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Variability in transport of terrigenous material on the shelves and the deep Arctic Ocean during the Holocene

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Abstract

Arctic coastal zones serve as a sensitive filter for terrigenous matter input onto the shelves via river discharge and coastal erosion. This material is further distributed across the Arctic by ocean currents and sea ice. The coastal regions are particularly vulnerable to changes related to recent climate change. We compiled a pan-Arctic review that looks into the changing Holocene sources, transport processes and sinks of terrigenous sediment in the Arctic Ocean. Existing palaeoceanographic studies demonstrate how climate warming and the disappearance of ice sheets during the early Holocene initiated eustatic sea-level rise that greatly modified the physiography of the Arctic Ocean. Sedimentation rates over the shelves and slopes were much greater during periods of rapid sea-level rise in the early and middle Holocene, as a result of the relative distance to the terrestrial sediment sources. However, estimates of suspended sediment delivery through major Arctic rivers do not indicate enhanced delivery during this time, which suggests enhanced rates of coastal erosion. The increased supply of terrigenous material to the outer shelves and deep Arctic Ocean in the early and middle Holocene might serve as analogous to forecast changes in the future Arctic.

To access the supplementary material for this article, please see supplementary files under Article Tools online.

Rapid changes in the environmental conditions of the Arctic have been observed over recent decades. These include decreasing summer and winter sea-ice extent, increasing annual river discharge, increasing areal extent of open-water areas over the Arctic shelves and lengthening of the open-water season (Peterson et al. 2002; Serreze et al. 2007; Kwok et al. 2009; Wagner et al. 2011; Stroeve et al. 2012; Fichot et al. 2013; Zhang et al. 2013).

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These changes will likely lead to important transformations in sedimentary environments and the pathways and processes of terrigeneous particulate cycling. In particular, they could play a role in sediment resuspension and coastal erosion (e.g., Atkinson 2005; Eicken et al. 2005; Carmack et al. 2006; Anisimov et al. 2007; Lantuit et al. 2012).

The impact of increased export of turbid waters from rivers and coastal regions on Arctic marine ecosystems remains uncertain; it could either increase delivery of nutrients and promote productivity or suppress photosynthesis in the light-limited algal populations by scattering absorbing sunlight (Retamal et al. 2008). An adequate understanding of the pathways of terrigenous material is needed to elucidate connections between sediment and ecosystem dynamics under a changing climate. Research efforts assessing recent trends and variability of terrigenous particulate matter inputs into the Arctic Ocean have been carried out during the past decades and discussed in reviews by Rachold et al. (2004), Macdonald et al. (2010), Forbes (2011) and Goñi et al. (2013). However, the ability to forecast the future significance of land-derived sedimentary inputs into the Arctic Ocean also needs to account for the natural baseline of sedimentary regimes and their variability in the past (e.g., Darby et al. 2006; Polyak et al. 2010).

The Quaternary history of the Arctic Ocean was marked by repeated waxing and waning of large ice sheets and associated sea-level fluctuations, causing repeated exposure/inundation of shallow shelves and dramatic changes in sedimentary environments, runoff and exchange with the adjacent world's oceans (Darby et al. 2006; Stein 2008; Jakobsson et al. 2011, 2014). Since the Last Glacial Maximum (LGM) 21 thousand years ago (Kya) the Arctic Ocean evolved towards its modern state, beginning with a relatively isolated basin with exposed shelf seas and a perennial ice pack with potentially very high thickness locally (Bradley & England 2008). The inundation of the shelves following the glacial sea-level lowstand, climatically driven changes in freshwater delivery by major rivers and variable sea-ice cover led to changes in terrigenous input and patterns of productivity across the Arctic. Understanding these dynamic processes is important for assessing modern and future changes in the Arctic. Parameters of past terrestrial input (e.g., past riverine discharge, coastal erosion) can serve as boundary conditions in models for a changing Arctic.

While regional data on the Arctic Ocean sedimentary patterns exist (e.g., Stein & Fahl 2000; Stein, Schubert et al. 2004; Yamamoto & Polyak 2009; Faux et al. 2011), there is no comprehensive pan-Arctic summary of the present state of knowledge about Holocene sediment sources, transport mechanisms and deposition of terrigenous material in the Arctic Ocean. Variability through the Holocene (last 11 700 years) provides a basic reference frame for modern observations because it tracks a changing climate in the Arctic since the LGM and is punctuated by intervals of warmer and colder climates compared to those captured by modern observations (e.g., Łącka et al. 2015; this paper provides an overview focusing on the variability of sediment transport processes on the shallow shelf seas of the Arctic Ocean on different time scales (present-day observations and palaeo-records), as well as a summary focusing on the increasing extents of shelf seas since the beginning of the Holocene on a pan-Arctic scale with regard to the pathways of terrestrial input. It presents a review and highlights how many of the boundary conditions that are changing in the Arctic today, also changed in a similar way during the early Holocene. (Throughout this article we use early, middle and late Holocene to denote times between 11.7 and 8.2 Kya, 8.2 and 4.2 Kya, and 4.2 Kya and the present, respectively [Walker et al. 2012].)

Overview of the history of the Arctic Ocean, LGM–present

The formation of large ice sheets during the last glacial event culminated in a reduction in global sea level by about 120–140 m, as well as major regional isostatic adjustments (Fairbanks 1989; Lambeck et al. 2002; Peltier & Fairbanks 2006). Consequently, the areas of the Arctic Ocean and its shelf regions were reduced by ca. 50% and ca. 80%, respectively (Fig. 1). The spatial reduction of the shelves in combination with larger surrounding landmasses, land-based ice sheets and glaciers, as well as a perennial sea-ice cover had profound effects on the Arctic hydrography, sediment fluxes, biogeochemical cycling and biological productivity (e.g., Nørgaard-Pedersen et al. 1998; Darby et al. 2006; Darby 2008; Jakobsson et al. 2014). The transition from full glacial conditions of the LGM to warmer, interglacial conditions during the Holocene marked the most recent substantial reorganization of the Arctic Ocean system.

The maximum insolation in the Northern Hemisphere in the early Holocene (Berger 1978; Laskar et al. 2004) was a primary driving force behind climatic warming that led to the decay of large ice sheets and subsequent sea-level rise. Rising seas inundated vast Arctic shelves and eventually led to the resumption of Pacific inflow via the shallow Bering Strait. While eustatic sea level had risen by ca. 60 m from the LGM to the beginning of the Holocene (11.7 Kya), it rose another ca. 60 m during the early to mid-Holocene (until about 6 Kya) in response

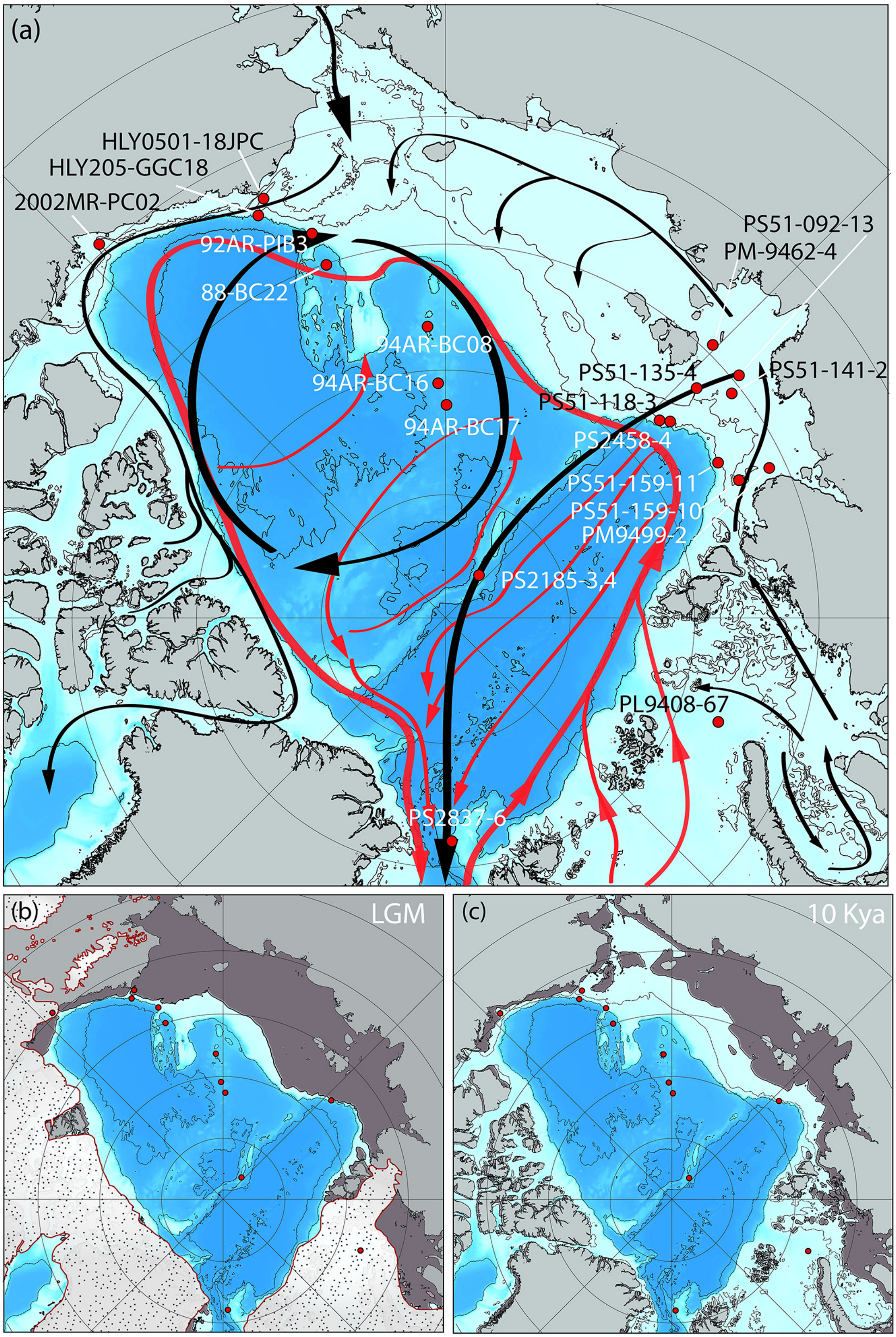

Fig. 1 (a) The modern Arctic Ocean and its constituent seas. Blue arrows indicate the surface circulation and red arrows show the flow of Atlantic Water. Locations and names are given for sediment cores shown in Fig. 6. (b) Physiography of the Arctic with ice sheet extents and associated sea-level lowering during the Last Glacial Maximum (LGM), 21–18 Kya, and (c) near the start of the Holocene, 10 Kya.

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to ongoing ice-sheet decay (Bard et al. 1998; Fairbanks 1989; Peltier & Fairbanks 2006; Carlson & Clark 2012; Fig. 1). During this time, the depositional regime on the shelves shifted from terrestrial–fluvial to marine as coastlines retreated southwards as a result of the marine transgression.

Changes in sedimentation rates on many of the Arctic shelf seas, concurrent with changes of geochemical and micropalaeontological environmental indicators, provide evidence of rapidly southward-retreating coastlines until near the end of the middle Holocene (ca. 5 Kya) (Bauch et al. 2001; de Vernal et al. 2005; Keigwin et al. 2006; Darby et al. 2009; Pieńkowski et al. 2013). This coincided with the period of most rapid sea-level rise, which lasted until 7 Kya. Both the reduced rate of sea-level rise and the fact that most of the shallow Arctic shelves had been inundated by this time contribute to the idea that modern depositional environment on the shelves was established by the end of the middle Holocene (Bauch et al. 2001; Stein, Dittmers et al. 2004).

At present the shelf areas surrounding the Arctic Ocean are characterized by high riverine input. Riverine waters are not only a critical source for low salinity waters, but they also carry high nutrient loads and fuel biological production (e.g., Smith et al. 2003; Trimble & Baskaran 2005). The terrestrial material delivered to the Arctic Ocean by riverine input and coastal erosion either accumulates on the shelf or is transported further offshore by currents or sea ice (e.g., Stein 2000, 2008; Wegner et al. 2005). Throughout the Holocene, as more of the shelf seas were inundated, formation of shore-fast sea ice and the incorporation of sediments into newly formed sea ice became more widespread. These sediments were then transported by the prevailing sea-ice drift systems: the Transpolar Drift and the Beaufort Gyre across the Arctic Ocean (e.g., Stein 2008). As glaciers retreated from shelf breaks and coastlines at the end of the LGM, the origin of ice-rafted debris (IRD) in Arctic sediments shifted from iceberg to sea-ice dominated (Darby & Bischof 2004; Darby et al. 2006). The transport of sediment-laden sea ice from the shelves to the Arctic basins was likely enhanced by the onset of the present-day activity of the Beaufort Gyre and the Transpolar Drift.

Sediment sources

Riverine input

Surface waters of the Arctic Ocean only account for approximately 0.1% of the global ocean volume, but receive 11% of the modern global river discharge (Shiklomanov 2000; Fichot et al. 2013). This large freshwater supply is essential for the stratification of the uppermost water column (Steele & Boyd 1998). It is particularly important for the maintenance of the Arctic Halocline, a water layer, 100 to 200 m thick, in the central Arctic Ocean characterized by a high salinity gradient which prevents heat exchange between the convective mixed upper layer and subsurface/intermediate Atlantic Water layer (Bourgain & Gascard 2011). Rivers also transport particulate and dissolved terrigenous material from large continental drainage basins (Fig. 2). Modern riverine sediment input is assumed to be the most important source of sediment to the Arctic Ocean besides coastal erosion (Stein 2008).

During the early and middle Holocene, warmer conditions led to the riverine transport of large amounts of glacial sediments towards the river deltas, onto the shelves and into the deep Arctic basins. Evidence of warmer conditions is supported by terrestrial and marine changes across the Arctic (e.g., Kaufmann et al. 2004) and reduced sea-ice conditions north of Greenland and throughout the Canadian Arctic Archipelago (Jakobsson et al. 2010). However, the palaeoceanographic data from the Chukchi and Beaufort seas suggest that a strong halocline and dense sea-ice cover persisted throughout the early and middle Holocene (de Vernal et al. 2005; Farmer et al. 2011; de Vernal et al. 2013). No evidence for enhanced outflow from Arctic rivers has been identified in sediment records. Most recorded events occurred during deglaciation and are associated with increased outflow of the Eurasian (Lena) and North American (Mackenzie) rivers before the Holocene (Rutter 1995; Fisher et al. 1995; Fisher et al. 2002; Spielhagen et al. 2005; Murton et al. 2010). Evidence for a prominent cooling event at the end of the early Holocene (8.2 Kya) is found in Greenland ice core records and marine sediments from large regions of the northern North Atlantic. Marine proxy data indicate that this event lasted ca. 150–250 years (e.g., Alley et al. 1997; Kleiven et al. 2008; Werner et al. 2013) and was triggered by the massive outburst flood from the proglacial lakes Agassiz/Ojibway during the final collapse of the Laurentide Ice Sheet (e.g., Stuiver et al. 1995; Barber et al. 1999; Rohling & Pälike 2005).

Reconstructions based on the coupled atmosphere–ocean global climate model ECHO-G suggest that there was a slight increase in total Arctic river discharge ($+0.35\% \pm 0.45\%$), with an increase in the Eurasian Arctic river discharge ($+2.14\% \pm 0.56\%$) but a decrease in the North American river discharge between 7 Kya and 1800 AD ($-4.62 \pm 0.64\%$; Supplementary Table S1; Wagner et al. 2011). The increasing discharge trends

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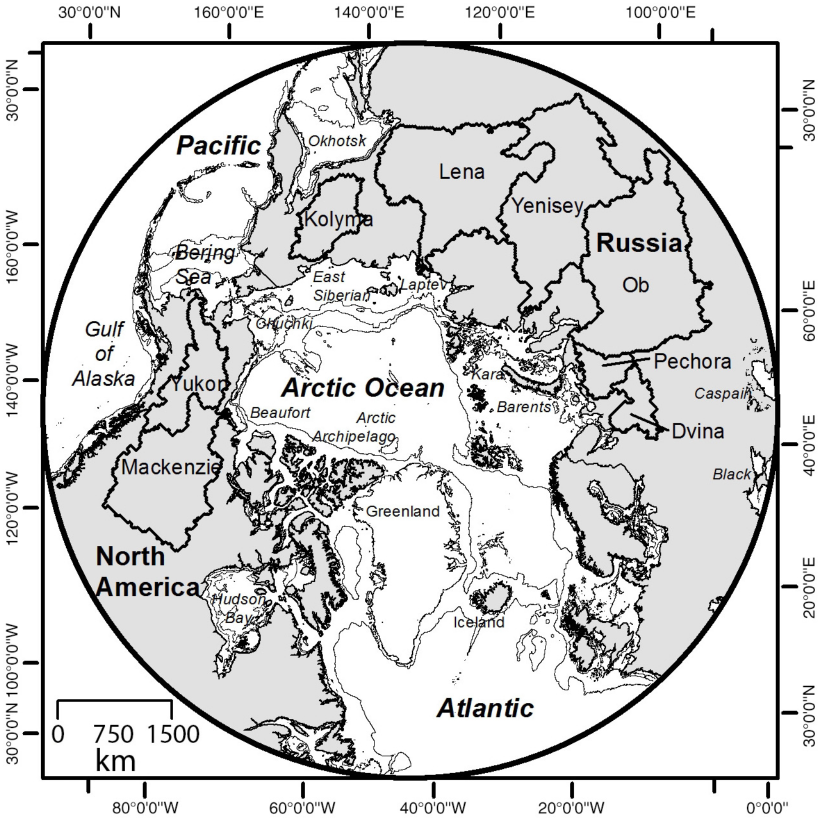

Fig. 2 Major oceanic basins, major rivers and watersheds corresponding to names and basins listed in Supplementary Table S1. The 50-, 100- and 1000-m bathymetric contour levels are shown (from the General Bathymetric Chart of the Oceans, one-minute grid, version 2 (Jakobsson et al. 2008). Drainage areas are based on Vorosmarty et al. (2000a, b).

from the Eurasian rivers Dvina, Pechora, Ob, Yenisei and Lena are associated with a positive precipitation and evaporation relation owing to decreased summer temperatures, as well as an intensification of continental high pressure cells, cloud formation and increased precipitation (Wagner et al. 2011). The strong decline in river discharge of the Mackenzie River system during the Holocene was associated with reduced atmospheric moisture transport, sea-level pressure increase and decreasing continental precipitation during summer (Wagner et al. 2011; Fig. 3).

Present-day trends in Arctic river discharge show an increase in total river influx into the Arctic Ocean during recent decades (Peterson et al. 2002; Zhang et al. 2013). However, river discharge trends are not uniform between the Eurasian and North American Arctic (Lammers et al. 2001; Peterson et al. 2002; Shiklomanov & Shiklomanov 2003; Shiklomanov & Lammers 2010).

A "back-of-the-envelope" estimate for changes in Arctic Ocean sediment flux (Supplementary Table S1) was calculated based on regression analysis for present-day discharge values and sediment fluxes as provided by Gordeev (2006). Using Shapiro-Wilks tests, we transformed both total suspended matter (TSM) and discharge by the natural log to follow a normal distribution. Although not included in the summary results (Supplementary Table S1), the Yukon River discharge and sediment record was included in the non-linear regression, based on values provided in Holmes et al. (2002). All rivers with a non-linear relationship between their sediment and water discharge were analysed using a third order polynomial regression ($n = 13$, adjusted R^2 0.92, $p < 0.001$), as:

$$f(x) = 33.71099 - 18.87968x + 3.01744x^2 - 0.14274x^3 \quad (1)$$

Rivers with a linear relationship between sediment and water discharge were considered in a separate negative regression model ($n = 15$, adjusted R^2 0.72, $p < 0.0001$), as follows,

$$f(x) = -6.7130 + 0.9413x \quad (2)$$

This simple approach allowed us to estimate Holocene sediment flux using discharge values provided by Wagner

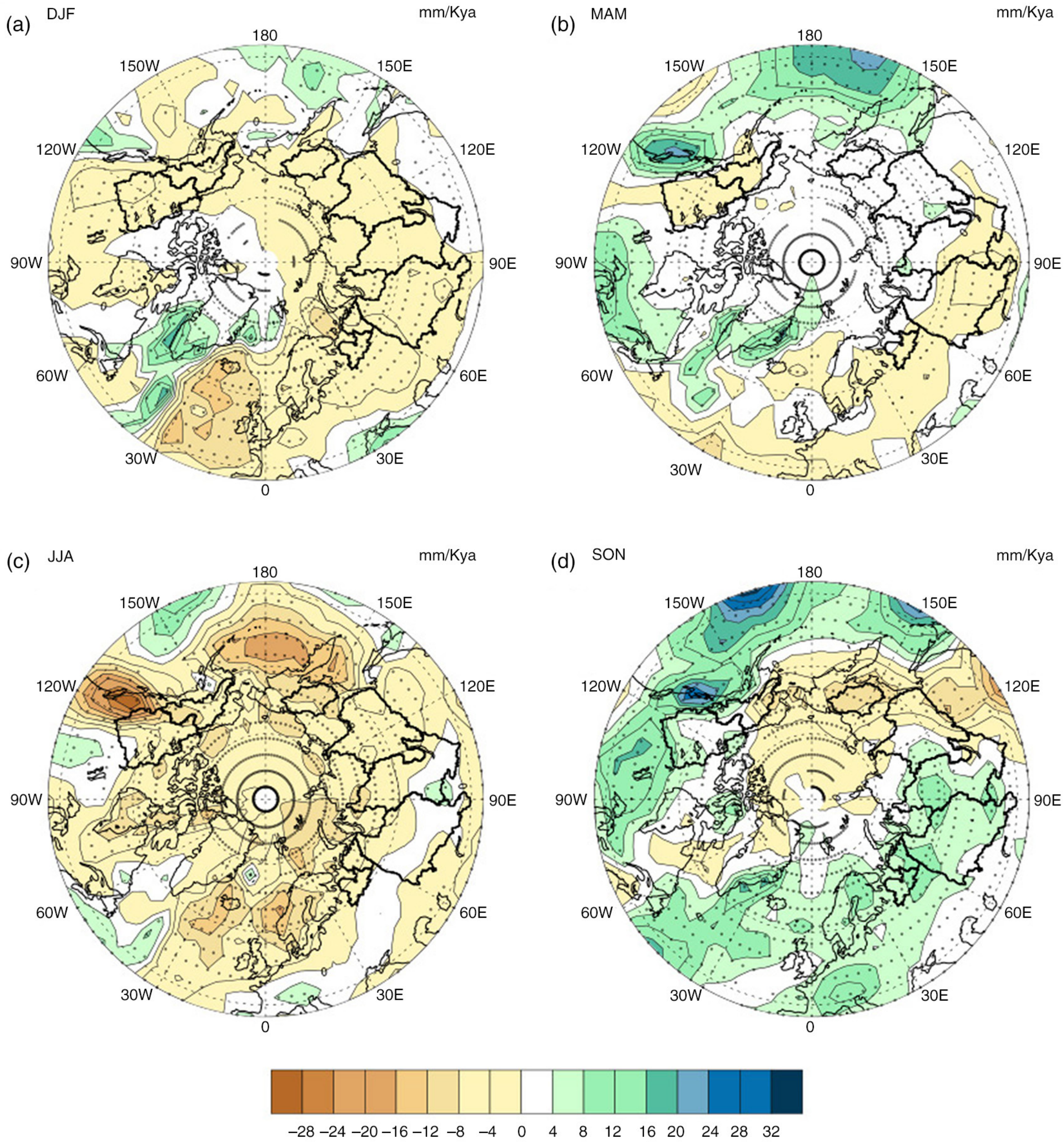

Fig. 3 Trends in precipitation (mm/Ky) between the middle Holocene and 1800 AD (pre-industrial period) for (a) winter (December–January–February), (b) spring (March–April–May), (c) summer (June–July–August) and (d) autumn (September–October–November). Source data from Wagner et al. (2011). A coupled atmosphere–ocean general circulation model, ECHO-G (Legutke & Voss 1999), was used to produce the simulation. Trends are calculated using a Mann Kendall Sen slope analytical approach (Yue et al. 2002). Trend strength is shown with colours ranging from negative values (brown/yellow tones) to positive values (green/blue tones). Significance is denoted by black circles to represent the 95% confidence interval. Major basins as shown in Fig. 2 are also illustrated.

et al. (2011; Supplementary Table S1). Generally estimated Holocene riverine suspended matter discharge trends are lower compared to modern-day (Supplementary Table S1), although results vary depending on whether riverine discharge was increasing or decreasing. The Mackenzie River, being somewhat of an outlier in the data set, was slightly under-predicted by the regression approach.

Coastal erosion

Recent estimates of the sediment flux and organic carbon (OC) flux from coastal erosion into the Arctic Ocean are around 430 Tg sediment y^{-1} and 4.9–14 Tg OC y^{-1} (Fig. 4, Supplementary Table S2 and references therein). This represents about twice the river sediment flux, yet less than half of the river OC flux (Supplementary

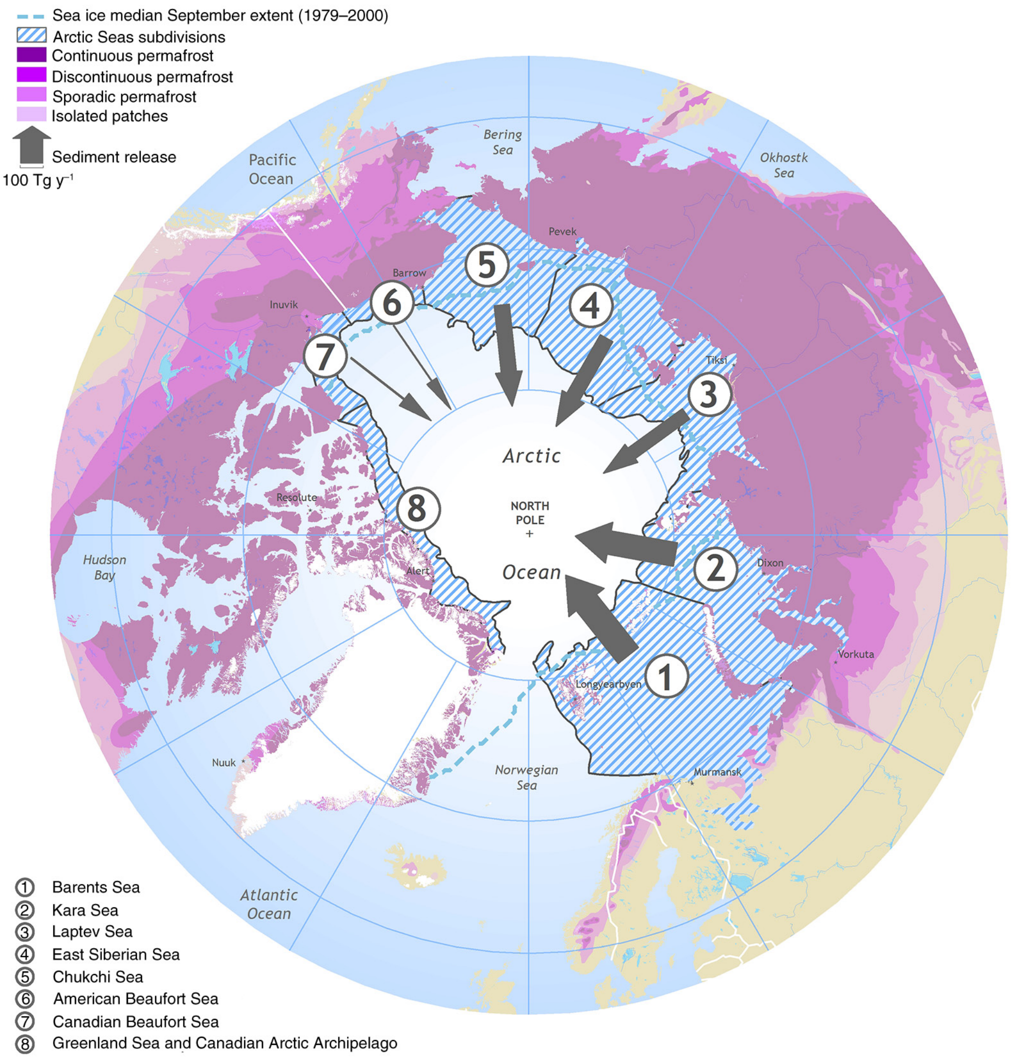

Fig. 4 Modern sediment contribution (Tg y^{-1}) from coastal erosion into the Arctic Ocean divided by marginal sea areas (after Brown et al. 2002).

Table S1 and references therein). The coastal material is probably mostly trapped within the nearshore area. Regional estimates of sediment and OC release to the Arctic Ocean are available from several places (Fig. 4). In Alaska, Jorgenson & Brown (2005) and Ping et al. (2011) provided updated calculations on the release of sediment (2.1–3.3 Tg y^{-1}) and OC (0.15–0.18 Tg y^{-1}) from coastal erosion, based on their calculations on long-term erosion rates (1950–2000) and field sampling. For the Canadian portion of the Beaufort Sea Coast, Hill et al. (1991) estimated a mean sediment input of 5.6 Tg y^{-1}, while Grigoriev & Rachold (2003) provided a mean sediment input for the Laptev Sea Coast to be 58.4 Tg y^{-1}. In the Kara Sea, Streletskaya et al. (2009) computed fluxes of OC (0.40 Tg a^{-1}) and re-estimated values published earlier by Vasiliev et al. (2005) of 0.35 Tg a^{-1}. In the Laptev and East Siberian seas, Vonk et al. (2012) calculated an annual coastal erosion flux of OC of 3.7 and 7.3 Tg y^{-1}, respectively (Supplementary Table S2) using new field-based measurements from the shelf, instead of coastal exposures. There is evidence from some areas for recent acceleration in the rate of coastal erosion (Jones et al. 2009; Günther et al. 2013; Günther et al. 2015), related in part to more open water and higher wave energy, rising sea levels and more rapid thermal abrasion along coasts with high volumes of ground ice (Forbes 2011).

It is important to note that the fate of sediments and OC once eroded from the cliff remains largely unknown (Stein & Macdonald 2004) and that the release of dissolved organic matter from melting ground ice in permafrost has not been estimated (Fritz et al. 2015). The estimated present-day range in OC release from erosion of coastal permafrost (4.9–14 Tg y^{-1}; Supplementary

Table S2) is smaller than the annual carbon dioxide emissions estimated from terrestrial permafrost (40.0–84.0 Tg C y^{-1}; McGuire et al. 2009), although estimations of OC release from coastal erosion generally refer to the coasts directly facing the Arctic Ocean only, omitting much of the Canadian Archipelago (consisting largely of bedrock coasts). Coastal erosion is, however, expected to accelerate due to increasing exposure to wave fetch and storms caused by recent reductions in sea ice (Forbes 2011), which may increase the annual coastal delivery of sediments, carbon and nutrients and may alter the biogeochemical setting on the upper shelves in the Arctic. In some places, coastal erosion has been shown to increase by a factor of three or four through a coupling with reducing summer sea-ice extent (Barnhart et al. 2014). This highlights the potential of coastal erosion to generate fluctuations in sediment supply of greater magnitude than rivers, which react to environmental forcing in a much smoother way, as shown by the current trends in river discharge constrained to a ±5% window.

Sediment supply from coastal erosion in the past, beyond observational timescales, is difficult to quantify as it depends on erosion of a coastline whose original configuration is not known (Hill et al. 1991), as well as a variety of mechanisms that are difficult to assess in the geological past. Large parts of the shallow circum-Arctic shelves were subaerially exposed during the LGM (Svendsen et al. 2004; Jakobsson et al. 2014) and became flooded rapidly. This marine transgression came close to the present level by the end of the middle Holocene (Bauch et al. 1999). Before the Holocene sea-level highstand the coastal erosion fraction of the total sediment input was probably much larger, because considerable portions of sediments were released by coastal erosion when large land areas were inundated with rising sea level (Bauch et al. 2001).

Based on maximum sediment accumulation rates on the Laptev Sea shelf between 9 and 10 Kya, Stein (1998) and Bauch et al. (2001) concluded that climatic warming in the early Holocene and post-glacial sea-level rise caused enhanced coastal-/seafloor erosion and riverine runoff. Large amounts of OC accumulated on the Laptev Sea and eastern Kara Sea shelves, as documented by high accumulation rates of TOC during the early Holocene, probably derived from strong wave-based erosion and thermoabrasion of the coastal permafrost deposits (Stein 1998; Müller-Lupp et al. 2000; Stein & Fahl 2000). With retreating coastlines, the accumulation rates in the distal shelf areas were reduced successively (Müller-Lupp et al. 2000).

In the middle Holocene sediment fluxes in the Laptev Sea were more variable, partly due to rising sea level, spatially variable timing for the flooding of bathymetric features and coastline adjustments (Bauch et al. 2001). Even though the modern sea-level highstand was approached around 5 Kya, the depositional systems on the shelves probably took more time to become stable, which might explain why relative constant sediment fluxes onto the Laptev Sea shelf did not begin until about 4 Kya (Bauch et al. 2001). It is challenging to identify different terrestrial sources of organic matter but stable and radiocarbon isotope analyses can be used to trace and identify terrestrial sources on the shelf. For example, in the Laptev and East Siberian shelf seas, Vonk et al. (2012) showed that the input of coastal erosion dominates these shelf regions.

There are almost infinite possibilities to combine external factors determining the long-term pace of coastal erosion with internal factors determining the vulnerability to coastal erosion. Only a few of them can be directly measured or reconstructed throughout the Holocene. Aré et al. (2002) pointed out that the shoreface <10 m water depth is an additional source for sediment input to the Laptev Sea. Comparing modern subaerial erosion rates and nearshore sedimentations rates in the Laptev and East Siberian seas, Vonk et al. (2012) suggested that subsea erosion of the shoreface at water depths less than 30 m may transfer as much sediments and organic matter to the sea as the subaerial erosion of the cliff. However, the information available on seafloor erosion in shallow water depths is still insufficient to be included into sediment input calculations (Rachold et al. 2002). As pointed out earlier, rates of erosion during rapid sea-level rise must have been substantially higher than in the late Holocene and in the modern setting. Within the last 11 000 years, the shoreline in the Laptev and East Siberian seas has shifted its position southward by 300–800 km (Overduin et al. 2007). Nevertheless, it is still unclear how much of the formerly dry shelf areas became subject to cliff and shoreface erosion or if they were simply flooded. The most reasonable assumption, though not quantitatively differentiated, is a combination of both processes. Erosional discordances between late glacial terrestrial deposits and Holocene marine sediments are as widespread as submarine permafrost deposits dating into the LGM, which have not been eroded (e.g., Mackay 1972; Romanovskii et al. 2004; Overduin et al. 2007; Rachold et al. 2007).

Transport processes

Generally, along the outer parts of Arctic Ocean continental margins and across topographic highs in deep basins, sea ice is assumed to be the main contributor

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to sediment transport (Polyak et al. 2009). The across-shelf and slope transport of fine particles is additionally affected by bottom currents associated with internal tides, along-shelf flows, wind-forced upwelling- and downwelling currents, eddies and density flows (e.g., Pickart 2004; Davies & Xing 2005; Williams et al. 2008; Darby et al. 2009). On runoff-dominated shelf seas (Kara, Laptev and Beaufort seas), currents only contributed to the transport of sedimentary material with increasing sea level, inundation of the shelves and associated distance from terrestrial sources, after an early fluvial phase dominated by high terrestrial input from river discharge and coastal erosion which was largely captured in delta systems (Darby et al. 2006). However, unlike the Siberian shelf, the Mackenzie River in the Beaufort Sea drains into a deep glacially excavated cross-shelf trough. This contrasting physiography and isostatic adjustments in the Beaufort Sea following the retreat of the Laurentide Ice Sheet may have greatly influenced the timing and transport pathway of riverine material during Holocene transgression.

After reaching maximum Holocene sea level, modern depositional processes developed on the shelf seas: seasonal sea-ice formation, ice rafting, peak riverine input shortly after spring break-up, pulsed productivity during ice-free months and increased resuspension of bottom sediments and current transport during ice-free conditions and freeze-up (e.g., Macdonald 2000; McClimans et al. 2000; Bauch et al. 2001; Sternberg et al. 2001; Baskaran et al. 2003; Bauch et al. 2004; Stein, Schubert et al. 2004; Wegner et al. 2005). Today, shelf currents experience a strong seasonality with wind and ice as limiting factors (e.g., Harms & Karcher 1999; McClimans et al. 2000; Sternberg et al. 2001; Wegner et al. 2005; Schulze & Pickart 2012). The surface distribution of riverine water and river-derived material shows strong interannual variability, mainly attributed to atmospheric vorticity variations over the adjacent Arctic Ocean in summer (Guay et al. 2001; Macdonald et al. 2002; Viscosi-Shirley et al. 2003; Dmitrenko et al. 2005; Bauch et al. 2009; Yamamoto-Kawai et al. 2009; Wegner et al. 2013). On the shelves and slopes, at water depth below 100 m, currents do not show a seasonal cycle (e.g., Woodgate et al. 2001). Sedimentary environments on the Barents and Chukchi shelves are affected by the interaction of sub-Arctic waters (Atlantic- and Pacific-derived waters, respectively) and processes in the marginal ice zone (Darby et al. 2006). Away from the continental shelves, and on elevated ridges, sedimentation rates are low and consistent throughout the Holocene, suggesting that no changes in the dominant transport processes took place and implying that sea ice was the dominant sediment transport system (e.g., Darby et al. 2009).

Under modern conditions, sediment-laden sea ice provides an important transporting agent for off-shelf export of particulate material, particularly over the wide and shallow Siberian shelves (Nürnberg et al. 1994; Eicken et al. 1997; Pfirman et al. 1997; Eicken et al. 2000; Dethleff 2005), and to some extent also over the narrow, deeper North American shelves (Reimnitz et al. 1993; Eicken et al. 2005; Darby et al. 2009). The total sediment export from Arctic shelves via sea-ice drift provides a quantitatively important component to the Arctic Ocean sediment (14–42 Tg/y [Eicken 2004; Stein 2008]) and OC (0.34 Tg/y total POC and DOC [Eicken 2004]) budget, with particularly high contributions from the Laptev Sea shelf. Stein (2008) estimates that ca. 23% of modern sediments in the central Arctic Ocean (from the slopes to deep basins) were deposited from drifting sea ice, while up to 85% of sediments on the elevated ridges of the central Arctic are sea ice derived.

The source regions and drift patterns of terrigenous IRD in the Arctic Ocean have been studied using sedimentological proxy indicators such as detrital grain size and mineral composition (Darby & Bischof 1996, 2004; Dethleff et al. 2000; Andrews 2009), in addition to isotopic signatures of sediment inorganic matter such as Pb, Sr, Nd (Eisenhauer et al. 1994; Peregovich et al. 1999; Tütken et al. 2002; Maccali et al. 2013), and organic biomarkers such as *n*-alkanes, glycerol dialkyl glycerol tetraethers (Yunker et al. 1995; Fahl & Stein 1999; Yamamoto & Polyak 2009; Yunker et al. 2011). Data indicate that during the LGM the boundary conditions (thick, perennial sea-ice cover, greatly reduced water volume of the Arctic Ocean basin, surrounding continents characterized by vast ice sheets and permafrost) only allowed for minimal sea-ice transport (Yunker et al. 2009). This is in contrast to the deglacial period when disintegrating ice sheets discharged icebergs which dislocated a major share of coastal sediments. During the Holocene, iceberg rafting gradually became less important while transport of terrigenous material by sea ice became more dominant (Polyak & Jakobsson 2011). Sea-ice transport away from the shelves today is driven by the modern surface circulation in the Arctic Ocean dominated by the Beaufort Gyre in the Amerasian Basin and the Transpolar Drift flowing from the Siberian shelves along the Lomonosov Ridge to Fram Strait (e.g., Aagaard et al. 1985; Sellén et al. 2010; Fig. 1).

During the early Holocene, sea-level rise played a considerable role governing the conditions for sediment entrainment in ice. The generally cooler late Holocene climate (Wanner et al. 2008), sea-level rise and the inundation of the broad shallow shelves likely facilitated extensive suspension freezing processes to operate (Yunker et al. 2009; Macdonald & Gobeil 2012; Werner et al. 2013). As shelf areas expanded, the amount of sea ice formed on, and exported off, these shelves also increased, as did, most likely, the magnitude of sea-ice transport within the Beaufort Gyre and the Transpolar Drift. Both the surface circulation and inflow of Atlantic Water have changed since the LGM. The early Holocene strengthening of Atlantic Water inflow to the Arctic Ocean is implicated in the increased influx of marine organic matter to the Kara and Laptev continental slopes while terrigenous material was the predominant material source during the mid- and late Holocene (Stein et al. 2001). Atmospheric circulation patterns also played a key role, especially once sea level approached its modern level by the late Holocene (Fairbanks 1989; Bauch et al. 2001; Carlson & Clark 2012). It has been suggested that during the positive Arctic Oscillation phase (AO+), a strong Transpolar Drift sweeps closer to North America and feeds sea ice into a weaker Beaufort Gyre while the negative AO phase (AO −) results in a stronger Beaufort Gyre (e.g., Funder et al. 2011). As a result, during AO+ IRD originating from the Siberian shelves may reach the Chukchi and Beaufort shelves, while during AO − more IRD from North American sources exits via Fram Strait (Rigor et al. 2002). Darby & Bischof (2004) and Darby et al. (2012) compared Fe-oxide mineral grains in sediment cores from the Chukchi Sea shelf to a reference database of about 300 surface sediment samples and proposed millennial-scale patterns of AO-linked sea-ice transport. Over the past ca. 8000 years, IRD from the Kara Sea was deposited on the Chukchi shelf with a 1500-year periodicity, suggesting millennial cyclicity in the AO phases (Darby et al. 2012).

Other sea-ice transport records have been obtained from Fram Strait, the main gateway of Arctic sea-ice export to the Atlantic Ocean. Overall, the data in Fram Strait and the Nordic seas indicate an increase in sea-ice cover and export from the Arctic since 6 Kya based on IRD, elemental and isotopic composition of sediment, as well as the IP25 biomarker (e.g., Jennings et al. 2002; Andrews 2009; Andrews et al. 2010; Müller et al. 2012; Werner et al. 2013). However, large spatial variability in the intensity of ice rafting and reconstructed persistence of sea ice exists in records from this region (Moros et al. 2006; de Vernal et al. 2013). Based on elemental and isotopic evidence from sediment leachates and residues in central Fram Strait sediments, Maccali et al. (2013) propose that most of the IRD reaching Fram Strait was primarily derived from North American and possibly East Siberian sources, while sea-ice sediments from the Laptev Sea played a minor role.

Sinks

Sedimentation rates on continental shelves are generally considerably higher than in the central basins, especially in areas with high riverine inputs such as the Kara, Laptev and Beaufort seas, and in marginal ice zones such as the Barents Sea (Darby et al. 2006; Darby et al. 2009; Fig. 5). During the Holocene, sedimentation rates on the shelf seas varied considerably (Fig. 6). During the rapid post-glacial sea-level rise in the early and beginning of the middle Holocene, high sedimentation rates of ca. 350 cm/thousand years (Ky) were recorded in the Laptev Sea and OC accumulation of 150–700 g/cm^2/Ky was estimated from the Kara Sea. Thereafter sedimentation rates on the outer Laptev Sea shelf dropped to ca. 14 cm/Ky (Bauch et al. 2001) and decreased to ca. 3–5 cm/Ky afterward (Bauch et al. 1999; Bauch et al. 2001). During the last 2000 years, sediment accumulation on the Kara Sea was about 75 g/cm^2/Ky (Bauch et al. 1999; Stein & Fahl 2000; Stein, Dittmers et al. 2004; Fahl & Stein 2007; Supplementary Table S3). Sediment accumulation for the entire Holocene was estimated to about 194 Tg/y for the Kara Sea (Stein, Dittmers et al. 2004), which is about 20% of the average Holocene sediment accumulation for the entire Arctic Ocean (1008) Tg/y, Stein & Macdonald 2004) and about 67 Tg/y (Stein & Macdonald 2004) for the Laptev Sea (Supplementary Table S3).

On the Canadian Beaufort shelf, substantial changes in the freshwater flux and in surface and bottom water conditions occurred in the early to middle Holocene (Andrews & Dunhill 2004). The total sediment mass stored in the delta regions with an average Holocene accumulation rate in the Mackenzie Delta of ca. 136–163 Tg/y (Lewis 1988) appeared to be three times higher than the deposition on the shelf (Hill et al. 1991). In shelf areas influenced by the Mackenzie outflow, sedimentation rates have reached ca. 140 cm/Ky since 4 Ky (Bringue & Rochon 2012). The Chukchi shelf, formed during the Holocene as a marginal sea relatively distant from land, was influenced by surface water inflow from the Pacific Ocean through Bering Strait during most of the Holocene (Yashin & Kosheleva 1996). Average sedimentation rates in the Chukchi Sea were relatively high (ca. 60–220 cm/Ky) during the early and middle Holocene (de Vernal et al. 2005; Keigwin et al. 2006), suggesting a terrigenous sediment source and an active sea-ice or water mass system to carry the sediment material seaward. Shelf sedimentation rates today are very low in the order of 1–2 cm/Ky (de Vernal et al. 2005; Keigwin et al. 2006).

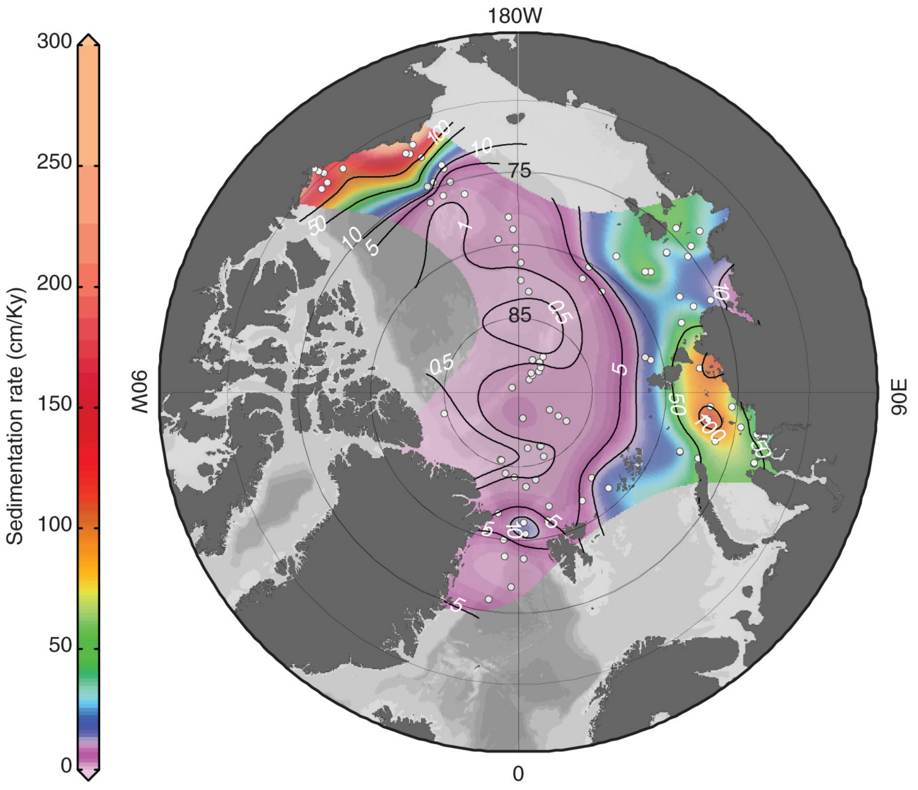

Fig. 5 Holocene sedimentation rates derived from ^{14}C dated sediments and gridded in the Ocean Data View software package (www.odv.awi.de/). The linear sedimentation rates were calculated without using a 0 age assumption for the seafloor.

On the Chukchi slope, sedimentation rates were very low (ca. 1 cm/Ky) throughout the Holocene (de Vernal et al. 2005).

Hein & Mudie (1991) investigated sediment cores from the north-western shelf off Axel Heiberg Island (Canadian Arctic Archipelago) and established a model for the Holocene sedimentary environment. They show that the Canadian Archipelago was characterized by rather high sedimentation rates >134 cm/Ky during the early Holocene contrasting with lower values thereafter ranging up to 7.4 cm/Ky with a high component of coarse IRD (Hein & Mudie 1991).

In the central Arctic, no clear change is observed in sedimentation rates during the middle Holocene. Generally they remained consistently low (Figs. 5, 6) with average accumulation rates of about 1–1 cm/Ky (Backman et al. 2004; Spielhagen et al. 2004). On the Alpha and northern Mendeleev ridges, beneath areas that are influenced by thick pack ice within the Beaufort Gyre, sedimentation rates may be less than 1 cm/Ky (Polyak et al. 2009) Across the Arctic Ocean, sedimentation rates generally increase towards the continental margins, with high sedimentation rates on continental slopes and on some shelves. Average Holocene rates vary between 10 and 300 cm/Ky (Darby et al. 1997; Nørgaard-Pedersen et al. 2003; Stein, Dittmers et al. 2004; Andrews & Dunhill 2004; Polyak et al. 2004; Keigwin et al. 2006; Rochon et al. 2006; Barletta et al. 2008; Darby et al. 2009; Lisé-Pronovost et al. 2009).

Conclusions and outlook

The input, distribution and fate of terrigenous sediment and organic matter in this material changed through the Holocene in response to sea-level rise, ice melt, rafting rates, sea-ice transport, riverine input, coastal erosion and current redistribution. During the early to middle Holocene, between 8 and 7 Kya, the sedimentary regime on the shelves shifted from dominant riverine input and coastal erosion derived sediment to marine deposition due to post-glacial sea-level rise and marine transgression. Currents on the shelves then became a determinant factor after a fluvial phase dominated by riverine input and coastal erosion. Even though the sedimentation rates were higher during the early to mid-Holocene, major Arctic rivers do not show enhanced delivery during this time. This suggests that sediment delivery was in response to enhanced rates of coastal erosion. However,

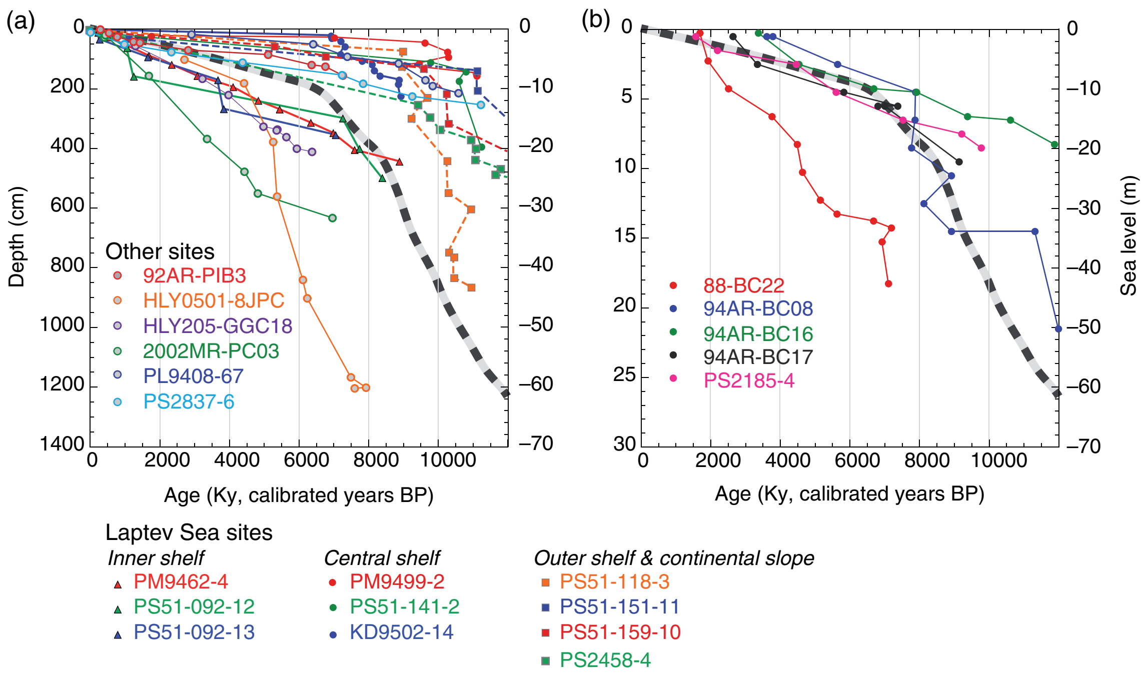

Fig. 6 Global sea level (black and grey dashed line) and published radiocarbon based sedimentation rates in the Arctic. Calibrated radiocarbon data are from Jakobsson et al. (2014) and for the Laptev Sea, Bauch et al. (2001). A subset of available cores was selected where enough radiocarbon dates exist to distinguish between early and late Holocene sedimentation rates. (a) High sedimentation rates are found on continental shelves and slopes across the Arctic, and where dates extend to the base of the Holocene, most seem to capture a period of high sedimentation associated with rapid sea-level rise lasting until 7 Kya. (b) In lower sedimentation rate areas, this trend is not clearly captured by existing records. See Fig. 1 for core locations.

this remains to be confirmed. After the deglaciation, terrigenous material transported by sea-ice drift became more dominant while iceberg rafting gradually achieved a less important role. However, the changes in sea-ice cover and drift patterns are still poorly known and are the topic of numerous ongoing research programmes. Most of these studies have focused on sediments deposited on elevated ridges in the central Arctic, intentionally biasing the results towards understanding the sea-ice rafted component of sediments. Therefore, balancing terrigenous sediment and OC export from the shelf to deep basins remains complicated. Budgets for sediment and OC export from the shelves remain poorly constrained due to the lack of information on the contribution of coastal erosion. Its contribution to sediment input needs to be better estimated.

Given the wide range of variation in suspended sediment supply, coastal erosion rates and sea-ice concentrations during the Holocene, high-resolution continental shelf and slope sediments spanning this interval could provide a critical link for examining how these changing boundary conditions will influence biogeochemical cycling and ecosystem dynamics in the future. However, only few high-resolution studies from the continental slopes and shelves exist to establish feedbacks between these processes and biogeochemical cycling and ecosystem dynamics. Continental shelf and slope sediments from the Holocene can be exploited in future studies to more fully address these interactions.

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