Introduction

The dynamic Arctic

Martin Jakobsson [a,*], Ólafur Ingólfsson [b,c], Antony J. Long [d], Robert F. Spielhagen [e]

[a] Department of Geological Sciences, Stockholm University, 106 91 Stockholm, Sweden
[b] University of Iceland, Iceland
[c] University Centre in Svalbard (UNIS), Norway
[d] Department of Geography, Durham University, Lower Mountjoy, South Road, Durham DH1 3LE, UK
[e] Academy of Sciences, Humanities and Literature, Mainz, and GEOMAR Helmholtz Centre of Ocean Research, Wischhofstr.1-3, D-24148 Kiel, Germany

ABSTRACT

Research campaigns over the last decade have yielded a growing stream of data that highlight the dynamic nature of Arctic cryosphere and climate change over a range of time scales. As a consequence, rather than seeing the Arctic as a near static environment in which large scale changes occur slowly, we now view the Arctic as a system that is typified by frequent, large and abrupt changes. The traditional focus on end members in the system — glacial versus interglacial periods — has been replaced by a new interest in understanding the patterns and causes of such dynamic change. Instead of interpreting changes almost exclusively as near linear responses to external forcing (e.g. orbitally-forced climate change), research is now concentrated on the importance of strong feedback mechanisms that in our palaeo-archives often border on chaotic behaviour. The last decade of research has revealed the importance of on-off switching of ice streams, strong feedbacks between sea level and ice sheets, spatial and temporal changes in ice shelves and perennial sea ice, as well as alterations in ice sheet dynamics caused by shifting centres of mass in multi-dome ice sheets. Recent advances in dating techniques and modelling have improved our understanding of leads and lags that exist in different Arctic systems, on their interactions and the driving mechanisms of change. Future Arctic research challenges include further emphases on rapid transitions and untangling the feedback mechanisms as well as the time scales they operate on.

© 2014 The Authors. Published by Elsevier Ltd. This is an open access article under the CC BY-NC-ND license (http://creativecommons.org/licenses/by-nc-nd/3.0/).

1. Introduction

The Arctic has a prominent role in scientific debate on global change. This is a consequence from that the region is changing faster than almost anywhere on Earth and from that such dynamic change in the Arctic has been a characteristic of the entire Cenozoic Era. Thus, quantitative palaeoclimate reconstructions suggest that Arctic temperature changes have been three or four times the corresponding hemispheric or globally averaged changes over the past 4 Ma (Miller et al., 2010).

Globally, the general trend of increasing air surface temperature over the last 15 years has slowed in recent years, and is currently four times less than predicted by simulations within Phase 5 of the Coupled Model Intercomparison Project (CMIP5) (Fyfe et al., 2013). However, over the same interval, global atmospheric CO_2 level has continued to increase (Francey et al., 2013) and the Arctic Ocean has experienced a rapid decline in summer sea ice extent and thickness (Stroeve et al., 2012) (Fig. 1). The lack of a strong correlation between global average air temperature, atmospheric CO_2 and Arctic summer sea ice provides one example that shows that Arctic environmental changes are heavily influenced by complex interplays between different feedback mechanisms. These include changes in glacier/ice sheet extent, snow cover and sea ice distribution that affect surface albedo, and atmospheric and oceanic circulation patterns. The Arctic also influences environmental change at lower latitudes, primarily through the global thermohaline circulation and modulation of atmospheric CO_2 and CH_4 concentrations (Overpeck et al., 1997).

Environmental variability in the Arctic is increasingly viewed as the norm, and there is a growing recognition that today's Arctic cryosphere (glaciers, sea ice, permafrost, gas hydrates) and biosphere (terrestrial, lacustrine, and marine) are not in steady state; they have changed and will continue to change in response to climate and other perturbations. Recognition that the Arctic has likely never been in steady state is a challenge to those of interested in reconstructing past change. What, for example, is the purpose of

* Corresponding author.
  E-mail address: martin.jakobsson@geo.su.se (M. Jakobsson).
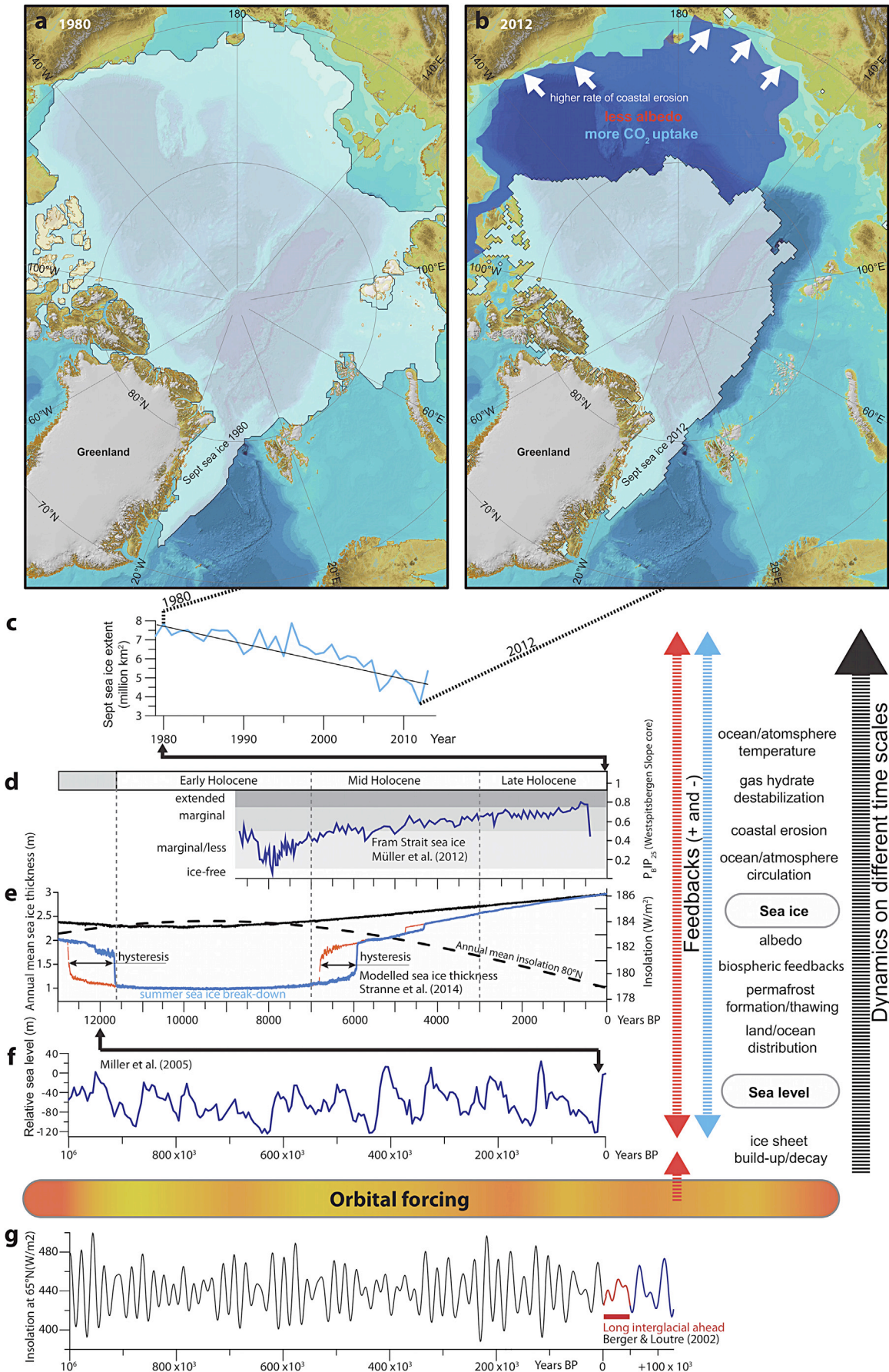
seeking to define a reconstruction of the maximum extent of an entire ice sheet, such as at the Last Glacial Maximum (LGM), if the age of that maximum extent was diachronous and the ice sheet was not in equilibrium with its climate?

The Arctic Palaeoclimate and Its Extremes (APEX) program was initiated in October 2004 in Brorfelde, Denmark, with the aim of better understanding the magnitude and frequency of past Arctic climate variability, especially the "extremes" versus the "normal" conditions of the climate system. The goal has been to highlight Arctic palaeoclimate changes through an interdisciplinary approach that integrates marine and terrestrial science, and through using modelling that is constrained by boundary conditions set by field observations.

It is the nature of the subject that research completed under APEX, as under its predecessors PONAM (Polar North Atlantic Margin: Late Cenozoic Evolution) (Elverhøi et al., 1998) and QUEEN (Quaternary Environments of the Eurasian North) (Thiede et al., 2004), has gravitated towards understanding end-member records of extreme events rather than signatures of transitions, be they gradual or abrupt, or indeed dynamic change within a particular state. Indeed, notwithstanding the attraction of such end-members, including our growing ability to apply reliable tools to identify maximum and minimum situations (e.g. maximum extent of ice, climate optimum, episodes of high relative or global sea level) in both time and space, we are increasingly appreciative of the fact that Arctic cryospheric and oceanic changes are time-transgressive.

From the perspective of Earth's orbit around the Sun, the present interglacial is expected to last for an exceptionally long interval, perhaps more than another 50,000 years (Berger and Loutre, 2002) (Fig. 1). The implication is that CO_2 forcing and dynamic feedback mechanisms will dictate climate change long into the future, and for this reason the forcing and feedbacks that link these processes are important future targets for Arctic research in the years to come.

This special issue contains a suite of articles that mark the completion of the APEX program. Collectively they provide a state-of-the-art record of current knowledge regarding Arctic Quaternary environmental change, and here we aim to review progress achieved under the PONAM-QUEEN-APEX programs and highlight the main scientific challenges that they have left us with.

2. History and current status

2.1. Palaeoglaciology

The year 1875 was a break-through year for Agassiz' (1840) Ice Age Theory, with the work of Croll (1875) on multiple ice ages through time marking the birth of palaeoglaciology as a scientific subject. Palaeoglaciology aims to outline the history of former ice sheets and cast light on their dynamics through time (Andersen and Borns, 1994), and over the past 120 years there have been ever more sophisticated reconstructions that seek to define the former extents of the Eurasian ice sheets e.g., Andersen (1981), Hughes et al. (1981), Svendsen et al. (2004a); see also reviews in Fastook and Hughes (2013) and Ingólfsson and Landvik (2013).

It is interesting to ask the question "How far have we advanced our understanding of palaeoglaciology since Geikie (1894) published his maps of ice sheet extents over Europe, the British Isles

and Scandinavia?" A partial answer to this question can be found by comparing these original maps with current versions, as we do in Fig. 2. What is astounding from this exercise is how remarkably similar Geikie's map from 1894 is to, by example, the recent reconstructions by QUEEN (Fig. 2). Such a comparison begs the question as to whether this means that the discipline has been treading water for much of the last century? We argue that it does not; that there are good reasons why the general maximum extents on base maps are little changed and there have indeed been major advances in our understanding of former ice sheet extents and in their dynamics. However, we also argue that we must now make a greater effort to illustrate the dynamics of these glacial system on maps and in other media; a far from trivial task!

As pointed out by Ingólfsson and Landvik (2013), there is a fundamental problem with regional palaeoglacial reconstructions because they synthesise large amounts of field data that contain problems, notably different spatial resolutions and often problematic age controls. The outcome of such efforts is therefore commonly a compromise of best fit reconstructions that simplify or over-look time-transgressive changes and ignore ice sheet dynamics; the ice sheets are reconstructed as if they are always close to steady-state equilibrium. In Europe and Eurasia, the resulting reconstructions tend to depict the ice sheets as relatively stable, concentric or single-domed rather than unstable and multi-domed, and, although ice streams may be acknowledged, the dynamic linking of the ice sheets to global and regional sea levels is often not accounted for. These reconstructions do not allow for the understanding that marine-based ice streams are inherently unstable (Jamieson et al., 2012) nor do they fully recognise that different sectors of an ice sheet experienced different histories, depending on the topography/bathymetry, sub-glacial conditions and glacial dynamics, as well as climate and sea-level forcing. These problems are particularly evident for the marine sectors of former ice sheets, because ice shelves and floating ice tongues are highly dynamic, yet do not leave clearly identifiable imprints of their maximum extents (Jakobsson et al., 2014). Landvik et al. (2014) also note that the distribution of glacigenic bedforms, which are used as the main data source for reconstructing past ice flows, are most informative about the most recent events with older landforms susceptible to erosion. There is, therefore, considerable work to be done to reconcile glacial geomorphology data with the dynamic ice margin behaviour predicted by ice sheet models (Kirchner et al., 2011). This includes reconciling the resolution of ice sheet models with the temporal and spatial complexities of the glacial geomorphological evidence that documents ice sheet build-up and decay (Evans et al., 2009).

A growing appreciation of the dynamic nature of Arctic glacier and ice sheet change also challenges the traditional view of the link between palaeoglaciology and climate change, across glacial–interglacial and stadial–interstadial transitions. Climatostratigraphic concepts are relatively easy to use at mid and low latitudes where glacial landforms and biostratigraphic indicators define end-members, but such concepts are much harder to use at higher latitudes (Backman et al., 2004; Alexanderson et al., 2014). Consequently, ice sheet advances and retreats are all too often interpreted as evidence for climate events, disregarding the possibility that they may reflect changes in ice dynamics, e.g., rapid changes in grounding-line position in response to sea-level oscillations. For this reason, whilst some suggest that over past glacial–interglacial

Fig. 1. The dynamic Arctic illustrated on different time scales. Orbital forcing (g) constitutes the main overarching climate driver on millennial time scales. Considering this parameter alone, the present interglacial is likely to last at least another 50,000 years (Berger and Loutre, 2002), although the net effect from feedbacks is far from known and remains a research challenge. On millennial time scales the sea level record follows from a build-up and decay of large ice sheets (f) with large feedback effects from, for example, changes of land/ocean distribution. The sea ice (a–e) is perhaps the Arctic component that best illustrates how the dynamics of the climate system is operating on different time scales.
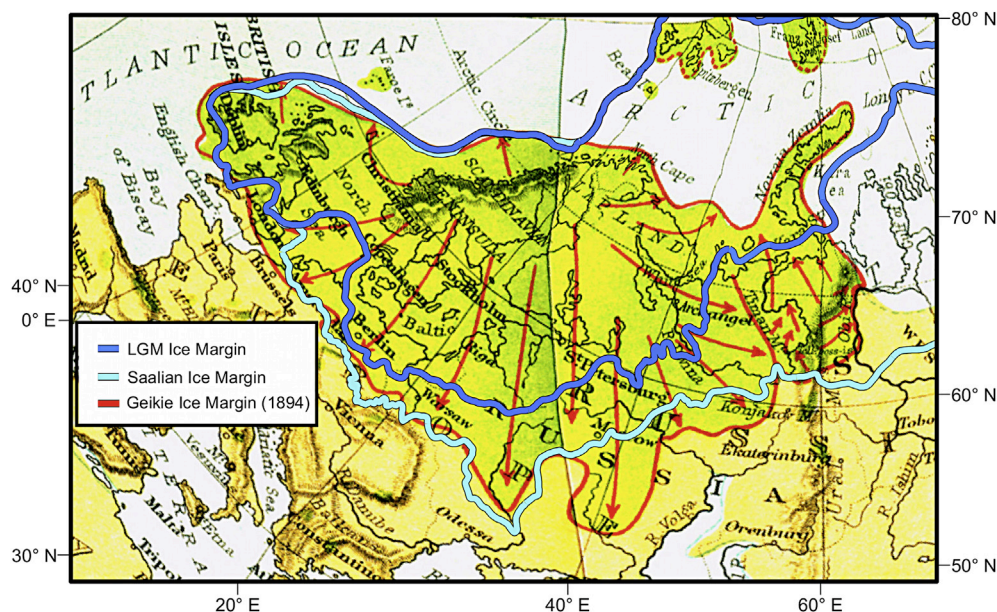
Fig. 2. Ice sheet extent published on the "Glacial Map of Asia" by Geikie (1894) compared with the Last Glacial Maximum (LGM) and Saalian ice sheet margins by the QUEEN program (Svendsen et al., 2004).

cycles, continental ice volume kept pace with slow, multi millennial-scale changes in climate forcing (Rohling et al., 2013b), there is an increasingly recognition that system feedbacks (Fig. 1) can readily cause ice sheet collapse, independent of strong climate forcing (Hughes, 2011; Ó Cofaigh, 2012; Mangerud et al., 2013; O'Leary et al., 2013). Understanding causal links that lead to such "tipping point" behaviour is a major challenge of Arctic palaeoglaciology.

There are several important advances in our understanding of Quaternary ice sheet extents and behaviour that extend beyond the one dimensional representation of an isochronous ice limit drawn on a map. First, the development of new dating methods, notable cosmogenic exposure dating, combined with improved understanding of the basal thermal regime of ice sheets, has enabled reconstructions of the former temporal dimension of the vertical extent of former ice sheets (Alexanderson et al., 2014; Stroeven et al., 2014). This has challenged long-standing paradigms that interpreted trim lines as evidence for the upper limits of ice sheets and instead has led to a more nuanced appreciation of the importance of cold-based ice, and the recognition that former ice thicknesses were greater than previously thought. This knowledge has important implications for reconstructions of down-ice flow lines, as well as overall ice volume at glacial maxima.

A second advance is the appreciation of the important role of ice streams and their geometry in controlling the dynamic behaviour of large parts of an ice sheet (e.g. Andreassen et al., 2014; Batchelor and Dowdeswell, 2014; Kleman and Applegate, 2014). Recent observations and reconstructions show that large-scale re-organizations of ice streams can significantly affect ice sheet dynamics over relatively short time scales (Winsborrow et al., 2012). In Greenland today, we see three or four major ice streams dominating the dynamic mass loss from the ice sheet, and that these ice streams can accelerate or slow-down in an unpredictable manner (Joughin et al., 2011). By thinning and accelerating, West Antarctic ice streams are contributing about 10% of the observed global sea level rise, and much of this ice loss is from Pine Island Glacier alone (Dutrieux et al., 2013). Such is the importance of ice streams to our understanding of the overall dynamics of the former ice sheets, during ice build-up and decay, that considerable effort is directed at unravelling their sensitivity to different forcing.

Conventional theory suggests that ice sheets and ice streams that are grounded below sea level are especially vulnerable to sea-level forcing, with the potential that sea-level jumps caused by ice sheet collapse can trigger further ice sheet instabilities. However, recent work is painting a more complex picture and challenging this long-held paradigm. For example, it has long been known that as an ice sheet loses mass, so the gravitational force of that ice mass on the adjacent ocean surface weakens (Simpson et al., 2009; Woodroffe et al., 2014). This so-called "direct effect" causes relative sea level close to an ice sheet or ice stream that is losing mass to fall and, in theory, help stabilise the ice sheet margin by reducing water depths. In addition, removal of ice mass from a retreating ice sheet is often associated with glacio-isostatic rebound, a process that also causes relative sea level to fall. On the other hand, an example of a destabilizing effect is the sudden loss of an ice shelf that extends in front of an ice stream, that may result in rapid ice stream acceleration as the buttressing force the ice shelf exerted is lost (Rignot et al., 2004). We begin to map traces of abrupt ice stream break-ups and retreats from glacial landforms preserved in the seafloor of both the Antarctic (Jakobsson et al., 2011) and the Arctic (Andreassen et al., 2014; Bjarnadóttir et al., 2014), that may well be the effects of former ice shelf collapses.

A third area of major advance is in our understanding of the dynamic effects of ocean forcing on ice sheet margin stability, especially those marine-based sections that are directly impacted by ocean temperatures. Warm water flowing beneath calving margins promotes significantly enhanced rates of basal melting, increased buoyancy and can lead to accelerated mass loss. This process is most clearly illustrated in the accelerated flow and retreat of Jakobshavns Isbrae (Greenland) in the last 15 years, during a period of time when warm Atlantic-sourced waters penetrated deep into the fjord system (Holland et al., 2008). A similar pattern of events is contributing the rapid collapse of Pine Island Glacier in Antarctica (Jacobs et al., 2011). This ocean coupling does not over-ride the importance of air temperature forcing, which remains a widely recognised control on ice sheet mass

balance, including through the enhanced supply of meltwater to the base of ice sheets that may accelerate ice velocities. It does, though, exemplify the complex controls that combined to influence marine terminating ice sheets today.

A fourth advance is the significant progress made in reconstructing ice limits offshore, using remotely sensed imagery as well as sea bed sediment cores. Within the APEX project, we report important new understanding of the spatial extent of, for example, the Greenland Ice Sheet in West Greenland (Dowdeswell et al., 2014; Lane et al., 2014). This is an essential development if we are to reconstruct how this ice sheet, and others that were grounded on the current continental shelf during initial deglaciation, responded to short-lived climate forcing such as the Younger Dryas (Ó Cofaigh et al., 2013).

In summary, the broad similarity between maps of Eurasian ice sheet extents drawn today and that of a hundred years ago or more masks significant advances in our understanding of the dynamic nature of ice sheet behaviour over a range of spatial and temporal scales. It is also true, however, that modern glaciological and oceanographic studies are not always appropriate analogues for the past, including previous interglacial (minima) ice-sheet configurations and during ice build-up and collapse. There is significant scope to improve our understanding of how ice sheets build during periods of high sea-level, whether the same atmosphere-ocean forcing that we see today operated in previous interglacials, or indeed whether the controls on ice sheet collapse during the exit from, for example, the LGM was typical of previous terminations or not.

2.2. Palaeoceanography

Reconstructions of oceanographic conditions in the central Arctic Ocean did not really begin until nearly half a century after Fridtjof Nansen compiled a bathymetric map that portrayed the central Arctic Ocean as a single deep featureless basin from a handful of lead line soundings acquired during the *Fram Expedition* 1893−1896 (Nansen, 1907). Extensive pack ice has prevented efficient mapping the Arctic Ocean seafloor, and each published map has systematically revealed a more complex seafloor, shaped by tectonics, ocean currents, and the glacial history, than the preceding one (e.g. Atlasov et al., 1964; Johnson et al., 1979; Perry et al., 1986; Jakobsson et al., 2012). While the bathymetry provides a long-term paleoceanographic record of the interactions of bottom currents, ice, geochemical processes, and biological activity with the seafloor, sediment cores are required to decipher the palaeoceanography in detail.

Sediment core studies within the APEX program published in this special issue provide a range of new insights into the Arctic Ocean palaeoceanography (Chauhan et al., 2014; Gibb et al., 2014; Immonen et al., 2014; Löwemark et al., 2014; Werner et al., 2014). These studies demonstrate how far we have progressed, specifically regarding the use of paleoceanographic proxies, since the first short cores raised from drifting ice islands in the 1950s and 1960s captured near surface sediments from the Arctic Ocean floor (Ericson et al., 1964; Hunkins and Tiemann, 1977). Only the construction of research icebreakers in the 1980s allowed targeted expeditions to the Arctic to obtain long, large-volume sediment cores for palaeoceanographic reconstructions. During the QUEEN project, we learned that earlier ideas of extremely low sedimentation rates (Clark, 1970) were based on a misinterpretation of the palaeomagnetic pattern in the sedimentary record and that the rates were rather on the scale of centimetres per kiloyear than millimetres (Backman et al., 2004). While this finding substantially advanced our ability to use sediment cores to study palaeoceanography, the central Arctic Ocean sedimentation rate of

centimetres per kiloyear is far from capturing the full dynamics and ongoing rate of change in the Arctic. It is also difficult to know what we capture with a proxy study of a sediment core; is what we reconstruct the extremes of paleoceanographic changes or a blurred averaged view? There is certainly not one answer to this questions, it will depend on several factors such as for example the proxy and core location.

The important role of the Arctic Ocean in driving the modern (interglacial) ocean circulation and heat transport was recognized by Nansen (1907), but due to the nearly land-locked Arctic Ocean physiographic configuration it was assigned a rather passive role during interglacials. It should be noted that Nansen's map from 1907 did not depict a deep Fram Strait simply because no soundings from the strait at that time had been collected. The CLIMAP reconstruction of the surface of the ice-age earth (CLIMAP Project Members, 1976) showed the Nordic Seas as perennially ice covered in the LGM and assumed that the Arctic Ocean had experienced the severest cold conditions. The last decades have seen a slow maceration of this contrasting view between glacial and interglacials. Evidence for a relatively strong advection of Atlantic Water to the Arctic in the LGM was found in the eastern Fram Strait where the associated moisture transfer from the sea surface to the atmosphere may have enhanced ice sheet growth on the Barents Sea (Hebbeln et al., 1994), and Hald et al. (2001) showed that Atlantic water repeatedly reached the polar North Atlantic during the Last Interglacial−Glacial cycle. It was assumed that this water mass reached only parts of the Eurasian Arctic (Sarnthein et al., 2003). This is in stark contrast to the interglacial Arctic Ocean, including present day conditions, when Atlantic Water contributes to the intermediate depth water masses well into the Makarov and Canada basins on the Amerasian side of the Arctic (Rudels et al., 2013).

Seafloor mapping, which began during the QUEEN program and continued during APEX, has revealed glacigenic landforms and ice grounded seabed in the central Arctic Ocean at depths >1000 m below present sea level, indicating the existence of marine based ice sheets including huge ice shelves (e.g. Polyak et al., 2001; Spielhagen et al., 2004; Niessen et al., 2013; Dove et al., 2014; Jakobsson et al., 2014). How could these have existed if warm Atlantic Water entered the Arctic Ocean during glacials as well as interglacials? A conceptual model has been developed that now reconciles both the influx of Atlantic Water and the existence of deep drafting ice. This model suggests that the glacial palaeoceanography of the glacial Arctic was characterized by less fresh water influx resulting in a more diffuse and deeper halocline than today that forced the Atlantic Water deeper (Jakobsson et al., 2010). This model is supported by geochemical data from ostracods, as reported by Cronin et al. (2012). Their trace metal analyses of ostracod shells suggest that Atlantic Water penetrated basin-wide during the coldest phases of the Last Glacial, albeit at deeper depth than present. In addition, Hoffmann et al. (2013) showed that a persistent deep water exchange existed between the Arctic Ocean and North Atlantic during the last 35 ka. Apparently, the Arctic Ocean never lost the oceanographic connection to the rest of the World's ocean during the Last Glacial, and it thus contributed to the global ocean circulation over this time period.

Sea ice is one of the most dynamic components of the cryosphere as illustrated recently by the large yearly variation in the spatial extent of the Arctic Ocean summer sea ice (Comiso, 2011) (Fig. 1). The question most often asked is "When will there be sea ice free summers in the Arctic?" (Overland and Wang, 2013). The follow-up question is "Has the Arctic recently experienced sea ice free summers?" While the high frequency dynamic sea ice swings cannot be fully captured in sediment core studies, the general trends may be revealed from studies of various types of proxies for

sea ice (Polyak et al., 2010; de Vernal et al., 2013). Several studies suggest that the Early Holocene (~6000–10,000 years BP) experienced less summer-sea ice than at present (e.g. Polyak et al., 2010; Funder et al., 2011; Müller et al., 2012), although not all studies are showing the exact same pattern (Dyke and England, 2003). Stranne et al. (2014) show, using numerical modelling, that the sea ice during the Early Holocene potentially could have moved over to a seasonal regime with sea ice-free summers due to the insolation maxima the Earth experienced at that time (Fig. 1).

3. Discussions and future challenges

The history of Quaternary geology contains numerous examples of revolutions in our approaches to science that resulted from anomalies that could not be explained by the universally accepted paradigm. In glacial geology, Agassiz's (1840) Ice Age theory and Croll's (1875) and Milankovitch's (1920) astronomical theory mark paradigm shifts that fundamentally changed our views of how ice sheets and climate evolved over time (Hays et al., 1976). Our perception of how the large Quaternary ice sheets and the cryospheric system evolved over interglacial–glacial cycles has, however, changed slowly in recent decades. We find evidence from ice core and marine oxygen isotope data that the Late Pleistocene continental ice sheets were characterised by slow growth and rapid decay. Palaeoglaciological reconstructions typically reflect this pattern with continuous, isochronuous ice margins reconstructed by connecting geomorphological features, especially end moraines, to define events in ice expansion and retreat (Lüthgens and Böse, 2012). However, as we note above, the glacial landform record is strongly biased towards extreme events and terminations, whilst records of ice sheet dynamics during their growth phase are poorly preserved or not preserved at all.

As outlined above, the focus of Arctic palaeoglaciology has over the past few decades been on the LGM. The extents of LGM ice sheets are now reasonably well understood (Clark and Mix, 2002; Clark et al., 2009) and we now know that growth of the ice sheets to their maximum positions occurred between 33.0 and 26.5 ka, and that nearly all ice sheets were at their LGM positions from 26.5 ka to 19–20 ka (Clark et al., 2009). We are now developing ever more sophisticated records of the dynamics of the deglaciations/terminations. Much of this new knowledge in the Arctic is drawn from newly collected marine geological data that reveals clear spatial and temporal variations in ice dynamics, with evidence for both active ice streaming and frozen-bed conditions at the maximum and during deglaciation (Ottesen and Dowdeswell, 2009; Winsborrow et al., 2010; Andreassen et al., 2014; Jakobsson et al., 2014; Landvik et al., 2014). However, there is most likely much more information about the dynamics of the Arctic still to be extracted from palaeorecords as we improve our methods. In view of the advances in our understanding of the Arctic cryospheric system made during the International Polar Year (IPY) 2007–08 and the APEX program 2004–12, several challenges and research tasks stand out:

- We need to focus on ice streams. The importance of ice streams for the geometry and stability of ice sheets has made the identification, location, and timing of ice stream activity essential for the reconstruction of palaeo-ice sheets and the interpretation of the associated landform record (Stokes and Clark, 2001; Bennett, 2003; Batchelor and Dowdeswell, 2014);
- We need to acknowledge in our reconstructions that the data-sets that we work with tend to be strongly biased towards extreme events and terminations. This calls for a holistic approach where it is recognized that apparent mismatches and enigmatic data may be caused by the complexity and chaotic

nature of the system rather than poor chronological or quality control of the data;
- We need to focus on internal forcing and feedbacks in the Arctic system, particularly those that result in non-linear or chaotic behaviour such as changes in sea ice extent and ocean circulation;
- We need to focus on rapid transitions and mode shifts, which in turn demands robust, high resolution chronologies;
- We need to search for ultra-high resolution records (decadal to century-scale) that enable us to reconstruct past environmental change on time scales comparable to current and near-future environmental change;
- We need to understand what were the leads and lags between different parts of the Arctic cryosphere/ocean, what caused them and how did they link to changes in the Southern Hemisphere?
- We need to understand if Arctic ice sheets can grow quickly, during "warm" periods and if this can explain the high frequency sea-level variations seen in archives from low latitudes (Rohling et al., 2013a).

Perhaps the next paradigm shift is towards recognising the unstable nature of Arctic cryosphere and Arctic environmental change more widely? That instability likely makes predicting the future a real challenge.

References

Agassiz, L., 1840. Etudes sur les glaciers (1840). Jent et Gassmann, Neuchâtel.
Alexanderson, H., Backman, J., Cronin, T.M., Funder, S., Ingólfsson, Ó., Jakobsson, M., Landvik, J.Y., Löwemark, L., Mangerud, J., März, C., Möller, P., O'Regan, M., Spielhagen, R.F., 2014. An Arctic perspective on dating Mid-Late Pleistocene environmental history. Quat. Sci. Rev.
Andersen, B.G., 1981. Late Weichselian Ice Sheets in Eurasia and Greenland. In: Denton, G.H., Hughes, T.J. (Eds.), The Last Great Ice Sheets. John Wiley and Sons, New York, pp. 1–65.
Andersen, B.G., Borns, H.W., 1994. The Ice Age World. Scandinavian University Press, Oslo.
Andreassen, K., Winsborrow, M.C.M., Bjarnadóttir, L.R., Rüther, D.C., 2014. Ice stream retreat dynamics inferred from an assemblage of landforms in the northern Barents Sea. Quat. Sci. Rev..
Atlasov, I.P., Vakar, V.A., Dibner, V.P., 1964. A New Tectonic Chart of the Arctic. Directorate of Scientific Information Services.
Backman, J., Jakobsson, M., Løvlie, R., Polyak, L., Febo, L.A., 2004. Is the central Arctic Ocean a sediment starved basin? Quat. Sci. Rev. 23, 1435–1454.
Batchelor, C.L., Dowdeswell, J.A., 2014. The physiography of High Arctic cross-shelf troughs. Quat. Sci. Rev..
Bennett, M.R., 2003. Ice streams as the arteries of an ice sheet: their mechanics, stability and significance. Earth-Sci. Rev. 61, 309–339.
Berger, A., Loutre, M.F., 2002. An exceptionally long Interglacial ahead? Science 297, 1287–1288.
Bjarnadóttir, L.R., Winsborrow, M.C.M., Andreassen, K., 2014. Deglaciation of the central Barents Sea. Quat. Sci. Rev. 2014.

Chauhan, T., Rasmussen, T.L., Noormets, R., Jakobsson, M., Hogan, K.A., 2014. Glacial history and paleoceanography of the southern Yermak Plateau since 132 ka BP. Quat. Sci. Rev..

Clark, D.L., 1970. Magnetic reversals and sedimentation rates in the Arctic Ocean. Geol. Soc. Am. Bull. 81, 3129–3134.

Clark, P.U., Dyke, A.S., Shakun, J.D., Carlson, A.E., Clark, J., Wohlfarth, B., Mitrovica, J.X., Hostetler, S.W., McCabe, A.M., 2009. The Last Glacial maximum. Science 325, 710–714.

Clark, P.U., Mix, A.C., 2002. Ice sheets and sea level of the Last Glacial maximum. Quat. Sci. Rev. 21, 1–7.

CLIMAP Project Members, 1976. The surface of the Ice-Age Earth. Science 191, 1131–1137.

Comiso, J.C., 2011. Large decadal decline of the arctic multiyear ice cover. J. Clim. 25, 1176–1193.

Croll, J., 1875. Climate and Time and Their Geological Relations: a Theory of Secular Changes of the Earth's Climate. Daldy, Isbister & Co, London.

Cronin, T.M., Dwyer, G.S., Farmer, J., Bauch, H.A., Spielhagen, R.F., Jakobsson, M., Nilsson, J., Briggs, W.M., Stepanova, A., 2012. Deep Arctic Ocean warming during the Last Glacial cycle. Nat. Geosci. 5, 631–634.

de Vernal, A., Gersonde, R., Goosse, H., Seidenkrantz, M.-S., Wolff, E.W., 2013. Sea ice in the paleoclimate system: the challenge of reconstructing sea ice from proxies – an introduction. Quat. Sci. Rev. 79, 1–8.

Dove, D., Polyak, L., Coakley, B., 2014. Widespread, multi-source glacial erosion on the Chukchi margin, Arctic Ocean. Quat. Sci. Rev..

Dowdeswell, J.A., Hogan, K.A., Cofaigh, C.O., Fugelli, E.M.G., Evans, J., Noormets, R., 2014. Late Quaternary ice flow in a West Greenland fjord and cross-shelf trough system: submarine landforms from Rink Isbrae to Uummannaq shelf and slope. Quat. Sci. Rev..

Dutrieux, P., Vaughan, D.G., Corr, H.F.J., Jenkins, A., Holland, P.R., Joughin, I., Fleming, A.H., 2013. Pine Island glacier ice shelf melt distributed at kilometre scales. Cryosphere 7, 1543–1555.

Dyke, A.S., England, J., 2003. Canada's most northerly postglacial bowhead whales (Balaena mysticetus): Holocene sea-ice conditions and polynya development. Arctic 56, 14–20.

Elverhøi, A., Dowdeswell, J.A., Funder, S., Mangerud, J., Stein, R., 1998. Glacial and oceanic history of the Polar North Atlantic Margins: an overview. Quat. Sci. Rev. 17, 1–10.

Ericson, D.B., Ewing, M., Wollin, G., 1964. Sediment cores from the Arctic and Subarctic seas. Science 144, 1183–1192.

Evans, D.J.A., Livingstone, S.J., Vieli, A., Ó Cofaigh, C., 2009. The palaeoglaciology of the central sector of the British and Irish Ice Sheet: reconciling glacial geo-morphology and preliminary ice sheet modelling. Quat. Sci. Rev. 28, 739–757.

Fastook, J.L., Hughes, T.J., 2013. New perspectives on paleoglaciology. Quat. Sci. Rev. 80, 169–194.

Francey, R.J., Trudinger, C.M., van der Schoot, M., Law, R.M., Krummel, P.B., Langenfelds, R.L., Paul Steele, L., Allison, C.E., Stavert, A.R., Andres, R.J., Rodenbeck, C., 2013. Atmospheric verification of anthropogenic CO_2 emission trends. Nat. Clim. Change 3, 520–524.

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.

Fyfe, J.C., Gillett, N.P., Zwiers, F.W., 2013. Overestimated global warming over the past 20 years. Nat. Clim. Change 3, 767–769.

Geikie, J., 1894. The Great Ice Age and its Relation to the Antiquity of man. London, third ed.

Gibb, O.T., Hillaire-Marcel, C., de Vernal, A., 2014. Oceanographic regimes in the northwest Labrador Sea since Marine Isotope Stage 3 based on dinocyst and stable isotope proxy records. Quat. Sci. Rev..

Hald, M., Dokken, T., Mikalsen, G., 2001. Abrupt climatic change during the Last Interglacial–Glacial cycle in the polar North Atlantic. Mar. Geol. 176, 121–137.

Hays, J.D., Imbrie, J., Shackleton, N.J., 1976. Variations in the Earth's orbit: pacemaker of the Ice Ages. Science 194, 1121–1132.

Hebbeln, D., Dokken, T., Andersen, E.S., Hald, M., Elverhøi, A., 1994. Moisture supply for northern ice-sheet growth during the Last Glacial maximum. Nature 370, 357–360.

Hoffmann, S.S., McManus, J.F., Curry, W.B., Brown-Leger, L.S., 2013. Persistent export of 231Pa from the deep central Arctic Ocean over the past 35,000 years. Nature 497, 603–606.

Holland, D.M., Thomas, R.H., Young, B.d, Ribergaard, M.H., Lyberth, B., 2008. Ac-celeration of Jakobshavn Isbræ triggered by warm subsurface ocean waters. Nat. Geosci. 1, 659–664.

Hughes, T., 2011. A simple holistic hypothesis for the self-destruction of ice sheets. Quat. Sci. Rev. 30, 1829–1845.

Hughes, T.J., Denton, G.H., Andersen, B.G., Schilling, D.H., Fastook, J.J., Lingl, C.S., 1981. The Last Great Ice sheets: a global view. In: Hughes, T.J., Denton, G.H. (Eds.), The Last Great Ice Sheets. John Wiley & Sons, New York, pp. 263–317.

Hunkins, K., Tiemann, W., 1977. Geophysical data summary for Fletcher's Ice Island (T3), May 1962–October 1974. Palisades. In: Talwani, M. (Ed.), Lamont-Doherty Survey of the World Ocean. Lamont-Doherty Earth Observatory of Columbia University, New York, pp. 1–219.

Immonen, N., Strand, K., Huusko, A., Lunkka, J.P., 2014. Imprint of Late Pleistocene continental processes visible in ice-rafted grains from the central Arctic Ocean. Quat. Sci. Rev..

Ingólfsson, Ó., Landvik, J.Y., 2013. The Svalbard–Barents Sea ice-sheet – historical, current and future perspectives. Quat. Sci. Rev. 64, 33–60.

Jacobs, S.S., Jenkins, A., Giulivi, C.F., Dutrieux, P., 2011. Stronger ocean circulation and increased melting under Pine Island glacier ice shelf. Nat. Geosci. 4, 519–523.

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., Stolldorf, 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., Krog Larsen, N., 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. Quat. Sci. Rev..

Jakobsson, M., Mayer, L., Coakley, B., Dowdeswell, J.A., Forbes, S., Fridman, B., Hodnesdal, H., Noormets, R., Pedersen, R., Rebesco, M., Schenke, H.W., Zarayskaya, Y., Accettella, A., Armstrong, A., Anderson, R.M., Bienhoff, P., Camerlenghi, A., Church, I., Edwards, M., Gardner, J.V., Hall, J.K., Hell, B., Hestvik, O., Kristoffersen, Y., Marcussen, C., Mohammad, R., Mosher, D., Nghiem, S.V., Pedrosa, M.T., Travaglini, P.G., Weatherall, P., 2012. The interna-tional bathymetric chart of the Arctic Ocean (IBCAO) version 3.0. Geophys. Res. Lett. 39, L12609.

Jakobsson, M., Nilsson, J., O'Regan, M., Backman, J., Löwemark, L., Dowdeswell, J.A., Mayer, L., Polyak, L., Colleoni, F., Anderson, L., Björk, G., Darby, D., Eriksson, B., Hanslik, D., Hell, B., Marcussen, C., Sellén, E., Wallin, Å., 2010. An Arctic Ocean ice shelf during MIS 6 constrained by new geophysical and geological data. Quat. Sci. Rev. 29, 3505–3517.

Jamieson, S.S.R., Vieli, A., Livingstone, S.J., Ó Cofaigh, C., Stokes, C., Hillenbrand, C.D., Dowdeswell, J.A., 2012. Ice-stream stability on a reverse bed slope. Nat. Geosci. 5, 799–802.

Johnson, G.L., Monahan, D., Grönlie, G., Sobczak, L., 1979. Sheet 5.17. Canadian Hy-drographic Service, O. In: General Bathymetric Chart of the Oceans (GEBCO) 5th Edition ed. Canadian Hydrographic Service, Ottawa.

Joughin, I., Smith, B.E., Howat, I.M., Scambos, T., Moon, T., 2011. Greenland flow variability from ice-sheet-wide velocity mapping. J. Glaciol. 56, 415–430.

Kirchner, N., Hutter, K., Jakobsson, M., Gyllencreutz, R., 2011. Capabilities and lim-itations of numerical ice sheet models: a discussion for Earth-scientists and modelers. Quat. Sci. Rev. 30, 3691–3704.

Kleman, J., Applegate, P.J., 2014. Durations and propagation patterns of ice sheet instability events. Quat. Sci. Rev..

Landvik, J.Y., Alexanderson, H., Henriksen, M., Ingólfsson, Ó., 2014. Landscape im-prints of changing glacial regimes during ice sheet build-up and decay: a conceptual model from Svalbard. Quat. Sci. Rev..

Lane, T.P., Roberts, D.H., Rea, B.R., Cofaigh, C.O., Vieli, A., Rodés, A., 2014. Controls upon the Last Glacial maximum deglaciation of the northern Uummannaq ice stream system, West Greenland. Quat. Sci. Rev..

Löwemark, L., März, C., O'Regan, M., Gyllencreutz, R., 2014. Arctic Ocean Mn-stratigraphy: genesis, synthesis and inter-basin correlation. Quat. Sci. Rev..

Lüthgens, C., Böse, M., 2012. From morphostratigraphy to geochronology – on the dating of ice marginal positions. Quat. Sci. Rev. 44, 26–36.

Mangerud, J., Goehring, B.M., Lohne, O.S., Svendsen, J.I., Gyllencreutz, R., 2013. Collapse of marine-based outlet glaciers from the Scandinavian ice sheet. Quat. Sci. Rev. 67, 8–16.

Milankovitch, M., 1920. Théorie mathématique des phénomènes thermique pro-duits per la radiation solaire. Gautier-Villars, Paris.

Miller, G.H., Brigham-Grette, J., Alley, R.B., Anderson, L., Bauch, H.A., Douglas, M.S.V., Edwards, M.E., Elias, S.A., Finney, B.P., Fitzpatrick, J.J., Funder, S.V., Herbert, T.D., Hinzman, L.D., Kaufman, D.S., MacDonald, G.M., Polyak, L., Robock, A., Serreze, M.C., Smol, J.P., Spielhagen, R., White, J.W.C., Wolfe, A.P., Wolff, E.W., 2010. Temperature and precipitation history of the Arctic. Quat. Sci. Rev. 29, 1679–1715.

Müller, J., Werner, K., Stein, R., Fahl, K., Moros, M., Jansen, E., 2012. Holocene cooling culminates in sea ice oscillations in Fram Strait. Quat. Sci. Rev. 47, 1–14.

Nansen, F., 1907. On North polar problems. Geogr. J. 30, 469–487.

Niessen, F., Hong, J.K., Hegewald, A., Matthiessen, J., Stein, R., Kim, H., Kim, S., Jensen, L., Jokat, W., Nam, S.-I., Kang, S.-H., 2013. Repeated Pleistocene glacia-tion of the East Siberian continental margin. Nat. Geosci. 6, 842–846.

O'Leary, M.J., Hearty, P.J., Thompson, W.G., Raymo, M.E., Mitrovica, J.X., Webster, J.M., 2013. Ice sheet collapse following a prolonged period of stable sea level during the Last Interglacial. Nat. Geosci. 6, 796–800.

Ó Cofaigh, C., 2012. Ice sheets viewed from the ocean: the contribution of marine science to understanding modern and past ice sheets. Philos. Trans. R. Soc. a-Math. Phys. Eng. Sci. 370, 5512–5539.

Ó Cofaigh, C., Dowdeswell, J.A., Jennings, A.E., Hogan, K.A., Kilfeather, A., Hiemstra, J.F., Noormets, R., Evans, J., McCarthy, D.J., Andrews, J.T., Lloyd, J.M., Moros, M., 2013. An extensive and dynamic ice sheet on the West Greenland shelf during the last glacial cycle. Geology 41, 219–222.

Ottesen, D., Dowdeswell, J.A., 2009. An inter-ice-stream glaciated margin: subma-rine landforms and a geomorphic model based on marine-geophysical data from Svalbard. Geol. Soc. Am. Bull. 121, 1647–1665.

Overland, J.E., Wang, M., 2013. When will the summer Arctic be nearly sea ice free? Geophys. Res. Lett. 40, 2097–2101.

Overpeck, J., Hughen, K., Hardy, D., Bradley, R., Case, R., Douglas, M., Finney, B., Gajewski, K., Jacoby, G., Jennings, A., Lamoureux, S., Lasca, A., MacDonald, G., Moore, J., Retelle, M., Smith, S., Wolfe, A., Zielinski, G., 1997. Arctic environ-mental change of the last four centuries. Science 278, 1251–1256.

Perry, R.K., Fleming, H.S., Weber, J.R., Kristoffersen, Y., Hall, J.K., Grantz, A., Johnson, G.L., Cherkis, N.Z., Larsen, B., 1986. Bathymetry of the Arctic Ocean. Geological Society of America Map and Chart Series. MC-56 ed. Bathymetry of the Arctic Ocean, Boulder, Colorado.

Polyak, L., Alley, R.B., Andrews, J.T., Brigham-Grette, J., Cronin, T.M., Darby, D.A., 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. Quat. Sci. Rev. 29, 1757–1778.

Polyak, L., Edwards, M.H., Coakley, B.J., Jakobsson, M., 2001. Ice shelves in the Pleistocene Arctic Ocean inferred from glaciogenic deep-sea bedforms. Nature 410, 453–459.

Rignot, E., Casassa, G., Gogineni, P., Krabill, W., Rivera, A., Thomas, R., 2004. Accelerated ice discharge from the Antarctic Peninsula following the collapse of Larsen B ice shelf. Geophys. Res. Lett. 31, L18401.

Rohling, E.J., Grant, K.M., Roberts, A.P., Larrasoaña, J.-C., 2013a. Paleoclimate variability in the Mediterranean and Red sea regions during the last 500,000 years: implications for Hominin migrations. Curr. Anthropol. 54, S183–S201.

Rohling, E.J., Haigh, I.D., Foster, G.L., Roberts, A.P., Grant, K.M., 2013b. A geological perspective on potential future sea-level rise. Sci. Rep. 3.

Rudels, B., Schauer, U., Björk, G., Korhonen, M., Pisarev, S., Rabe, B., Wisotzki, A., 2013. Observations of water masses and circulation with focus on the Eurasian Basin of the Arctic Ocean from the 1990s to the late 2000s. Ocean Sci. 9, 147–169.

Sarnthein, M., Pflaumann, U., Weinelt, M., 2003. Past extent of sea ice in the northern North Atlantic inferred from foraminiferal paleotemperature estimates. Paleoceanography 18, 1047.

Simpson, M.J.R., Milne, G.A., Huybrechts, P., Long, A.J., 2009. Calibrating a glaciological model of the Greenland ice sheet from the Last Glacial Maximum to present-day using field observations of relative sea level and ice extent. Quat. Sci. Rev. 28, 1631–1657.

Spielhagen, R.F., Baumann, K.H., Erlenkeuser, H., Nowaczyk, N.R., Norgaard-Pedersen, N., Vogt, C., Weiel, D., 2004. Arctic Ocean deep-sea record of northern Eurasian ice sheet history. Quat. Sci. Rev. 23, 1455–1483.

Stokes, C.R., Clark, C.D., 2001. Palaeo-ice streams. Quat. Sci. Rev. 20, 1437–1457.

Stranne, C., Jakobsson, M., Björk, G., 2014. Arctic Ocean perennial sea ice breakdown during the Early Holocene insolation maximum. Quat. Sci. Rev. http://dx.doi.org/10.1016/j.quascirev.2013.10.022.

Stroeve, J., Serreze, M., Holland, M., Kay, J., Malanik, J., Barrett, A., 2012. The Arctic's rapidly shrinking sea ice cover: a research synthesis. Clim. Change 110, 1005–1027.

Stroeven, A.P., Fabel, D., Margold, M., Clague, J.J., Xu, S., 2014. Investigating absolute chronologies of glacial advances in the NW sector of the Cordilleran Ice Sheet with terrestrial in situ cosmogenic nuclides. Quat. Sci. Rev..

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. Quat. Sci. Rev. 23, 1229–1271.

Thiede, J., Astakhov, V., Bauch, H., Bolshiyanov, D.Y., Dowdeswell, J.A., Funder, S., Hjort, C., Kotlyakov, V.M., Mangerud, J., Pyramikov, S.M., Saarnisto, M., Schluechter, C., 2004. What was QUEEN? Its history and international framework—an introduction to its final synthesis issue. Quat. Sci. Rev. 23, 1225–1227.

Werner, K., Frank, M., Teschner, C., Müller, J., Spielhagen, R.F., 2014. Neoglacial change in deep water exchange and increase of sea-ice transport through eastern Fram Strait: evidence from radiogenic isotopes. Quat. Sci. Rev..

Winsborrow, M.C.M., Andreassen, K., Corner, G.D., Laberg, J.S., 2010. Deglaciation of a marine-based ice sheet: Late Weichselian palaeo-ice dynamics and retreat in the southern Barents Sea reconstructed from onshore and offshore glacial geomorphology. Quat. Sci. Rev. 29, 424–442.

Winsborrow, M.C.M., Stokes, C.R., Andreassen, K., 2012. Ice-stream flow switching during deglaciation of the southwestern Barents Sea. Geol. Soc. Am. Bull. 124, 275–290.

Woodroffe, S.A., Long, A.J., Lecavalier, B.S., Milne, G.A., Bryant, C.L., 2014. Using relative sea-level data to constrain the deglacial and Holocene history of southern Greenland. Quat. Sci. Rev..