

THE OFFICIAL MAGAZINE OF THE OCEANOGRAPHY SOCIETY

Oceanography

CITATION

O'Regan, M., C.J. Williams, K.E. Frey, and M. Jakobsson. 2011. A synthesis of the long-term paleoclimatic evolution of the Arctic. *Oceanography* 24(3):66–80, <http://dx.doi.org/10.5670/oceanog.2011.57>.

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A Synthesis of the Long-Term Paleoclimatic Evolution of the Arctic

BY MATTHEW O'REGAN, CHRISTOPHER J. WILLIAMS,
KAREN E. FREY, AND MARTIN JAKOBSSON

ABSTRACT. Since the Arctic Ocean began forming in the Early Cretaceous 112–140 million years ago, the Arctic region has undergone profound oceanographic and paleoclimatic changes. It has evolved from a warm epicontinental sea to its modern state as a cold isolated ocean with extensive perennial sea ice cover. Our understanding of the long-term paleoclimate evolution of the Arctic remains fragmentary but has advanced dramatically in the past decade through analysis of new marine and terrestrial records, supplemented by important insights from paleoclimate models. Improved understanding of how these observations fit into the long-term evolution of the global climate system requires additional scientific drilling in the Arctic to provide detailed and continuous paleoclimate records, and to resolve the timing and impact of key tectonic and physiographic changes to the ocean basin and surrounding landmasses. Here, we outline the long-term paleoclimatic evolution of the Arctic, with a focus on integrating both terrestrial and marine records.

INTRODUCTION

The Arctic Ocean is the smallest and most isolated of the world's oceans. Centered over the northern pole, this body of nearly land-locked cold ocean water comprises less than one percent of the global ocean volume (Jakobsson, 2002). Nonetheless, the Arctic Ocean's perennial sea ice cover influences regional and global climate by reflecting incoming solar radiation in the summer (the *albedo* effect), by limiting heat exchange between the atmosphere and underlying warmer water masses in winter (Perovich et al., 2007), and through the influence of freshwater and sea ice export into the Norwegian-Greenland Sea on global

thermohaline circulation (Aagaard and Carmack, 1989).

The Arctic Ocean was not always frozen, inhospitable, and land-locked. Originating as a shallow, warm epicontinental sea in the Cretaceous, it remained largely isolated from the global ocean in the early Cenozoic until the evolution of the modern tectonic configuration, where a single deepwater connection between the Arctic and Atlantic Oceans formed through Fram Strait (Figure 1). Dramatic changes in the composition of fossilized flora and fauna found in exposed sedimentary rocks along the Arctic coast trace the history of this tectonic evolution and provide important constraints on Arctic paleoclimatic

evolution. However, to understand the wider evolution of the Arctic region, we need to evaluate terrestrial and marine sedimentary records together. The marine records provide the most continuous history because they capture continental conditions through terrestrial sediment inputs as well as coeval paleoceanographic changes as recorded by sediment fabric, microfossils, and geochemistry. Given the rapid decline in Arctic sea ice recorded by satellite instruments during the past decades, an improved understanding of the history and stability of perennial sea ice in the geologic past is of particular importance.

Inaccessibility of the Arctic Ocean for marine science has limited data collection so that only a fragmentary view of its paleoceanographic evolution exists. Sediment cores recovered from traditional icebreaking ships and floating ice camps typically recover only the upper 5–20 m of sediments. This core length samples the last few hundred thousand to million years (Polyak and Jakobsson, 2011, in this issue), whereas the longer-term Cenozoic evolution of the Arctic is locked within deeper-lying marine sediments. Exceptions exist at a few locations where erosion has left older sediments outcropping at the

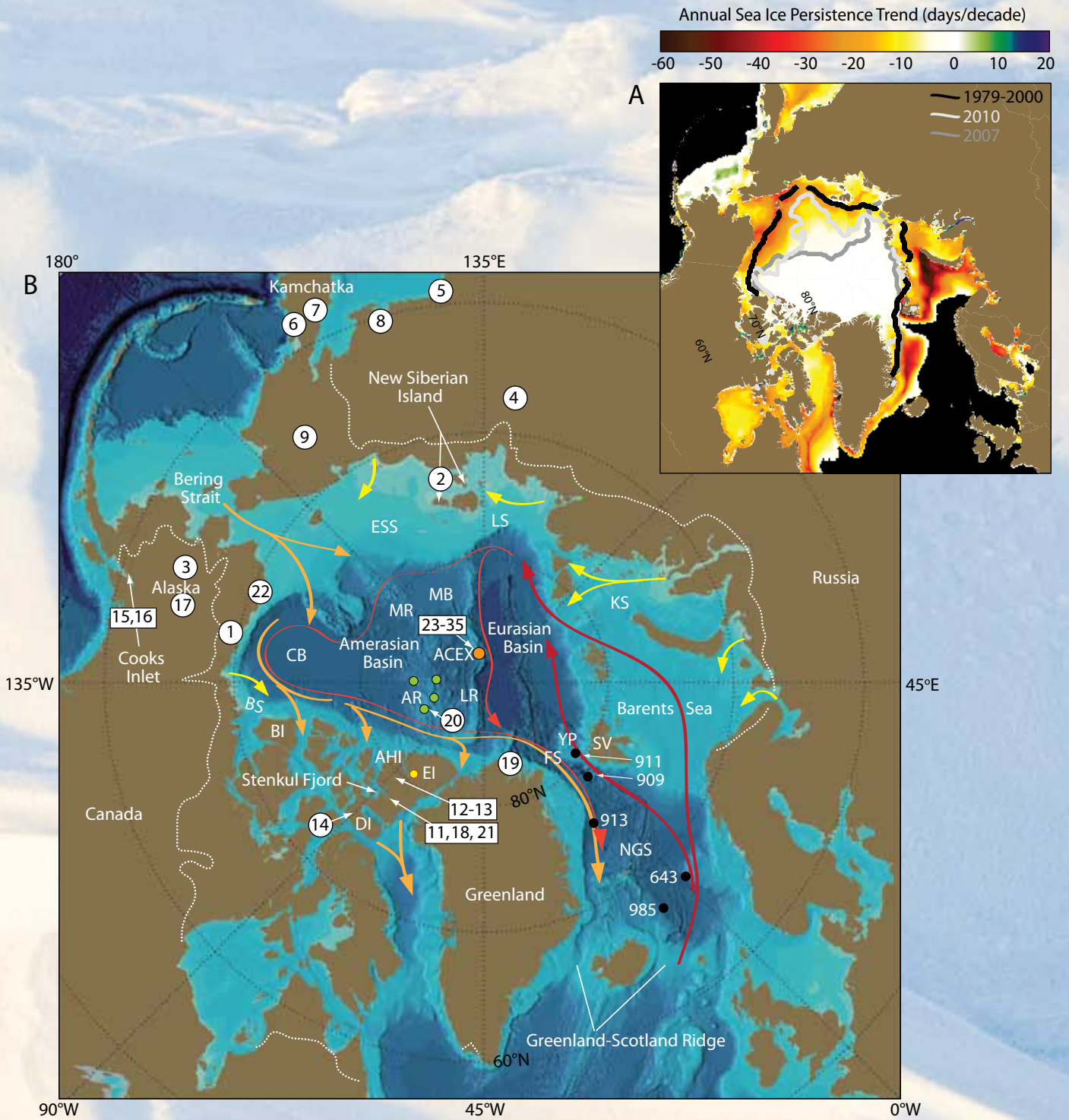


Figure 1. (A) Annual sea ice persistence trend for the period of satellite observations between 1979 and 2008. Isolines depict the mean September sea ice extent for 1979–2000, 2010, and 2007. This figure highlights the more dramatic reductions in sea ice that occur in marginal regions of the Arctic Ocean and emphasizes the influence of Atlantic and Pacific water inflow on sea ice persistence. (B) Bathymetric map of the Arctic Ocean (Jakobsson et al., 2008). The white dotted lines show the position of the modern tree line, south of which boreal forests occur today. Arrows outline major features of the modern ocean circulation system with Atlantic water inflow in red), river runoff in yellow, and Pacific water in orange. Numbers refer to localities discussed in the text and listed in Tables 1 and 2. Green circles indicate coring sites in the Amerasian Basin. Black circles are ODP/DSDP (Ocean Drilling Program/Deep Sea Drilling Project) sites in the Norwegian-Greenland Sea (NGS) and on the Yermak Plateau. AHI = Axel Heiberg Island. AR = Alpha Ridge. BI = Banks Island. BS = Beaufort Sea. CB = Canada Basin. DI = Devon Island. EI = Ellesmere Island. ESS = East Siberian Sea. FS = Fram Strait. KS = Kara Sea. LR = Lomonosov Ridge. LS = Laptev Sea. MR = Mendeleev Ridge. YP = Yermak Plateau. The yellow circle on Ellesmere Island is the location of the Eureka weather station.

Table 1. Published mean annual temperature (MAT) and cold month mean temperature (CMMT) estimates from terrestrial sites shown in Figure 3

#	Location	Age (Ma)	Epoch	MAT (°C)	CMMT (°C)	Reference
1	Northern Alaska	88	Coniacian	13.3	7.9	Spicer and Herman (2010)
2	Novosibirsk Islands, Siberia	90	Turonian	9.2	1.1	Spicer and Herman (2010)
3	Yukon-Koyukuk Basin	90	Cenomanian-Turonian	14.3	8	Spicer and Herman (2010)
4	Vilui Basin	95	Cenomanian-Maastrichtian	12.8	5.3	Spicer and Herman (2010)
5	Grebenka	98	Cenomanian	12.9	5.9	Spicer and Herman (2010)
6	Kamchatka	90	Turonian	7.7	-2.4	Spicer and Herman (2010)
7	Kamchatka	88	Coniacian	9.6	1.1	Spicer and Herman (2010)
8	Arman Ridge	88	Turonian-Coniacian	8.2	-2	Spicer and Herman (2010)
9	Tylpegyrgynai	88	Coniacian	8.4	-1.6	Spicer and Herman (2010)
10	Extrapolated	70	Maastrichtian	6.3 ± 2.2	-2 ± 3.9	Spicer and Herman (2010)
11	Ellesmere Island	52–53	Paleocene/Eocene	8	> 0	Eberle et al. (2010)
12	Axel Heiberg Island	45	Eocene	13.2 ± 2	N/A	Jahren and Sternberg (2003)
13	Axel Heiberg Island	45	Eocene	14.7 ± 0.7	3.7 ± 3.3	Greenwood et al. (2010)
14	Haughton Formation	22	Miocene/Oligocene	8 to 12	-4 to -7	Hickey et al. (1988)
15	Alaska: Cook Inlet	13	Miocene	11.5	N/A	Wolfe (1994)
16	Alaska: Cook Inlet	12	Miocene	4	N/A	Wolfe (1994)
17	Alaska: Interior	15.2	Miocene	9	N/A	White and Ager (1994)
18	Ellesmere Island	3–3.3	Pliocene	-4	N/A	Ballantyne et al. (2010)
19	Kap København	2.4	Pleistocene	-4	N/A	Funder et al. (2001)

Ma = millions of years ago

seabed, allowing them to be sampled with conventional corers. A single scientific drilling mission, Integrated Ocean Drilling Program Expedition 302 (Arctic Coring Expedition, or ACEX), targeted these deeper sediments in the central Arctic Ocean. In the summer of 2004, using a three-vessel fleet of icebreaking ships, ACEX cored 339 m of Cenozoic sediments on the crest of the Lomonosov Ridge near 87°N (Backman

and Moran, 2009). This record provides a critical template for interpreting oceanographic and climatic changes in the Arctic during the past 55 million years (Figure 1). Here, we provide a synthesis of results from this and other marine and terrestrial records that provide insight into the evolution of the Arctic Ocean, from the birth of the Amerasian Basin in the Cretaceous.

CRETACEOUS EPICONTINENTAL SEAS AND TEMPERATE CLIMATE

The Canada Basin is the largest and oldest deep basin in the Amerasian Arctic Ocean (Figure 1). Although its tectonic origin remains in part controversial, it likely opened as a result of seafloor spreading during the Early Cretaceous (112–140 million years ago; Lawver et al., 2002). The Alpha-Mendelev Ridge, interpreted as either an oceanic plateau or a segment of volcanically rifted continental crust, separates the Canada Basin from the younger Makarov Basin (Dove et al., 2010).

Prior to the opening of the Canada Basin, the proto-Arctic Ocean consisted of a series of shallow interconnected

Matthew O'Regan (oreganM1@cardiff.ac.uk) is Lecturer, School of Earth and Ocean Sciences, Cardiff University, Wales, United Kingdom. **Christopher J. Williams** is Associate Professor, Department of Earth & Environment, Franklin and Marshall College, Lancaster, PA, USA. **Karen E. Frey** is Assistant Professor, Graduate School of Geography, Clark University, Worcester, MA, USA. **Martin Jakobsson** is Professor, Department of Geological Sciences, Stockholm University, Sweden.

Table 2. Published sea surface temperature (SST) estimates from marine records shown in Figure 3

#	Location	Latitude (°N)	Age (Ma)	Epoch	Method	SST (°C)	Error	Reference
20	Alpha Ridge	80	70	Maastrichtian	TEX ₈₆	15	1	Jenkyns et al. (2004)
21	Ellesmere Island	78.80	57.5	Paleocene	δ ¹⁸ O	12	2	Tripati et al. (2001)
22	Alaska Slope	70.08	57–58	Paleocene	δ ¹⁸ O	16.5	5.5	Bice et al. (1996)
23	Lomonosov Ridge	87.87	≤ 55	Paleocene/Eocene	TEX ₈₆	17.5	0.5	Sluijs et al. (2006)*
24	Lomonosov Ridge	87.87	55	Paleocene/Eocene	TEX ₈₆	23	N/A	Sluijs et al. (2006)*
25	Lomonosov Ridge	87.87	≤ 53.5	Eocene	TEX ₈₆	22	1.4	Sluijs et al. (2009)*
26	Lomonosov Ridge	87.87	53.5	Eocene	TEX ₈₆	26.5	0.5	Sluijs et al. (2009)*
27	Lomonosov Ridge	87.87	49	Eocene	U ^k ₃₇	25	N/A	Weller and Stein (2008)*
28	Lomonosov Ridge	87.87	49	Eocene	TEX ₈₆	9	1	Brinkhuis et al. (2006)*
29	Lomonosov Ridge	87.87	48	Eocene	TEX ₈₆	13.5	0.5	Brinkhuis et al. (2006)*
30	Lomonosov Ridge	87.87	46	Eocene	U ^k ₃₇	15	N/A	Weller and Stein (2008)*
31	Lomonosov Ridge	87.87	45	Eocene	TEX ₈₆	8.2	1.4	Sangiorgi et al. (2008)*
32	Lomonosov Ridge	87.87	44.4	Eocene	TEX ₈₆	4.7	1	Sangiorgi et al. (2008)*
33	Lomonosov Ridge	87.87	44.4	Eocene	U ^k ₃₇	10	N/A	Sluijs et al. (2006)*
34	Lomonosov Ridge	87.87	18	Miocene	TEX ₈₆	19.7	1.5	Sangiorgi et al. (2008)*
35	Lomonosov Ridge	87.87	18	Miocene	U ^k ₃₇	13	2	Weller and Stein (2008)*

* Higher-resolution records are available in the references marked with asterisks. Ma = millions of years ago.

epicontinental seas, with gateways connecting to the Tethys and Pacific Oceans (Torsvik et al., 2002). Upper Jurassic to Cretaceous organic-rich black shales occur in most of the circum-Arctic sedimentary basins, suggesting high biological productivity and/or poor bottom water ventilation (Stein, 2008). On land, fossil wood deposits on Svalbard, and Ellesmere and Axel Heiberg islands indicate diverse conifer-dominated forests and cool-temperate climatic conditions in the Early Cretaceous (Harland et al., 2007).

After the formation of the Canada Basin, the Arctic Ocean likely remained intermittently connected to other oceans through a succession of gateways that include Turgay Strait, the Western Interior Seaway, and Bering Strait (Figure 2). Reptile fossil records, including turtles and champsosaurs

(crocodilians), occur in Late Cretaceous deposits on Axel Heiberg Island (Tarduno et al., 1998). These taxa are ectotherms and imply mild winters with a mean annual temperature (MAT) of > 14°C, and a cold month mean temperature (CMMT) of > 5.5°C. These Arctic reptilian records are consistent with paleobotanical temperature constraints derived from fossil floras in northern Alaska and Yukon (Spicer and Herman, 2010; Figure 3), which together suggest climatic conditions comparable to those found today in regions of the Iberian Peninsula.

Marine records from lower latitudes indicate peak warmth in the Cenomanian-Turonian (99.6–88.6 million years ago) followed by cooling in the Campanian and Maastrichtian (83.5–65.5 million years ago; Wilson et al., 2002; Jenkyns et al.,

2004). Fossil vegetation in terrestrial Arctic deposits support this view. By the end of the Cretaceous (65.5 million years ago), cold-tolerant redwoods replaced previously abundant warm-adapted conifers and diverse angiosperm assemblages that were common in the Early Cretaceous (> 100 million years ago), while frost-intolerant ginkgoes and cycads became rare. Cooling also restricted the stature and growth rates of Late Cretaceous conifer forests compared to the Albian to Cenomanian forests (112–93.6 million years ago; Spicer and Herman, 2010).

Organic-rich Late Cretaceous sediments recovered in cores from the Amerasian Basin reveal periods of pronounced water-column anoxia or dysoxia as occurs in the Atlantic and Tethys Oceans during this time (Jenkyns et al., 2004; Davies et al.,

2009). The occurrence of these black shales suggests high marine productivity combined with relatively warm seasonal sea surface conditions (Clark, 1988; Davies et al., 2009). Sea surface temperature (SST) estimates of ~ 15°C for this time (Jenkyns et al., 2004) likely record summer temperatures when there was sufficient light to promote surface-water productivity. Laminated diatom mats found in Late Cretaceous cores from Alpha Ridge in the Amerasian Basin reveal strong seasonal changes in productivity occurring in a highly stratified summer ocean (Davies et al., 2009). Intervening laminae containing fine-grained terrigenous sediments are interpreted as ice-rafted debris and suggest at least intermittent winter sea ice formation (Davies et al., 2009).

Other evidence for subzero winter temperatures in the Late Cretaceous includes frost damage in tree rings of preserved conifer wood on Ellesmere Island, implying that temperatures below -10°C may have occurred during the late growing season (Falcon-Lang et al., 2004). Such cool Late Cretaceous temperatures have been reproduced in some climate models. For example, results from a coupled

ocean-atmosphere model for the Campanian (70.6–83.5 million years ago; CO₂ = 1,680 ppmv) produced mean SSTs in the Arctic of 4°C, subzero MATs in some circum-Arctic regions, and the development of very limited coastal sea ice in winters (Otto-Bliesner et al., 2002).

By the end of the Cretaceous, possibly coincident with inferred cooler Maastrichtian (65.5–70.6 million years ago) climates, the Arctic Ocean became more isolated as connections through the Western Interior Seaway and Bering Strait closed (Spicer and Herman, 2010).

EARLY PALEOGENE WARMTH

For most of the Paleogene (65.5–23 million years ago), the Arctic was more isolated than today. In the late Paleocene (~ 56 million years ago), seafloor spreading extended from the rapidly widening North Atlantic into the Arctic Ocean (Brozena et al., 2003). At this time, the Lomonosov Ridge, a narrow fragment of continental crust, separated from the Barents-Kara shelf (Kristoffersen, 1990). Seafloor spreading in the Eurasian Basin predates the opening of the Norwegian-Greenland Sea, and it would be tens of millions of years before a deepwater connection

through Fram Strait was established. Shallow seaways across the proto-Norwegian-Greenland Sea and through Turgay Strait were likely the only connections to the global ocean at this time (Figure 3). Northward movement of the Greenland microplate initiated the Eurekan and Ellesmere orogenies, inducing uplift along northern Canada, Greenland, and Svalbard. These collisions are thought to have closed the shallow-water connection through the Canadian Arctic Archipelago (Brozena et al., 2003) and consequently further restricted Arctic circulation.

The late Paleocene and early Eocene are recognized as periods of prolonged global warmth (Zachos et al., 2008) associated with elevated greenhouse gas concentrations (Figure 3). Peak Cenozoic warmth is also captured in Arctic paleoclimate records from this time. Conifers, especially those of the taxodiaceae, thrived in early Cenozoic Arctic wetlands. Deciduous needle-leaf conifers occupied peat-forming lowland wetlands, whereas deciduous broadleaf plants occupied better-drained floodplains (McIver and Basinger, 1999). Some of these polar forests had large biomass, were moderately productive,

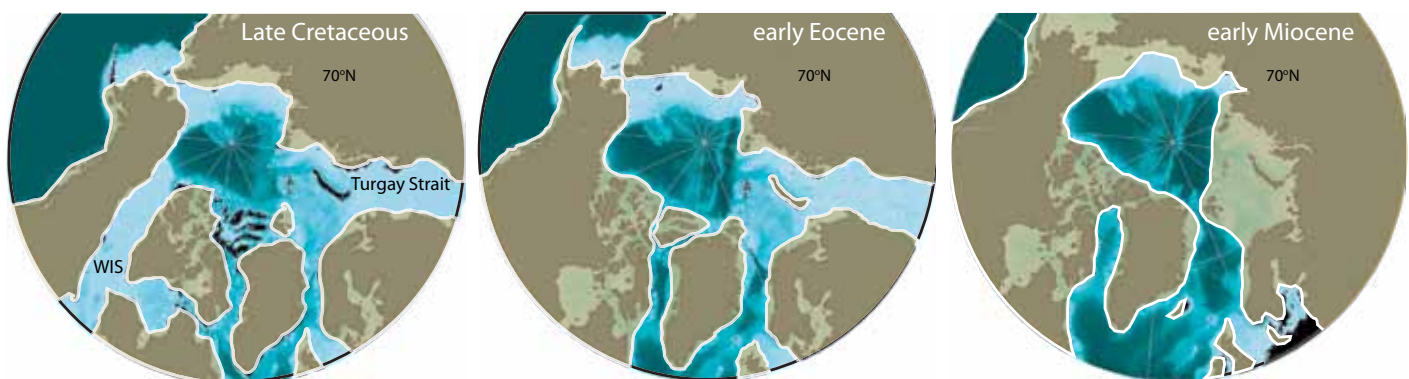


Figure 2. Paleogeographic reconstructions of the Arctic Ocean during the Late Cretaceous (~ 70 million years ago), early Eocene (50 million years ago), and early Miocene (17.5 million years ago). WIS = Western Interior Seaway. Reconstructions made using *GPlates* show the rotated continental positions at different periods in the geologic past (black outlines). Brown overlays show approximate shorelines.

and were ecologically similar to modern temperate forests at lower latitudes (Figure 3). Estimated rates of carbon sequestration are similar to modern old-growth forests of the Pacific Northwest (USA) and are near the average values for temperate freshwater floodplain

forests in North America (Williams et al., 2003). These floodplain forests persisted in the Arctic to at least the early middle Eocene (~ 48–49 million years ago) on Axel Heiberg Island with MAT estimates ranging from 8 to 15°C (Eberle et al., 2010; Greenwood et al.,

2010). Fossil crocodylians and other thermophilic vertebrates found in early Eocene Ellesmere Island deposits imply a CMMT of 0 to 4°C (Eberle et al., 2010).

The Lower Paleogene sediments recovered from the Lomonosov Ridge during ACEX indicate deposition in

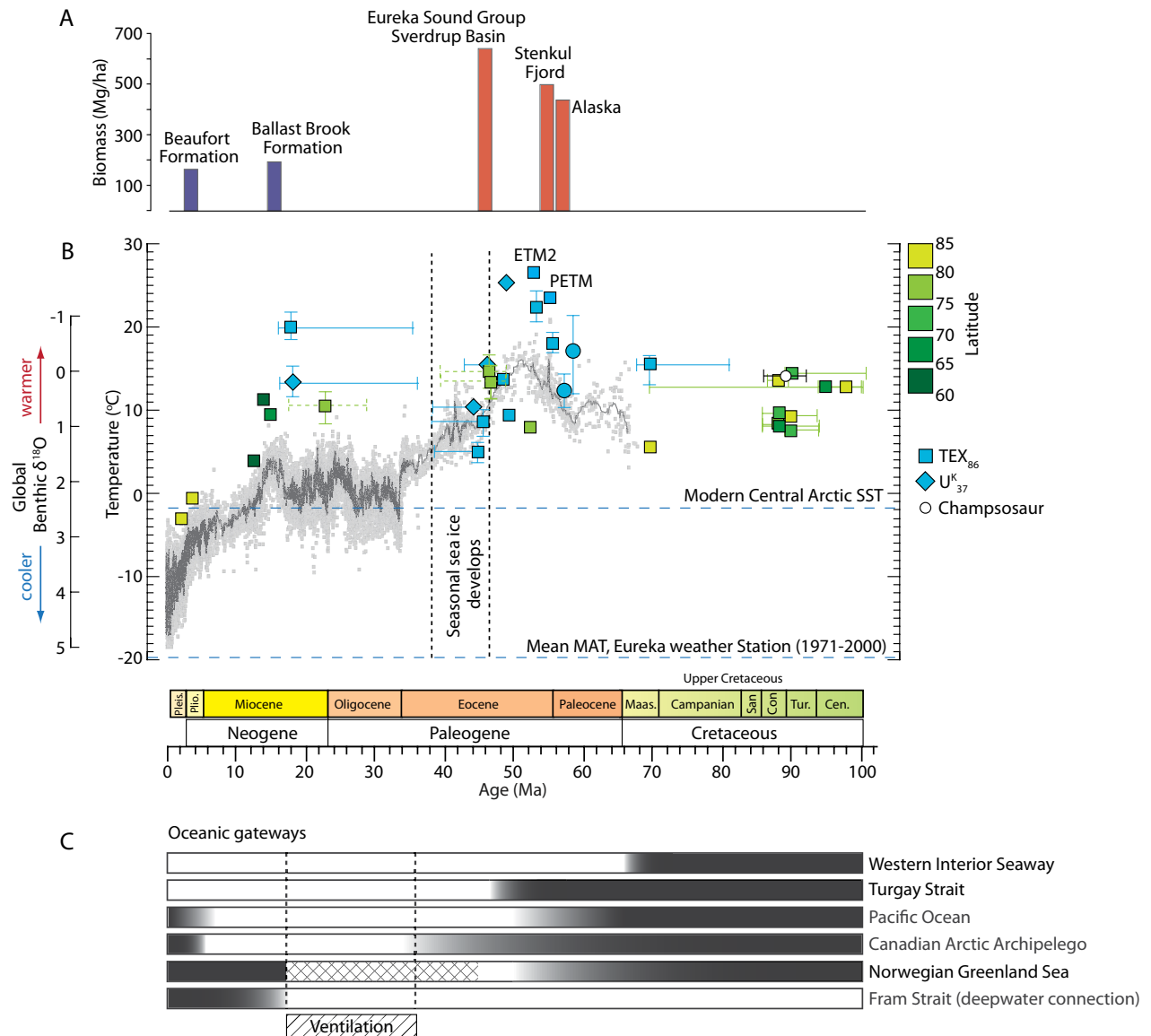


Figure 3. Summary paleoclimate data from the Arctic. (A) Biomass estimates of fossilized forests from well-studied formations in the Canadian Arctic Archipelago and Alaska. (B) Compiled air and sea surface temperatures from published studies of terrestrial (green) and marine (blue) records (Tables 1 and 2). Terrestrial data are color coded by paleolatitude. Temperatures are overlain on the global benthic $\delta^{18}O$ curve of Zachos et al., (2008), illustrating global climate trends from the warmer Paleogene greenhouse world, to the cooler Neogene icehouse world. (C) Summary of the timing for major gateway events. Black = open. White = closed. Timing of the ventilation of the intermediate and bottom waters of the Arctic is shown, with the wide range representing uncertainty based on currently proposed age models for the Arctic Coring Expedition (ACEX) record. Hatching for the Norwegian-Greenland Sea illustrates uncertainty regarding how this shallow seaway evolved during the late Eocene to early Miocene. Ma = millions of years ago.

a warm, strongly stratified, eutrophic basin with oxygen-deficient bottom waters (Stein et al., 2006). Reconstructed SSTs reveal an overall warming in the late Paleocene from 18°C to over 23°C during the Paleocene-Eocene Thermal Maximum (PETM; Sluijs et al., 2006) 56 million years ago, with even higher temperatures (26–27°C) during the Eocene Thermal Maximum 2 (ETM2) (53.5 million years ago; Sluijs et al., 2009). Palm spores found in sediments during ETM2 suggest that CMMTs were > 8°C on nearby continental landmasses (Sluijs et al., 2009). This extreme high-latitude warmth has not been reproduced in paleoclimate models without prescribing very high (e.g., > 4400 ppmv) atmospheric CO₂ concentrations (Huber and Caballero, 2011).

MIDDLE EOCENE COOLING: SEASONAL SEA ICE FORMATION

By the early middle Eocene (48–49 million years ago), the final closure of Bering and Turgay Straits, and very limited connection through the proto-Norwegian-Greenland Sea, further isolated the Arctic Ocean (Onodera et al., 2008; Figure 2). Minimal oceanic exchange resulted in the development of a freshwater lid in the Arctic Ocean and the widespread occurrence of the free-floating freshwater fern *Azolla* (Brinkhuis et al., 2006). Modern *Azolla* tolerate salinities from 1 to 5.5‰, suggesting very fresh and uniform surface water conditions throughout the Arctic. The *Azolla* phase, lasting ~ 0.8 million years, may have ended as warm saline surface waters again entered the Arctic through the expanding Norwegian-Greenland Sea connection (Brinkhuis et al., 2006). In the latest early

Eocene and middle Eocene, the ACEX cores record finely laminated sediments with diverse and well-preserved assemblages of marine siliceous and organic walled microfossils (Stickley et al., 2008). Accompanying SST estimates show a clear cooling trend through the Eocene (Figure 3) as is evident in global compilations (Stein, 2008; Zachos, et al., 2008). Offsets between the TEX₈₆ and U^k₃₇ proxies (Figure 3) may result from different seasonal growth patterns or water masses. For example, while the U^k₃₇-based SST is derived from biomarkers produced by photosynthetic marine microbes and reflects temperatures in the shallow euphotic zone (upper 10 m), *Crenarchaeota* (from which TEX₈₆ estimates are derived) are not dependent on light for growth and may live deeper in the water column (Stein, 2008).

The first conclusive evidence for the return of ice in the ACEX record occurs during the middle Eocene (Moran et al., 2006; St. John, 2008). These sediments are characterized by fine laminations containing both ice-rafted debris and sea ice-dependent fossil diatoms, indicating regularly paced seasonal sea ice formation (Stickley et al., 2009). This sea ice formation occurs when SST estimates are between 8° and 12°C (Figure 3). In comparison, the seasonally sea ice-covered Gulf of Bothnia in the Baltic Sea has mean annual SSTs of 4° to 7°C.

The onset of regularly paced seasonal sea ice in the Arctic predates or possibly coincides with the earliest recorded appearance of glacially sourced ice-rafted debris in the Norwegian-Greenland Sea (between 44 and 30 million years ago; Eldrett et al., 2007; Tripathi et al., 2008). How synchronous these events are depends on the age model applied to

the ACEX record. The biostratigraphically derived age model (Backman et al., 2008) indicates an onset for episodic sea ice formation ~ 47.5 million years ago and regularly paced seasonal ice at ~ 47 million years ago, while an alternate chronology based on osmium isotopes places the onset of episodic sea ice at 44 million years ago (Poirier and Hillaire-Marcel, 2011).

LATE EOCENE TO MIOCENE: VENTILATION OF THE ARCTIC OCEAN

The most dramatic change in the nature of deposition in the ACEX record is a shift from freshwater influenced biosiliceous and organic-rich deposits to fossil-poor glaciomarine silty clays (Figure 4). This transition represents the “ventilation” of the intermediate and deep waters of the Arctic Ocean, which were strongly stratified and oxygen deficient for much of the early Paleogene. This ventilation process is attributed to the initial deepening and widening of Fram Strait around 17.5 million years ago, allowing a critical two-way surface exchange between the Arctic Ocean and Norwegian-Greenland Sea to commence (Jakobsson et al., 2007). The timing, however, is age-model dependent. In the original and most widely used ACEX age model, Arctic ventilation occurred above a 26 million year hiatus that separated middle Eocene (44.4 million years ago) from late early Miocene (18.2 million years ago) sediments (Backman et al., 2008). In contrast, radiometric ages derived from osmium isotopes date the ventilation of the Arctic almost 20 million years earlier in the late Eocene (~ 36 million years ago). This alternate chronology argues against a pronounced hiatus in the ACEX record (Poirier and

Hillaire-Marcel, 2011).

Absolute ages notwithstanding, the problem of the major sedimentological and facies changes identified in the “transitional” interval of the ACEX record are difficult to reconcile without accepting a break in deposition. Moreover, the presence of a hiatus is supported by an unconformity seen in seismic data on the Lomonosov Ridge (Bruvold et al., 2010) as well as clear evidence of reworking in the transitional ACEX sediments (Sangiorgi et al., 2008).

Clearly, the Eocene to early Neogene was a dynamic stage in Arctic evolution, but the corresponding hiatus and/or severely condensed interval in the ACEX record have hampered our ability to reconstruct this phase of Arctic paleoclimatic history. Therefore, the response of the Arctic to global changes associated with the Eocene-Oligocene climate transition, which represents the expansion of Antarctic ice sheets and the end of the early Cenozoic greenhouse (Coxall and Pearson, 2007) is largely unknown. The Oligocene is poorly represented on Arctic margins, but cooling from the early to middle Oligocene is reported from paleobotanical records from the Richards Formation of the Northwest Territories Canada, involving extinction of thermophilic taxa and an increase in cooler temperate deciduous and conifer forests (Graham, 1999).

In the Norwegian-Greenland Sea, terrestrial palynological indices and organic biomarkers preserved in marine sediments (Ocean Drilling Program [ODP] Sites 913, 985, and 643; Figure 1) document a CMMT cooling of ~ 5°C across the Eocene-Oligocene boundary (Eldrett et al., 2009). When integrated with climate model simulations from the Eocene

(CO₂ = 1,120 ppmv) and Oligocene (560 ppmv), this regional temperature drop is enough to establish thick winter sea ice and thinner perennial sea ice in the Arctic (Eldrett et al., 2009). This time is the earliest in which perennial sea ice in the Arctic is suggested by either model- or field-based evidence.

MIOCENE: EVIDENCE FOR PERENNIAL ICE IN THE ARCTIC?

Terrestrial Miocene records from the Arctic record a pattern of substantial climatic cooling. The oldest Miocene estimates of terrestrial climate conditions are from plant fossils of the Houghton Formation on Devon Island, northern Canada (~ 22 million years ago; Figure 1; Hickey et al., 1988). These plant fossils indicate a humid, cool-temperate climate with a MAT of between 8° and 12°C and a CMMT between -7° and -4°C. Cooler, but still warm, conditions continued into the middle Miocene as evidenced by temperate fossil plants recovered from the Mary Sachs Gravel on Banks Island (Hills et al., 1974). Coeval deposits to the north at Ballast Brook contain the remains of *Pinaceae*-dominated fossil forests. These lowland forests were comparable in size, biomass, and productivity to modern cool temperate swamp forests and larger-than-modern, *Pinaceae*-dominated, southern-boreal forests in Canada (Williams et al., 2008).

Age control for these paleobotanical records is poor and the relationship with the Middle Miocene Climate Optimum (MMCO; 15–17 million years ago) recognized globally in deep-sea records is unknown (Shevenell et al., 2004). Global cooling following MMCO is interpreted as marking the expansion of the East Antarctic Ice Sheet (Pekar and DeConto, 2006) and was accompanied

by a reduction in atmospheric CO₂ concentrations from ~ 500 ppmv to ~ 300 ppmv (Kürschner et al., 2008). The best quantitative estimate of terrestrial Arctic cooling across this interval is from Cook Inlet, Alaska, where a reduction in the MAT from 11.5° to 4°C occurs between 12 and 13 million years ago (Wolfe, 1994). Pollen and spore assemblages from interior Alaska also provide a MAT of 9°C at 15.2 million years ago (White and Ager, 1994), with subsequent cooling proceeding until 11 million years ago (White et al., 1997). Increased

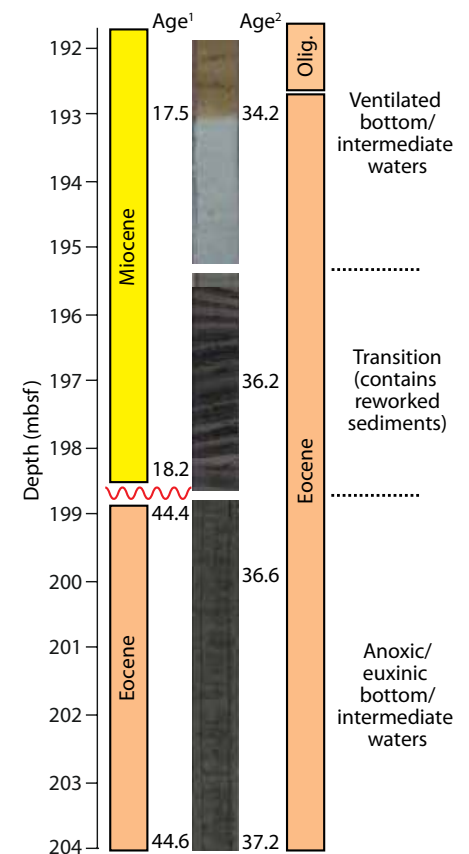


Figure 4. Interval of the ACEX record that records the ventilation of intermediate and bottom waters of the Arctic Ocean. Two age models are proposed for this interval by (1) Backman et al. (2008), and (2) Poirier and Hillaire-Marcel (2011). Core images (not to scale) show the general lithology associated with different depth intervals. For an in-depth discussion of paleoenvironmental changes across this zone see Sangiorgi et al. (2008).

amounts of ice-rafted material at ODP Site 909 also suggest the existence of a calving ice sheet in the northern Barents Sea (east of Svalbard) between ~ 12 and 15 million years ago, whereas much of MMCO appears to have been ice-free (Knies and Gaina, 2008).

Neogene sediments in the ACEX record are generally microfossil poor, making it difficult to derive direct paleoclimate or sea ice proxies. However, the onset of perennial ice was inferred by combining modern sea ice drift times with databases on the dominant source regions of clay, heavy mineral, and detrital iron-oxide grains (Krylov et al., 2008; Darby, 2008). Clay and heavy mineral assemblages suggest an onset for perennial ice around 13 million years ago (Krylov et al., 2008), while analysis of detrital iron-oxide grains indicates far-field sea ice transport from all circum-Arctic shelves before this time. These data extend the presumed inception of perennial ice beyond 14 million years ago (Darby, 2008), but do have the sampling resolution to address the persistence of perennial ice in the Arctic since this time.

Global climate model simulations of the late to middle Miocene exist for a variety of atmospheric CO₂ concentrations (Steppuhn et al., 2007; Tong et al., 2009; Micheels et al., 2009). Most of these models include an ice-free Greenland with tundra vegetation and a closed Bering Sea. When coupled to a simple thermodynamic sea ice model, they produce both seasonal and, in some instances, perennial sea ice in the Arctic. For example, with a CO₂ concentration of 353 ppmv, summer sea ice extent (June–July–August [JJA]) of 9.4×10^6 km³ is reported for the late Miocene (11–7 million years ago; Steppuhn et al., 2007); this compares

to the average JJA extent from satellite records between 1979 and 2010 of 9.64×10^6 km³ (Stroeve and Meier, 2010), suggesting perennial ice conditions. At higher CO₂ levels (700 ppmv), the same model produces summer sea ice extent of only 1.5×10^6 km³, which is more compatible with seasonal sea ice conditions that would be unlikely to survive beyond the late summer melt and September sea-ice minimum.

An important finding of all these models is the development of a strong positive temperature anomaly over northern Greenland and the Canadian Arctic Archipelago when the Greenland Ice Sheet is removed. In the modern Arctic, the thickest and most persistent sea ice occurs in this region, and it is the last area of the Arctic predicted to contain perennial ice in Intergovernmental Panel on Climate Change (IPCC) predictions for the future (IPCC, 2007). How applicable these observations are for the geologic past remains unclear. A more direct analysis of spatial sea ice patterns in the Miocene is needed to address the compatibility of perennial sea ice with the warm temperatures indicated by fossilized forests with temperate plants growing in coastal regions of the Canadian Arctic Archipelago (Fyles et al., 1994).

PLIOCENE: VEGETATIVE DECLINE AND ICE SHEET GROWTH

Invasion of Pacific mollusks to the North Atlantic suggests that flooding of Bering Strait occurred ~ 4.5 million years ago (Verhoeven et al., in press). Following flooding, flow through Bering Strait was directed southward, with modern-type inflow from the Pacific occurring ~ 3.6 million years ago (Marincovich

and Gladenkov, 2001). With renewed Atlantic and Pacific exchange, the Pliocene Arctic Ocean became increasingly similar to its modern counterpart.

The Pliocene is widely regarded as the time when continental-sized ice sheets began to develop in the Northern Hemisphere, between 3.6 and 2.4 million years ago (Mudelsee and Raymo, 2005). However, there are very few age-calibrated Arctic Ocean records extending back this far (Matthiessen et al., 2009; Polyak et al., 2010). Microfossils from poorly dated Pliocene sediments of the Beaufort-Mackenzie Basin, northern Alaska, and Greenland suggest more moderate ocean temperatures than today and reduced summer sea ice conditions (Polyak et al., 2010).

Extensive upper Miocene to Pliocene braided river deposits and the fossil remains of fringing forests are found along the western edge of the Canadian Arctic Archipelago (the Beaufort Formation). These boreal forests were dominated by *Larix* and *Picea* that suggest cooler conditions than those of the conifer-hardwood type found in the Miocene Ballast Brook Formation. Measurements of fossil trees in the Beaufort Formation on Banks Island indicate average diameters of 21 cm and heights of 12.3 m—nearly identical to modern boreal forest trees growing at 68°N in the Mackenzie River delta, and substantially larger than modern taiga (recent work of author Williams).

The only SST estimates for the Pliocene come from Fram Strait, where inflowing Atlantic water temperatures were as high as 18°C (Robinson, 2009). These temperatures occurred during the transient middle Pliocene warm period (~ 3–3.3 million years ago). Temperature estimates from middle Pliocene peat

deposits on Ellesmere Island record a MAT of -0.4°C (Ballantyne et al., 2010; Figure 3) and are consistent with the idea of cold winter conditions, supporting the existence of seasonal sea ice.

It was not until after the Pliocene warm period that extensive growth of the Greenland Ice Sheet occurred, likely in response to a further decrease in atmospheric CO_2 concentration (Lunt et al., 2008). Evidence of episodic expansion of the northern Barents Ice Sheet from 3.6 million years ago has also been reported, transitioning toward more regional-scale glaciations between 3.6 and 2.4 million years ago (Knies et al., 2009; Matthiessen et al., 2009). On Greenland, these earlier glaciations were followed by interglacial episodes involving drastic retreat of the ice sheet (Funder et al., 2001).

Terrestrial evidence from the Hvitland beds on Ellesmere Island indicate a switch from forest to open tundra near the end of the Pliocene (Fyles et al., 1998), and the disappearance of forests more generally from the Canadian Arctic Archipelago (White et al., 1997). The advance of ice sheets in the late Pliocene and Pleistocene may have cut the many fjord-like channels that currently divide the Canadian Arctic Islands (Harrison et al., 1999) and form the final modern gateway to the global ocean.

QUATERNARY: CIRCUM-ARCTIC ICE SHEETS AND SHELVES

Large ice sheets repeatedly advanced to the edge of the Arctic Ocean throughout the Quaternary. The most obvious and dramatic evidence of these advances occurs in the many glacially excavated troughs and seaward-lying fan deposits found along the Greenland, Barents, and Canadian margins. These fan deposits,

similar in shape and size to those found around Antarctica today, were formed when large ice sheets extended across the broad continental shelves of the Arctic and subarctic seas (Ó Cofaigh et al., 2003). Along the Barents Sea margin, between Svalbard and mainland Norway, seismic and borehole data suggest that large-scale ice streaming in these troughs intensified in the early to middle Pleistocene (Laberg et al., 2010). No equivalent records exist in front of the large glacially excavated troughs that drained the larger Laurentide Ice Sheet along the Canadian Arctic Archipelago.

Geophysical data, including high-resolution subbottom profiling and multibeam mapping, demonstrate that Quaternary glacial ice, in the form of ice shelves or large tabular icebergs, scoured many regions of the Arctic seafloor. These scoured surfaces include isolated topographic highs that are found in modern water depths of up to 1000 m, attesting to the size of the ice sheets that fringed the Arctic Ocean (Jakobsson et al., 2010b; Polyak and Jakobsson, 2011, in this issue).

Quaternary marine sediments from the central Arctic Ocean remain difficult to date due to the lack of biogenic material deposited or preserved in them. Existing chronologies and multiproxy-based interpretations of some Arctic Ocean cores suggest that perennial sea ice persisted during late Quaternary interglacial/interstadial episodes (Nørgaard-Pedersen et al., 2003; Cronin et al., 2010; Polyak et al., 2010). These records generally have a low temporal resolution, and may not capture the full range of sea ice conditions during these times. For example, several recently studied higher-resolution Holocene marine sediment records from the Arctic

Ocean suggest that summer Arctic sea ice cover was considerably reduced during most of the early Holocene, with possible periods of ice-free summers in the central Arctic Ocean during the Holocene Thermal Maximum (Jakobsson et al., 2010a).

DISCUSSION

The high northern latitudes constitute one of the most rapidly warming places on the planet today, with profound impacts on terrestrial and marine systems predicted in the near future (IPCC, 2007). Enhanced Arctic warming, or polar amplification of global temperature change, is a phenomenon captured by almost all climate models (Holland and Bitz, 2003), and it is evident in both warmer and colder periods of the geologic past (Miller et al., 2010). The rapidly declining Arctic sea ice cover captured in satellite records from recent decades is one of the most striking examples of the Arctic's sensitivity to global climate change (Stroeve et al., 2007; Wang and Overland, 2009). Multimodel ensemble mean estimates under "business-as-usual" scenarios in the IPCC Fourth Assessment Report, and subsequent reassessments using recent sea ice minimums, indicate that a return to seasonal ice conditions may occur anywhere between 2050 to well beyond 2100, corresponding to atmospheric CO_2 levels of 520 to > 700 ppmv (Wang and Overland, 2009; IPCC, 2007; Figure 5).

Projected into the past, this level exceeds most proxy-based estimates for CO_2 during the last 15–20 million years; it is only exceeded when crossing the transition from the Neogene icehouse world to the Paleogene greenhouse world (Figure 5). At first glance, a CO_2 threshold for the existence of perennial

ice of ~ 500 ppmv is compatible with available paleodata from the Arctic Ocean. Seasonal sea ice is known to have occurred in the Arctic during the Eocene, when CO₂ levels were likely > 1,000 ppmv (Stickley et al., 2009), and it is consistent with future projections of seasonal ice in all IPCC scenarios. When late Miocene boundary conditions are applied, paleomodeling also indicates that seasonal ice persists until CO₂ levels exceed 1,500 ppmv (Micheels et al., 2009).

Our limited insights into the establishment of perennial ice in the past come from the model-based results of Eldrett et al. (2009) for the early Oligocene and Steppuhn et al. (2007) for the late Miocene where perennial ice exists when atmospheric CO₂ is set at 560 and 353 ppmv, respectively. The inferred onset for perennial ice in the Miocene (or earlier) from the ACEX record also fits

with these findings (Krylov et al., 2008; Darby, 2008). However, the applicability of this relationship in the geologic past remains extremely speculative. In addition to large uncertainties between and within existing proxy-based CO₂ estimates (Figure 5), the overall sensitivity of Earth's climate system to past greenhouse gas concentrations is complex. For example, the early and middle Pliocene warm periods, when mean global temperatures were 3–4°C above pre-industrial temperatures, occurred when atmospheric CO₂ concentrations (365 and 415 ppmv) were close to modern levels (Pagani et al., 2010).

Part of this increased sensitivity may be attributed to changes in boundary conditions in the past. For example, the high terrestrial MAT reported for the middle Pliocene from Ellesmere Island (-0.4°C) and the warmth of inflowing Atlantic water through Fram Strait are

not reproduced using fully coupled ocean-atmosphere models for this time period (Robinson, 2009). However, increasing the depth of the Greenland-Scotland Ridge from the modern day ~ 500 m to 1,500 m produces a large-enough increase in the transport of warm North Atlantic surface waters into the Norwegian-Greenland Sea and Arctic Ocean to largely reconcile observed and modeled SST estimates (Robinson et al., in press). The role of inflowing Atlantic and Pacific waters on patterns of sea ice are well documented in modern times (Polyakov et al., 2005; Shimada et al., 2006), and illustrated by the decrease in sea ice persistence seen in Figure 1a. Changing basic physiographic boundary conditions that alter water-mass properties, patterns, and rates of past circulation are clearly important for understanding the geologic past. Processes that influence these boundary

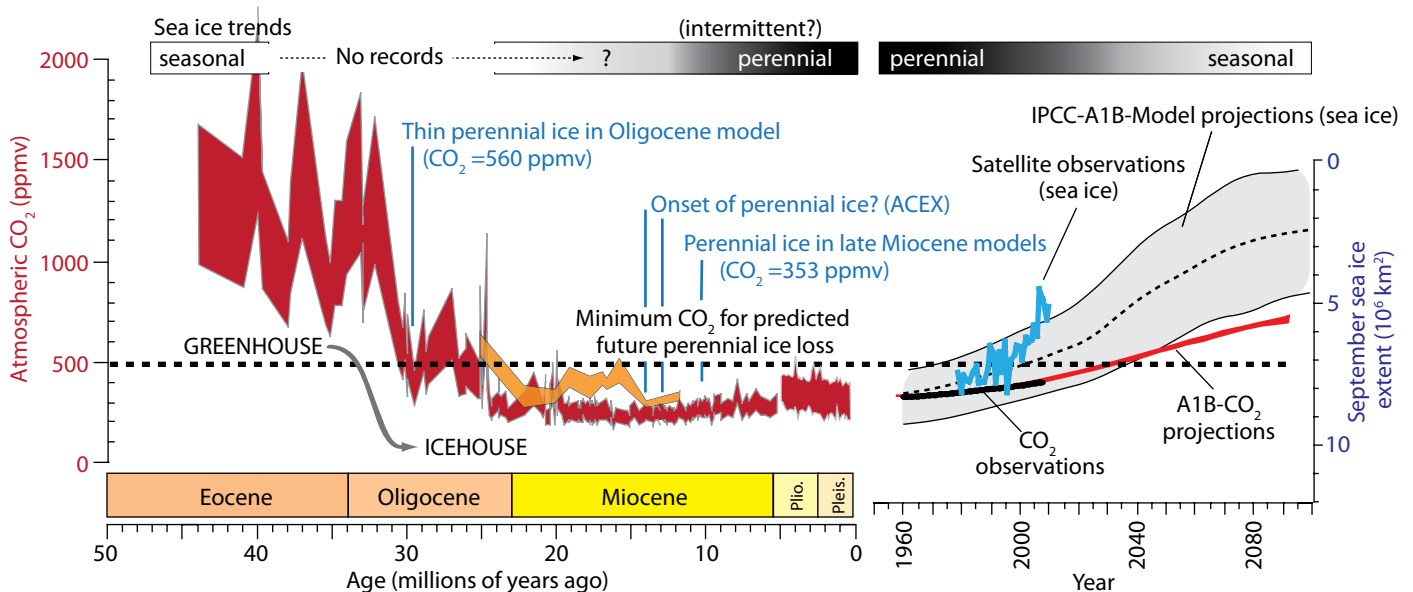


Figure 5. CO₂ and sea ice. Comparison of the modern, future (Intergovernmental Panel on Climate Change (IPCC) A1B predictions) and past (proxy-based; Pagani et al., 2005, 2010, in red and Kürschner et al., 2008, in orange) atmospheric CO₂ concentrations with satellite-derived September sea ice extent (blue line; Stroeve and Meier, 2010), ensemble mean projections of IPCC climate models (grey shaded region), and insights into the evolution of seasonal and perennial sea ice in the Arctic from marine sediments and modeling results (noted in figure). The bar along the top provides an overview of our fragmentary understanding of when seasonal and perennial sea ice formed in the Arctic, and when it may disappear in the near future.

conditions operate on a variety of time scales that include glacially controlled sea level variations, slower tectonically controlled subsidence, and opening rates of major gateways that occurred during the evolution of the modern Arctic.

Improved understanding of past atmospheric circulation patterns is equally important as, and not necessarily independent from, changing oceanic exchange, because the atmospheric circulation patterns have been shown to exert a strong influence on sea ice distribution, thickness, and drift speeds in modern and Holocene analyses (Dyck et al., 2010). Atmospheric forcing also impacts the dispersal of sediments by sea ice and needs to be considered when interpreting provenance source changes in the geologic past, such as those used in the ACEX record to infer the onset of perennial sea ice. Resolving the onset and persistence of perennial sea ice in the geologic past remains a key and yet poorly constrained piece of the wider paleoclimatic evolution of the Arctic.

SUMMARY AND FUTURE OUTLOOK

Terrestrial and marine data reveal dramatic paleoclimatic and oceanographic changes in the Arctic since the Cretaceous. Increasingly sophisticated analytical techniques are being applied to quantify past climatic conditions using the many fossil floras collected from Arctic coastlines and found in marine sediments recovered from the ocean floor. The overall patterns of warming and cooling derived from these studies fit, to a first order, with global climate reconstructions, illustrating progressive cooling since peak warmth in the early Paleogene (Figure 3). However, with few exceptions, which include early


Paleocene and Eocene hyperthermal events, the middle Pliocene warm period, and late Quaternary interglacial periods, there are few well-calibrated and continuous time series that provide quantitative estimates of past Arctic climatic conditions.

An improved understanding of how the evolution of the Arctic is related to the global climate system requires integration of marine and terrestrial proxies. Given the snapshot nature of fossilized terrestrial floras preserving time slices that could span 10,000–50,000 years, it is difficult to link them directly to marine time series, a problem exacerbated by the paucity of available marine records. Furthermore, the modern sensitivity of the Arctic strongly argues for rapid environmental changes in the geologic past that can only be captured and quantified through analysis of age-calibrated marine sediments. These reconstructions must account for the large-scale changes to boundary conditions that influence oceanic and atmospheric circulation.

To acquire these records and improve our understanding of the magnitude, rates, and driving mechanisms of Arctic paleoclimatic change requires a dedicated effort toward renewed scientific drilling in the Arctic Ocean. While it is unlikely that a single drilling site can address all of the outstanding questions, targeting sites that can provide insights into marine and terrestrial climates is necessary to provide a more complete understanding of the region's climatic history and to facilitate future data-model integration.

ACKNOWLEDGEMENTS

MO and MJ thank the Bert Bolin Centre for Climate Research at Stockholm University. KF's work on this paper was supported by the NASA Ocean Biology

and Biogeochemistry Program (Grant NNX10AH71G) and NSF Arctic Natural Sciences Program (Grant 0804773). We also thank J. Backman, H. Coxall and J. Lerback for constructive comments on the manuscript and helpful reviews by D. Darby and M. Robinson. 

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SIDEBAR | Millennial-Scale Arctic Climate Change of the Last 3.6 Million Years: Scientific Drilling at Lake El'gygytgyn, Northeast Russia

By Julie Brigham-Grette, Martin Melles,
Pavel Minyuk, and Christian Koeberl

Successful deep drilling at Lake El'gygytgyn (67°30'N, 172°05'E), in the center of western Beringia, recovered 315 m of sediment, representing the longest time-continuous sediment record of past climate change in the terrestrial Arctic. The core was taken using the DOSECC GLAD800 (Global Lake Drilling 800 m) hydraulic/rotary system engineered for extreme weather, using over-thickened lake ice as a drilling platform. El'gygytgyn is a Yup'ik name that has been variously translated as "the white lake" or "the lake that never thaws." Today, the lake maintains an ice cover nine to 10 months per year.

Cyclic changes in the shape and orientation of Earth's orbit around the Sun influence climate. Before about 900,000 years

- glaciation in the Northern Hemisphere back to 44 Ma from ice-rafted debris in the Greenland Sea. *Earth and Planetary Science Letters* 265:112–122, <http://dx.doi.org/10.1016/j.epsl.2007.09.045>.
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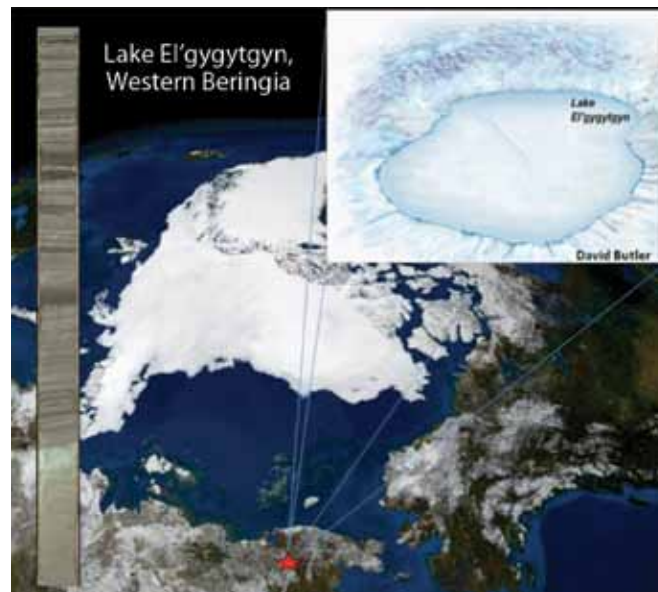


Figure 1. Lake El'gygytgyn (red star) is located 100 km north of the Arctic Circle in the middle of Chukotka, northeast Russia. The lake is 12 km in diameter and 175 m deep, situated inside an 18 km diameter meteorite crater (inset). The Arctic map shows the minimum summer sea ice extent of 2007 (from NOAA). The sediments taken from the lake, like those shown in the column on the left, contain evidence of Arctic change over the past 3.6 million years that can be compared to evidence from the Arctic Basin and marginal seas.