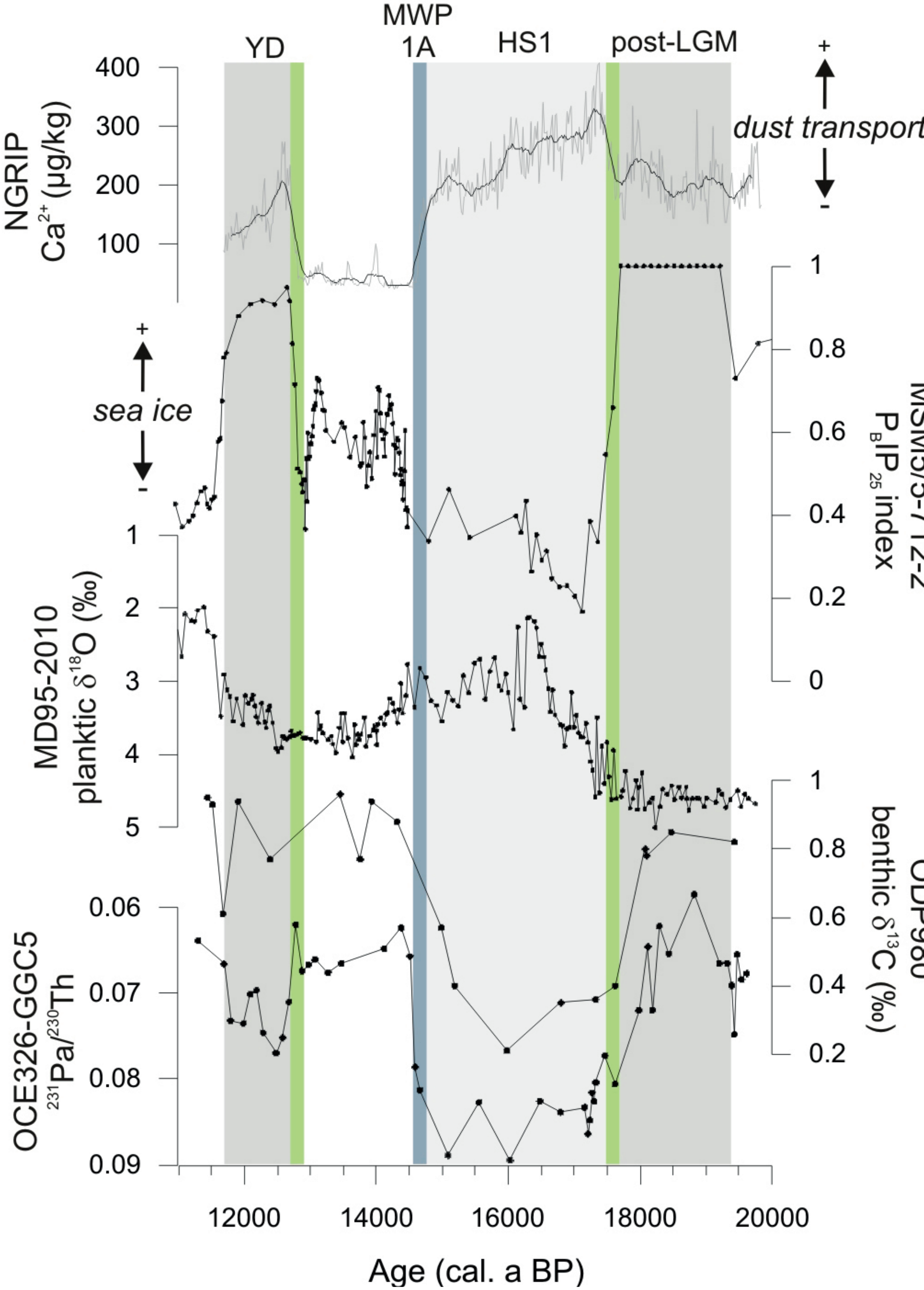

Fig. 1: Compilation of proxy data documenting deglacial changes in the Greenland ice core dust content (Ca^{2+}), sea-ice cover (P_BIP_{25}) in Fram Strait, ocean surface freshening ($\partial^{18}O$) at the Vøring Plateau, ocean ventilation ($\partial^{13}C$) in the eastern North Atlantic and AMOC (Atlantic Meridional Overturning Circulation) strength ($^{231}Pa/^{230}Th$) in the subtropical North Atlantic.

Abb. 1: Zusammenstellung von Proxydaten über deglaziale Änderungen im Staubgehalt in grönländischen Eiskernen (Ca^{2+}), in der Meereisbedeckung (P_BIP_{25}) in der Framstraße, in der Ozeanaussüßung ($\partial^{18}O$) am Vøringplateau, in der Ozeanventilierung ($\partial^{13}C$) im östlichen Nordatlantik und in der Stärke der AMOC (Atlantic Meridional Overturning Circulation) ($^{231}Pa/^{230}Th$) im subtropischen Nordatlantik.

salinity decrease of Arctic Ocean surface waters, a long lasting and perennial sea-ice cover developed. A southward expansion of this post-LGM sea-ice maximum into the subpolar North Atlantic (Fig. 2) and the formation of landfast sea ice might have reduced the further calving of icebergs from the adjacent ice sheets or, at least, it would have hampered the mobility of floating icebergs. Importantly, such a perennial sea-ice cover could have promoted an unusual heat accumulation in intermediate water depths CRONIN et al. 2012) which supports MARCOTT et al. (2011) who argued that only a subsurface warming in the subpolar North Atlantic could have triggered the massive release of icebergs from the Laurentide Ice Sheet during Heinrich Event 1 (17.5–16.8 ka BP, HEMMING 2004, MCMANUS et al. 2004). A post-LGM sea-ice maximum thus could have been a crucial prerequisite for such a scenario. By reducing the drift and thus the export of sea ice through Fram Strait, atmospheric blocking conditions could have favoured the accumulation of such a perennial (and "immobile") sea-ice cover in the Arctic Ocean (SCHOLZ et al. 2015).

An abrupt decline in P_BIP_{25} values at 17.6 ka BP, eventually marks a break-up of the post-LGM perennial sea ice and the return of ice-free summers in eastern Fram Strait during Heinrich Event 1 (Figs. 1, 2). At the same time, decreasing $\partial^{18}O$ values recorded at the Vøring Plateau (MD95-2010; DOKKEN & JANSEN 1999) reveal a rapid sea surface freshening in the Norwegian Sea that probably lead to a strong stratification and a reduced ocean ventilation as is indicated by a significant drop in benthic $\partial^{13}C$ values observed at ODP site 980 (Figs. 1, 2; MCMANUS et al. 1999). A rise in the $^{230}Pa/^{231}Th$ ratio in a sediment core from the subtropical North Atlantic finally depicts a large-scale weakening of the Atlantic Meridional Overturning Circulation (AMOC) during Heinrich Stadial 1 (Figs. 1, 2; MCMANUS et al. 2004). In regard of these observations it might be concluded that the abrupt break-up of a perennial sea-ice cover and the subsequent discharge of huge amounts of sea ice and icebergs into the North Atlantic very likely intensified the AMOC slow-down and/or the displacement of the locus of deep-water formation during Heinrich Stadial 1. At this stage, however, only sensitivity experiments performed with climate models may allow to disentangle (and quantify) the individual contribution of sea ice and icebergs to this AMOC perturbation. Interestingly, the sea-ice break-up coincides with a shift towards higher Calcium ion concentra-

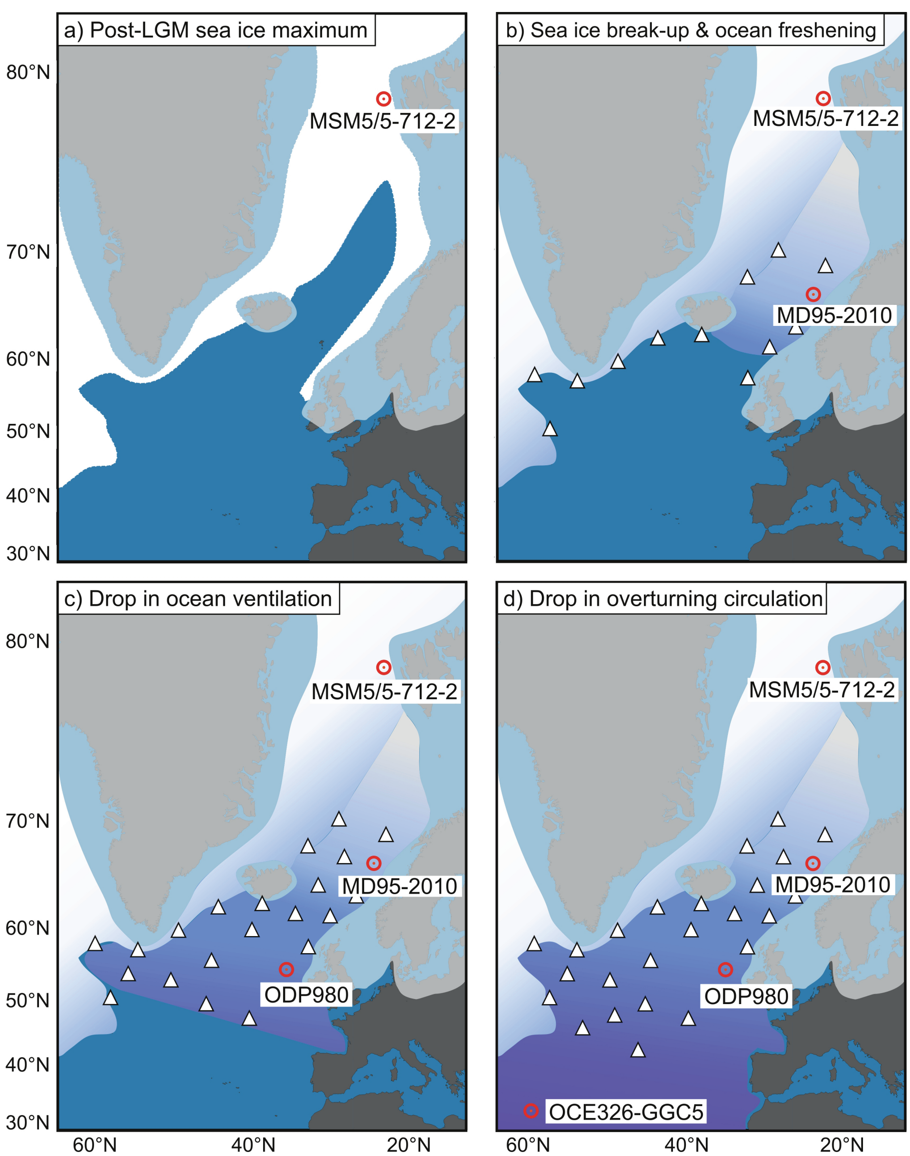

Fig. 2: Proposed scenario for the palaeoceanographic evolution in the subpolar North Atlantic during Heinrich Event 1. Extent of the Greenland, Iceland and Fennoscandian Ice Sheet (after MANGERUD et al. 2004, DYKE et al. 2002) and core sites of proxy records discussed in the text are indicated. White triangles refer to iceberg discharge.

Abb. 2: Mögliches Szenario der paläozeanographischen Entwicklung im subpolaren Nordatlantik während Heinrich-Ereignis 1. Die Ausdehnung der grönländischen, isländischen und fennoskandischen Eisschilde (nach MANGERUD et al. 2004, DYKE et al. 2002) und die Kernpositionen der Proxy-Datensätze, die im Text diskutiert werden sind angedeutet. Weiße Dreiecke zeigen den Eisbergtransport an.

tions (Ca^{2+}) in the NGRIP ice core (Fig. 1; RASMUSSEN et al. 2008). Variations in the Ca^{2+} content in ice cores are commonly interpreted to reflect variability in atmospheric dust transport in response to aridity changes in the source areas and/or atmospheric circulation patterns and wind strength (FISCHER et al. 2007, MCGEE et al. 2010). The rapid rise in the NGRIP dust content hence might be related to a strengthening of the westerlies, which, by carrying relatively warm air towards the subpolar North Atlantic, could have promoted the 17.6 ka sea-ice break-up. Further decreasing $\partial^{18}O$ values at the Vøring Plateau (reflecting a sustained freshening of the sea surface, DOKKEN & JANSEN 1999) are accompanied by continuously increasing P_BIP_{25} values that mark a successive re-expansion of sea ice in northern Fram Strait since 17.2 ka BP. Similar to the intensification of sea-ice coverage during the sea-level rise at 19 ka BP, this recovery seems to be boosted by another meltwater pulse 1A at ca. 14.6 ka BP (MWP-1A; DESCHAMPS et al. 2012) and potentially decreasing westerlies (Fig. 1).

A second sea-ice maximum prevailed at the core site during the Younger Dryas and coincided with another perturbation of the AMOC depicted by the $^{230}Pa/^{231}Th$ record from the subtropical North Atlantic (Fig. 1). In contrast to the perennial post-LGM "sea-ice plug", the Younger Dryas sea-ice maximum seems to result from an enormous discharge of drift ice via Fram Strait, which agrees with earlier observations of an increased export of sea ice into the subpolar North Atlantic (BRADLEY & ENGLAND 2008, NOT & HILLAIRE-MARCEL 2012, CABEDO-SANZ et al. 2013; see MÜLLER & STEIN 2014 for further discussion).

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