

RESEARCH/REVIEW ARTICLE

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).

These changes will likely lead to important transformations in sedimentary environments and the pathways and processes of terrigenous 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., Łacka 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 land-masses, 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

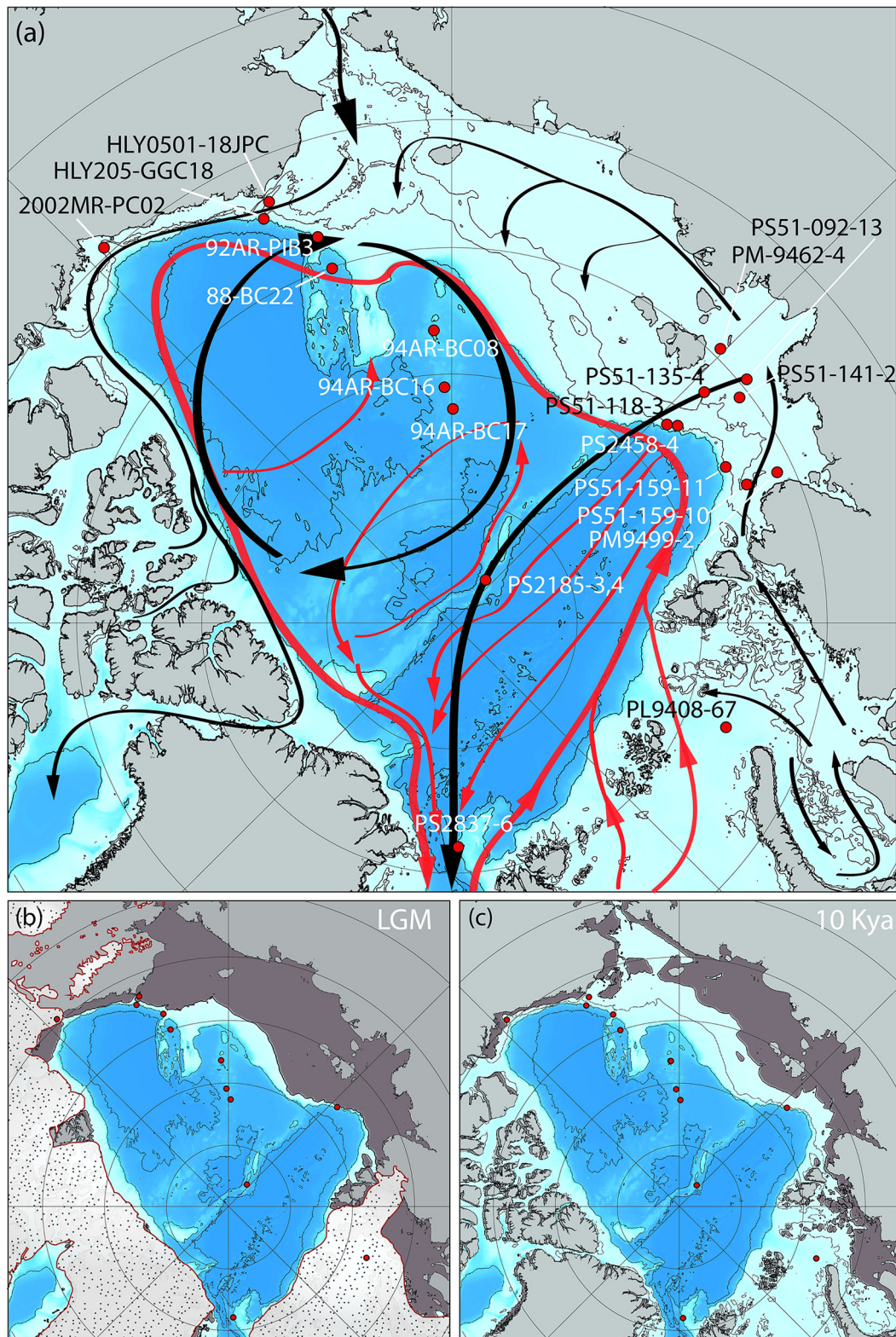


Fig. 1 (a) The modern Arctic Ocean and its constituent seas. Blue arrows indicate the surface circulation and red arrows show the flow of Atlantic Water. Locations and names are given for sediment cores shown in Fig. 6. (b) Physiography of the Arctic with ice sheet extents and associated sea-level lowering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

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

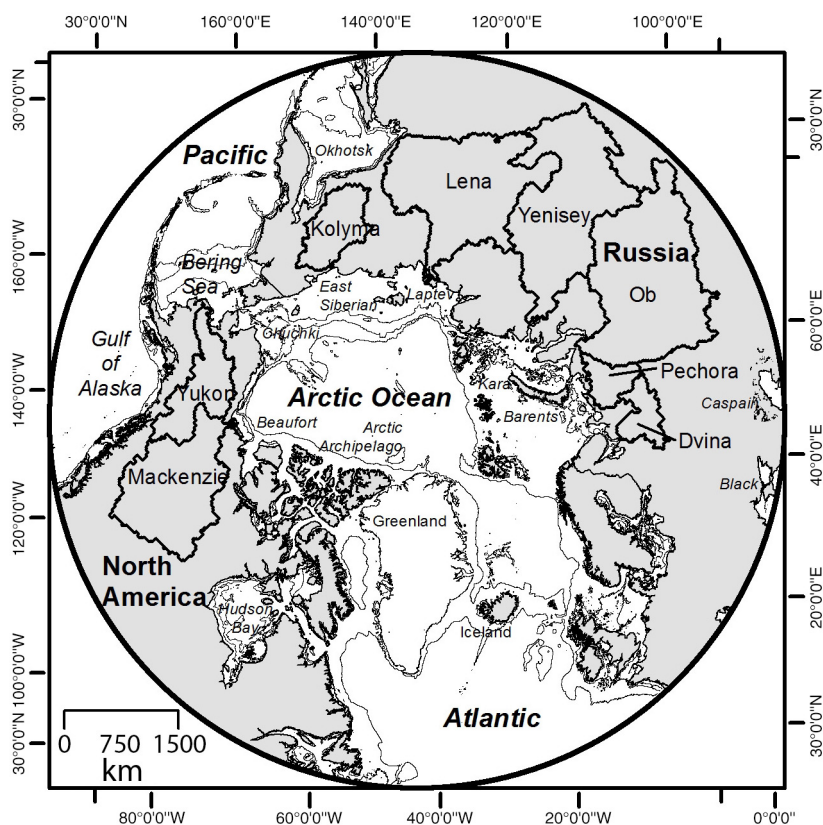


Fig. 2 Major oceanic basins, major rivers and watersheds corresponding to names and basins listed in Supplementary Table S1. The 50-, 100- and 1000-m bathymetric contour levels are shown (from the General Bathymetric Chart of the Oceans, one-minute grid, version 2 (Jakobsson et al. 2008). Drainage areas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

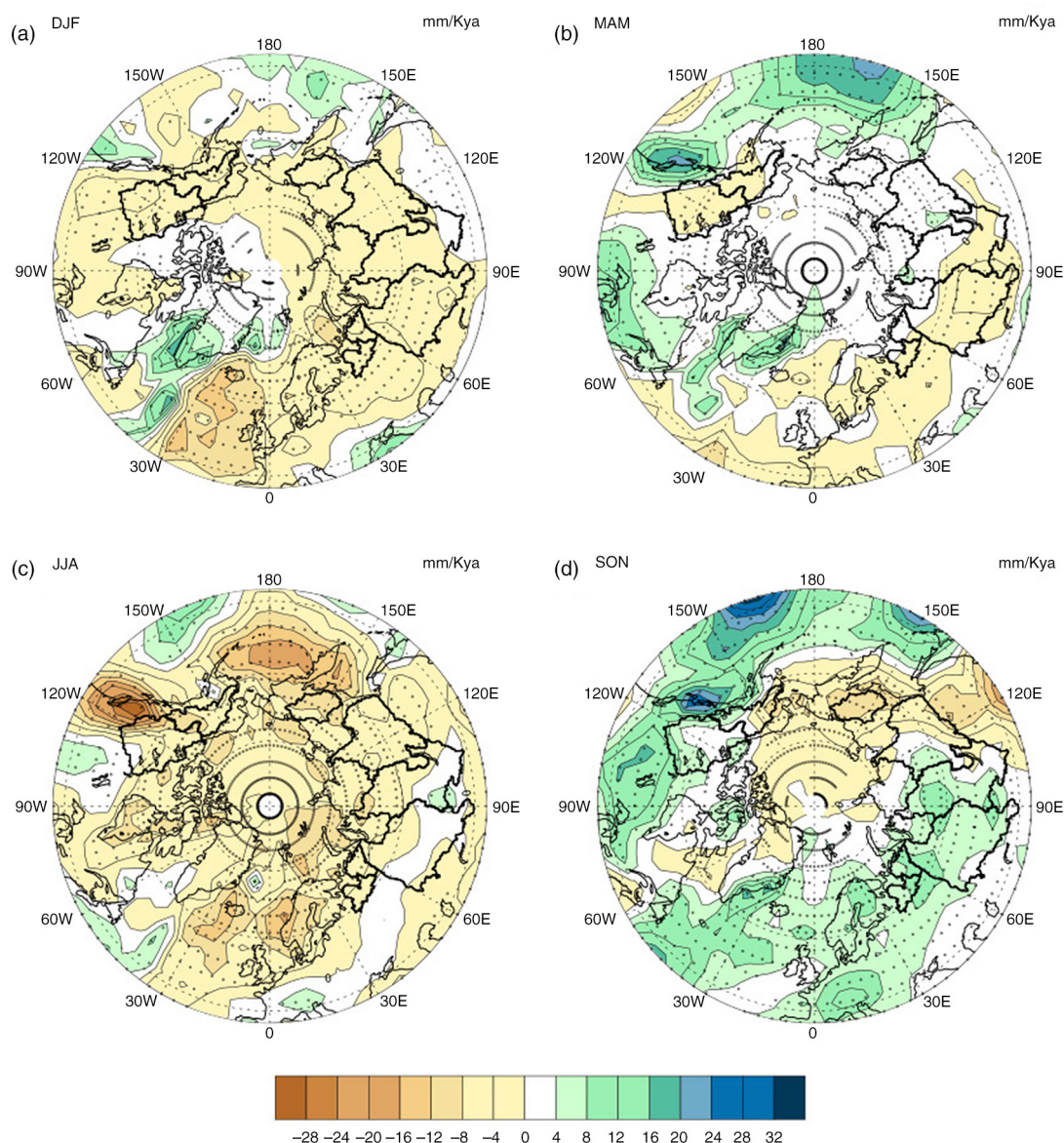


Fig. 3 Trends in precipitation (mm/Ky) between the middle Holocene and 1800 AD (pre-industrial period) for (a) winter (December–January–February), (b) spring (March–April–May), (c) summer (June–July–August) and (d) autumn (September–October–November). Source data from Wagner et al. (2011). A coupled 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

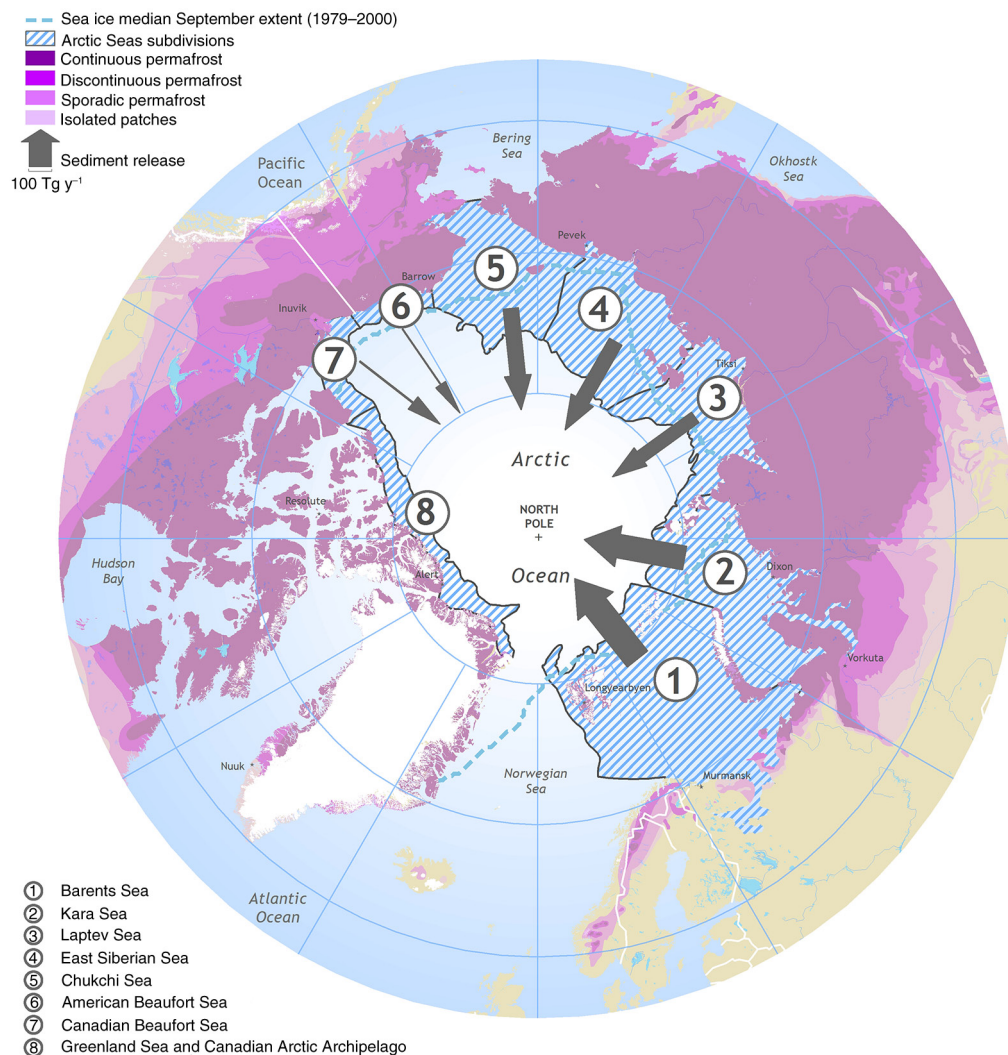


Fig. 4 Modern sediment contribution (Tg y^{-1}) from coastal erosion into the Arctic Ocean divided by marginal sea areas (after Brown et al. 2002).

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 ($2.1\text{--}3.3 \text{ Tg y}^{-1}$) and OC ($0.15\text{--}0.18 \text{ Tg y}^{-1}$) 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, Streletskaia 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 ($4.9\text{--}14 \text{ Tg y}^{-1}$; Supplementary

Table S2) is smaller than the annual carbon dioxide emissions estimated from terrestrial permafrost ($40.0\text{--}84.0 \text{ Tg C yr}^{-1}$; 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 $\pm 5\%$ 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 $<10 \text{ m}$ 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 $300\text{--}800 \text{ km}$ (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

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/cm²/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/cm²/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).

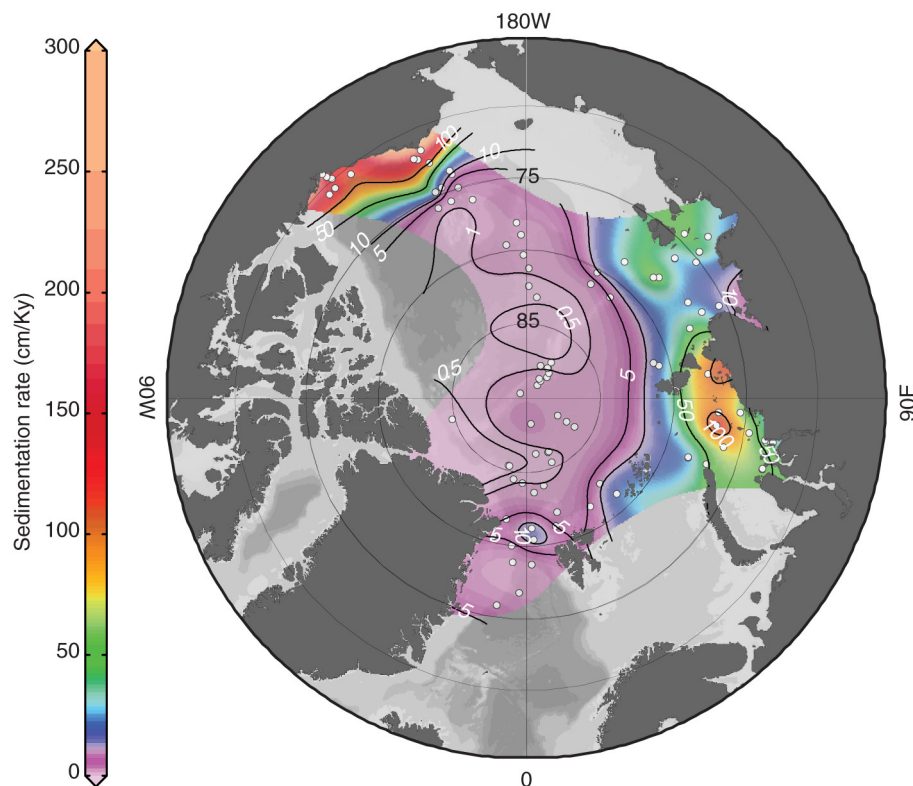


Fig. 5 Holocene sedimentation rates derived from ^{14}C dated sediments and gridded in the Ocean Data View software package (www.odv.awi.de/). The linear sedimentation rates were calculated without using a 0 age assumption for the seafloor.

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,

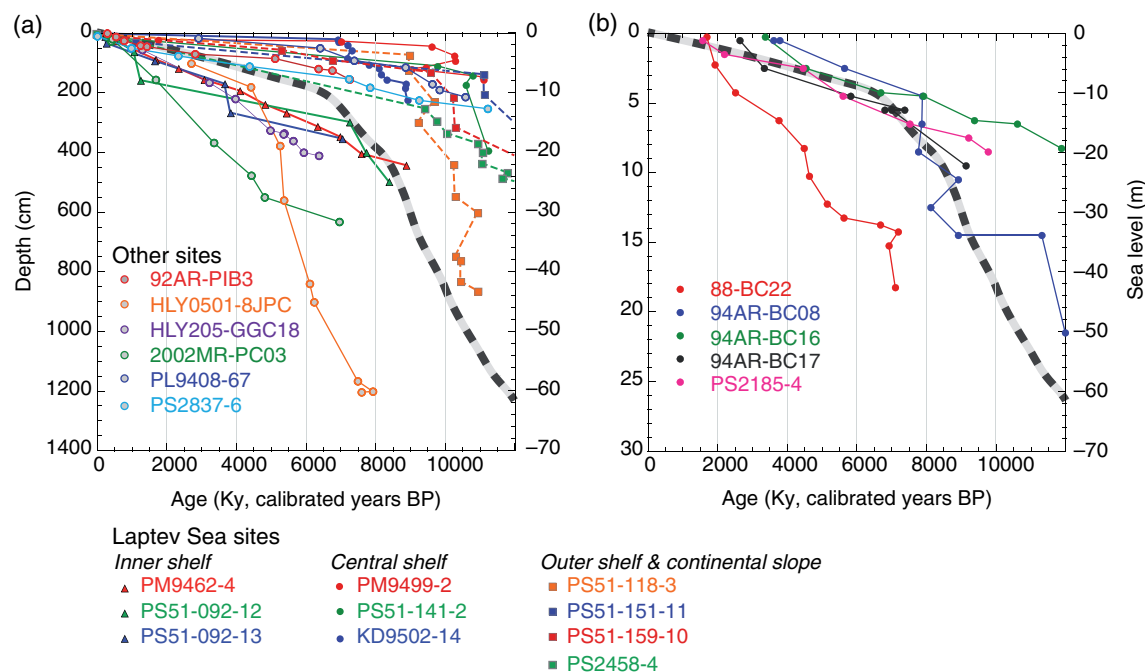


Fig. 6 Global sea level (black and grey dashed line) and published radiocarbon based sedimentation rates in the Arctic. Calibrated radiocarbon data are from Jakobsson et al. (2014) and for the Laptev Sea, Bauch et al. (2001). A subset of available cores was selected where enough radiocarbon dates exist 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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References

- Aagaard K., Swift J.H. & Carmack E. 1985. Thermohaline circulation in the Arctic Mediterranean seas. *Journal of Geophysical Research—Oceans* 90, 4833–4846.
- Alley R.B., Mayewski P.A., Sowers T., Stuiver M., Taylor K.C. & Clark P.U. 1997. Holocene climatic instability: a

- prominent, widespread event 8200 yr ago. *Geology* 25, 483–486.
- Andrews J.T. 2009. Seeking a Holocene drift ice proxy: non-clay mineral variations from the SW to N-central Iceland shelf: trends, regime shifts, and periodicities. *Journal of Quaternary Science* 24, 664–676.
- 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.
- Andrews J.T., Jennings A.E., Coleman G.C. & Eberl D.D. 2010. Holocene variations in mineral and grain-size composition along the East Greenland glaciated margin (ca 67°–70°N): local versus long-distance sediment transport. *Quaternary Science Reviews* 29, 2619–2632.
- Anisimov O.A., Vaughan D.G., Callaghan T.V., Furgal C., Marchant H., Prowse T.D., Vilhjálmsson H. & Walsh J.E. 2007. Polar regions (Arctic and Antarctic). In M.L. Parry et al. (eds.): *Climate change 2007: impacts, adaptation and vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*. Pp. 653–685. Cambridge: Cambridge University Press.
- Aré F.E., Grigoriev M.N., Hubberten H.W., Rachold V., Razumov S. & Schneider W. 2002. Comparative shoreface evolution along the Laptev Sea Coast. *Polarforschung* 70, 135–150.
- Atkinson D.E. 2005. Observed storminess patterns and trends in the Circum-Arctic coastal regime. *Geo-Marine Letters* 25, 98–109.
- Backman J., Jakobsson M., Løvlie R., Polyak L. & Febo L.A. 2004. Is the central Arctic Ocean a sediment starved basin? *Quaternary Science Review* 23, 1435–1454.
- Barber D.C., Dyke A., Hillaire-Marcel C., Jennings A.E., Andrews J.T., Kerwin M.W., Bilodeau G., McNeely R., Souton J., Morehead M.D. & Gagnon J.-M. 1999. Forcing of the cold event of 8,200 years ago by catastrophic drainage of Laurentide lakes. *Nature* 400, 344–348.
- Bard E., Arnold M., Mangerud J., Paterne M., Labeyrie L., Duprat J., Melieres M.-A., Sonstegaard E. & Duplessy J.-C. 1998. The North Atlantic atmosphere–sea surface ¹⁴C gradient during the Younger Dryas climate event. *Earth and Planetary Science Letters* 126, 275–287.
- Barletta F., St-Onge G., Channell J.E.T., Rochon A., Polyak L. & Darby D.A. 2008. High-resolution paleomagnetic secular variation and relative paleointensity records from the western Canadian Arctic: implication for Holocene stratigraphy and geomagnetic field behaviour. *Canadian Journal of Earth Sciences* 45, 1265–1281.
- Barnhart K.R., Overeem I. & Anderson R.S. 2014. The effect of changing sea ice on the physical vulnerability of Arctic coasts. *The Cryosphere* 8, 1777–1799.
- Baskaran M., Swarzenski P.W. & Porcelli D. 2003. Role of colloidal material in the removal of ²³⁴Th in the Canada Basin of the Arctic Ocean. *Deep-Sea Research Part I* 50, 1353–1373.
- Bauch D., Dmitrenko I.A., Wegner C., Hoelemann J.A., Kirillov S.A., Timokhov L.A. & Kassens H. 2009. Exchange of Laptev Sea and Arctic Ocean halocline waters in response to atmospheric forcing. *Journal of Geophysical Research—Oceans* 114, C05008, doi: <http://dx.doi.org/10.1029/2008JC005062>
- Bauch H.A., Erlenkeuser H., Bauch D., Nueller-Lupp T. & Taldenkova E. 2004. Stable oxygen and carbon isotopes in modern benthic foraminifera from the Laptev Sea shelf: implications for reconstructing proglacial and profluvial environments in the Arctic. *Marine Micropaleontology* 51, 285–300.
- Bauch H.A., Kassens H., Erlenkeuser H., Grootes P.M. & Thiede J. 1999. Depositional environment of the Laptev Sea (Arctic Siberia) during the Holocene. *Boreas* 28, 194–204.
- Bauch H.A., Kassens H., Naidina O.D., Kunz-Pirrung M. & Thiede J. 2001. Composition and flux of Holocene sediments on the eastern Laptev Sea shelf, Arctic Siberia. *Quaternary Research* 55, 344–351.
- Berger A.L. 1978. Long term variations of daily insolation and Quaternary climatic changes. *Journal of the Atmospheric Sciences* 35, 2362–2367.
- Bourgain P. & Gascard J.C. 2011. The Arctic Halocline and its interannual variability from 1997 to 2008. *Deep-Sea Research Part I* 58, 745–756.
- Bradley R.S. & England J.H. 2008. The younger Dryas and the sea of ancient ice. *Quaternary Research* 70, 1–10.
- Bringue M. & Rochon A. 2012. Late Holocene paleoceanography and climate variability over the Mackenzie Slope (Beaufort Sea, Canadian Arctic). *Marine Geology* 291, 83–96.
- Brown J., Ferrians O., Heginbottom J.A. & Melnikov E. 2002. *Circum-Arctic map of permafrost and ground-ice conditions. Version 2. Subset “permaice”*. Boulder, CO: National Snow and Ice Data Center.
- Carlson A.E. & Clark P.U. 2012. Ice sheet sources of sea level rise and freshwater discharge during the last deglaciation. *Reviews of Geophysics* 50, RG4007, doi: <http://dx.doi.org/10.1029/2011RG000371>
- Carmack E.C., Barber D., Christensen J., Macdonald R.W., Rudles B. & Sakshaug E. 2006. Climate variability and physical forcing of the food webs and the carbon budget on panarctic shelves. *Progress in Oceanography* 71, 124–181.
- Darby D.A. 2008. Arctic perennial ice cover over the last 14 million years. *Paleoceanography* 23, PA1S07, doi: <http://dx.doi.org/10.1029/2007PA001479>
- Darby D.A. & Bischof J.F. 1996. A statistical approach to source determination of lithic and Fe oxide grains: an example from the Alpha Ridge, Arctic Ocean. *Journal of Sedimentary Research Section A* 66, 599–607.
- Darby D.A. & Bischof J.F. 2004. A Holocene record of changing Arctic Ocean ice drift, analogous to the effects of the Arctic Oscillation. *Paleoceanography* 19, PA1027, doi: <http://dx.doi.org/10.1029/2003PA000961>

- Darby D.A., Bischof 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., Ortiz J., Polyak L., Lund S., Jakobsson M. & Woodgate R.A. 2009. The role of currents and sea ice in both slowly deposited central Arctic and rapidly deposited Chukchi–Alaskan margin sediments. *Global and Planetary Change* 68, 58–72.
- Darby D.A., Ortiz J.D., Grosch C.E. & Lund S.P. 2012. 1,500-year cycle in the Arctic Oscillation identified in Holocene Arctic sea-ice drift. *Nature Geosciences* 5, 897–900.
- 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.
- Davies A.M. & Xing J.X. 2005. The effect of a bottom shelf front upon the generation and propagation of near-inertial internal waves in the coastal ocean. *Journal of Physical Oceanography* 35, 976–990.
- Dethleff D. 2005. Entrainment and export of Laptev Sea ice sediments, Siberian Arctic. *Journal of Geophysical Research—Oceans* 110, C07009, doi: <http://dx.doi.org/10.1029/2004JC002740>
- Dethleff D., Rachold V., Tinteln M. & Antonow M. 2000. Modern sea-ice transport of riverine sediments from the Laptev Sea to the Fram Strait based on clay mineral studies. *International Journal of Earth Sciences* 89, 496–502.
- de Vernal A., Hillaire-Marcel C. & Darby D.E. 2005. Variability of sea ice cover in the Chukchi Sea (western Arctic Ocean) during the Holocene. *Paleoceanography* 20, PA4018, doi: <http://dx.doi.org/10.1029/2005PA001157>
- de Vernal A., Hillaire-Marcel C., Rochon A., Fréchette B., Henry M., Solignac S. & Bonnet S. 2013. Dinocyst-based reconstructions of sea ice cover concentration during the Holocene in the Arctic Ocean, the northern North Atlantic Ocean and its adjacent seas. *Quaternary Science Reviews* 79, 111–121.
- Dmitrenko I.A., Kirillov S.A., Eicken H. & Markova N. 2005. Wind-driven summer surface hydrography of the eastern Siberian shelf. *Geophysical Research Letters* 32, L14613, doi: <http://dx.doi.org/10.1029/2005GL023022>
- Eicken H. 2004. The role of Arctic sea ice in transporting and cycling terrestrial organic matter. In R. Stein & R.W. Macdonald (eds.): *The organic carbon cycle in the Arctic Ocean*. Pp. 45–53. Heidelberg: Springer.
- Eicken H., Gradinger R., Gaylord A., Mahony A., Rigor I. & Melling H. 2005. Sediment transport by sea ice in the Chukchi and Beaufort seas: increasing importance due to changing ice conditions? *Deep-Sea Research Part II* 52, 3281–3302.
- Eicken H., Kolatschek J., Freitag J., Lindemann F., Kassens H. & Dmitrenko I. 2000. A key source area and constraints an entrainment for basin-scale sediment transport by Arctic sea ice. *Geophysical Research Letters* 27, 1919–1922.
- Eicken H., Reimnitz E., Alexandrov V., Martin T., Kassens H. & Viehoff T. 1997. Sea-ice processes in the Laptev Sea and their importance for sediment export. *Continental Shelf Research* 17, 205–233.
- Eisenhauer A., Spielhagen R.F., Frank M., Hentzschel G., Mangini A., Kubik P.W., Dittrich-Hannen B. & Billen T. 1994. ¹⁰Be record of sediment cores from high northern latitudes: implications for environmental and climatic changes. *Earth and Planetary Science Letters* 124, 171–184.
- Fahl K. & Stein R. 1999. Biomarkers as organic-carbon-source and environmental indicators in the late Quaternary Arctic Ocean. *Marine Chemistry* 63, 293–309.
- Fahl K. & Stein R. 2007. Biomarker records, organic carbon accumulation, and river discharge in the Holocene southern Kara Sea (Arctic Ocean). *Geo-Marine Letters* 27, 13–25.
- Fairbanks R.G. 1989. A 17,000-year glacioeustatic sea level record: influence of glacial melting rates on the Younger Dryas event and deep-ocean circulation. *Nature* 342, 637–642.
- Farmer J.R., Cronin T.M., de Vernal A., Dwyer G.S., Keigwin L.D. & Thunell R.C. 2011. Western Arctic Ocean temperature variability during the last 8000 years. *Geophysical Research Letters* 38, L24602, doi: <http://dx.doi.org/10.1029/2011GL049714>
- Faux J.F., Belicka L.L. & Harvey H.R. 2011. Organic sources and carbon sequestration in Holocene shelf sediments from the western Arctic Ocean. *Continental Shelf Research* 31, 1169–1179.
- Fichot C.G., Kaiser K., Hooker S.B., Amon R.M.W., Babin M., Bélanger S., Waler S.A. & Benner R. 2013. Pan-Arctic distributions of continental runoff in the Arctic Ocean. *Scientific Reports* 3, article no. 1053, doi: <http://dx.doi.org/10.1038/srep01053>
- Fisher D.A., Koerner R.M. & Reeh N. 1995. Holocene climatic records from Agassiz Ice Cap, Ellesmere Island, NWT, Canada. *The Holocene* 5, 19–24.
- Fisher T.G., Smith D.G. & Andrews J.T. 2002. Preboreal oscillation caused by a glacial Lake Agassiz flood. *Quaternary Science Reviews* 21, 873–878.
- Forbes D.L. 2011. *State of the Arctic coast 2010. Scientific review and outlook*. Geesthacht, Germany: Helmholtz-Zentrum Geesthacht.
- Fritz M., Opel T., Tanski G., Herzsuh U., Meyer H., Eulenburg A. & Lantuit H. 2015. Dissolved organic carbon (DOC) in Arctic ground ice. *The Cryosphere* 9, 737–752.
- Funder S., Goosse H., Jepsen H., Kaas E., Kjær K.H., Korsgaard N.J., Larsen N.K., Linderson H., Lyså A., Möller P., Olsen J. & Willerslev E. 2011. A 10,000-year record of Arctic Ocean sea-ice variability—view from the beach. *Science* 333, 747–750.
- Gofñi M.A., O'Connor A.E., Kuzyk Z.Z., Yunker M.B., Gobeil C. & Macdonald R.W. 2013. Distribution and sources of organic matter in surface marine sediments across the North American Arctic margin. *Journal of Geophysical Research—Oceans* 118, 4017–4035.
- Gordeev V.V. 2006. Fluvial sediment flux to the Arctic Ocean. *Geomorphology* 80, 94–104.

- Grigoriev M.N. & Rachold V. 2003. The degradation of coastal permafrost and the organic carbon balance of the Laptev and East Siberian seas. In M. Phillips et al. (eds.): *Permafrost: proceedings of the Eighth International Conference on Permafrost*. Pp. 319–324. Rotterdam: AA Balkema Publishers.
- Guay C.K., Falkner R.D., Muench R.D., Mensch M., Frank M. & Bayer R. 2001. Wind-driven transport pathways for Eurasian Arctic river discharge. *Journal of Geophysical Research—Oceans* 106, 11469–11480.
- Günther F., Overduin P.P., Sandakov A.V., Grosse G. & Grigoriev M.N. 2013. Short- and long-term thermo-erosion of ice-rich permafrost coasts in the Laptev Sea region. *Biogeosciences* 10, 4297–4318.
- Günther F., Overduin P.P., Yakshina I.A., Opel T., Baranskaya A.V. & Grigoriev M.N. 2015. Observing Muostakh disappear: permafrost thaw subsidence and erosion of a ground-ice-rich island in response to Arctic summer warming and sea ice reduction. *The Cryosphere* 9, 151–178.
- Harms I.H. & Karcher M.J. 1999. Modeling the seasonal variability of hydrography and circulation in the Kara Sea. *Journal of Geophysical Research—Oceans* 104, 13431–13448.
- Hein F.J. & Mudie P.J. 1991. Glacial-marine sedimentation, Canadian polar margin north of Axel Heiberg Island. *Géographie Physique et Quaternaire* 45, 213–227.
- Hill P.R., Blasco S.M., Harper J.R. & Fissel D.B. 1991. Sedimentation in the Canadian Beaufort Shelf. *Continental Shelf Research* 11, 821–842.
- Holmes R.M., McClelland J.W., Peterson B.J., Shiklomanov I.A., Shiklomanov A.I., Zhulidov A.V., Gordeev V.V. & Bobrovitskaya N.N. 2002. A circumpolar perspective on fluvial sediment flux to the Arctic Ocean. *Global Biogeochemical Cycles* 16, article no. 1098, doi: <http://dx.doi.org/10.1029/2001GB001849>
- Jakobsson M., Anderson J.B., Nitsche F.O., Dowdeswell J.A., Gyllencreutz R., Kirchner N., O'Regan M.A., Alley R.B., Anandakrishnan S., Mohammad R., Eriksson B., Fernandez R., Kirshner A., Minzoni R., Stollendorf T. & Majewski W. 2011. Geological record of ice shelf breakup and grounding line retreat, Pine Island Bay, west Antarctica. *Geology* 39, 691–694.
- Jakobsson M., Andreassen K., Bjarnadóttir L.R., Dove D., Dowdeswell J.A., England J.H., Funder S., Hogan K., Ingólfsson Ó., Jennings A., Larsen N.K., Kirchner N., Landvik J.Y., Mayer L., Mikkelsen N., Möller P., Niessen F., Nilsson J., O'Regan M., Polyak L., Nørgaard-Pedersen N. & Stein R. 2014. Arctic Ocean glacial history. *Quaternary Science Reviews* 92, 40–67.
- Jakobsson M., Long A., Ingólfsson O., Kjaer K.H. & Spielhagen R.F. 2010. New insights on Arctic Quaternary climate variability from palaeo-records and numerical modelling. *Quaternary Science Reviews* 29, 3349–3358.
- Jakobsson M., Macnab R., Mayer L., Anderson R., Edwards M., Hatzky J., Schenke H.W. & Johnson P. 2008. An improved bathymetric portrayal of the Arctic Ocean: implications for ocean modeling and geological, geophysical and oceanographic analyses. *Geophysical Research Letters* 35, L07602, doi: <http://dx.doi.org/10.1029/2008GL033520>
- Jennings A.E., Knudsen K.L., Hald M., Hansen C.V. & Andrews J.T. 2002. A mid-Holocene shift in Arctic sea-ice variability on the East Greenland Shelf. *The Holocene* 12, 49–58.
- Jorgenson M.T. & Brown J. 2005. Classification of the Alaskan Beaufort Sea coast and estimation of carbon and sediment inputs from coastal erosion. *Geo-Marine Letters* 25, 69–80.
- Jones B.M., Arp C.D., Jorgenson M.T., Hinkel K.M., Schmutz J.A. & Flint P.L. 2009. Increase in the rate and uniformity of coastline erosion in Arctic Alaska. *Geophysical Research Letters* 36, L03503, doi: <http://dx.doi.org/10.1029/2008GL036205>
- Kaufmann D.S., Ager T.A., Anderson N.J., Anderson P.M., Andrews J.T., Bartlein P.J., Brubaker L.B., Coats L.L., Cwynar L.C., Duvall M.L., Dyke A.S., Edwards M.E., Eisner W.R., Gajewski K., Geirsdóttir A., Hu F.S., Jennings A.E., Kaplan M.R., Kerwin M.W., Lozhkin A.V., MacDonald G.M., Miller G.H., Mock C.J., Oswald W.W., Otto-Bliesner B.L., Porinchu D.F., Rühland K., Smol J.P., Steig E.J. & Wolfe B.B. 2004. Holocene thermal maximum in the western Arctic (0–180°W). *Quaternary Science Reviews* 23, 529–560.
- Keigwin L.D., Donnelly 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.
- Kleiven H.F., Kissel C., Laj C., Ninnemann U.S., Richter T.O. & Cortijo E. 2008. Reduced North Atlantic Deep Water coeval with the glacial Lake Agassiz freshwater outburst. *Science* 319, 60–64.
- Kwok R., Cunningham G.F., Wensnahan M., Rigor I., Zwally H.J. & Yi D. 2009. Thinning and volume loss of the Arctic Ocean sea ice cover: 2003–2008. *Journal of Geophysical Research—Oceans* 114, C07005, doi: <http://dx.doi.org/10.1029/2009JC005312>
- Łącka M., Zajaczkowski M., Forwick M. & Szczucinski W. 2015. Late Weichselian and Holocene paleoceanography of Storfjordrenna, southern Svalbard. *Climate of the Past* 11, 587–603.
- Lambeck K., Esat T.M. & Potter E.-K. 2002. Links between climate and sea levels for the past three million years. *Nature* 419, 199–206.
- Lammers R.B., Shiklomanov A.I., Vörösmarty C.J., Fekete B.M. & Petersen B.J. 2001. Assessment of contemporary Arctic river runoff based on observational discharge records. *Journal of Geophysical Research—Atmospheres* 106, 3321–3334.
- Lantuit H., Overduin P., Couture N., Wetterich S., Aré F., Atkinson D., Brown J., Cherkashov G., Drozdov D., Forbes D., Graves-Gaylord A., Grigoriev M., Hubberten H.-W., Jordan J., Jorgenson T., Ødegård R., Ogorodov S., Pollard W., Rachold V., Sedenko S., Solomon S., Steenhuisen F., Streletskaia I. & Vasiliev A. 2012. The Arctic Coastal Dynamics Database: a new classification scheme and statistics on Arctic permafrost coastlines. *Estuaries and Coasts* 35, 383–400.

- Laskar J., Robutel P., Joutel F., Gastineau M., Correia A.C.M. & Levrard B. 2004. A long-term numerical solution for the insolation quantities of the Earth. *Astronomy and Astrophysics* 428, 261–285.
- Legutke S. & Voss R. 1999. *The Hamburg atmosphere–ocean coupled model ECHO-G. Technical Report 18*. Hamburg: German Climate Computer Center.
- Lewis C.P. 1988. *Mackenzie Delta sedimentary environments and processes. Unpublished contract report*. Ottawa: Sediment Survey Section, Environment Canada.
- Lisé-Pronovost A., St-Onge G., Brachfeld S., Barletta F. & Darby D. 2009. Paleomagnetic constraints on the Holocene stratigraphy of the Arctic Alaskan margin. *Global and Planetary Change* 68, 85–99.
- Maccali J., Hillaire-Marcel C., Carignan J. & Reisberg L.C. 2013. Geochemical signatures of sediments documenting Arctic sea-ice and water mass export through Fram Strait since the Last Glacial Maximum. *Quaternary Science Reviews* 64, 136–151.
- Macdonald R.W. 2000. Arctic estuaries and ice: a positive-negative estuarine couple. In E.L. Lewis et al. (eds.): *The freshwater budget of the Arctic Ocean*. Pp. 383–407. Dordrecht: Kluwer.
- Macdonald R.W., Anderson L.G., Christensen J.P., Miller L.A., Semiletov I.P. & Stein R. 2010. Polar margins: the Arctic Ocean. In K.K. Liu et al. (eds.): *Carbon and nutrient fluxes in continental margins: a global synthesis*. Pp. 291–303. New York: Springer.
- Macdonald R.W. & Gobeil C. 2012. Manganese sources and sinks in the Arctic Ocean with reference to periodic enrichments in basin sediments. *Aquatic Geochemistry* 18, 565–591.
- Macdonald R.W., McLaughlin F.A. & Carmack E.C. 2002. Fresh water and its sources during SHEBA drift in the Canada Basin of the Arctic Ocean. *Deep-Sea Research Part I* 49, 1769–1785.
- Mackay J.R. 1972. Offshore permafrost and ground ice, southern Beaufort Sea, Canada. *Canadian Journal of Earth Sciences* 9, 1550–1561.
- McClimans T., Johnson D.R., Krosshavn D.R., King S.E., Carroll J. & Grenness O. 2000. Transport processes in the Kara Sea. *Journal of Geophysical Research—Oceans* 105, 14121–14139.
- McGuire A.D., Anderson L.G., Christensen T.R., Dallimore S., Guo L., Hayes D.J., Heimann M., Lorenson T.D., Macdonald R.W. & Roulet N. 2009. Sensitivity of the carbon cycle in the Arctic to climate change. *Ecological Monographs* 79, 523–555.
- Moros M., Andrews J.T., Eberl D.D. & Jansen E. 2006. Holocene history of drift ice in the northern North Atlantic: evidence for different spatial and temporal modes. *Paleoceanography* 21, PA2017, doi: <http://dx.doi.org/10.1029/2005PA001214>
- Müller J., Werner K., Stein R., Fahl K., Moros M. & Jansen E. 2012. Holocene cooling culminates in sea ice oscillations in Fram Strait. *Quaternary Science Reviews* 47, 1–14.
- Müller-Lupp T., Erlenkeuser H., Bauch H.A., Hefter J., Kassens H. & Thiede J. 2000. Input of terrestrial organic matter into the Laptev Sea during the Holocene—evidence from stable carbon isotopes. *Journal of Earth Sciences* 89, 563–568.
- Murton J.B., Bateman M.D., Dallimore S.R., Teller J.T. & Yang Z. 2010. Identification of Younger Dryas outburst flood path from Lake Agassiz to the Arctic Ocean. *Nature* 464, 740–743.
- Nørgaard-Pedersen N., Spielhagen R.F., Erlenkeuser H., Grootes P.M., Heinemeier J. & Knies J. 2003. Arctic Ocean during the Last Glacial Maximum: Atlantic and polar domains of surface water mass distribution and ice cover. *Paleoceanography* 18, article no. 1063, doi: <http://dx.doi.org/10.1029/2002PA000781>
- 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.
- 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.
- Overduin P.P., Hubberten H.-W., Rachold V., Romanovskii N., Grigoriev M. & Kasymkaya M. 2007. The evolution and degradation of coastal and offshore permafrost in the Laptev and East Siberian seas during the last climatic cycle. *Geological Society of America Special Papers* 426, 97–111.
- Peltier W.R. & Fairbanks R.G. 2006. Global glacial volume and Last Glacial Maximum duration from an extended Barbados sea level record. *Quaternary Science Reviews* 25, 3322–3337.
- Peregovich B., Hoops E. & Rachold V. 1999. Sediment transport to the Laptev Sea (Siberian Arctic) during the Holocene—evidence from the heavy mineral composition of fluvial and marine sediments. *Boreas* 28, 205–214.
- Peterson B.J., Holmes R.M., McClelland J.W., Vörösmarty C.J., Lammers R.B., Shiklomanov A.I., Shiklomanov I.A. & Rahmstorf S. 2002. Increasing river discharge to the Arctic Ocean. *Science* 298, 2171–2173.
- Pfirman S.L., Colony R., Nürnberg D., Eicken H. & Rigor I. 1997. Reconstructing the origin and trajectory of drifting Arctic sea ice. *Journal of Geophysical Research—Oceans* 102, 12575–12586.
- Pickart R.S. 2004. Shelfbreak circulation in the Alaskan Beaufort Sea: mean structure and variability. *Journal of Geophysical Research—Ocean* 109, C04024, doi: <http://dx.doi.org/10.1029/2003JC001912>
- Pieńkowski A.J., England J.H., Furze M.F.A., Blasco S., Mudie P.J. & MacLean B. 2013. 11,000 yrs of environmental change in the Northwest Passage: a multiproxy core record from central Parry Channel, Canadian High Arctic. *Marine Geology* 341, 68–85.
- Ping C.-L., Michaelson G.J., Guo L., Jorgenson M.T., Kanevskiy M., Shur Y., Dou F. & Liang J. 2011. Soil carbon and material fluxes across the eroding Alaska Beaufort Sea coastline. *Journal of Geophysical Research—Biogeosciences* 116, G02004, doi: <http://dx.doi.org/10.1029/2010JG001588>

- Polyak L., Alley R.B., Andrews J.T., Brigham-Grette J., Cronin T.M., Darby D.E., Dyke A.S., Fitzpatrick J.J., Funder S., Holland M., Jennings A.E., Miller G.H., O'Regan M., Savelle J., Serreze M., St. John K., White J.W.C. & Wolff E. 2010. History of sea ice in the Arctic. *Quaternary Science Reviews* 29, 1557–1778.
- Polyak L., Bischof J., Ortiz J.D., Darby D.A., Channell J.E.T., Xuan C., Kaufmann D.S., Løvlie R., Schneider D.A., Eberl D.D., Adler R.E. & Council E. 2009. Late Quaternary stratigraphy and sedimentation patterns in the western Arctic Ocean. *Global and Planetary Change* 68, 5–17.
- 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. *Palaeogeography, Palaeoclimatology, Palaeoecology* 203, 73–93.
- Polyak L. & Jakobsson M. 2011. Quaternary sedimentation in the Arctic Ocean: recent advances and further challenges. *Oceanography* 24, 52–64.
- Rachold V., Bolshiyakov D.Y., Grigoriev M.N., Hubberten H.-W., Junker R., Kunitsky V.V., Merker F., Overduin P. & Schneider W. 2007. Nearshore Arctic subsea permafrost in transition. *Eos, Transactions of the American Geophysical Union* 88, 149–150.
- Rachold V., Eicken H., Gordeev V.V., Grigoriev M.N., Hubberten H.W., Lisitzin A.P., Shevchenko V.P. & Schirrmeister L. 2004. Modern terrigenous organic carbon input to the Arctic Ocean. In R. Stein & R. MacDonald (eds.): *The organic carbon cycle in the Arctic Ocean*. Pp. 33–55. Berlin: Springer.
- Rachold V., Grigoriev M.N. & Bauch H.A. 2002. An estimation of the sediment budget in the Laptev Sea during the last 5000 years. *Polarforschung* 70, 151–157.
- Reimnitz E., Barnes P.W. & Weber W.S. 1993. Particulate matter in pack ice of the Beaufort Gyre. *Journal of Glaciology* 39, 186–198.
- Retamal L., Bonilla S. & Vincent W.F. 2008. Optical gradients and phytoplankton production in the Mackenzie River and the coastal Beaufort Sea. *Polar Biology* 31, 363–379.
- Rigor I.G., Wallace J.M. & Colony R.L. 2002. Response of sea ice to the Arctic Oscillation. *Journal of Climate* 15, 2648–2663.
- Rochon A., Scott D.B., Schell T.M., Blasco S., Bennett R. & Mudie P.J. 2006. Evolution of sea surface conditions during the Holocene: comparison between eastern (Baffin Bay and Hudson Strait) and western (Beaufort Sea) Canadian Arctic. *Eos, Transactions of the American Geophysical Union* 87, Fall Meeting Supplement, abstract no. U43B–0867.
- Rohling E.P. & Pälike H. 2005. Centennial-scale climate cooling with a sudden cold event around 8,200 years ago. *Nature* 434, 975–979.
- Romanovskii N.N., Hubberten H.W., Gavrillov A.V., Tumskey V.E. & Kholodov A.L. 2004. Permafrost of the east Siberian Arctic shelf and coastal lowlands. *Quaternary Science Reviews* 23, 1359–1369.
- Rutter N. 1995. Problematic ice sheets. *Quaternary International* 28, 19–37.
- Schulze L.M. & Pickart R.S. 2012. Seasonal variation of upwelling in the Alaskan Beaufort Sea: impact of sea ice cover. *Journal of Geophysical Research—Oceans* 117, C06022, doi: <http://dx.doi.org/10.1029/2012JC007985>
- Sellén E., O'Regan M. & Jakobsson M. 2010. Spatial and temporal Arctic Ocean depositional regimes: a key to the evolution of ice drift and current patterns. *Quaternary Science Reviews* 29, 3644–3664.
- Serreze M.C., Holland M.M. & Stroeve J. 2007. Perspectives on the Arctic's shrinking sea-ice. *Science* 315, 1533–1536.
- Shiklomanov I.A. 2000. Appraisal and assessment of world water resources. *Water International* 25, 11–32.
- Shiklomanov I.A. & Lammers R.B. 2010. Record Russian river discharge in 2007 and the limits of analysis. *Environmental Research Letters* 4, article no. 045015, doi: <http://dx.doi.org/10.1088/1748-9326/4/4/045018>
- Shiklomanov I.A. & Shiklomanov A.I. 2003. Climate change and the dynamics of river runoff in the Arctic Ocean. *Water Resources* 30, 591–601.
- Smith J.N., Moran S.B. & Macdonald R.W. 2003. Shelf-basin interactions in the Arctic Ocean based on ^{210}Pb and Ra isotope tracer distributions. *Deep-Sea Research Part I* 50, 397–416.
- Spielhagen R.F., Baumann K.H., Erlenkeuser H., Nowaczyk N.R., Nørgaard-Pedersen N., Vogt C. & Weiel D. 2004. Arctic Ocean deep-sea record of northern Eurasian ice sheet history. *Quaternary Science Reviews* 23, 1455–1483.
- Spielhagen R.F., Erlenkeuser H. & Siebert C. 2005. History of freshwater runoff across the Laptev Sea (Arctic) during the last deglaciation. *Global and Planetary Change* 48, 187–207.
- Steele M. & Boyd T. 1998. Retreat of the cold halocline layer in the Arctic Ocean. *Journal of Geophysical Research—Oceans* 103, 10419–10435.
- Stein R. 1998. *Arctic Paleo-River Discharge (APARD): a new research programme of the Arctic Ocean Science Board (AOSB)*. Reports on Polar Research 279. Bremerhaven: Alfred Wegener Institute.
- Stein R. 2000. Circum-Arctic river discharge and its geological record: an introduction. *International Journal of Earth Sciences* 89, 447–449.
- Stein R. 2008. *Arctic Ocean sediments: processes, proxies, and paleoenvironment*. Amsterdam: Elsevier.
- Stein R., Bousein B., Fahl K., Garcia de Oteyza T., Knies J. & Niessen F. 2001. Accumulation of particulate organic carbon at the Eurasian continental margin during late Quaternary times: controlling mechanisms and paleoenvironmental significance. *Global and Planetary Change* 31, 87–104.
- Stein R., Dittmers K., Fahl K., Kraus M., Matthiesen J., Niessen F., Pirrung M., Polyakova Ye., Schoster F., Steinke T. & Fütterer D.K. 2004. Arctic (palaeo) river discharge and environmental change: evidence from the Holocene Kara Sea sedimentary record. *Quaternary Science Review* 23, 1485–1511.
- Stein R. & Fahl K. 2000. Holocene accumulation of organic carbon at the Laptev Sea continental margin (Arctic Ocean): sources, pathways, and sinks. *Geo-Marine Letters* 20, 27–36.

- Stein R. & Macdonald R.W. 2004. Organic carbon budget: Arctic Ocean vs. global ocean. In R. Stein & R.W. Macdonald (eds.): *The organic carbon cycle in the Arctic Ocean*. Pp. 315–322. Berlin: Springer.
- Stein R., Schubert C.J., Macdonald R.W., Fahl K., Harvey H.R. & Weiel D. 2004. The central Arctic Ocean: distribution, sources, variability and burial of organic carbon. In R. Stein & R.W. Macdonald (eds.): *The organic carbon cycle in the Arctic Ocean*. Pp. 295–314. Berlin: Springer.
- Sternberg R.W., Aagaard K., Cacchione D.A., Wheatcroft R.A., Beach R.A., Roach A.T. & Marsden M.A.H. 2001. Long-term near-bed observations of velocity and hydrographic properties in the northwest Barents Sea with implications for sediment transport. *Continental Shelf Research* 21, 509–529.
- Streletskaia I., Vasiliev A. & Vanstein B. 2009. Erosion of sediment and organic carbon from the Kara Sea coast. *Arctic, Antarctic, and Alpine Research* 41, 79–87.
- Stroeve J., Serreze M., Holland M., Kay J., Malanik J. & Barrett A. 2012. The Arctic's rapidly shrinking sea ice cover: a research synthesis. *Climatic Change* 110, 1005–1027.
- Stuiver M., Grootes P.M. & Braziunas T.F. 1995. The GISP2 $\delta^{18}\text{O}$ climate record of the past 16,500 years and the role of the sun, ocean, and volcanoes. *Quaternary Research* 44, 341–354.
- Svendsen J.I., Alexanderson H., Astakhov V.I., Demidov I., Dowdeswell J.A., Funder S., Gataullin V., Henriksen M., Hjort 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., Matiouchkov 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.
- Trimble S.M. & Baskaran M. 2005. The role of suspended particulate matter in ^{234}Th scavenging and ^{234}Th -derived export fluxes of POC in the Canada Basin of the Arctic Ocean. *Marine Chemistry* 96, 1–19.
- Tütken T., Eisenhauer A., Wiegand B. & Hansen B.T. 2002. Glacial–interglacial cycles in Sr and Nd isotopic composition of Arctic marine sediments triggered by the Svalbard/Barents Sea ice sheet. *Marine Geology* 182, 351–372.
- Vasiliev A., Kanevskiy M., Cherkashov G. & Vanshtein B. 2005. Coastal dynamics at the Barents and Kara Sea key sites. *Geo-Marine Letters* 25, 110–120.
- Viscosi-Shirley C., Pisias N. & Mammone K. 2003. Sediment source, transport pathways and accumulation patterns on the Siberian-Arctic's Chukchi and Laptev shelves. *Continental Shelf Research* 23, 1201–1225.
- Vonk J.E., Sanchez-Garcia L., van Dongen B.E., Alling V., Kosmach D., Charkin A., Semiletov I.P., Dudarev O.V., Shakhova N., Roos P., Eglinton T.I., Andersson A. & Gustafsson O. 2012. Activation of old carbon by erosion of coastal and subsea permafrost in Arctic Siberia. *Nature* 489, 137–140.
- Vorosmarty C.J., Fekete B.M., Meybeck M. & Lammers R. 2000a. Geomorphometric attributes of the global system of rivers at 30-minute spatial resolution (STN-30). *Journal of Hydrology* 237, 17–39.
- Vorosmarty C.J., Fekete B.M., Meybeck M. & Lammers R. 2000b. A simulated topological network representing the global system of rivers at 30-minute spatial resolution (STN-30). *Global Biogeochemical Cycles* 14, 599–621.
- Wagner A., Lohmann G. & Prange M. 2011. Arctic river discharge trends since 7 ka BP. *Global and Planetary Change* 79, 48–60.
- Walker M.J.C., Berkelhammer M., Björck S., Cwynar L.C., Fisher D.A., Long A.J., Lowe J.J., Mewmha R.M., Rasmussen S.O. & Weiss H. 2012. Formal subdivision of the Holocene Series/Epoch: a discussion paper by a working group of INTIMATE (Integration of ice-core, marine and terrestrial records) and the Subcommission on Quaternary Stratigraphy (International Commission on Stratigraphy). *Journal of Quaternary Science* 27, 649–659.
- Wanner H., Beer J., Büttikofer J., Crowley T.J., Cubasch U., Flückiger J., Goosse H., Grosjean M., Joos F., Kaplan J.O., Küttel M., Müller S.A., Prentice I.C., Solomina O., Stockberg T.F., Tarasov P., Wagner M. & Widmann M. 2008. Mid- to late Holocene climate change: an overview. *Quaternary Science Reviews* 27, 1791–1828.
- Wegner C., Bauch D., Hölemann J.A., Hölemann Janout M.A., Heim B., Novikhin A., Kassens H. & Timokhov I. 2013. Interannual variability of surface and bottom sediment transport on the Laptev Sea shelf during summer. *Biogeosciences* 10, 1117–1129.
- Wegner C., Hölemann J.A., Dmitrenko I., Kirillov S. & Kassens H. 2005. Seasonal variations in sediment dynamics on the Laptev Sea shelf (Siberian Arctic). *Global and Planetary Change* 48, 126–140.
- Werner K., Spielhagen R.F., Bauch D., Hass H.C. & Kandiano E. 2013. Atlantic Water advection versus sea-ice advances in the eastern Fram Strait during the last 9 ka: multiproxy evidence for a two-phase Holocene. *Paleoceanography* 28, 283–295.
- Williams W.J., Melling H., Carmack E.C. & Ingram R.G. 2008. Kugmallit Valley as a conduit for cross-shelf exchange on the Mackenzie Shelf in the Beaufort Sea. *Journal of Geophysical Research* 113, C02007, doi: <http://dx.doi.org/10.1029/2006JC003591>
- Woodgate R., Aagaard K., Muench R., Gunn J., Björck G., Rudels B., Roach A.T. & Schauer U. 2001. The Arctic Ocean boundary current along the Eurasian slope and the adjacent Lomonosov Ridge: water mass properties, transports and transformations from moored instruments. *Deep-Sea Research Part I* 48, 1757–1792.
- Yamamoto M. & Polyak L. 2009. Changes in terrestrial organic matter input to the Mendeleev Ridge, western Arctic Ocean, during the Late Quaternary. *Global and Planetary Change* 68, 30–37.
- Yamamoto-Kawai M., McLaughlin F.A., Carmack E.C., Nishino S., Shimada K. & Kurita N. 2009. Surface freshening of the Canada Basin, 2003–2007: river runoff versus sea ice meltwater. *Journal of Geophysical Research—Oceans* 114, C00A05, doi: <http://dx.doi.org/10.1029/2008JC005000>

- Yashin D.S. & Kosheleva V.A. 1996. Holocene sediments of the Russian east-Arctic seas. *Berichte zur Polarforschung* 212, 185–189.
- Yue S., Pilon P. & Cavadias G. 2002. Power of Mann-Kendall and Spearman's rho tests for detecting monotonic trends in hydrological series. *Journal of Hydrology* 259, 254–271.
- Yunker M.B., Macdonald R.W. & Snowdon L.R. 2009. Glacial to postglacial transformation of organic input pathways in Arctic Ocean basins. *Global Biogeochemical Cycles* 23, GB4016, doi: <http://dx.doi.org/10.1029/2009GB003503>
- Yunker M.B., Macdonald R.W., Snowdon L.R. & Fowler B.R. 2011. Alkane and PAH biomarkers as tracers of terrigenous organic carbon in Arctic Ocean sediments. *Organic Geochemistry* 42, 1109–1146.
- Yunker M.B., Macdonald R.W., Velthamp D.J. & Cretney W.J. 1995. Terrestrial and marine biomarkers in a seasonally ice-covered Arctic estuary—integration of multivariate and biomarker approaches. *Marine Chemistry* 49, 1–50.
- Zhang X., He J., Zhang J., Polyakov I., Gerdes R., Inoue J. & Wu P. 2013. Enhanced poleward moisture transport and amplified northern high latitude wetting trend. *Nature Climate Change* 3, 47–51.