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Arctic Ocean glacial history☆

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ABSTRACT

While there are numerous hypotheses concerning glacial–interglacial environmental and climatic regime shifts in the Arctic Ocean, a holistic view on the Northern Hemisphere's late Quaternary ice-sheet extent and their impact on ocean and sea-ice dynamics remains to be established. Here we aim to provide a step in this direction by presenting an overview of Arctic Ocean glacial history, based on the present state-of-the-art knowledge gained from field work and chronological studies, and with a specific focus on ice-sheet extent and environmental conditions during the Last Glacial Maximum (LGM). The maximum Quaternary extension of ice sheets is discussed and compared to LGM. We bring together recent results from the circum-Arctic continental margins and the deep central basin; extent of ice sheets and ice streams bordering the Arctic Ocean as well as evidence for ice shelves extending into the central deep basin. Discrepancies between new results and published LGM ice-sheet reconstructions in the high Arctic are highlighted and outstanding questions are identified. Finally, we address the ability to simulate the Arctic Ocean ice sheet complexes and their dynamics, including ice streams and ice shelves, using presently available ice-sheet models. Our review shows that while we are able to firmly reject some of the earlier hypotheses formulated to describe Arctic Ocean glacial conditions, we still lack information from key areas to compile the holistic Arctic Ocean glacial history.

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1. Introduction

The glacial history of the Arctic Ocean involves the build-up and decay of marine-based ice sheets on the continental shelves, the development and disintegration of ice shelves, and significant changes in ocean-circulation regimes and sea-ice cover. None of the four other world ocean areas experienced such dramatic physiographic and environmental changes as the Arctic Ocean through the Quaternary glacial–interglacial cycles. This has been recognized for nearly a century, but a lack of direct field observations led to several postulated, rather contradictory, hypotheses concerning glacial–interglacial cycles in the Arctic Ocean (Donn and Ewing, 1966; Broecker, 1975; Hughes et al., 1977). When early hypotheses on the environmental setting of the glacial Arctic were developed, i.e. suggesting on one the hand an extensive ice shelf in the central Arctic Ocean during glacial periods (Mercer, 1970) and on the other hand sea-ice free conditions (Donn and Ewing, 1966), there were few field data available to test them. The modern perennial Arctic Ocean sea-ice cover has delayed data collection, but during the last decade, in particular during the last years with substantially reduced summer sea-ice extent, data collection has increased by an order of magnitude (Polyak and Jakobsson, 2011).

Since the Arctic Palaeoclimate and its Extremes (APEX) program started in 2007 as a continuation of two preceding programs PONAM (The Late Cenozoic Evolution of the Polar North Atlantic Margins, 1988–1994 (Elverhøi et al., 1998a)) and QUEEN (the Quaternary Environment of the Eurasian North, 1996–2002 (Thiede et al., 2004)) numerous field campaigns to the Arctic Ocean have been carried out (Jakobsson et al., 2010a). These have revealed new insights into the extent of ice sheets on the continental margins bordering the central Arctic Ocean, and how they fed into ice shelves that occupied regions of the central basin. Here we present an overview of present knowledge on the Arctic Ocean glacial history. It is divided into regions where the state-of-the art glacial history is presented based on mapped glaciogenic landforms, sediment stratigraphy and established chronologies (Fig. 1). We address the spatial extent of ice sheets that occupied the northernmost Arctic continental shelves and drained into the Arctic Ocean, including their possible extensions as ice shelves. The central Artic Ocean is treated as a separate region with a focus on how the marine sediment record has documented glacial–interglacial cycles. We also include recent developments concerning numerical simulations of Arctic ice sheets and glacial paleoceanographic conditions. We focus the overview on the Last Glacial Maximum (LGM) and the maximum extent of Quaternary ice sheets. The overarching question is what do we currently know about the past extent of ice sheets, ice streams and ice shelves, and related oceanographic changes, in the Arctic Ocean during the Quaternary? Which are the most important outstanding questions today? Finally, all data presented in our review allow us to revisit and shed new light on previous hypotheses regarding glacial conditions in the Arctic Ocean.

2. Background

2.1. The glacial Arctic Ocean: hypotheses and theories

In the 1950s and 1960s the driving mechanisms behind the glacial cycles were debated. Following two papers on the topic (Ewing and Donn, 1956, 1958), Donn and Ewing (1966) suggested that a sea-ice free Arctic Ocean was required as a moisture source to build up the northern components of the large Northern Hemisphere ice sheets. Furthermore, they suggested that sea-ice formation in the Arctic Ocean towards the end of glaciation led to ice sheet decay due to an efficient blockade of the moisture required to form precipitation. Their theory implied that changes in Arctic Ocean sea-ice extent were a dominant control on Northern Hemisphere glacial–interglacial dynamics. The Milankovitch theory advocating an orbital forcing behind glacial–interglacial cycles (Milankovitch, 1920) was at the time beginning to gain ground (Broecker, 1966), but was still being met by scepticism until the 1970s when more deep sea sediment cores became available and dating methods improved (Hays et al., 1976). Although the Arctic Ocean sea-ice extent still is considered a relevant factor for the moisture supply and mass balance of the large Quaternary ice sheets (Colleoni et al., 2009), the overall ice–age cycles are believed to be paced by orbital parameters (Imbrie et al., 1992). The first sediment cores from the central Arctic Ocean retrieved from drifting ice stations (Clark, 1971) did not contribute to this original debate due to the irregular preservation of calcium carbonate microfossils that prevented consistent application of key paleoceanographic proxies and hampered the establishment of reliable age models (Backman et al., 2004; Alexanderson et al., 2013).

Another hypothesis that was formulated before much field data were available from the central Arctic Ocean suggested that a vast floating ice shelf covered the deep waters around the North Pole during past glacial maxima. Although previously postulated by Sir William Thomson in 1888 as a likely consequence of a glacial climate, Mercer (1970) was the first to promote this hypothesis based mainly on physiographic analogies between the Arctic Ocean and West Antarctica. Several authors picked up on the ice shelf theory and developed it further (Broecker, 1975; Hughes et al., 1977; Grosswald, 1980; Denton and Hughes, 1981; Grosswald and Hughes, 1999, 2008) (Fig. 2). In its most extreme form, a 1000 m thick ice shelf was hypothesized to have covered the entire Arctic Ocean, even south of the Fram Strait. This massive ice shelf was argued to be a critical stabilizing element, by exerting backpressure, for marine ice sheets grounded on continental shelves and flowing into the Arctic Ocean (Grosswald and Hughes, 1999). The hypothesis of an Arctic Ocean ice shelf was considered extreme by much of the glaciological community, although by the mid-1990s evidence indicating deep grounding of ice, likely derived from ice shelves, began to be documented (Vogt et al., 1994; Jakobsson, 1999; Jakobsson et al., 2001, 2008b; Polyak et al., 2001). Subsequently, the mapping of widespread glaciogenic bedforms and the dating of sediment cores retrieved from areas of ice grounding on submarine ridges in the Arctic Ocean, now support the presence of an ice shelf in the Amerasian Basin of the central Arctic Ocean, in particular during Marine Isotope Stage (MIS) 6, ~135 ka BP (Jakobsson et al., 2010b). The development and stability of this ice shelf is supported by a conceptual oceanographic model indicating that the influx of Atlantic water occurred at a much greater depth during glacial periods than today, thus preventing this relatively warm water mass from reaching into the Amerasian Basin where it would cause basal melting of an ice shelf (Jakobsson et al., 2010b). This pattern of glacial paleo-circulation would in turn mean that ice shelves had a smaller likelihood of developing in the Eurasian Basin of the Arctic Ocean, where they would be exposed to warm inflowing Atlantic water.

Ice shelves may also form through a combination of seaward extension of glaciers and extensive multiyear thickening of land-fast sea ice, i.e. *sikussak*, established along the coast and in fjords (Jeffries, 1992). Bradley and England (2008) postulated that this kind of extremely thick multi-year sea-ice cover developed towards the end of the Last Glacial period as a consequence of a more stagnant Arctic Ocean with a lower relative sea level and a diminished influx of warm Atlantic water. Such pervasive thick sea ice, termed *paleocrystic ice*, is suggested to have been massively