Supplementary information

Episodic fresh surface waters in the Eocene Arctic Ocean. Henk Brinkhuis, Stefan Schouten, Margaret E. Collinson, Appy Sluijs, Jaap S. Sinninghe Damsté, Gerald R. Dickens, Matthew Huber, Thomas M. Cronin, Jonaotaro Onodera, Kozo Takahashi, Jonathan P. Bujak, Ruediger Stein, Johan van der Burgh, James S. Eldrett, Ian C. Harding, André F. Lotter, Francesca Sangiorgi, Han van Konijnenburg-van Cittert, Jan W. de Leeuw Jens Matthiessen, Jan Backman, Kathryn Moran

Evaporation minus precipitation from fully coupled Eocene simulations

As described elsewhere[1,2] we have performed long equilibrated fully coupled Eocene simulations. Here we show zonally and annually averaged evaporation minus precipitation results averaged over 50 years at the end of an equilibrated Eocene simulation carried out with 560 ppm CO_2 (Fig. S1). There is net precipitation at high latitudes in the Eocene (as today), which does not prove to be sensitive to variations in boundary conditions. Hence, a geographically isolated Arctic Ocean will ultimately become fresh.

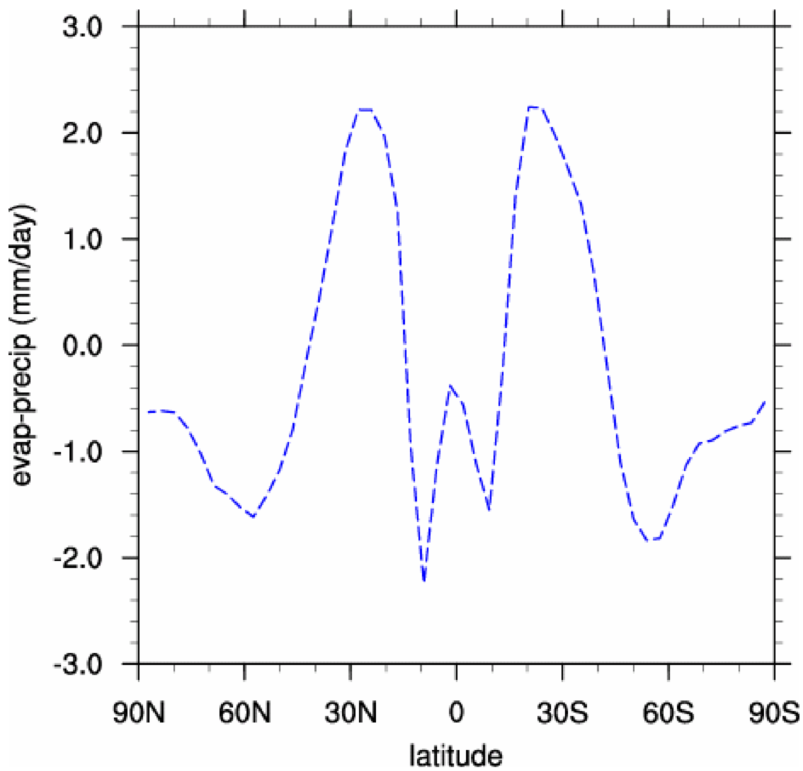


Fig. S-1.
Eocene simulation of latitudinal distribution of evaporation minus precipitation.

Records of abundant *Azolla* remains in the sub Arctic and Nordic seas

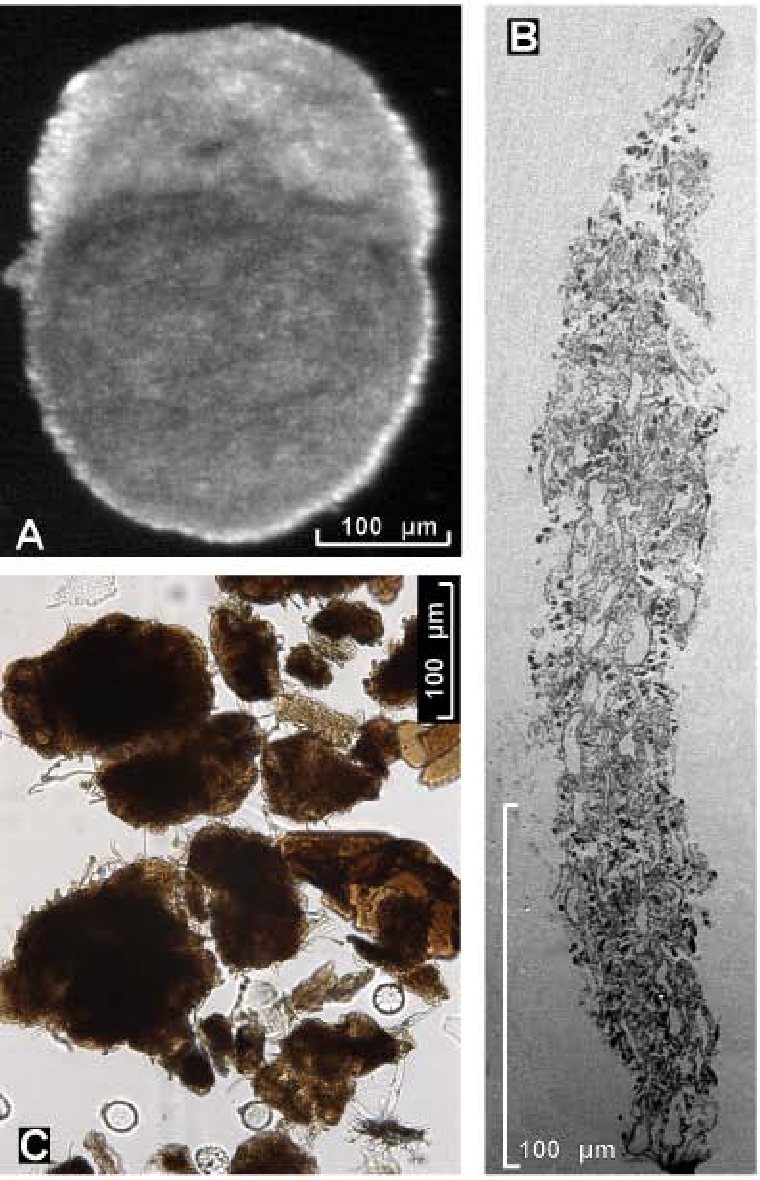
Surprisingly, the basal middle Eocene “*Azolla* pulses” have only barely made it into the published literature; only a few scientific ocean drilling and/or outcrop studies mention them at all (e.g., refs. 3-5). The phase was however picked up in hundreds of commercial oil and gas exploration wells through confidential palynological and micropaleontological studies around the sub-Arctic and Nordic seas. Usually dealing with ditch cuttings, notably the termination of the event was and is used for well correlations, and is actually mentioned in various informal zonal schemes of the regions involved (e.g., refs. 6,7). Detailed, independent age calibration is unfortunately invariably lacking in the early scientific and commercial studies, but the phase is universally bracketed by the same set of bioevents throughout the region (e.g., the last abundant occurrences of the marine dinoflagellate cysts *Eatonicysta ursulae* and *Charlesdowniea columna*) indicating that they are synchronous. Only very recently, the termination of the *Azolla* phase has been calibrated against mid magnetochron C21r (~48.3 Ma) at three sites from the Greenland and Norwegian seas[5] (Fig. 2).

We compiled notably industrial palynological information through numerous, mainly informal channels as most information is still confidential to oil and gas exploration companies. We have combined such reports with our (HB, JPB) own work as far as confidentiality allows and results are summarized in Fig. S-3 and Table S-1.

1. Huber, M. & Sloan, L. C. Heat transport, deep waters, and thermal gradients: Coupled simulation of an Eocene Greenhouse Climate. *Geophysical Research Letters* **28**, 3481-3484 (2001).
2. Huber, M. & Caballero, R. Eocene El Niño: Evidence for Robust Tropical Dynamics in the "Hothouse". *Science* **299**, 877-881 (2003).
3. Boulter, M. C. Pollen and spore events from the marine Tertiary of North Europe. *Journal of Micropalaeontology* **5**, 75-84 (1986).
4. Heilmann-Clausen, C. in *Early Paleogene Stage Boundaries. Abstracts and Field Trip Guides.* (ed. Molina, E.) 19 (University of Zaragoza, Zaragoza, Spain, 1996).
5. Eldrett, J. S., Harding, I. C., Firth, J. V. & Roberts, A. P. Magnetostratigraphic calibration of Eocene-Oligocene dinoflagellate cyst biostratigraphy from the Norwegian-Greenland Sea. *Marine Geology* **204**, 91-127 (2004).
6. Bujak, J. P. & Mudge, D. C. A high-resolution North Sea Eocene dinocyst zonation. *Journal of the Geological Society, London* **151**, 449-462 (1994).
7. Gradstein, F. M. & Agterberg, F. in *Quantitative Stratigraphic Correlation* (eds. Cubitt, J. M. & Reyment, R. A.) 119 **-** 175 (John Wiley & Sons, Chinchester, UK, 1982).

Fig. S-2

Additional photographs showing the morphology of the *Azolla* mega- and microspores (A-C) and sub-millimetre scale microlaminations (D-H) from Hole 302-4A-11X.



(A) Combined transmitted and reflected light photograph of a megaspore apparatus showing distal (lower and darker) megaspore and proximal (upper and paler) float zone; (B) TEM of a microspore massula cluster (contents of one sporangium) in section showing fully developed and expanded microspores, electron dense (black) structures are sections through glochidia; (C) LM photograph of dispersed microspore massulae showing mature glochidia extended from surface and hence ready to anchor onto megaspore filosum as has occurred in Figs. 3A and 3B.

(D & G) and (E & H) comprise approximately the same images with LM (G, H) and SEM with backscatter detector (D, E). Biosilica-rich layers are white in LM and dark grey in SEM whilst organic rich layers are dark orange to black in LM and paler grey in SEM. (F) SEM showing the flaky texture of the organic- rich layers (pale grey), which contain clay minerals, indicated with elemental analysis; the biosilica rich layers are composed almost entirely of three-dimensionally preserved siliceous microplankton (in this case dominantly chrysophyte cysts seen in section).

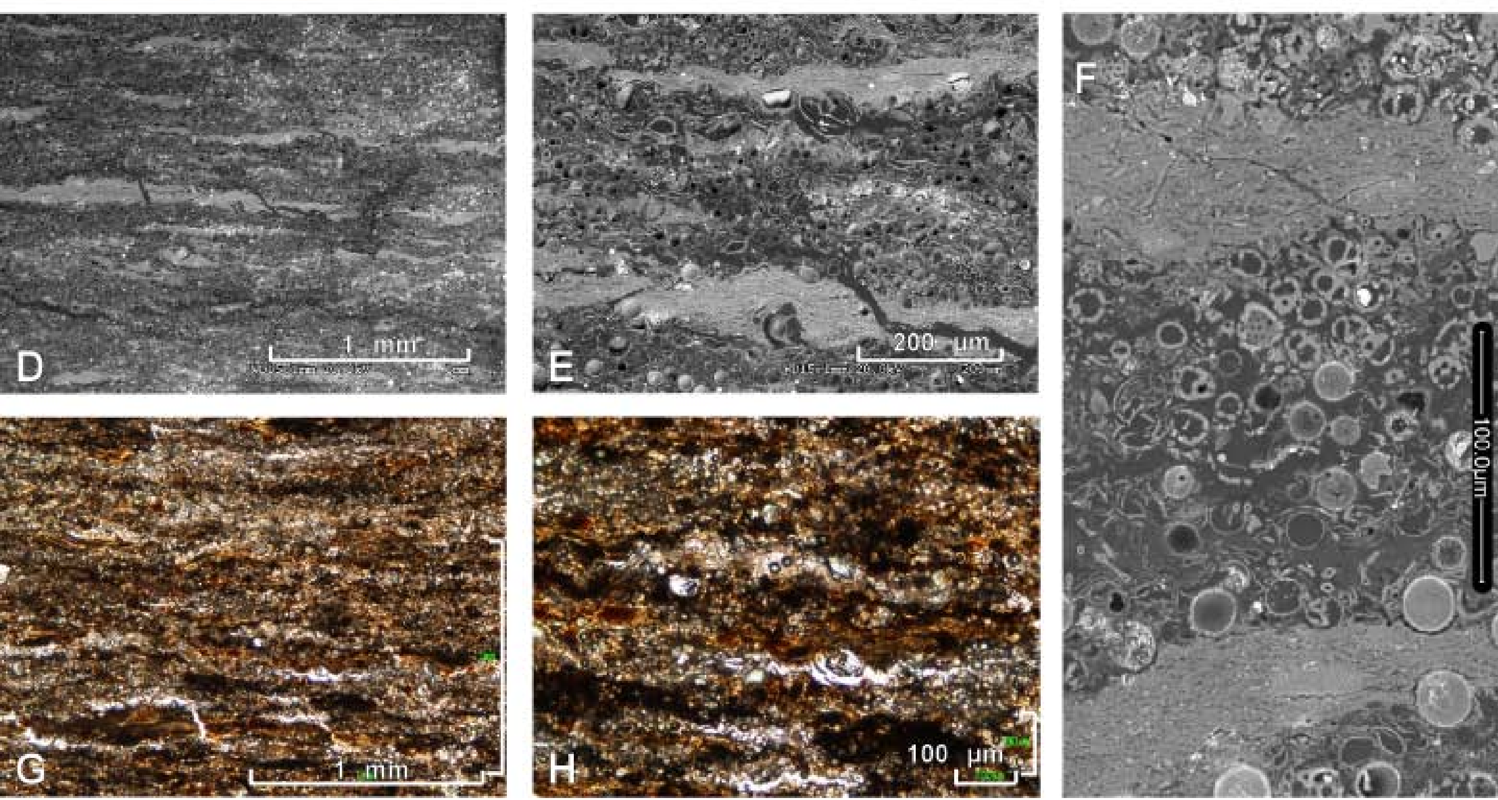
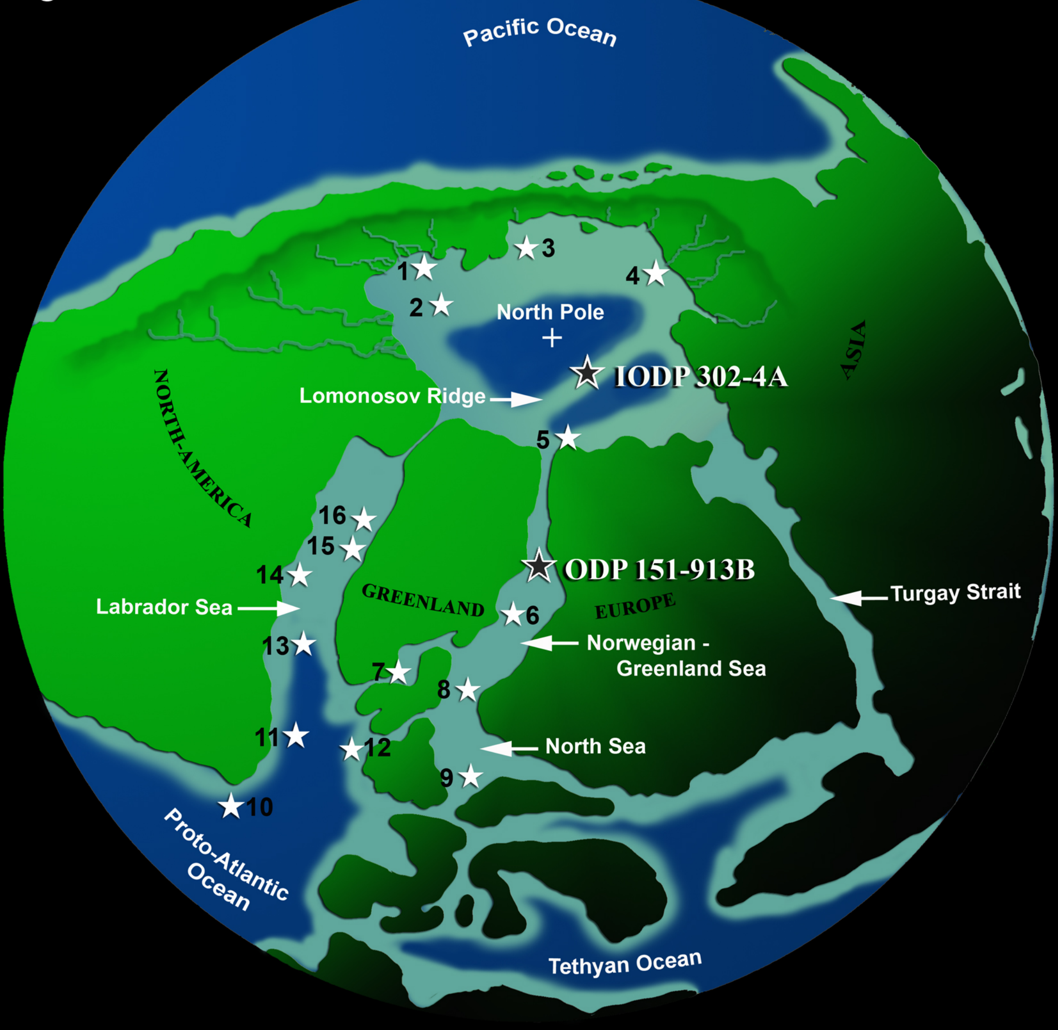


Fig S-3



Pacific Ocean
1
2
3
4
North Pole
IODP 302-4A
Lomonosov Ridge
ASIA
NORTH-AMERICA
5
16
15
14
ODP 151-913B
GREENLAND
EUROPE
Labrador Sea
6
Turgay Strait
13
Norwegian - Greenland Sea
7
8
11
12
North Sea
9
10
Proto-Atlantic Ocean
Tethyan Ocean

Table S-1
Wells with earliest middle Eocene Azolla abundances in the various regions of the nordic seas numbered in Fig. S-3.

Region number (Fig. S-3)	Representative wells
Regions 1-2 MacKenzie Delta & Beaufort Basin	Langley E-29 Mallik A-06 Nuktak C-22 Reindeer D-27 Taglu G-33 Titalik K-26 Upluk M-38
Region 3 North slope Alaska	Abel State 1 Aurora 1 Beechey Point 1 Belcher 1 Duck Island Unit 1 East Mikkelsen Bay 1 Foggy Island Bay State 1 Mikkelsen Bay 13-9-19 Point Thompson Unit 1 Point Thompson Unit 2 Prudhoe Bay 1 West Mikkelsen Bay 1
Region 4 Siberian Shelf	confidential
Region 5 Barentsz Sea	confidential Norsk Hydro, Statoil
Region 6 Norwegian - Greenland sea	confidential ODP 913B DSDP 338 ODP 642
Region 7 Faeroe-Shetland Basin	206/1-1A 206/2-1 206/3-1 206/5-1 208/17-1 208/19-1 209/3-1 209/4-1 209/6-1 209/9-1 214/27-2 214/30-1
Regions 8-9 North Sea Basin	9/17-2 15/30-1 16/16a-3 16/17-3 16/26-2 16/26-5 16/29-4 16/3-1 16/7-2 16/7a-14 21/12-1 21/17-2 21/17-3 21/18-1 21/18-5 9/17-2 Danish outcrops
Region 10 Grand Banks, Scotian Shelf	confidential
Region 11 Labrador, Hopedale Basin	Bjarni O-82 Snorri j-90 North Leif I-05
Region 12 Atlantic, Rockall Bank	confidential
Region 13 Labrador, South Saglek Basin	Karlsefni A-16
Region 14 Labrador, North Saglek Basin	confidential
Region 15 Baffin Sea, Sisimut Basin	confidential
Region 16 Baffin Sea, Nuussuaq Basin	confidential