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The Younger Dryas and the Sea of Ancient Ice

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Abstract

We propose that prior to the Younger Dryas period, the Arctic Ocean supported extremely thick multi-year fast ice overlain by superimposed ice and firn. We re-introduce the historical term *paleocrystic* ice to describe this. The ice was independent of continental (glacier) ice and formed a massive floating body trapped within the almost closed Arctic Basin, when sea-level was lower during the last glacial maximum. As sea-level rose and the Barents Sea Shelf became deglaciated, the volume of warm Atlantic water entering the Arctic Ocean increased, as did the corresponding egress, driving the paleocrystic ice towards Fram Strait. New evidence shows that Bering Strait was resubmerged around the same time, providing further dynamical forcing of the ice as the Transpolar Drift became established. Additional freshwater entered the Arctic Basin from Siberia and North America, from proglacial lakes and meltwater derived from the Laurentide Ice Sheet. Collectively, these forces drove large volumes of thick paleocrystic ice and relatively fresh water from the Arctic Ocean into the Greenland Sea, shutting down deepwater formation and creating conditions conducive for extensive sea-ice to form and persist as far south as 60°N. We propose that the forcing responsible for the Younger Dryas cold episode was thus the result of extremely thick sea-ice being driven from the Arctic Ocean, dampening or shutting off the thermohaline circulation, as sea-level rose and Atlantic and Pacific waters entered the Arctic Basin. This hypothesis focuses attention on the potential role of Arctic sea-ice in causing the Younger Dryas episode, but does not preclude other factors that may also have played a role.
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It is widely accepted that the Younger Dryas cold episode (YD) from ~11.0–10.0 ka ^{14}C yr BP[2] resulted from an abrupt reduction in the North Atlantic thermohaline circulation occasioned by a massive influx of freshwater. However, there is no consensus on the source of the freshwater. Until recently, the prevailing view ascribed the source to meltwater drainage around the southern and eastern margins of the waning Laurentide Ice Sheet through the St. Lawrence Seaway (Teller et al., 2002). However, several studies have found little geomorphological, chronological or paleoceanographic support for such a connection at the onset of the YD (Keigwin and Jones, 1995; De Vernal et al., 1996; Lowell et al., 2005; Broecker 2006a). The interpretation of these records has recently been challenged by Carlson et al. (2007) who argue that there is a geochemical signal of meltwater drainage through the St. Lawrence Seaway at the start of the YD, in a core from south of Newfoundland. They estimate that there was an abrupt increase in freshwater flux (of 0.06–012 Sv) from lakes around the Laurentide Ice Sheet margin and that this freshwater disrupted the Atlantic Meridional Overturning Circulation. They also suggest that there was an “intra-YD event” when a change in the position of the Laurentide ice margin led to freshwater being discharged northward, into the Beaufort Sea. Tarasov and Peltier (2005, 2006) also argued for a northward discharge of freshwater into the Arctic Ocean. They used an ice sheet model constrained by geophysical parameters, relative sea-level data and geomorphological evidence, to estimate regional discharge from proglacial lakes and marginal rivers around the northwest margin of the Laurentide Ice Sheet. Using multiple simulations with varying sets of input variables, they suggest that maximum freshwater drainage from the NW Laurentide Ice Sheet (Keewatin Dome) reached 0.09–0.16 Sv at the onset of the

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[2] In the most recent Greenland oxygen isotope record (from NGRIP), which is exceptionally well-dated, the Younger Dryas episode spans 12,896–11,703 cal yr BP (Rasmussen et al., 2006). This corresponds to ~10,950 to 10,050 ^{14}C yr BP, based on CALIB 5.0.

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Younger Dryas episode. They argue that this pulse of freshwater entered the Beaufort Sea and traversed the Arctic Ocean, exiting via Fram Strait, directly to the critical locale of the North Atlantic Deepwater (NADW) formation, thereby shutting down this system. However, the field evidence to support their argument is equivocal, being dependent on the precise position of the Laurentide ice margin and the chronology of the northwest outlet that was bedrock-controlled (with associated glacioisostatic adjustments). In a review of the evidence, Dyke (2004) concluded that the glacial geological and chronological record supports an eastward rather than northward drainage of Lake Agassiz for most of the YD, until ~10.3 ka ^{14}C yr BP when the northwest outlet was operational.

Mercer (1969, 1970) pointed to the Arctic Ocean as a possible source of North Atlantic ice that may have triggered the YD cooling, but he conceived of the Arctic Ocean as having supported a vast marine ice shelf, grounded in places and fed by shore-based glaciers. This model of "*floating expanses of glacier ice*" (Mercer 1969) was based on parallels that he drew with the modern West Antarctic Ice Sheet. Mercer's concept for the Arctic Ocean was developed further by Hughes et al. (1977) and Hughes and Denton (1981). They pictured the Arctic Ocean as covered by "*an Arctic Ice Sheet that behaved as a single Pole-centered dynamic system*" (Grossvald and Hughes, 2002) supplied by ice sheets on the surrounding landmasses or continental shelves and draining out into the North Atlantic. However, geomorphological research has provided little evidence for such a complete inundation of the circum-Arctic region by ice sheets. Several ice streams are now recognized as having emanated from the Canadian Arctic Archipelago (CAA) and Greenland (Kaplan et al., 2001; Stokes et al., 2005; Dyke et al., 2002; England et al., 2006, 2007) but much of the northern coast of Siberia was ice-free throughout the Weichselian (e.g. Möller et al., 1999; Brigham-Grette et al., 2003; Svendsen et al., 2004). Similarly, in Alaska, no ice margins calved directly into the Arctic Ocean, although there was extensive glaciation of the Brooks Range during MIS 2. The model of an extensive Arctic Ocean ice cover was further developed by Moore (2005) who suggested that large tabular icebergs from calving glaciers, with average thicknesses of 200–400 m, occupied much of the Arctic Basin prior to the YD. However, given the limited locations where ice calved into the Arctic Basin, it seems unlikely that such large icebergs from calving ice streams would have constituted a major component of the overall Arctic Ocean ice cover. Furthermore, if ice cover over the Arctic Ocean was both thick and pervasive (as we argue here) ice discharge from ice streams and glaciers that reached the coast would have been limited by the buttressing effect of the sea-ice itself. Duplessy et al. (1996) argued for an Arctic Ocean source of freshwater during the YD, on the basis of the isotopic composition of planktonic foraminifera from the North Atlantic. The lack of a Laurentide Ice Sheet meltwater signal farther south led them to conclude that sea-ice from the Arctic Ocean was a more plausible mechanism for the freshening of the North Atlantic and its consequent effects on deepwater formation.

Here we expand on the conclusions of Duplessy et al. (1996) and propose that exceptionally thick sea-ice, which developed on the Arctic Ocean during MIS 2, was the critical source of freshwater to the North Atlantic, supplemented by drainage from the Laurentide Ice Sheet and Siberian rivers. This freshwater disrupted NADW formation, resulting in the climatic anomalies associated with the Younger Dryas episode. We argue that the Arctic Ocean ice cover was much thicker than modern multi-year sea-ice, and did not depend on input from glaciers or ice sheets. This hypothesis does not conflict with arguments that freshwater was also discharged through the St. Lawrence drainage (as proposed, for example by Carlson et al., 2007); freshwater from both regions may have disrupted North Atlantic Deepwater formation, either simultaneously or sequentially.

To distinguish the unique characteristics of the Arctic Ocean during MIS 2, we adopt the term *paleocrystic ice*, first used by Nares (1878) to describe the exceptionally old and thick ice ("*floes…of gigantic thickness with a most uneven surface and covered with deep snow…*") that he encountered off the coast of Ellesmere Island (Canada) (Fig. 1). In fact, this "*sea of ancient ice*" (Alcock, 1877)–extending up to 300 miles (480 km) from the northern coast of Ellesmere Island–was traversed by A. Markham during his attempt to reach the North Pole in 1876 (Markham, 1878). Other 19th century explorers made similar note of exceptionally thick ice with a characteristically rounded, hummocky surface, rising as much as 10 m above sea-level, that was distinct from the disturbed and fractured multi-year sea-ice with which they were familiar (cf. Mikkelson, 1907). Although the literature of the day is replete with discussions about the causes of this unusually thick ice, it appears that such floes were distinct from the sea-ice pressure ridges that are widespread today north of Greenland, and from calving icebergs or tabular ice floes (cf. Greely 1886; Koch 1926). In fact, the descriptions of paleocrystic ice encountered by Markham and others are reminiscent of *sikussak*, thick masses of sea-ice overlain by firn that were common in the constricted fiords of northern Greenland in the late 19th and early 20th century (Koch, 1926). They are also reminiscent of the exceptionally thick (40 m) sea-ice ice shelves of northern Ellesmere Island that have remained landfast for thousands of years (Lemmen et al., 1988). These explorers most likely saw the last remnants of multi-year paleocrystic ice, perhaps only centuries old and dating from the Little Ice Age, but we argue that late-glacial conditions in the Arctic Ocean were far more severe, with much lower temperatures and minimal ice movement. We therefore propose that, prior to the Younger Dryas chron, most of the Arctic Ocean was capped by exceptionally thick paleocrystic ice that had accumulated for millennia, resulting in a "sea of ancient ice" far thicker and more extensive than anything encountered by 19th century explorers. Furthermore, several conditions combined to release this ice into the North Atlantic ~13,000 cal yr BP, resulting in a shutdown or significant reduction in NADW formation and the resulting Younger Dryas cold period.

Ancient and modern Arctic Ocean sea-ice

During MIS 2, several conditions would have favored the extensive development of paleocrystic ice (Fig. 2). First, lower glacio-eustatic sea-level reduced the area of the Arctic Ocean by

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Figure 1. Watercolor painting of a floeberg at Simmon's Island (northern Ellesmere Island, Canada) from Moss (1878) who described the scene as follows: *"The great stratified masses of salt ice that lie grounded along the shores of the Polar Sea are nothing more than fragments broken from the edges of the perennial floes. We call them floebergs in order to distinguish them from, and yet express their kinship to, icebergs—the latter and their parent glaciers belong to more southern regions...The floeberg itself was not a large one, but it afforded an excellent example of the structure of polar floe. We could not but wonder what enormous force had pushed it upwards on the sloping beach till its flat upper surface stood forty feet above the floes around it. The lower half was made of what may be called conglomerate ice, the upper was stratified with the usual white and blue layers—white where the ice was spongy with air-cells, blue in the denser layers in between. High overhead might be seen in a section, in olive-tinted ice, of what had once been a summer pool, and on top of all, like sugar on a cake, lay last season's snow, slowly condensing into ice."* We believe this painting provides an eye-witness view of some of the paleocrystic floes that formed during the Little Ice Age, but were breaking up by the end of the 19th century. Moss provided a perspicacious description of the structure of paleocrystic ice, with stratified firn and superimposed ice overlying a basal layer of sea-ice. Paleocrystic floes that formed during Marine Isotope Stage 2 would have been considerably thicker.

up to ~32%,[3] severing its connection to the Pacific Ocean and reducing its connection to the North Atlantic. Ice sheets grounded on the shallow Barents Sea, and covered Svalbard (Landvik et al., 1998), leaving Fram Strait as the sole link (then only ~300 km wide) between the Arctic Ocean and the North Atlantic. Elsewhere during MIS 2, all connections between the Arctic Ocean and the North Atlantic, via the CAA, were blocked by grounded and coalescent Greenland–Innuitian–Laurentide ice sheets that persisted until after the YD chron (England et al., 2006). Furthermore, North Pacific water was excluded from the Arctic Ocean by the Bering Land Bridge (Elias et al., 1996; Elias, 2001).

During MIS 2, there is evidence for seasonally open water along what would have been the edge of the former Svalbard and Barents Sea Ice Sheets, as far east as the Laptev Sea (Taldenkova et al., in press), but in general sedimentation rates were very low. Seasonally open water may have been restricted to a narrow coastal margin, essentially as a boundary current; however, the amount of Atlantic water and its geographical extent in this period is not well established. There may also have been coastal polynas driven by offshore katabatic winds from the adjacent ice sheets (Knies et al., 1999; Vogt et al., 2001; Taldenkova et al., in press). Nevertheless, there is no evidence for a major input of Atlantic water into the Arctic Basin as a whole during MIS 2, and we contend that the influence of warm Atlantic water entering the Arctic Basin was minimal until the Barents Sea Ice Sheet had broken up and water from the south could freely penetrate that region. In effect, during MIS 2, the Arctic Ocean became an enclosed and oceanographically isolated, "Mediterranean sea" with only a narrow zone of ingress and egress through Fram Strait.

Paleotemperature estimates from Greenland boreholes indicate that mean annual temperatures during MIS 2 were 20–25°C lower than today (Cuffey and Clow, 1997; Dahl-Jensen et al., 1998). This was the result of an orbitally-induced reduction in summer radiation and the restriction of warm air masses entering the Arctic Basin by sea-ice and ice sheets to the south which created baroclinic zones that effectively steered cyclones away from the interior of the Arctic Ocean. As a result, both atmospheric dynamics and the ingress of sub-ice Atlantic waters were severely diminished compared to today, greatly reducing mobilization and export of sea-ice from the Arctic Basin. Minimal sub-surface heat flux through the ice, extremely restricted ice dynamics, very low air temperatures and reduced insolation, would have worked in concert to establish an immobile sea-ice regime within the enclosed, circulation-restricted Arctic Basin.

Although snowfall on the Arctic Ocean would have been low during MIS 2 (perhaps an order of magnitude less than the modern average of ~30 cm water equivalent; Warren et al., 1999), ablation also would have been minimal, allowing most snow to accumulate as firn. Furthermore, any surface meltwater likely would have re-frozen as superimposed ice and in the absence of a net export of sea-ice, the combination of these surface conditions would have resulted in ice of exceptional thickness (cf. Walker and Wadhams, 1979). As shown by Crary (1960), given a positive surface mass balance and sub-ice heat flux close to zero, paleocrystic ice can thicken to in excess of 100 m within a few centuries. This was also recognized by

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[3] The Arctic Ocean as defined by Jakobsson (2002) is 9,458,536 km^2. The area below −120 m is 6,444,574 km^2 or ~68% of its area today.

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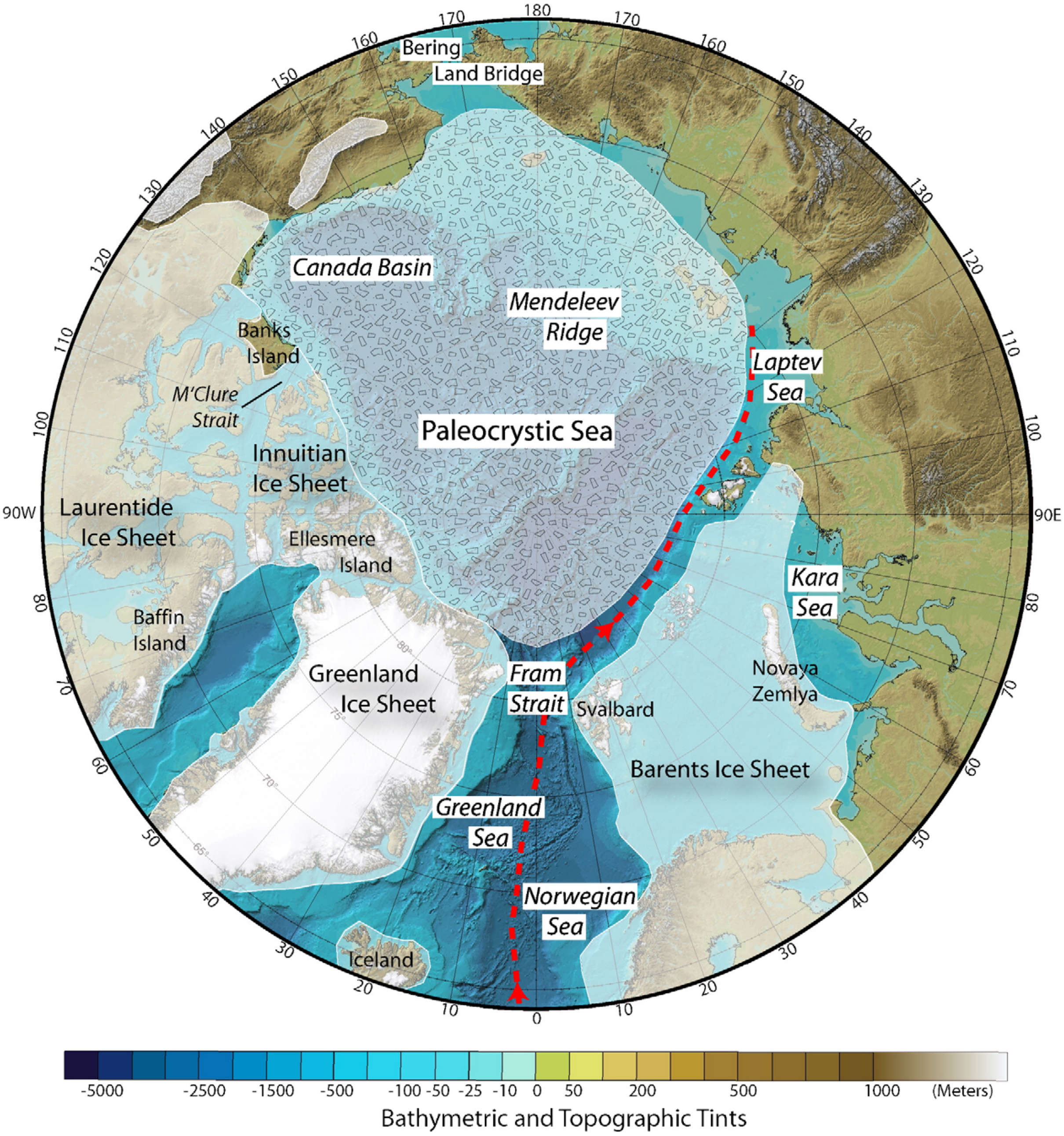

Figure 2. Schematic diagram showing the hypothesized extent of paleocrystic ice in the Arctic Ocean at the end of MIS 2. Warm Atlantic waters skirted the Eurasian coast as a narrow coastal current as far east as the Laptev Sea (dashed red line) but the extent of open water was minimal, and probably only seasonal. It had little effect on the extent of paleocrystic ice or its movement within the Arctic Ocean Basin; sea-level was more than 60 m below present, exposing broad areas of the Siberian continental shelf, where the thick ice was grounded.

Maykut (1986) who noted, "*the combination of a small Fw [sub-ice heat flux] and high snowfall can produce ice of almost any thickness…*", though of course this will not happen if the ice is seasonally exported from the Arctic Basin. Hence, very limited ice movement within a small, land-locked Arctic Ocean would have been a critical factor in allowing such conditions to occur. Subsequently, when sea-level rose and circulation was restored to the Arctic Ocean, the stored paleocrystic ice was available for discharge into the North Atlantic. Most importantly, these floes would have been composed of predominantly freshwater.

Extremely thick sea-ice occurs today along the northern coast of Ellesmere Island (~83°N), where landfast ice shelves up to 40 m thick can be found (Lemmen et al., 1988). These ice shelves are composed of a core of shore-based sea-ice sandwiched between superimposed ice on top and re-frozen brackish water below, added by basal accretion. This ice stratigraphy is clearly seen in the isotopic and salinity profiles of ice cores collected from both the Ward Hunt Ice Shelf and from floating ice islands, all derived from northern Ellesmere Island (Jeffries, 1992). These ice shelves are unique in the Northern Hemisphere, favored by

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extreme cold and the stabilizing effect of prevailing onshore surface currents. We emphasize that these are sea-ice ice shelves (Lemmen et al., 1988) that are genetically distinct from Antarctic-type ice shelves that are contiguous with (and fed by) land-based glaciers. As Markham and other explorers discovered, sea-ice ice shelves were much more extensive along northern Ellesmere Island (and possibly in other parts of the CAA) at the end of the Little Ice Age (AD ~1300–1900).

Today, ice thickness in the Arctic Ocean averages ~2–3 m, reflecting the balance between heat loss to the atmosphere and heat flux from Atlantic Water below (Vinje et al., 1998; Rothrock et al., 1999; Wadhams and Davis, 2000). During summer months, temperatures rise sufficiently to melt much of this ice, the remainder of which is either entrained in the anti-cyclonic Beaufort Gyre or transported across the Arctic Basin by the Transpolar Drift, to be expelled into the North Atlantic via the East Greenland Current. Today, less than 50% of the sea-ice remains in the Arctic Ocean for more than 1 yr. This multi-year ice can be quite thick (5–8 m) but the thickest ice in the Arctic Ocean is associated with pressure ridges (caused by sea-ice convergence) that have keels reaching to depths of 50 m in some areas. In contrast, it is only where ice dynamics is severely restricted that landfast sea-ice ice shelves can attain thicknesses of 40 m or more (without ridging), as found along the coast of northern Ellesmere Island today. Such ice shelves serve as a useful analogue for the paleocrystic ice that likely characterized much of the Arctic Basin during MIS 2.

How thick were the proposed LGM paleocrystic floes in the Arctic Ocean? There is no *prima facie* evidence to answer this. Such ice would have had no isostatic effect and contained little ice-rafted debris (IRD), except in areas where sediment was entrained through localized grounding. Furthermore, it would have had a miniscule effect on the oceanic δ^{18}O content because relatively little isotopically-light snowfall would have been sequestered on the paleocrystic ice within the Arctic Basin. Once melted, it would also have had minimal impact on sea-level rise (being of low salinity, its volume would be only slightly greater than the more saline water it displaced). Perhaps its most important signal would be that of minimal (essentially zero) sedimentation beneath the ice, because there would have been no, or severely limited, biological productivity or ice-rafted deposition (IRD). This paucity of sedimentation is, in fact, the predominant characteristic of most cores during MIS 2 throughout the western and central Arctic Ocean, including the Mendeleev Ridge (Phillips and Grantz, 1997; Nørgaard-Pedersen et al., 1998, 2003; Darby et al., 1997, 2006; Polyak et al., 2004). According to Poore et al. (1999) sediment deposition from "*12–24 ka* [^{14}C yr BP] *is very condensed or absent from these records*" while Polyak et al. (2004) report, "*an interval of drastically declined sedimentation rates, possibly including a hiatus, between ca. 13 ka and at least 19 ka…this episode possibly started as early as 24–25 ka…The non-deposition… points to an exceptionally heavy ice cover during the Last Glacial Maximum (LGM)…as a cause of non-deposition. This interpretation is consistent with extremely low abundance or complete absence of biogenic remains during the low-sedimentation interval and immediately above it.*"

We suggest that similar periods of minimal or non-deposition have repeatedly affected sedimentation rates within the inner-most Arctic Basin during the coldest episodes of the Pleistocene, when the glacial periods were dominated by paleocrystic floes. As a result, estimating sedimentation rates by simple linear interpolation between chronostratigraphic markers (paleomagnetic or radioisotopic) is probably not meaningful (cf. Backman et al., 2004). Indeed, it may be that most Arctic Ocean sediments are of interglacial (or interstadial) age, especially within the Canada Basin which is the most isolated sector of the Arctic Basin.

When did this sea of ancient ice break-up? It seems most likely that the demise of the paleocrystic ice began when:

a) sea-level rose, enabling warm Atlantic waters to freely circulate across the deglaciated Barents Shelf into the Arctic Ocean, and Pacific waters to flood into the Arctic Ocean through the resubmerged Bering Strait
b) the surface circulation in the Arctic Ocean, especially the Transpolar Drift, became re-established leading to the export of paleocrystic ice floes from the Arctic Basin through a widening Fram Strait
c) glacial meltwater and proglacial lakes drained into the Arctic Ocean, supplementing the freshwater being exported as paleocrystic ice into the North Atlantic. We discuss each of these issues in turn.

Sea-level rise and the return of Atlantic and Pacific water

Sea-level began to rise ~20,000 yr BP and had reached at least −70 to −60 m (global eustatic) by 13,000 cal yr BP (Lambeck and Chappell, 2001; Siddall et al., 2003). At −60 m, the area of the Arctic Ocean increased by at least 11% (716,000 km^2) from its LGM extent[4]. Over half of this change resulted from flooding of the newly exposed continental shelves of the Barents and Kara seas following break-up of marine-based ice sheets there, allowing warm Atlantic water to re-enter the Arctic Basin. Cores from off the coast of Svalbard, and even as far east as the Laptev Sea, show an increase in Atlantic water from ~13–11 ^{14}C ka BP (Ślubowska-Woldengen et al., 2007; Taldenkova et al., in press). Although the Barents–Kara Sea Ice Sheet began to break-up before ~15 ^{14}C ka BP, the Barents Sea shelf between Svalbard and Novaya Zemlya remained inaccessible to Atlantic water until ~13 to 12 ^{14}C ka BP (Lubinski et al., 2001). We speculate that it was the massive influx of this water, as sea-level rose over the shallow continental shelf, which contributed to renewed circulation within the Arctic Ocean, with compensatory egress of ice-choked surface water through a widening Fram Strait. The importance of this late-glacial transgression is underscored by the fact that today 50% of all the Atlantic water entering the Arctic Ocean does so via the Barents Sea (Nørgaard-Pedersen et al., 2003). In addition, new evidence shows that Pacific water must also have entered the Arctic Basin via Bering Strait by approximately the same

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[4] Estimates of changes in area do not consider isostatic adjustments that certainly took place as marginal ice sheets receded.

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time (13 cal ka BP) based on new fossil evidence from Banks Island, western Canadian Arctic Archipelago (England and Furze, in press). There, concordant radiocarbon dates (AMS) were obtained on the Pacific mollusk *Cyrtodaria kurriana*[5], collected from deglacial raised marine deposits (conventional radiocarbon ages, 12,380±110 BP, TO-12496, and 12,345±30, UCIAMS-24794). To further test these results, AMS dates were also obtained on *Hiatella arctica* from the same deposit (11,970±100, TO-12497 and 12,170±25, UCIAMS-24793), that confirm ages of at least 12,000 ^{14}C yr BP. Correction for the marine reservoir age of the seawater in which these organisms grew was also applied; current values for the CAA range from 410 yr (Mangerud and Gullikson, 1975) to 740 yr (Dyke et al., 2002 *pers. comm.*). The resulting mean ^{14}C age of the northern Banks Island samples is ~11.5 ka BP (reservoir-corrected by 740 yr), and their calibrated ages range from ~13.2 to 13.4 cal ka BP (at 2 sigma, $\partial r > 0.95$, Calib 5.1; Hughen et al., 2004: England and Furze, in press). Based on the recent dating of live-collected, pre-bomb samples of marine mollusks from the western Canadian Arctic, we have used a marine reservoir correction of 740 yr to calculate the ages of *C. kurriana* and associated species on northern Banks Island (Dyke et al. unpublished data). We note that studies of late-glacial fauna in the inland waters of Georgia Basin and Puget Lowlands, NE Pacific Ocean, range from 950±50 yr to as high as 1200±130 yr at valley-head sites (Hutchinson et al., 2004). This is similar to a previous estimate (~1.1 ka) for the reservoir age of marine shells collected from glaciomarine sediments in the same area (Kovanen and Easterbrook 2002). Applying these greater reservoir ages would still leave our dates on *C. kurriana* at least as old as the onset of the YD, but in the absence of any supporting evidence, a reservoir age > 740 yr for the Banks Island samples would simply be arbitrary.

The only other record of *C. kurriana* in the early Holocene Arctic Basin that we have found comes from estuarine (brackish) waters in the inner Laptev Sea (from a core recovered at a water depth of 45 m). There, the occurrence of *C. kurriana* is attributed to an Atlantic rather than a Pacific source. However, the arrival of *C. kurriana* in the Laptev Sea is bracketed by *Portlandia* bivalves which date 9685±50 and 10,260±55 BP, and thus the *C. kurriana* there are several thousand years *younger* than the samples we report from Banks Island (Bauch et al., 2001; Taldenkova et al., in press). Furthermore, *C. kurriana* has not been collected throughout the length of the intervening coastline between these two localities (>3000 km apart, England and Furze, in press) rendering this alternate migration even more problematic. Therefore, we assume that *C. kurriana* on Banks Island records the re-entry of Pacific waters into the Arctic Ocean by this time. This is the earliest postglacial occurrence of Pacific fauna to be reported from the Canadian Arctic, and indicates an earlier date for the resubmergence of Bering Strait than previously proposed (Elias et al., 1996; Dyke and Savelle 2001; Keigwin et al., 2006). Furthermore, given the lack of evidence for a molluscan refugia in continental shelf waters of the western Arctic Ocean during MIS 2, Dyke (in Kaufman et al., 2004) proposed that the arrival of *Hiatella arctica* and *Portlandia arctica* in the western CAA would also record the resubmergence of Bering Strait (~13,000 cal yr BP) which is similar to the chronology of *C. kurriana* reported here.

Arctic ice circulation

The opening of Bering Strait would have provided an important flow of Pacific water into the Arctic Basin. Although the sea surface gradient (density difference) driving the surface circulation between the Arctic and Pacific Oceans is unknown at this time, we assume a northward flow by 11.5 ^{14}C ka BP because this would be required for the widespread entry of Pacific mollusks to the western Canadian Arctic at this time. Together with the increasing volume of inflowing Atlantic water, we propose that a dynamic circulation became established within the Arctic Ocean that included an early Transpolar Drift, driving the paleocrystic ice towards Fram Strait. Additionally, rising sea-level would have continued to displace previously grounded sea-ice, facilitating further mobilization of the paleocrystic floes (including associated ice-rafted debris; cf. Nurnberg et al., 1994). We can estimate the relevant freshwater contribution to the North Atlantic as shown in Table 1. If we assume that paleocrystic floes were 99% freshwater and ice cover over the Arctic Basin averaged 50 m in thickness (similar to the Ellesmere ice shelves today), the discharge of freshwater through Fram Strait is equivalent to ~10.2 Sv (using a 1 yr reference). For comparison, the estimated volume of water discharged from the Lake Agassiz/Ojibway system (Kinojévis stage) at 8.2 cal ka BP was ~5.2 Sv (1 yr reference) (Teller et al., 2002). Today, ~0.16 Sv of ice and freshwater exits the Arctic Basin through Fram Strait annually (Dickson et al., 2007).

Proglacial lake drainage

There is clear evidence for a large discharge of freshwater to the Laptev Sea from a Siberian source at ~13 cal ka BP, recorded as an isotopically-light signal in marine foraminifera (Spielhagen et al., 2005). This freshwater discharge must have contributed to the massive flux of low salinity water passing through Fram Strait and into the Greenland Sea around the start

Table 1

Area of Arctic Ocean today[1]	9.54×10^{12} m^2
Arctic Ocean[2] area reduced to 75.7%,	7.221×10^{12} m^2
50 m of ice over Arctic Ocean	361×10^{12} m^3 of ice
Ice density 0.9	325×10^{12} m^3 (water equivalent)
Assumed freshwater equivalent of 99% of paleocrystic ice volume	322×10^{12} m^3 (freshwater equivalent)
1 Sv for 1 yr $=10^6$ m$^3\times31.5\times10^6$	31.5×10^{12} m^3
Discharge of 322×10^{12} m^3 w.e	10.2 Sv[3]

[1] As defined by Jakobsson, 2002.

[2] Area with sea-level at −60 m, assuming no isostatic adjustments.

[3] Over 1 yr.

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[5] Although well over one thousand samples of postglacial shells have been collected throughout the Canadian Arctic Archipelago, this species has not been recorded elsewhere in deglacial sediments. Furthermore, this complete absence of *C. kurriana* to the north and east in the CAA, together with its modern distribution along the north coast of Alaska and the Mackenzie delta, southward to eastern Kamchatka strongly points to a Pacific source.

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of the Younger Dryas. There may also have been freshwater drainage of 0.09–0.16 Sv from the northwestern margin of the Laurentide Ice Sheet later in the YD (cf. Dyke, 2004; Andrews and Dunhill, 2004; Teller et al., 2005; Tarasov and Peltier, 2005). Without knowing how long it would have taken to discharge either the paleocrystic ice or the freshwater from ice-dammed lakes to the North Atlantic (or indeed how thick it was), it is not possible to compute accurately the probable rate of freshwater discharge through Fram Strait at the start of the YD. However, we note that most multi-year sea-ice today is exported from the Arctic Ocean within a decade and that the Great Salinity Anomaly of the 1990's moved through the Arctic Ocean in even less time. Given that the discharge interval for the proposed paleocrystic ice is unavoidably arbitrary, we have simply combined the two estimates of freshwater input noted above (10.2 and 0.09–0.16 Sv) and distributed that over 30 yr, providing an estimate of ~0.34 Sv yr^{-1}. If the mean thickness was more than 50 m, this value would be correspondingly larger. Is this enough to significantly reduce North Atlantic deepwater formation?

Modelling experiments by Knutti et al. (2004) in which they gradually increase the flux of freshwater to the North Atlantic (over the zone 50–70°N) show that with a freshwater flux of only 0.2–0.25 Sv NADW formation begins to rapidly decline.

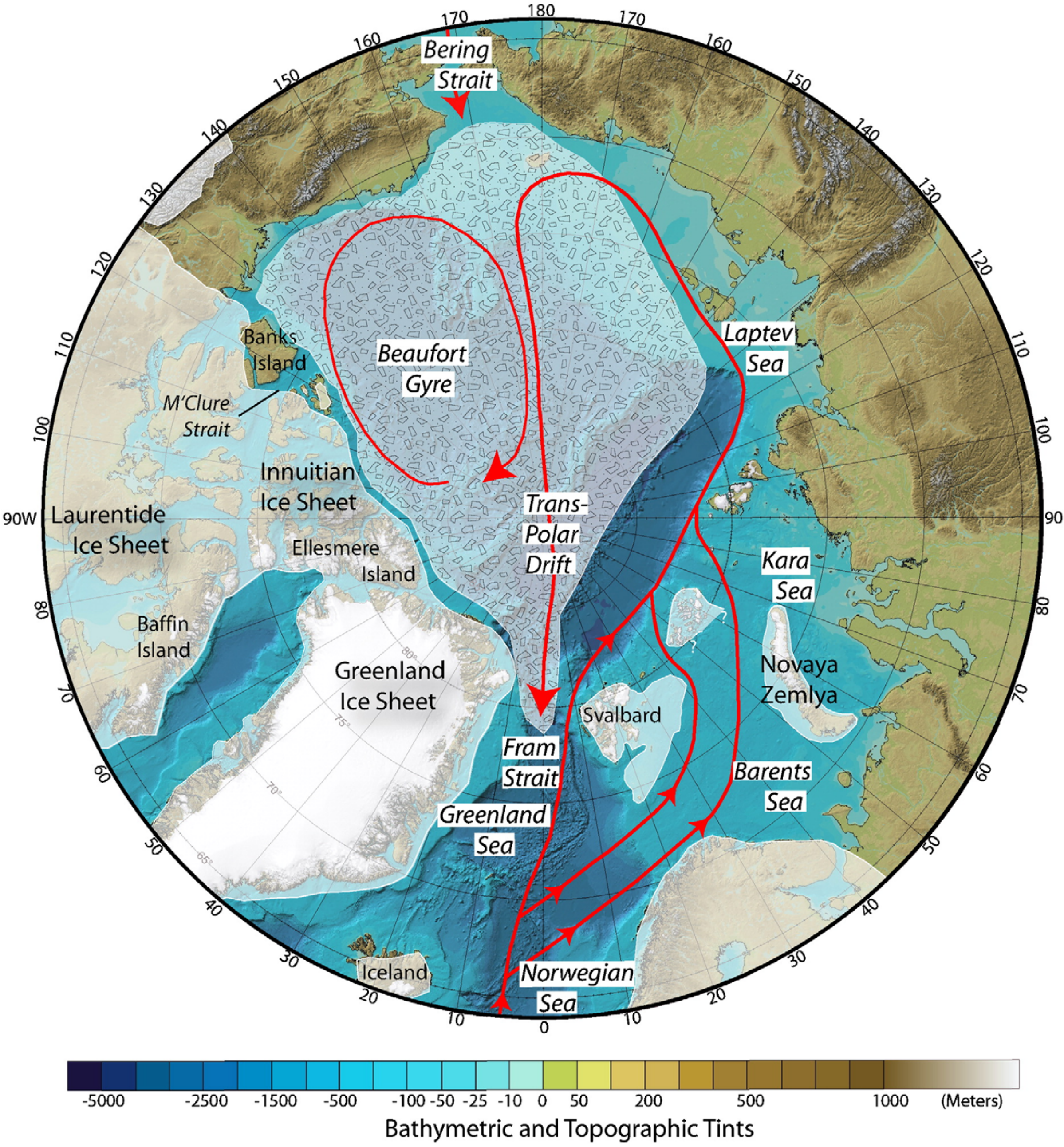

Figure 3. Schematic diagram of the hypothesized situation just prior to the Younger Dryas episode, after sea-level rose, leading to the break-up of the Barents Sea Ice Sheet. As warm Atlantic waters began circulating around the Arctic Ocean (red lines) and Pacific waters breached Bering Strait, thick masses of paleocrystic ice were forced out of the Arctic Ocean through Fram Strait, directly towards the key areas of North Atlantic deepwater formation in the Greenland/Iceland/Norwegian Sea.

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LeGrande et al. (2006) introduced much larger volumes of freshwater (2.5–5 Sv) into the North Atlantic via Hudson's Strait, but just as a pulse for up to 1 yr, obtaining changes in NADW that were consistent with events associated with the 8.2 cal ka BP event seen in many paleoclimatic records. However, their simulation did not involve perturbation of the NADW formation regions in the Greenland–Iceland–Norwegian Sea but rather in the freshwater structure of the Labrador Sea and areas farther south. We argue that the Greenland–Iceland–Norwegian Sea is the critical area of NADW formation and it is this region which is most vulnerable to freshwater discharges via the Arctic Ocean. As noted by Aagaard and Carmack, (1989), "*the large freshwater output from the Arctic Ocean passes perilously close to the weakly stratified convective gyres* [in the Greenland and Iceland Seas] *and…the stratification in these gyres is easily perturbed…*". Our estimate of the potential freshwater discharge from the Arctic Ocean appears to be sufficient to cause a general collapse of NADW formation in the main source area, and once Bering Strait was breached, additional low salinity Pacific water traversing the Arctic Basin may have helped to sustain the perturbation to NADW that the paleocrystic ice and associated freshwater initiated (Keigwin and Cook, 2007; England and Furze, in press).

All modeling experiments indicate that recovery from a severe disturbance to the thermohaline circulation takes far longer than the time involved in the initial disruption, which helps to explain why the YD episode lasted far longer than the initial cause. Furthermore, the massive flux of paleocrystic ice into the Greenland Sea should likely have facilitated the formation of additional sea-ice by thermal and salinity stratification of near-surface waters. Such a flotilla of sea-ice would have reduced the oceanic heat flux to icebergs entrained within it, favoring their transport of IRD from the Greenland and Laurentide Ice Sheets far southward into the North Atlantic. Numerous studies now point to sea-ice as having been a critical factor in triggering the YD cold episode, and abrupt climatic changes in general (Renssen and Isarin, 1998, 2001; Gildor and Tziperman, 2003; Piotrowski et al., 2004; Li et al., 2005; Stanford et al., 2006; Broecker, 2006b). We note that paleoceanographic indicators of sea-ice extent suggest that it was pervasive as far south as ~60°N during the Younger Dryas (from the Faeroes and the northern Shetland Islands in the west, to northern Newfoundland in the east) (de Vernal and Hillaire-Marcel, 2006; Koç et al., 1993). Extensive sea-ice would also have led to reduced ventilation of the deep ocean and consequent atmospheric and oceanographic radiocarbon anomalies. Recent evidence indicates that marine reservoir ages in the North Atlantic did increase from ~400 to 600 yr during the YD interval, followed by a reduction to ~300 yr as the sea-ice melted and an overturning circulation resumed (Bondevik et al., 2006; Cao et al., 2007). It is also of interest that recent work by Knies et al. (2007) indicates freshwater discharge from the Arctic Ocean to the Greenland Sea has been a recurrent pattern after major glaciations over the past 0.8 myr.

Conclusion

We propose a hypothesis in which the discharge of massive amounts of thick paleocrystic ice from the Arctic Ocean at ~11 ^{14}C ka BP was responsible for an abrupt reduction in North Atlantic deepwater formation in the Greenland Sea, and that this was an important factor in triggering the Younger Dryas climate anomaly. This ice accumulated in the constricted Arctic Ocean Basin during MIS 2 when sea-level was low, the influx of warm Atlantic water to the Basin was minimal and air temperatures were greatly reduced. As sea-level rose, Bering Strait was breached, the Barents and Kara Sea marine ice sheets broke up, and warm Atlantic water quickly spread throughout the Arctic Ocean Basin (Fig. 3). At the same time, air temperatures rose and a more dynamic atmospheric and oceanic circulation was established, forcing the paleocrystic ice into the critical regions of NADW formation in the Greenland–Iceland–Norwegian Seas. Thermal and salinity stratification of near-surface waters facilitated the formation of additional sea-ice which extended the zone of cooling farther south, extending the southern limit of iceberg penetration and associated IRD in the North Atlantic. Although the Younger Dryas cold episode may have had more than one freshwater trigger, we propose that the export of extremely thick and ancient sea-ice from the Arctic Ocean played a salient role as sea-level rose and Atlantic and Pacific waters re-entered the Arctic Basin prior to the onset of the Younger Dryas.

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References

Aagaard, K., Carmack, E.C., 1989. The role of sea ice and other freshwater in the Arctic circulation. Journal of Geophysical Research 94, 14485–14498.

Alcock, R., 1877. Address to the Royal Geographical Society. Proceedings of the Royal Geographical Society of London 21, 407–477.

Andrews, J.T., Dunhill, G., 2004. Early to mid-Holocene Atlantic water influx and deglacial meltwater events, Beaufort Sea slope, Arctic Ocean. Quaternary Research 61, 14–21.

Backman, J., Jakobsson, M., Løvlie, R., Polyak, L., Febo, L.A., 2004. Is the central Arctic Ocean a sediment starved basin? Quaternary Science Reviews 23, 1435–1454.

Bauch, H.A., Mueller-Lupp, T., Taldenkova, E., Speilhagen, R.F., Kassens, H., Grootes, P.M., Thiede, J., Heinemeier, J., Petryashov, V.V., 2001. Chronology of the Holocene transgression at the North Siberian margin. Global and Planetary Change 31, 125–139.

Bondevik, S., Mangerud, J., Birks, H.H., Gulliksen, S., Reimer, P., 2006. Changes in North Atlantic radiocarbon reservoir ages during the Allerød and Younger Dryas. Science 312, 1514–1517.

Brigham-Grette, J., Gualtieri, L.M., Glushkova, O., Hamilton, T.D., Mostoller, D., Kotov, A., 2003. Chlorine-36 and ^{14}C chronology support a limited Last Glacial Maximum across central Chukotka, Northeastern Siberia, and no Beringian Ice Sheet. Quaternary Research 59, 386–398.

Broecker, W.S., 2006a. Was the Younger Dryas triggered by a flood? Science 312, 1146–1148.

Broecker, W.S., 2006b. Abrupt climate change revisited. Global and Planetary Change 54, 211–215.

Cao, L., Fairbanks, R.G., Mortlock, R.A., Risk, M.J., 2007. Radiocarbon reservoir age of high latitude North Atlantic surface water during the last deglacial. Quaternary Science Reviews 26, 732–742.

Carlson, A.E., Clark, P.U., Haley, B.A., Klinkhammer, G.P., Simmons, K., Brook, E.J., Meissner, K.J., 2007. Geochemical proxies of North American

https://doi.org/10.1016/j.yqres.2008.03.002 Published online by Cambridge University Press

freshwater routing during the Younger Dryas cold event. Proceedings of the National Academy of Sciences 104, 6556–6561.

Crary, A.P., 1960. Arctic ice island and ice shelf studies. Part 1. Arctic 11, 2–42.

Cuffey, K.M., Clow, G.D., 1997. Temperature, accumulation and ice sheet elevation in central Greenland through the last deglacial transition. Journal of Geophysical Research 102C, 26383–26396.

Dahl-Jensen, D., Mosegaard, K., Gundestrup, N., Clow, G.D., Johnsen, S.J., Hansen, N., Balling, A.W., 1998. Past temperatures directly from the Greenland ice sheet. Science 282, 268–271.

Darby, D.A., Bischoff, J.F., Jones, G.A., 1997. Radiocarbon chronology of depositional regimes in the western Arctic Ocean. Deep-Sea Research Part II, 44, 1745–1757.

Darby, D.A., Polyak, L., Bauch, H.A., 2006. Past glacial and interglacial conditions in the Arctic Ocean and marginal seas — a review. Progress in Oceanography 71, 129–144.

De Vernal, A., Hillaire-Marcel, C., 2006. Provincialism in trends and high frequency changes in the northwest North Atlantic during the Holocene. Global and Planetary Change 54, 263–290.

De Vernal, A., Hillaire-Marcel, C., Bilodeau, G., 1996. Reduced meltwater outflow from the Laurentide ice margin during the Younger Dryas. Nature 381, 774–777.

Dickson, R., Rudels, B., Dye, S., Karcher, M., Meincke, J., Yashayaev, I., 2007. Current estimates of freshwater flux through Arctic and Subarctic seas. Progress in Oceanography 73, 210–230.

Duplessy, J.C., Labeyrie, L.D., Paterne, M., 1996. North Atlantic sea surface conditions during the Younger Dryas cold event. In: Andrews, J.T., Austin, W.E.N., Bergsten, H., Jennings, A.E. (Eds.), Late Quaternary Paleoceanography of the North Atlantic Margins. Geological Society Special Publication, vol. 111, pp. 167–176. The Geological Society, London.

Dyke, A.S., 2004. An outline of North American deglaciation with emphasis on central and northern Canada. In: Ehlers, J., Gibbard, P.L. (Eds.), Quaternary glaciations-extent and chronology, part II. North America. Developments in Quaternary Science, vol. 2, pp. 373–424.

Dyke, A.S., Savelle, J.M., 2001. Holocene history of the Bering Sea Bowhead whale (*Balaena mysticetus*) in the Beaufort Sea summer grounds off southwestern Victoria Island, western Canadian Arctic. Quaternary Research 55, 371–379.

Dyke, A.S., Andrews, J.T., Clark, P.U., England, J.H., Miller, G.H., Shaw, J., Viellette, J.J., 2002. The Laurentide and Innuitian ice sheets during the Last Glacial Maximum. Quaternary Science Reviews 21, 9–31.

Elias, S.A., 2001. Beringian paleoecology: results from the 1997 workshop. Quaternary Science Reviews 20, 7–13.

Elias, S.A., Short, S.K., Nelson, C.H., Birks, H.H., 1996. Life and times of the Bering land bridge. Nature 382, 60–63.

England, J.H., Furze, M.F., (in press). New evidence from the western Canadian Arctic Archipelago for the resubmergence of Bering Strait. Quaternary Research.

England, J.H., Atkinson, N., Bednarski, J.B., Dyke, A.S., Hodgson, D.A., Ó Cofaigh, C., 2006. The Innuitian Ice Sheet: configuration, dynamics and chronology. Quaternary Science Reviews 25, 689–703.

England, J.H., Furze, M., Doupé, J., 2007. New perspectives on the NW Laurentide Ice Sheet: implications for the NE extremity of Beringia, paleoclimate and the role of episodic ice shelves during deglaciation. Abstracts, 37th International Arctic Workshop, Skaftafell, Iceland, pp. 96–97.

Gildor, H., Tziperman, E., 2003. Sea-ice switches and abrupt climate change. Proceedings of the Royal Society London of Series A, vol. 361, pp. 1935–1944.

Greely, A.W., 1886. Arctic exploration, with reference to Grinnell Land. Proceedings of the Royal Geographical Society and Monthly Record of Geography, New Monthly Series, vol. 8, pp. 156–176.

Grossvald, M.G., Hughes, T.J., 2002. The Russian component of an Arctic Ice Sheet during the Last Glacial Maximum. Quaternary Science Reviews 21, 121–146.

Hughen, K.A., Baillie, M.G.L., Bard, E., Beck, J.W., Bertrand, C.J.H., Blackwell, P.G., Buck, C.E., Burr, G.S., Cutler, K.B., Damon, P.E., Edwards, R.L., Fairbanks, R.G., Friedrich, M., Guilderson, T.P., Kromer, B., McCormac, G., Manning, S., Ramsey, C.B., Reimer, P.J., Reimer, R.W., Remmele, S., Southon, J.R., Stuiver, M., Talamo, S., Taylor, F.W., van der Plicht, J., Weyhenmeyer, C.E., 2004. Marine radiocarbon age calibration, 0–26 cal kyr BP. Radiocarbon 46, 1059–1086.

Hughes, T., Denton, G.H., 1981. The Arctic Ice Sheet: an outrageous hypothesis. In: Denton, G.H., Hughes, T.J. (Eds.), The Last Great Ice Sheets. J. Wiley, Chichester.

Hughes, T., Denton, G., Grosswald, M., 1977. Was there a late-Würm Arctic Ice Sheet? Nature 266, 596–602.

Hutchinson, I., James, T.S., Reimer, P.J., Bornhold, B.D., Clague, J.J., 2004. Marine and limnic radiocarbon reservoir corrections for studies of late- and postglacial environments in Georgia Basin and Puget Lowland, British Columbia, Canada and Washington, USA. Quaternary Research 61, 193–203.

Jakobsson, M., 2002. Hypsometry and volume of the Arctic Ocean and its constituent seas. Geochemistry, Geophysics, Geosystems 3. doi:10.1029/2001GC000302.

Jeffries, M.O., 1992. Arctic ice shelves and ice islands: origin, growth and disintegration, physical characteristics, structural stratigraphic variability, and dynamics. Reviews of Geophysics 30, 245–267.

Kaplan, M.R., Miller, G.H., Steig, E.J., 2001. Low-gradient outlet glaciers (ice streams?) drained the Laurentide ice sheet. Geology 29, 343–346.

Kaufman, D.S., et al., 2004. Holocene thermal maximum in the western Arctic (0–180°W). Quaternary Science Reviews 23, 529–560.

Keigwin, L.D., Jones, G., 1995. The marine record of deglaciation from the continental margin off Nova Scotia. Paleoceanography 10, 973–985.

Keigwin, L.D., Cook, M.S., 2007. A role for North Pacific salinity in stabilizing North Atlantic climate. Paleoceanography 22. doi:10.1029/2007PA001420.

Keigwin, L.D., Donelly, J.P., Cook, M.S., Driscoll, N.W., Brigham-Grette, J., 2006. Rapid sea-level rise and Holocene climate in the Chukchi Sea. Geology 34, 861–864.

Knies, J., Vogt, C., Stein, R., 1999. Late Quaternary growth and decay of the Svalbard/Barents Sea ice sheet and paleoceanographic evolution in the adjacent Arctic Ocean. Geological Marine Letters 18, 195–202.

Knies, J., Matthiessen, J., Mackensen, A., Stein, R., Vogt, R., Frederichs, T., Nam, S.-I., 2007. Effects of Arctic freshwater forcing on thermohaline circulation during the Pleistocene. Geology 35, 1075–1078.

Knutti, R., Fluckiger, J., Stocker, T.F., Timmermann, A., 2004. Strong hemispheric coupling of glacial climate through freshwater discharge and ocean circulation. Nature 430, 851–856.

Koç, N., Jansen, E., Haflidason, H., 1993. Paleoceanographic reconstructions of surface ocean conditions in the Greenland, Iceland and Norwegian seas through the last 14 ka based on diatoms. Quaternary Science Reviews 12, 115–140.

Koch, L., 1926. Ice cap and sea ice in North Greenland. Geographical Review 16, 98–107.

Kovanen, D.J., Easterbrook, D.J., 2002. Paleodeviations of radiocarbon marine reservoir values for the northeast Pacific. Geology 30, 243–246.

Lambeck, K., Chappell, J., 2001. Sea level change through the last glacial cycle. Science 292, 679–686.

Landvik, J.Y., Bondevik, S., Elverhøi, A., Fjeldskaar, W., Mangerud, J., Salvigsen, O., Siegert, M.J., Svendsen, J.I., Vorren, T.O., 1998. The last glacial maximum of Svalbard and the Barents Sea Area: ice sheet extent and configuration. Quaternary Science Reviews 17, 43–75.

LeGrande, A.N., Schmidt, G.A., Shindell, D.T., Field, C.V., Miller, R.L., Koch, D.M., Faluvegi, G., Hoffmann, G., 2006. Consistent simulations of multi-proxy responses to an abrupt climate change event. Proceedings National Academy of Sciences of the United States of America 103, 837–842.

Lemmen, D.S., Evans, D.J.A., England, J., 1988. Ice shelves of northern Ellesmere Island, NWT. The Canadian Geographer 32, 363–367.

Li, C., Battisti, D.S., Schrag, D.P., Tziperman, E., 2005. Abrupt climate shifts in Greenland due to displacements of the sea ice edge. Geophysical Research Letters 32, L18702. doi:10.1029/2005GL023492.

Lowell, T., Waterson, N., Fisher, T., Loope, H., Glover, K., Comer, G., Hajdas, I., Denton, G., Schaefer, V., Rinterknecht, V., Broecker, W., Teller, J., 2005. Testing the Lake Agassiz meltwater trigger for the Younger Dryas. EOS 86, 365, 372.

Lubinski, D.J., Polyak, L., Forman, S.L., 2001. Freshwater and Atlantic water inflows to the deep northern Barents and Kara Seas since ca. 13 ^{14}C ka: foraminifera and stable isotopes. Quaternary Science Reviews 20, 1851–1879.

Mangerud, J., Gullikson, S., 1975. Apparent radiocarbon ages of recent marine shells from Norway, Spitsbergen, and Arctic Canada. Quaternary Research 5, 263–273.

https://doi.org/10.1016/j.yqres.2008.03.002 Published online by Cambridge University Press

Markham, A.H., 1878. The Great Frozen Sea. Daldy, Isbister and Co., London. 440pp.

Maykut, G.A., 1986. The surface heat and mass balance. In: Untersteiner, N. (Ed.), The Geophysics of Sea Ice. (NATO ASI B146). Plenum Press, New York, pp. 395–463.

Mercer, J.H., 1969. A former ice sheet in the Arctic Ocean. Palaeogeography, Palaeoclimatology, Palaeoecology 8, 19–27.

Mercer, J.H., 1970. The Allerød Oscillation: a European climatic anomaly? Arctic and Alpine Research 1, 227–234.

Mikkelson, E., 1907. Mr. Mikkelsen's ice-expedition in the Beaufort Sea. Geographical Journal 30, 517–524.

Möller, P., Bolshiyanov, D.Y., Bergsten, H., 1999. Weichselian geology and palaeoenvironmental history of the central Taymyr Peninsula, Siberia, indicating no glaciation during the last global glacial maximum. Boreas 28, 92–114.

Moore, T.C., 2005. The Younger Dryas: from whence the fresh water? Paleoceanography 20, PA4021. doi:10.1029/2005PA001170.

Moss, E.L., 1878. Shores of the Polar Sea; A Narrative of the Arctic Expedition of 1875–6. Marcus Ward, London. 83pp.

Nares, G.S., 1878. Narrative of a voyage to the Polar Sea during 1875–6 in H.M. ships "Alert" and "Discovery". Sampson Low, Marston, Searle and Rivington, London, vol. 1. 395pp.

Nørgaard-Pedersen, N., Spielhagen, R.F., Thiede, J., Kassens, H., 1998. Central Arctic surface ocean environment during the past 80,000 years. Paleoceanography 13, 193–204.

Nørgaard-Pedersen, N., Spielhagen, R.F., Erlenkeuser, H., Grootes, P.M., Heinemeier, J., Knies, J., 2003. The Arctic Ocean during the Last Glacial Maximum: Atlantic and Polar domains of surface water mass distribution and ice cover. Paleoceanography 18, 1063. doi:10.1029/2002PA000781.

Nürnberg, D., Wollenburg, I., Dethleff, D., Eicken, H., Kassens, H., Letzig, T., Reimnitz, E., Thiede, J., 1994. Sediments in Arctic sea ice: implications for entrainment, transport and release. Marine Geology 119, 185–214.

Phillips, R.L., Grantz, A., 1997. Quaternary history of sea ice and paleoclimate in the Amerasia basin, Arctic Ocean, as recorded in the cyclical strata of Northwind Ridge. Geological Society of America Bulletin 109, 1101–1115.

Piotrowski, A.M., Goldstein, S.L., Hemming, S.R., Fairbanks, R., 2004. Intensification and variability of ocean thermohaline circulation through the last deglaciation. Earth and Planetary Science Letters 225, 205–220.

Polyak, L., Curry, W.B., Darby, D.A., Bischof, J., Cronin, T.M., 2004. Contrasting glacial/interglacial regimes in the western Arctic Ocean as exemplified by a sedimentary record from the Mendeleev Ridge. Palaeoecology 203, 73–94.

Poore, R.Z., Osterman, L., Curry, W.B., Phillips, R.L., 1999. Late Pleistocene and Holocene meltwater events in the western Arctic Ocean. Geology 27, 759–762.

Rasmussen, S.O., Andersen, K.K., Svensson, A.M., Steffensen, J.P., Vinther, B.M., Clausen, H.B., Siggaard-Andersen, M.-L., Johnsen, S.J., Larsen, L.B., Dahl-Jensen, D., Bigler, M., Röthlisberger, R., Fischer, H., Goto-Azuma, K., Hansson, M.E., Ruth, U., 2006. A new Greenland ice core chronology for the last glacial termination. Journal of geophysical research 111, D06102. doi:10.1029/2005JD006079.

Renssen, H., Isarin, R.F.B., 1998. Surface temperature in NW Europe during the Younger Dryas. AGCM simulation compared with temperature reconstructions. Climate Dynamics 14, 33–44.

Renssen, H., Isarin, R.F.B., 2001. Data-model comparison of the Younger Dryas event: Discussion. Canada Journal of Earth Science 38, 477–478.

Rothrock, D.A., Yu, Y., Maykut, G.A., 1999. Thinning of the Arctic sea ice cover. Geophysical Research Letters 26, 3469–3472.

Siddall, M., Rohling, E.J., Almogi-Labin, A., Hembleton, Ch., Meischner, D., Schmelzer, I., Smeed, D.A., 2003. Sea-level fluctuations during the last glacial cycle. Nature 423, 853–858.

Šlubowska-Woldengen, M., Rasmussen, T.L., Koç, N., Klitgaard-Kristensen, Nilsen, F., Solheim, A., 2007. Advection of Atlantic water to the western and northern Svalbard shelf since 17,500 cal yr BP. Quaternary Science Reviews 26, 463–478.

Spielhagen, R.F., Erlenkeuser, H., Siegert, C., 2005. History of freshwater runoff across the Laptev Sea (Arctic) during the last deglaciation. Global and Planetary Change 48, 187–207.

Stanford, J.D., Rohling, E.J., Hunter, S.E., Roberts, A.P., Rasmussen, S.O., Bard, E., McManus, J., Fairbanks, R.G., 2006. Timing of meltwater pulse 1a and climate response to meltwater injections. Paleoceanography 21. doi:10.1029/2006PA001340.

Stokes, C.R., Clark, C.D., Darby, D.A., Hodgson, D.A., 2005. Late Pleistocene ice export into the Arctic Ocean from the M'Clure Strait Ice Stream, Canadian Arctic Archipelago. Global and Planetary Change 49, 139–162.

Svendsen, J.I., Alexanderson, H., Astakhov, V.I., Demidov, I., Dowdeswell, J.A., Funder, S., Gataullin, V., Henriksen, M., Hjört, C., Houmark-Nielsen, M., Hubberten, H.W., Ingólfsson, Ó., Jakobsson, M., Kjær, K.H., Larsen, E., Lokrantz, H., Lunkka, J.P., Lyså, A., Mangerud, J., Matioushkov, A., Murray, A., Möller, P., Niessen, F., Nikolskaya, O., Polyak, L., Saarnisto, M., Siegert, C., Siegert, M.J., Spielhagen, R.F., Stein, R., 2004. Late Quaternary ice sheet history of northern Eurasia. Quaternary Science Reviews 23, 1229–1271.

Taldenkova, E., Bauch, H.A., Stepanova, A., Strezh, A., Dem'yankov, S., Ovsepyan, Y., (in press). Postglacial to Holocene history of the Laptev Sea continental margin: paleoenvironmental implications of benthic assemblages. Quaternary International.

Tarasov, L., Peltier, W.R., 2005. Arctic freshwater forcing of the Younger Dryas. Nature 435, 662–665.

Tarasov, L., Peltier, W.R., 2006. A calibrated deglacial drainage chronology for the North American continent: evidence of an Arctic trigger for the Younger Dryas. Quaternary Science Reviews 26, 659–688.

Teller, J.T., Leverington, D.W., Mann, J.D., 2002. Freshwater outbursts to the oceans from glacial Lake Agassiz and their role in climate change during the last deglaciation. Quaternary Science Reviews 21, 879–887.

Teller, J.T., Boyd, M., Yang, Z., Kor, P.S.G., Fard, A.M., 2005. Alternative routing of Lake Agassiz overflow during the Younger Dryas: new dates, paleotopography, and a re-evaluation. Quaternary Science Reviews 24, 1890–1905.

Vinje, T., Nordlund, N., Kvambekk, A.A., 1998. Monitoring ice thickness in Fram Strait. Journal of Geophysical Research-Oceans C103 (10), 10437–10449.

Vogt, C., Knies, J., Spielhagen, R., Stein, R., 2001. Detailed mineralogical evidence for two nearly identical glacial/deglacial cycles and Atlantic water advection to the Arctic Ocean during the last 90,000 years. Global and Planetary Change 31, 23–44.

Wadhams, P., Davis, N.R., 2000. Further evidence of ice thinning in the Arctic Ocean. Geophysical Research Letters 24, 3973–3975.

Walker, E.R., Wadhams, P., 1979. Thick sea-ice floes. Arctic 32, 140–147.

Warren, S.G., Rigor, I.G., Untersteiner, N., Radionov, V.F., Bryazgin, N.N., Aleksandrov, Y.I., Colony, R., 1999. Snow depth on Arctic sea ice. Journal of Climate 12, 1814–1829.

https://doi.org/10.1016/j.yqres.2008.03.002 Published online by Cambridge University Press