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1 **Orbital, tectonic and oceanographic controls on Pliocene climate**  
2 **and atmospheric circulation in Arctic Norway**

3 Sina Panitz<sup>1</sup>, Ulrich Salzmann<sup>1</sup>, Bjørg Risebrobakken<sup>2</sup>, Stijn De Schepper<sup>2</sup>, Matthew J.  
4 Pound<sup>1</sup>, Alan M. Haywood<sup>3</sup>, Aisling M. Dolan<sup>3</sup>, Daniel J. Lunt<sup>4</sup>

5 <sup>1</sup>Department of Geography and Environmental Sciences, Faculty of Engineering and  
6 Environment, Northumbria University, Newcastle upon Tyne NE1 8ST, UK,  
7 ulrich.salzmann@northumbria.ac.uk, matthew.pound@northumbria.ac.uk

8 <sup>2</sup>Uni Research Climate, Bjerknes Centre for Climate Research, Jahnebakken 5, 5007 Bergen,  
9 Norway, bjorg.risebrobakken@uni.no, stijn.deschepper@uni.no

10 <sup>3</sup>School of Earth and Environment, University of Leeds, Woodhouse Lane, Leeds LS2 9JT,  
11 UK, A.M.Haywood@leeds.ac.uk, A.M.Dolan@leeds.ac.uk

12 <sup>4</sup>School of Geographical Sciences, University of Bristol, University Road, Bristol BS8 1SS,  
13 UK, D.J.Lunt@bristol.ac.uk

14 **Corresponding author:** Sina Panitz (E-mail: sina.panitz@gmail.com)

15 **Abstract**

16 During the Pliocene Epoch, a stronger-than-present overturning circulation has been invoked  
17 to explain the enhanced warming in the Nordic Seas region in comparison to low to mid-  
18 latitude regions. While marine records are indicative of changes in the northward heat  
19 transport via the North Atlantic Current (NAC) during the Pliocene, the long-term terrestrial  
20 climate evolution and its driving mechanisms are poorly understood. We present the first  
21 two-million-year-long Pliocene pollen record for the Nordic Seas region from Ocean Drilling  
22 Program (ODP) Hole 642B, reflecting vegetation and climate in Arctic Norway, to assess the

23 influence of oceanographic and atmospheric controls on Pliocene climate evolution. The  
24 vegetation record reveals a long-term cooling trend in northern Norway, which might be  
25 linked to a general decline in atmospheric CO<sub>2</sub> concentrations over the studied interval, and  
26 climate oscillations primarily controlled by precession (23 kyr), obliquity (54 kyr) and  
27 eccentricity (100 kyr) forcing. In addition, the record identifies four major shifts in Pliocene  
28 vegetation and climate mainly controlled by changes in northward heat transport via the  
29 NAC. Cool temperate (warmer than present) conditions prevailed between 5.03–4.30 Ma,  
30 3.90–3.47 Ma and 3.29–3.16 Ma and boreal (similar to present) conditions predominated  
31 between 4.30–3.90 Ma, 3.47–3.29 and after 3.16 Ma. A distinct decline in sediment and  
32 pollen accumulation rates at c. 4.65 Ma is probably linked to changes in ocean currents,  
33 marine productivity and atmospheric circulation. Climate model simulations suggest that  
34 changes in the strength of the Atlantic Meridional Overturning Circulation during the Early  
35 Pliocene could have affected atmospheric circulation in the Nordic Seas region, which would  
36 have affected the direction of pollen transport from Scandinavia to ODP Hole 642B.

37 Keywords: pollen, vegetation, Pliocene, North Atlantic Current, Central American Seaway

## 38 **1. Introduction**

39 During the Pliocene Epoch (5.33–2.59 Ma), global mean annual temperatures were 2–3°C  
40 warmer than present (Haywood et al., 2013). Due to positive feedback mechanisms in the  
41 Arctic, warming was particularly pronounced at high latitudes (Dowsett et al., 2013). On the  
42 land masses surrounding the Nordic Seas, cool temperate and boreal forests reached further  
43 north during the Pliocene into regions that are presently covered by subarctic boreal forests  
44 and Arctic tundra (Bennike et al., 2002; Panitz et al., 2016; Verhoeven et al., 2013; Willard,  
45 1994). The enhanced warming in the Nordic Seas region has been ascribed to a stronger than  
46 present Atlantic Meridional Overturning Circulation (AMOC) and thus North Atlantic

47 Current (NAC) (Haug et al., 2001; Raymo et al., 1996, 1992). However, an increase in the  
48 strength of the AMOC during the Pliocene is not simulated by all climate models (Zhang et  
49 al., 2013). In both marine and terrestrial climate model simulations for the Pliocene,  
50 temperatures are underestimated at high latitudes and remain below temperatures based on  
51 data reconstructions (Dowsett et al., 2013; Salzmann et al., 2013). Palaeogeographic  
52 differences have been suggested to account for the data-model mismatch. Simulations with an  
53 altered palaeogeography (North Atlantic and Baltic river input, lowered Greenland-Scotland  
54 Ridge and exposed Barents Sea) show a strong high latitude warming and weaker AMOC  
55 (Hill, 2015). Closing the Bering Strait and the Canadian Arctic Archipelago has been shown  
56 to increase warming at high latitudes and to strengthen the AMOC (Otto-Bliesner et al.,  
57 2017). Model experiments to assess Pliocene terrestrial temperature change indicate that high  
58 insolation, increased CO<sub>2</sub> concentrations and a closed Arctic gateway enhance high-latitude  
59 warming (Feng et al., 2017). However, the low resolution and poor age control of most  
60 terrestrial records limit the quantification of data-model mismatch at high latitudes (Feng et  
61 al., 2017).

62 Heat is transported to the Arctic Ocean via the Norwegian Atlantic Current (NwAC), the  
63 continuation of the NAC in the eastern Nordic Seas. Pliocene marine records of sea surface  
64 temperature (SST) and palaeoceanographic changes in the North Atlantic and Nordic Seas  
65 indicate repeated variations in the northward heat transport via the NAC (Bachem et al.,  
66 2017; De Schepper et al., 2013; Lawrence et al., 2009; Naafs et al., 2010; Risebrobakken et  
67 al., 2016). The development of a modern-like surface ocean circulation in the Nordic Seas  
68 around 4.5 Ma has been linked to the establishment of a northward flow through the Bering  
69 Strait and a shoaling of the Central American Seaway (CAS) (De Schepper et al., 2015). In  
70 Ocean Drilling Program (ODP) Hole 642B increased abundances of the dinoflagellate species  
71 *Protoceratium reticulatum* after 4.2 Ma suggest increased Atlantic water influence at the site

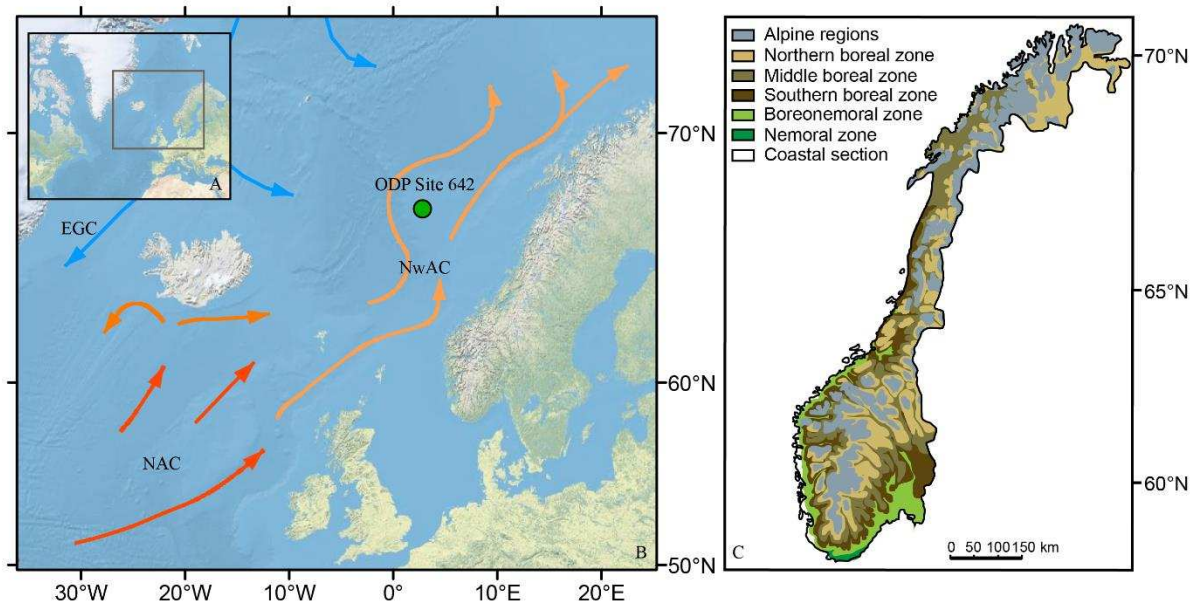
72 and the establishment of a modern-like NwAC (De Schepper et al., 2015). Alkenone-derived  
73 SSTs in Hole 642B show a pronounced cooling at 4.3 Ma, with temperature decreasing by  
74  $\sim 5^{\circ}\text{C}$  to values fluctuating around the Holocene average, which might be linked to a  
75 strengthening of the East Greenland Current (EGC) and reduced amplitude of obliquity  
76 forcing (Bachem et al., 2017). Carbon isotope changes in Hole 642B are indicative of a well-  
77 ventilated Norwegian Sea comparable to the present situation (Risebrobakken et al., 2016).  
78 Increasing surface water densities have been inferred at the same site which may be the result  
79 of increased Atlantic water influence already from 4.6 Ma (Risebrobakken et al., 2016). Early  
80 Pliocene oceanographic changes in the Caribbean indicate that the shoaling of the CAS  
81 between 4.8 and 4.0 Ma is associated with a strengthening of the AMOC (Groeneveld et al.,  
82 2008; Haug et al., 2001; Osborne et al., 2014; Steph et al., 2010). However, benthic carbon  
83 and oxygen isotope records from the Atlantic suggest that deep water circulation remained  
84 unaffected by the shoaling of the CAS (Bell et al., 2015). Neogene palaeofloras from North  
85 America and Western Eurasia indicate that the difference in the thermal gradients between  
86 these two continents developed between the late Miocene and late Pliocene, possibly in  
87 response to the intensification of the AMOC after the shoaling of the CAS during the early  
88 Pliocene (Utescher et al., 2017). A pronounced warming in the Norwegian Sea took place  
89 around 4.0 Ma in response to a strengthened northward heat transport potentially due to the  
90 CAS shoaling or a deepening of the Greenland-Scotland Ridge (Bachem et al., 2017). The  
91 presence of a warmer NwAC is supported by a corresponding depletion of planktic  $\delta^{18}\text{O}$  in  
92 Hole 642B (Risebrobakken et al., 2016). Contemporaneous cooling in the Iceland Sea  
93 resulted in the establishment of a strong zonal gradient and strengthened surface circulation  
94 in the Nordic Seas (Bachem et al., 2017; Herbert et al., 2016). The presence of warm surface  
95 waters in the Norwegian Sea might have contributed, in addition to regional tectonic uplift, to  
96 the development of seasonal sea ice in the Eurasian sector of the Arctic Ocean around 4 Ma

97 (Knies et al., 2014) by enhancing evaporation and precipitation, and thus Arctic freshwater  
98 supply (Bachem et al., 2017). The impact of these palaeoceanographic changes on the  
99 terrestrial climate evolution in northern Norway and potential links to the shoaling of the  
100 CAS are unknown.

101 For the Late Pliocene (Piacenzian, 3.60–2.58 Ma), SST reconstructions show a variable  
102 pattern in the magnitude of warming, with the largest anomalies being recorded in the Iceland  
103 and Greenland Seas (Dowsett et al., 2013; Knies et al., 2014; Schreck et al., 2013) and the  
104 lowest in the Norwegian Sea (Bachem et al., 2017, 2016). Decreasing SSTs in the Norwegian  
105 Sea between 3.65 and 3.30 Ma are suggested to be the result of a reduced influence of the  
106 NAC on the NwAC (Bachem et al., 2017). A new multi-proxy study shows that during the  
107 Piacenzian vegetation and climate changes in northern Norway coincide with variations in  
108 Atlantic water influence and SST changes in the Norwegian Sea (Panitz et al., 2017).

109 Whereas most Pliocene terrestrial records show warmer-than-present climatic conditions, the  
110 reconstruction of terrestrial climate evolution and variability before the onset of extensive  
111 Pleistocene Northern Hemisphere Glaciation (NHG) has, however, been hampered by the  
112 short temporal coverage of existing records in the Nordic Seas region (Bennike et al., 2002;  
113 Verhoeven et al., 2013; Willard, 1994). Here, we investigate the relation between Pliocene  
114 oceanographic changes in the North Atlantic and Nordic Seas and terrestrial climate changes  
115 in northern Norway over a two-million-year long time period.

116 This study presents a Pliocene (5.03–3.14 Ma) high-resolution pollen record for the Nordic  
117 Seas region, reflecting vegetation changes in northern Norway. The new Early Pliocene  
118 pollen record from ODP Hole 642B is combined with the previously published Late Pliocene  
119 pollen record from the same site (Panitz et al., 2016) and compared to SST and water mass  
120 changes in the Norwegian Sea (Bachem et al., 2017; De Schepper et al., 2015; Risebrobakken  
121 et al., 2016). Climate model output is presented to assess potential changes in pollen transport



**Figure 1:** Location of (A) the study area in the North Atlantic and (B) ODP Hole 642B in the Norwegian Sea. (C) Modern vegetation of Norway modified after Moen (1987). In (B), colour coding of currents indicates the relative temperature: dark orange = warm; light orange = moderately warm; blue = cold. EGC = East Greenland Current, NAC = North Atlantic Current and NwAC = Norwegian Atlantic Current.

122 to the site by wind in response to changes in AMOC strength due to the shoaling of the CAS.  
 123 The aim of this study is to assess (1) the long-term controls on vegetation and climate  
 124 changes in northern Norway, (2) the response of vegetation changes to the variability of the  
 125 NAC, and (3) the potential effects of early Pliocene oceanographic changes on pollen  
 126 transport to the site.

## 127 **2. Oceanographic setting and modern vegetation of Norway**

128 ODP Hole 642B was recovered during Leg 104 and is situated about 400–450 km off the  
 129 coast of Norway on the outer Vøring Plateau in the Norwegian Sea (67°13.2'N, 2°55.8'E,  
 130 1286 m water depth, Shipboard Scientific Party (1987); Figure 1). A branch of the NwAC,  
 131 which is an extension of the warm NAC, flows northward on either side of the plateau (Orvik  
 132 and Niiler, 2002). At present, the influence of these warm waters results in relatively mild  
 133 climatic conditions in Scandinavia (Furevik, 2000). Boreal forest extends over most of

134 Norway with pure deciduous forests only found along the south coast. The proportion of  
135 deciduous and thermophilic elements decreases with increasing latitude, and altitude of the  
136 Scandinavian mountains (Moen, 1987). In southern Scandinavia, the altitudinal limit of the  
137 tree line is reached at ~1200 m above sea level, with alpine tundra predominating beyond the  
138 tree limit (Moen, 1999). The tree line steadily declines with increasing latitude until tundra  
139 prevails at sea level in northernmost Norway (Moen, 1999, 1987). Based on the analysis of  
140 two (sub)surface samples from Hole 642B, the pollen signal has been shown to be  
141 representative of the prevailing vegetation in northern Norway (Panitz et al., 2016). The  
142 predominance of wind-pollinated taxa in the (sub)surface and Pliocene samples suggests that  
143 pollen is mainly transported to the site by wind. While plumes of cold fjord water enter the  
144 Norwegian Sea during spring at present and extend up to 100 km offshore (Mork, 1981), such  
145 plumes most likely did not develop during the Pliocene due to the absence of fjords and a  
146 reduced ice cover. There is no evidence of the existence of large rivers during the Pliocene,  
147 with modest sedimentation along the Norwegian continental margin during the Middle  
148 Eocene to Pliocene. Sedimentation rates increased greatly with the onset of NHG around  
149 2.6 Ma (Eidvin et al., 2000; Faleide et al., 2008).

### 150 **3. Materials and Methods**

#### 151 **3.1. Age model**

152 The age model for the Pliocene section of ODP Hole 642B is based on the updated magnetic  
153 stratigraphy of Bleil (1989) to the ATNTS2012 time scale (Hilgen et al., 2012) and  
154 correlation of the benthic  $\delta^{18}\text{O}$  curve from Hole 642B to the global LR04 benthic  $\delta^{18}\text{O}$  stack  
155 between 4.147 and 3.14 Ma (Lisiecki and Raymo, 2005; Risebrobakken et al., 2016). A major  
156 hiatus exists in the Late Pliocene section of the record after 3.14 Ma (Bleil, 1989;  
157 Risebrobakken et al., 2016). The tie points for the age model (Supplementary Table 1) are



158 shown alongside the sedimentation rate in Figure 3 (Risebrobakken et al., 2016), with  
159 changes in sedimentation rate reflecting the position of the tie points.

### 160 **3.2. Sample preparation and pollen analysis**

161 A total of 128 samples were selected for pollen analysis between 83.55 and 66.95 metres  
162 below sea floor (mbsf) from ODP Hole 642B, ranging in age from 5.03 to 3.14 Ma  
163 (Risebrobakken et al., 2016). The samples were pre-sieved in Bergen, Norway through a  
164 63 µm mesh to retain foraminifera for oxygen isotope analysis (Risebrobakken et al., 2016).  
165 A potential bias in the pollen data due to the loss of larger Pinaceae grains has been excluded  
166 by comparison of sieved and unsieved samples (Panitz et al., 2016). Sample preparation was  
167 carried out at the Palynological Laboratory Services Ltd, North Wales and Northumbria  
168 University, Newcastle, using standard palynological techniques (Faegri and Iversen, 1989). In  
169 order to calculate pollen concentrations, one *Lycopodium clavatum* spore tablet was added to  
170 each sample (Stockmarr, 1971). The treatment with cold HCl (20%) was followed by the use  
171 of cold, concentrated HF (48%) to remove carbonates and silicates, respectively. An  
172 additional wash with hot (c. 80°C) HCl (20%) was conducted to remove fluorosilicates. After  
173 back-sieving the sediment through a 10 µm screen, the residue was mounted on glass slides  
174 using glycerol-gelatine jelly. Pollen analysis was carried out using a Leica Microscope (DM  
175 2000 LED) at magnifications of 400x and 1000x. The identification of pollen and spores was  
176 aided by the pollen reference collection at Northumbria University and the use of literature  
177 (e.g. Beug, 2004). Reworked pollen and spores were differentiated from in situ grains based  
178 on the thermal maturity of the exine, with reworked grains having orange to brown colours,  
179 and/or their presence outside their stratigraphic range. Particularly reworked gymnosperm  
180 pollen showed a high degree of compression, a faint alveolar structure of the saccae and  
181 mineral imprints (de Vernal and Mudie, 1989a, 1989b; Willard, 1996). In situ *Lycopodium*  
182 *clavatum* spores differed in colour from the marker spores.

183 For the majority of samples more than 300 pollen and spore grains were counted. Only 20  
 184 samples yielded a total count of less than 300 grains. Percentages of pollen and spores were  
 185 calculated based on the pollen sum, excluding *Pinus* pollen as well as unidentified and  
 186 reworked pollen and spores. The pollen sum excluding *Pinus* pollen regularly exceeds 170  
 187 pollen and spores (for further detail see Supplementary Material). The software Tilia was  
 188 used to generate pollen diagrams and perform stratigraphically constrained cluster analysis  
 189 for the delimitation of pollen zones (Grimm, 1990, 1987). Pollen accumulation rates (PARs)  
 190 were calculated based on the following formula:

191 (1) 
$$PAR = C \times \rho \times S$$

192 with PAR in grains/(cm<sup>2</sup> kyr), C being the pollen concentration (grains/g dry weight),  $\rho$  the  
 193 dry bulk density (g/cm<sup>3</sup>) and S the sedimentation rate (cm/kyr). PARs have been calculated to  
 194 compensate for fluctuations in the sedimentation rate that can affect pollen concentrations  
 195 (Traverse, 1988). Pollen and spore taxa have been bioclimatically grouped following the  
 196 modern distribution of their nearest living relatives (Table 1).

197 Table 1: Pollen and spore taxa from ODP Hole 642B attributed to the bioclimatic zones  
 198 plotted in Figure 6.

<b>Bioclimate groups</b>	<b>Attributed pollen and spore taxa</b>
<b>Cool temperate forests</b>	<i>Carpinus</i> , <i>Carya</i> , <i>Corylus</i> , <i>Ilex</i> , <i>Ostrya</i> , <i>Pterocarya</i> , <i>Quercus</i> , <i>Sciadopitys</i> , <i>Taxus</i> , <i>Tsuga</i> , <i>Ulmus</i>
<b>Boreal forests</b>	<i>Abies</i> , <i>Alnus</i> , <i>Betula</i> , <i>Cupressaceae</i> , <i>Juniperus</i> , <i>Picea</i>
<b>Boreal and alpine peatlands and heathlands</b>	<i>Asteraceae</i> , <i>Ericaceae</i> , <i>Lycopodium</i> spp., <i>Sphagnum</i>

### 199 **3.3. Time series analysis**

200 In order to detect cyclicity within the vegetation changes, a continuous wavelet transform was  
201 carried out using a Morlet wavelet (Torrence and Compo, 1998). Due to the low pollen  
202 counts between 4.56 and 4.37 Ma, we only analysed the time interval from 4.37 to 3.14 Ma.  
203 For wavelet analysis, the unevenly spaced data was interpolated on 1000-year time steps prior  
204 to analysis in PAST3. In order to test whether peaks in the spectrum are significant against  
205 the red-noise background, we applied REDFIT (Schulz and Mudelsee, 2002). The analyses  
206 were performed on the relative abundance of Pinus pollen which dominates throughout the  
207 record.

### 208 **3.4. Climate model description**

209 Climate model output from the Hadley Centre coupled atmosphere-ocean climate model  
210 (HadCM3, Gordon et al., 2000) has been used to assess potential changes in pollen transport  
211 by wind to ODP Hole 642B in response to changes in AMOC strength, following the  
212 shoaling of the CAS. Previous studies have shown that closing the CAS is an effective means  
213 of increasing AMOC strength in a coupled atmosphere-ocean climate model (Lunt et al.,  
214 2008a, 2008b). HadCM3 has been shown to reproduce the large scale features of Pliocene  
215 climate (Haywood et al., 2013). It has been used for a number of Pliocene climate modelling  
216 studies and was the first coupled atmosphere-ocean climate model (Haywood and Valdes,  
217 2004) to run using boundary conditions defined by the PRISM project based at the US  
218 Geological Survey.

219 The simulations shown here have used PRISM2 boundary conditions (following Dowsett et  
220 al., 1999). In one experiment the CAS is specified as open (hereafter referred to as OCAS)  
221 and the other the CAS is closed (hereafter referred to as CCAS; simulations are comparable  
222 to those presented in (Lunt et al., 2008b). These changes were made to assess the potential  
223 variability in AMOC strength on regional atmospheric circulation and pollen transport from

224 Scandinavia to ODP Hole 642B. We focus on the model output surface wind speeds and  
225 atmospheric pressure during spring (March, April, May) as most plants disperse pollen during  
226 that season.

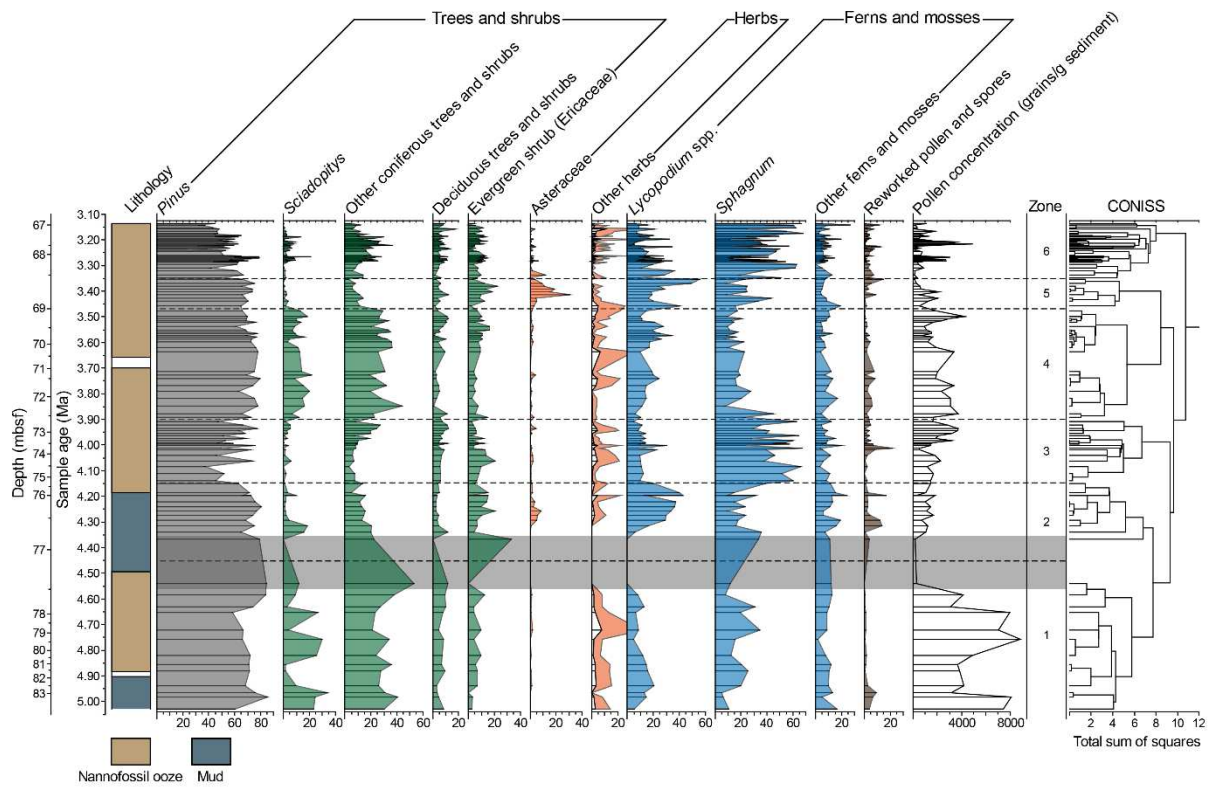
## 227 **4. Results**

### 228 **4.1. Pliocene pollen assemblages and vegetation reconstruction**

229 The Pliocene pollen record of ODP Hole 642B is divided into six pollen zones (Figure 2).  
230 The complete pollen record is provided in Supplementary Material Figure 1.

#### 231 **Pollen Zone 1**

232 The lowermost pollen zone (PZ 1, 83.55–77.38 mbsf, 5.03–4.51 Ma, 15 samples, two  
233 samples at the top of the zone were excluded from relative abundance calculations shown in  
234 Figure 2 due to low counts) is characterised by high abundances of *Pinus* pollen and other  
235 boreal to temperate coniferous tree and shrub taxa (*Abies*, Cupressaceae, *Juniperus* type,  
236 *Picea*, *Sciadopitys*, *Taxus* and *Tsuga*). Together with the occurrence of temperate deciduous  
237 taxa (*Carpinus*, *Carya*, *Pterocarya* and *Quercus*), PZ 1 is indicative of the presence of  
238 diverse cool temperate mixed forests in northern Norway (Figure 2). Fluctuations in the  
239 proportions of the temperate taxon *Sciadopitys* suggest that the interval was interrupted by  
240 cooler intervals that were more boreal in character. Notable are the very high pollen  
241 concentrations throughout PZ1 that decrease markedly at the top of the zone (Figure 2). The  
242 environmental interpretation of the pollen assemblages at the transition from PZ 1 to PZ 2 is  
243 hampered due to low pollen counts. The presence of mainly boreal tree and shrub taxa  
244 (*Alnus*, *Betula*, Ericaceae, *Fraxinus*, *Juniperus* type and *Pinus*) and mosses (*Huperzia* and  
245 *Sphagnum*) may be an indication of the prevalence of boreal forests and tundra environments.



246

**Figure 2:** Abundances of pollen and spores and taxa groups in the Pliocene sediments of ODP Hole 642B. Coloured area for abundances of “other herbs” represents a 5-fold exaggeration of percentages (white area). Percentages of pollen and spores were calculated based on the pollen sum, excluding Pinus, unidentified and reworked pollen and spores. Only for the calculation of Pinus percentages were the counts of Pinus pollen included in the pollen sum. Depth is indicated in metres below sea floor (mbsf). Grey horizontal bar delimits samples with low pollen counts (<100). Samples with a total count of less than 40 grains are not shown. The lithology of the Pliocene section of Hole 642B was obtained from the original report (Shipboard Scientific Party, 1987).

247 The thermophilic but cold-tolerant taxon *Tsuga* is also present, presumably growing at  
 248 favourable sites (see Supplementary Material).

249 **Pollen Zone 2**

250 In the middle part of pollen zone 2 (PZ 2, 76.60–75.29 mbsf, 4.30–4.15 Ma, 14 samples, two  
 251 samples at the base of the zone were excluded from relative abundance calculations shown in  
 252 Figure 2 due to low counts) the predominance of cool temperate forests is inferred from the  
 253 relative high abundance of *Sciadopitys* pollen. The subsequent decrease in the percentages of

254 Sciadopitys pollen and increase in the relative proportion of Asteraceae and Ericaceae pollen  
255 as well as Lycopodium spores (incl. Lycopodium annotinum, Lycopodium clavatum,  
256 Lycopodium inundatum and Lycopodium spp.; Figure 2) is interpreted to reflect a southward  
257 shift of cool temperate mixed forests and an opening of the vegetation at higher altitudes due  
258 to a lowering of the treeline, leading to the development of alpine herb fields/heathlands  
259 under a boreal climate.

### 260 **Pollen Zone 3**

261 At the beginning of pollen zone 3 (PZ 3, 75.29–72.60 mbsf, 4.15–3.90 Ma, 19 samples), the  
262 relative abundance of Pinus pollen declines slightly whereas that of Sphagnum spores  
263 markedly increases. In conjunction with low proportions of other coniferous trees and shrubs  
264 taxa, these pollen assemblage changes suggest that boreal forest prevailed and peatlands  
265 expanded due to further cooling and/or wetter conditions (Figure 2).

### 266 **Pollen Zone 4**

267 In pollen zone 4 (PZ 4, 72.60–69.02 mbsf, 3.90–3.47 Ma, 25 samples), pollen of Pinus and  
268 other coniferous trees and shrubs predominate the assemblages, suggesting a re-establishment  
269 of cool temperate climatic conditions in northern Norway (Figure 2).

### 270 **Pollen Zone 5**

271 After this prolonged warm interval, the proportions of Asteraceae and Ericaceae pollen and  
272 Lycopodium spores increase in pollen zone 5 (PZ 5, 69.02–68.54 mbsf, 3.47–3.35 Ma, 9  
273 samples, Figure 2), indicating an expansion of herb fields/heathlands at higher altitudes in  
274 response to the establishment of cooler climatic conditions and an associated lowering of the  
275 tree line. Together with the predominance of Pinus pollen and low abundances of other

276 coniferous trees and shrubs, this suggests that boreal forests and alpine herb fields/heathlands  
277 prevailed in northern Norway under subarctic climatic conditions.

## 278 **Pollen Zone 6**

279 In the uppermost pollen zone (PZ 6, 68.54–66.95 mbsf, 3.35–3.14 Ma, 46 samples) the  
280 overall decline in the relative abundance of *Pinus* pollen and increasing proportion of  
281 *Sphagnum* spores is interpreted to represent the expansion of peatlands at the expense of  
282 forests (Figure 2). Abundance peaks in the temperate taxon *Sciadopitys* point to reoccurring  
283 warmer, and thus highly variable, climatic conditions (Panitz et al., 2016). Throughout PZ 2  
284 to 6, pollen concentrations are relatively low in comparison to those within PZ 1 (Figure 2).

## 285 **4.2. Climate model results**

286 During Northern Hemisphere (NH) spring (March, April, May), model results for both  
287 experiments indicate a predominantly westerly to southwesterly wind between 45°N and  
288 ~65–70°N (Figure 4). Between ~65–70°N and 75°N the airflow is predominantly easterly in  
289 the Nordic Seas. Whilst the dominant direction of flow south of ~65–70°N is predominantly  
290 westerly to southwesterly, over the Scandinavian land mass the details of circulation are more  
291 complex. In particular, we highlight in Figure 4 the region in central and northern  
292 Scandinavia where there is a tendency for easterly flow. The tendency for easterly flow over  
293 central and northern Scandinavia is enhanced in the OCAS scenario (Figure 4).

294 In the CCAS scenario, AMOC is increased relative to the OCAS scenario, with a  
295 corresponding enhancement in ocean heat transport in the NH (see Lunt et al., 2008b). This in  
296 turn alters the regional temperature and atmospheric pressure gradients over Northern Europe  
297 and the Nordic Seas (Figure 4; Lunt et al., 2008b). The result of which is to encourage  
298 stronger westerly and southwesterly flow (Figure 4), creating a corresponding suppression of  
299 easterly flow from central and northern Scandinavia into the Nordic Seas in the CCAS

300 scenario (Figure 4). These results are most clearly expressed by surface wind and pressure  
301 patterns (Figure 4), however we have examined the nature of circulation and pressure at  
302 higher altitudes (not shown) in the atmosphere and in each case find the potential for easterly  
303 flow from Scandinavia is enhanced in the weaker AMOC scenario (OCAS).

## 304 **5. Discussion**

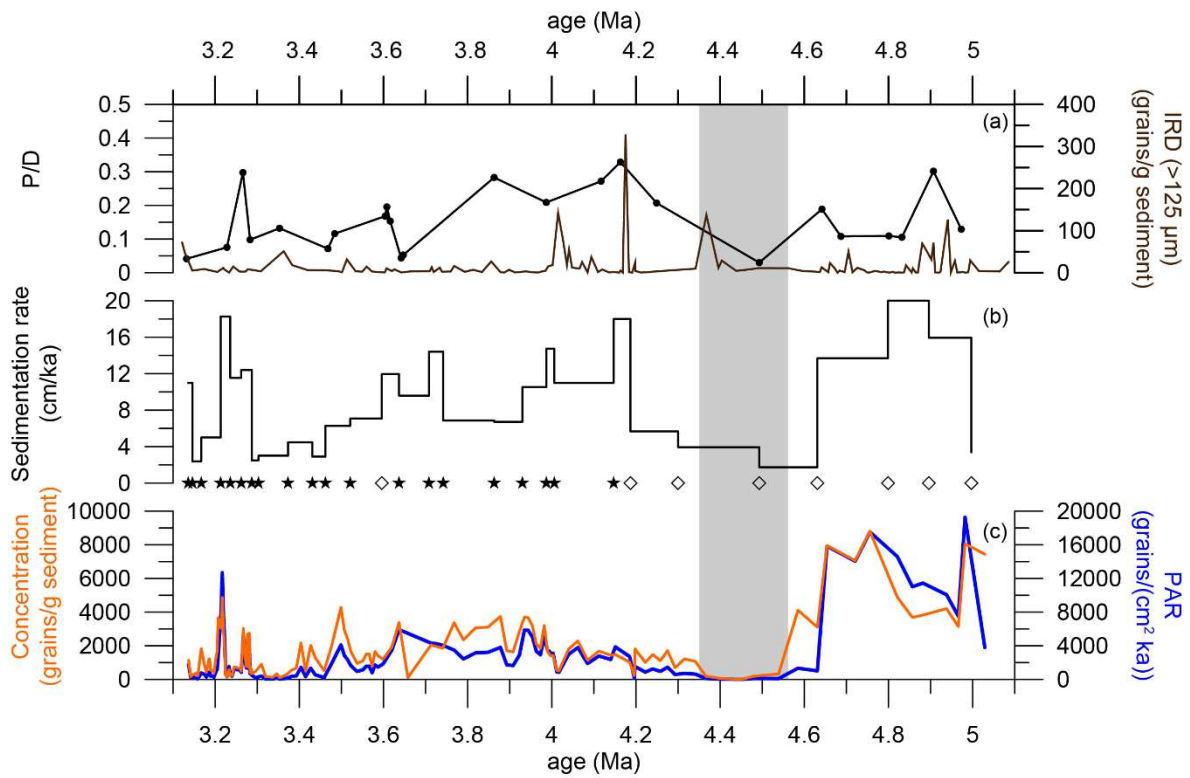
### 305 **5.1. Pollen Accumulation Rates indicate changes in ocean and atmospheric** 306 **circulation at c. 4.6 Ma**

307 A distinct decline in sedimentation rate, pollen concentration and PAR at c. 4.65 Ma (Figure  
308 2 and 3) suggests that changes in atmospheric circulation, ocean currents and/or taphonomic  
309 processes may have affected the transport, deposition and/or preservation of pollen (e.g.  
310 Dupont, 2011). The strong correlation between PARs, which takes fluctuations in  
311 sedimentation rates into account, and sedimentation rates in our record suggests potential  
312 changes in the sedimentary regime or source area. We can confidently discard any major  
313 influence of fluvial sediment transport from the Scandinavian mainland during the Pliocene.  
314 During the Oligocene to Pliocene, the inner Norwegian Sea continental shelf was the main  
315 depocentre for sediments from western Scandinavia. Hemipelagic sediments were deposited  
316 on the shelf and pelagic ooze on the slope and rise (Eidvin et al., 2014). West of the  
317 continental shelf, pelagic sedimentation (biogenic ooze) accumulated during the Oligocene to  
318 Pliocene (Eidvin et al., 2014). ODP Hole 642B is located ~450 km off the Norwegian coast at  
319 a water depth of ~1300 meter below sea level on the Vøring plateau, which was unaffected  
320 by sediment supply from Scandinavia. The Hole 642B pollen record also shows a low  
321 pollen/dinocyst (P/D) ratio (Figure 3) and a dominance of long-distance, wind-pollinated taxa  
322 (such as *Pinus*, Figure 2), both indicating a very low influence of sea level and sediment  
323 accumulation changes, if compared to Quaternary glacials and interglacials (McCarthy et al.,



2003; McCarthy and Mudie, 1998). The pollen record does not show any change in the proportions of reworked pollen grains or a shift in vegetation composition at 4.65 Ma (Figure 2), indicating that preservation issues or changes in pollen production on the mainland are an unlikely cause for the decline in PAR.

At Hole 642B, stable carbon isotope values indicate an increase in bottom water ventilation between 4.65 and 4.40 Ma, reaching values closer to the Holocene mean (Risebrobakken et al., 2016). A decline in dinocyst and acritarch accumulation rates suggests a contemporaneous reduction in primary productivity (De Schepper et al., 2015), which might have affected the sinking of pollen grains to the sea floor (Dupont, 2011). These oceanographic changes broadly coincide with the deep subsidence of the Hovgård Ridge in the Fram Strait and the shoaling of CAS, with the latter resulting in an increased AMOC (Haug et al., 2001; Risebrobakken et al., 2016; Steph et al., 2010). The Neogene AMOC and its varying intensity prior to the closure of CAS during the Early Pliocene is a matter of debate. Modelling results indicate that both oceanographic circulation and associated heat transport were considerably reduced with an open CAS when compared to present-day conditions (e.g. Lunt et al., 2008b), whereas palaeobotanical evidence suggests a Pliocene steepening of the shallow thermal latitudinal gradients that existed in North America and Western Eurasia throughout the Miocene (Utescher et al., 2017). These changes might have also influenced the predominant mode of pollen transport which largely depends on the regional climate and the distance of the site from the source area (Mudie and McCarthy, 2006). Today, the main atmospheric circulation pattern in the North Atlantic region is determined by the difference in pressure between the subtropical Azores high and the subpolar Icelandic low (Furevik, 2000). During the early Zanclean, atmospheric circulation changes in the Nordic Seas region might have occurred in response to the shoaling of the CAS and its effect on the AMOC (Haug et al., 2001; Steph et al., 2010).

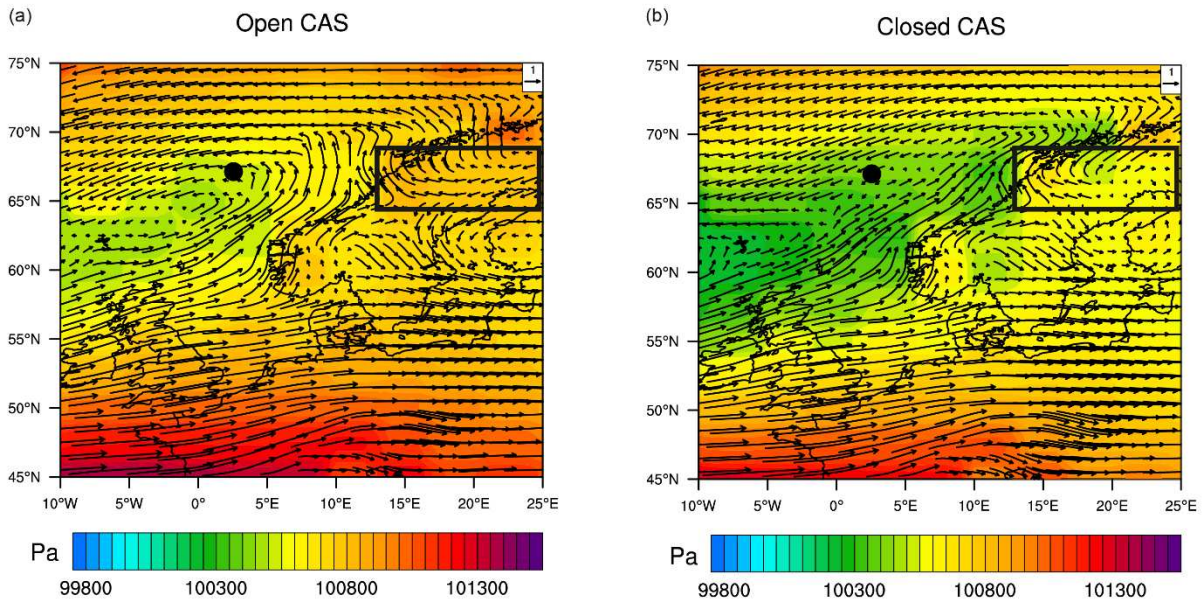


350

351 **Figure 3:** Sedimentological data from ODP Hole 642B. (a) pollen (P) and dinoflagellate cyst  
 352 (D) ratio (De Schepper et al., 2015) and ice rafted debris (IRD) (Jansen et al., 1990); (b)  
 353 sedimentation rate and age control points based on magnetic reversals (diamonds) and  
 354 correlation of the benthic  $\delta^{18}\text{O}$  values to the LR04 global benthic  $\delta^{18}\text{O}$  stack (stars)  
 355 (Risebrobakken et al., 2016); (c) pollen concentrations and pollen accumulation rates (PARs)  
 356 (this study). Grey horizontal bar delimits samples with low pollen counts (<100).

357

358



**Figure 4:** Model predictions for wind vectors (arrows,  $\text{m s}^{-1}$ ) and mean sea level pressure (Pa) in spring (March, April, May) in the Nordic Seas region with an (a) open and (b) closed Central American Seaway (CAS). Black circle marks the location of ODP Hole 642B in the Norwegian Sea ( $67^{\circ}\text{N}$ ,  $3^{\circ}\text{E}$ ). Black box shows an area in central/northern Scandinavia where the wind strength and direction changes significantly between the two simulations and is referred to within the main text.

359 To test the hypothesis of AMOC related atmospheric circulation changes affecting pollen  
 360 transport to Hole 642B (potentially, but not uniquely, associated with a shoaling of the CAS),  
 361 mean surface wind velocities during spring were compared from experiments with an OCAS  
 362 and CCAS (Figure 4). In both experiments the predominant atmospheric flow in the Nordic  
 363 Seas is westerly and south-westerly. However, the pattern of atmospheric circulation over the  
 364 Scandinavian land mass is more complex. Of particular note, is the easterly flow moving out  
 365 into the Nordic Seas over central and northern Scandinavia. This easterly flow is suppressed  
 366 in the CCAS scenario, therefore we suggest that the potential for pollen transport from  
 367 Scandinavia to Hole 642B is enhanced under weaker AMOC scenarios during the Pliocene  
 368 (e.g. OCAS).

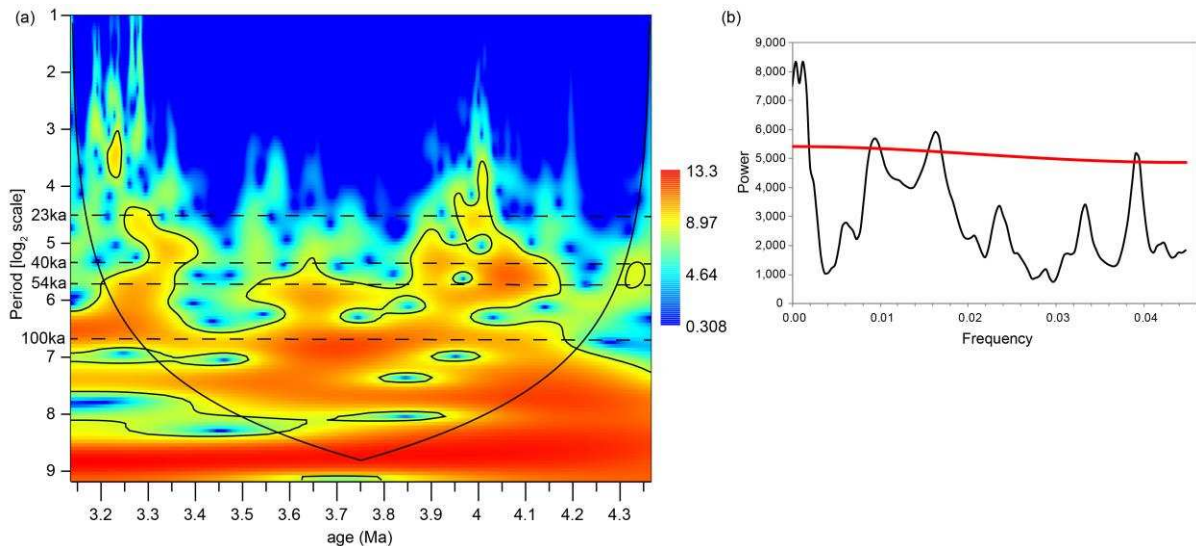
369 Whilst the timing of CAS closure is widely debated, our HadCM3 simulations suggest that a  
 370 closing of the CAS could impact wind-fields over Norway (associated with an increase in the  
 371 AMOC with a closing CAS). Therefore, this provides a potential explanation for part of the

372 decrease in PAR after 4.65 Ma, as this lies within the uncertainty related to the timing of  
373 CAS closure (Haug et al., 2001; Steph et al., 2010). However, we also acknowledge that there  
374 are other potential mechanisms (e.g. palaeogeographic changes in the Arctic; Otto-Bliesner et  
375 al., 2017) that could cause a change in Pliocene AMOC and are not associated with the  
376 closure of CAS, which could therefore affect pollen deposition at Hole 642B.

## 377 **5.2. Long-term cooling and climatic cyclicity**

378 The Pliocene pollen record from Hole 642B reveals four major changes in vegetation and  
379 climate in northern Norway, with cooler, boreal conditions developing at 4.30 Ma and 3.47  
380 Ma and warmer, cool temperate conditions at 3.90 Ma and 3.29 Ma (Figure 2). These  
381 changes are indicative of repeated latitudinal shifts of the northern boundary of the deciduous  
382 forest zone. Possible controls on the long-term vegetation changes in northern Norway  
383 include declining atmospheric CO<sub>2</sub> concentrations and astronomical forcing.

384 Over the almost two-million-year-long record, the relative abundance of the thermophilic  
385 taxon *Sciadopitys* shows a continuous decline during subsequent warm intervals (Figure 2).  
386 At present, *Sciadopitys* is endemic to Japan where it thrives on well-drained slopes in a  
387 temperate and wet climate (Ishikawa and Watanabe, 1986). During the Neogene, *Sciadopitys*  
388 was a common element in the temperate forests of the Northern Hemisphere, forming part of  
389 many different plant communities that inhabited diverse environments from lowland swamps  
390 to high-altitude forests (e.g. Figueiral et al., 1999). In northern Norway, the decline of this  
391 species throughout the Pliocene may be indicative of a progressive cooling of climate that is  
392 also evident in other Pliocene terrestrial and marine records (e.g. Lawrence et al., 2009; Naafs  
393 et al., 2010; Verhoeven et al., 2013). Decreasing atmospheric CO<sub>2</sub> concentrations have been



394

**Figure 5:** (a) Spectral analysis based on continuous wavelet transform of the relative abundance changes of *Pinus* pollen. Signal power is shown with a colour scale (red = higher). The black contour line indicates the significance level corresponding to  $p=0.05$ ; and (b) REDFIT power spectrum (black line) testing whether peaks in the spectrum are significant against the red-noise background (Schulz and Mudelsee, 2002). False-alarm confidence level (red line) has been set to 90%.

395 suggested to be the main driver for the long-term cooling throughout the Pliocene leading to  
 396 the onset of NHG (e.g. Lunt et al., 2008a; Martínez-Botí et al., 2015).

397 Continuous wavelet transform of *Pinus* pollen percentages reveals the influence of ~23-kyr  
 398 precession, ~40 and 54-kyr obliquity for some intervals and relatively strong ~100-kyr  
 399 eccentricity cycles (Figure 5). Low-frequency, large-amplitude changes linked to eccentricity  
 400 could also be identified in the stable oxygen and carbon isotope records from Hole 642B  
 401 (Risebrobakken et al., 2016). For the vegetation record, REDFIT identifies significance for  
 402 the 100-kyr eccentricity, 54-kyr obliquity and the 23-kyr precession cycles (Figure 5). A  
 403 dominance of precession cycles during the Pliocene has also been described from a  
 404 compilation of Mediterranean SSTs and marine biomarker accumulation (Herbert et al.,  
 405 2015). REDFIT could not identify significant 40-kyr obliquity cycles previously described  
 406 from other marine sites in the North Atlantic for the Early and Late Pliocene (Figure 5)

407 (Lawrence et al., 2009; Naafs et al., 2010). However, it should be noted that the spectral and  
408 power spectrum analysis of the Hole 642B pollen record is limited due to the unevenly  
409 distributed sampling interval, which likely explains why wavelet transform could identify  
410 obliquity and precession cycles in two, relatively densely sampled intervals only. While  
411 astronomical forcing appears to be present in the Pliocene vegetation changes in northern  
412 Norway, palaeogeographic and palaeoceanographic changes during the studied time interval  
413 seem to have had a stronger influence on the long-term climate evolution of Scandinavia.

### 414 **5.3. Pliocene vegetation change and North Atlantic current variability**

#### 415 **5.3.1. Zanclean (5.3–3.6 Ma)**

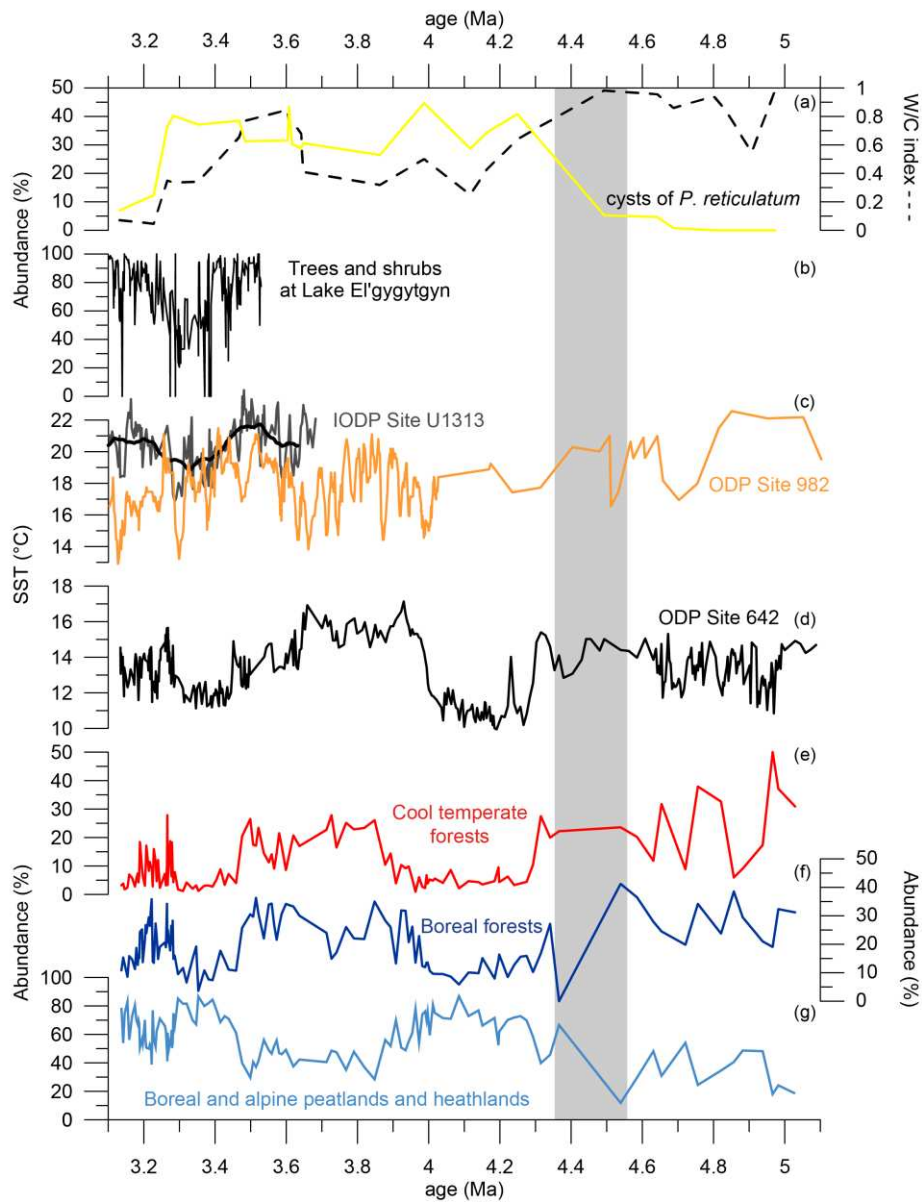
416 During the early Zanclean (5.03–4.51 Ma), cool temperate deciduous to mixed forests  
417 prevailed in northern Norway (Figure 2). Whether pure deciduous or mixed forests existed in  
418 the lowlands of the Scandinavian mountains is not clear from the pollen signal due to the low  
419 abundances of deciduous elements (see also Panitz et al., 2016). The latter is an artefact of  
420 the distance of the site from the shore which also results in the over-representation of *Pinus*  
421 pollen (e.g. Mudie and McCarthy, 2006). The presence of deciduous or mixed forests in  
422 northern Norway suggests a northward shift of the northern limit of these forest zones by 4–  
423 8° latitude, corresponding to an increase in average annual and July temperatures of at least  
424 2–4°C and 4°C, respectively (Moen, 1999). A similar magnitude of warming is observed in  
425 alkenone-derived SST estimates from Hole 642B, with SSTs up to ~3°C higher than the  
426 Holocene average between 5.0 and 4.64 Ma (Figure 6) (Bachem et al., 2017). The alkenone-  
427 derived SSTs are likely biased towards summer temperatures as the main growth period of  
428 modern alkenone producing organisms occurs during the summer at higher altitudes due to  
429 reduced incoming solar radiation during winter (Bachem et al., 2016 and references therein).  
430 At ODP Site 982, which is situated in the path of the NAC before it enters the Norwegian

431 Sea, SSTs were ~6–12°C higher than present between 5.1 and 4.5 Ma (Figure 6) (Herbert et  
432 al., 2016), indicating that warmer-than-present Atlantic water entered the Nordic Seas.

433 At c. 4.90–4.85 Ma, 4.72 Ma and 4.63 Ma, the establishment of boreal forests and the  
434 development of peatlands at higher altitudes due to a lowering of the treeline are indicative of  
435 cooler climatic conditions in northern Norway (Figure 2). Around 4.90–4.80 Ma, glacial  
436 expansions have been inferred from ice-rafted debris (IRD) deposits in the Nordic Seas  
437 (Fronval and Jansen, 1996; Jansen and Sjøholm, 1991; St. John and Krissek, 2002). In the  
438 Norwegian Sea, IRD deposits point to the presence of sea-terminating glaciers around the  
439 Nordic Seas at 4.9 Ma (Figure 3) (Bachem et al., 2017; Jansen et al., 1990). This cooling is  
440 also recorded in alkenone-derived SST estimates from Hole 642B (Figure 6) (Bachem et al.,  
441 2017). Dinocyst assemblages from Hole 642B reveal the influence of warm temperate  
442 Atlantic water in the Norwegian Sea during the early Zanclean, but show a cooling in the  
443 warm/cold index around 4.90 Ma (Figure 6) (De Schepper et al., 2015). At the same time,  
444 enriched planktic and benthic  $\delta^{18}\text{O}$  values suggest increased surface and bottom water  
445 densities due to lower water temperatures (Risebrobakken et al., 2016). The cooling is also  
446 evident in alkenone-based SSTs from ODP Site 907 in the Iceland Sea (De Schepper et al.,  
447 2015; Herbert et al., 2016). The prevalence of mixed and boreal forests in northern Norway  
448 around 4.90 Ma suggests that an extensive glaciation in Scandinavia is unlikely (Figure 2).  
449 However, variable climatic conditions in northern Norway between 5.03 and 4.51 Ma are in  
450 agreement with repeated cooling phases and related expansions of small-scale glaciations  
451 around the Nordic Seas (Fronval and Jansen, 1996).

452 At Hole 642B, very low PARs occur between 4.56 and 4.37 Ma (Figure 2; see section 5.1 for  
453 discussion). The pollen assemblage of the first sample above this interval is indicative of the  
454 presence of boreal forests and tundra environments in northern Norway. This interpretation  
455 should, however, be regarded with caution due to the low pollen counts. At 4.34 Ma, cool





456

457 **Figure 6:** Comparison of predominant vegetation and climate in northern Norway during the  
 458 Pliocene to other Pliocene marine and terrestrial proxy records in the Northern Hemisphere.  
 459 (a) relative abundance changes of the dinocyst cyst of *Protoceratium reticulatum* (yellow)  
 460 and the warm (W)/cold (C) water index (De Schepper et al., 2015); (b) relative abundance  
 461 changes of trees and shrubs at Lake El'gygytyn in NE Siberia (Andreev et al., 2014); (c)  
 462 alkenone-derived sea surface temperature (SST) estimates at ODP Site 982 (orange) (Herbert  
 463 et al., 2016; Lawrence et al., 2009) and IODP Site U1313 (grey) and the 100 kyr moving  
 464 average (black) (Naafs et al., 2010); (d) SST estimates from ODP Hole 642B (Bachem et al.,  
 465 2017); relative abundance changes of (e) cool temperate forest taxa, (f) boreal forest taxa and  
 466 (g) boreal and alpine peatland and heathland taxa. For climatic grouping see Table 1. Grey  
 467 bar highlights the interval with low pollen accumulation rates and counts.



468 temperate mixed forests indicate climate conditions similar to those before the interval with  
469 low PARs. At 4.30 Ma, the development of herb fields/heathlands at higher altitudes,  
470 followed by the expansion of peatlands at 4.15 Ma and the prevalence of boreal forests,  
471 suggests cooler climatic conditions until 3.90 Ma (Figure 2). This cooling on land coincides  
472 with the development of a modern-like NwAC between 4.50 and 4.30 Ma, as indicated by the  
473 appearance of cysts of *Protoceratium reticulatum* and an increase in cool-water dinocysts,  
474 that indicate a spread of cooler but still temperate waters across the Norwegian Sea (Figure 6)  
475 (De Schepper et al., 2015). This is supported by planktic  $\delta^{18}\text{O}$  values from Hole 642B which  
476 indicate an increase in surface water salinities and/or cooling after 4.65 Ma (Risebrobakken et  
477 al., 2016). Alkenone-derived SST estimates for Hole 642B show a cooling at 4.30 Ma (Figure  
478 6), suggesting reduced northward heat transport via the NAC (Bachem et al., 2017). At Site  
479 982 in the North Atlantic, a slight cooling between 4.3 and 4.0 Ma coincides with  
480 reconstructed temperature changes at Hole 642B (Figure 6). However, it should be noted that  
481 the full SST variability at Site 982 is likely not recorded due to the low temporal resolution  
482 (see also Lawrence et al., 2009). At ODP Site 907 in the Iceland Sea, the gradual  
483 disappearance of dinocyst species between 4.50 and 4.30 Ma likely reflects decreasing water  
484 temperatures and salinity due to the establishment of a proto-EGC (Schreck et al., 2013). The  
485 increased export of cool Arctic waters into the Nordic Seas via a modern-like EGC has been  
486 linked to the prolonged establishment of northward water flow through the Bering Strait,  
487 possibly as a result of the shoaling of the CAS (De Schepper et al., 2015; Schreck et al.,  
488 2013; Verhoeven et al., 2011).

489 In northern Norway, diverse mixed forests and temperate climatic conditions re-established at  
490 3.90 Ma (Figure 2). This warming is preceded by a rise in SSTs in the Norwegian Sea by  
491  $\sim 6^\circ\text{C}$  between 4.0 and 3.93 Ma (Figure 6) (Bachem et al., 2017) and reduced surface water  
492 densities (Risebrobakken et al., 2016), suggesting an increased inflow of warm Atlantic water

493 as a result of an enhanced northward heat transport, following the shoaling of the CAS (Steph  
494 et al., 2010). The magnitude of warming seen in the Norwegian Sea (+ ~5°C compared to the  
495 Holocene average) is comparable to an inferred increase of July temperatures of at least 4°C  
496 in northern Norway, based on the latitudinal shift of vegetation zones (Moen, 1999). The  
497 warming in northern Norway also coincides with the emergence of seasonal sea ice in the  
498 Eurasian sector of the Arctic Ocean, with an increased sea ice export possibly  
499 counterbalancing the northward heat transport via a stronger AMOC (Knies et al., 2014). This  
500 is supported by Pliocene stable oxygen and carbon isotope records from Hole 642B, which  
501 indicate the presence of a warmer NwAC and a vigorous upper water column circulation  
502 between 4.0 and 3.65 Ma (Risebrobakken et al., 2016).

### 503 **5.3.2. Piacenzian (3.6–2.6 Ma)**

504 In northern Norway, temperate climatic conditions prevailed until 3.47 Ma (Figure 2),  
505 corresponding to SSTs up to 6°C higher than present in the Norwegian Sea and North  
506 Atlantic, indicating northward transport of warm Atlantic surface water (Figure 6) (Bachem  
507 et al., 2017; Lawrence et al., 2009; Naafs et al., 2010). At Hole 642B, a sharp decline in the  
508 relative abundance of coniferous trees and shrubs (excluding *Pinus*) between 3.48 and  
509 3.46 Ma leads to the predominance of boreal forest and indicates a change towards subarctic  
510 climate conditions in northern Norway. This cooling coincides with a distinct decrease in  
511 alkenone-derived SST by ~2°C in the Norwegian Sea at 3.45 Ma (Figure 6) (Bachem et al.,  
512 2017). There is also indications for an increase in surface water densities in response to  
513 decreasing temperatures (Risebrobakken et al., 2016). A cooling is also recorded at Integrated  
514 Ocean Drilling Program (IODP) Site U1313 at the north-eastern edge of the subtropical gyre  
515 around 3.48–3.47 Ma (Figure 6) (Naafs et al., 2010). Following a brief warming at 3.45 Ma at  
516 Site U1313, a subsequent gradual decline in SSTs suggests a weakened NAC and northward  
517 heat transport (Naafs et al., 2010). A long-term cooling of alkenone-derived SSTs at ODP

518 Site 982 in the northern North Atlantic, starting at 3.5 Ma, is indicative of a gradual change of  
519 climate before the intensification of NHG (Lawrence et al., 2009). At Site 982, obliquity-  
520 driven high-amplitude SST variations during the Piacenzian are superimposed by a long-term  
521 cooling trend (Figure 6). Lawrence et al. (2009) propose that the high amplitude variations at  
522 Site 982 were caused by changes in the position of the westerlies as a result of orbitally  
523 forced insolation changes, affecting the position of the NAC.

524 At 3.29 Ma, corresponding to the onset of warm climatic conditions during the mid-  
525 Piacenzian (3.264–3.025 Ma), a return of cool temperate forests to northern Norway is in  
526 agreement with an increase in alkenone-derived SSTs by  $\sim 3^{\circ}\text{C}$  in the Norwegian Sea (Figure  
527 6) (Bachem et al., 2017; Panitz et al., 2017). A decrease in surface water densities at the site  
528 is also indicative of the presence of warmer waters in the Norwegian Sea (Risebrobakken et  
529 al., 2016). A northward shift of the NAC and accompanied re-establishment of northward  
530 heat transport is inferred from an increase in SSTs, and dinocyst assemblage changes around  
531 3.29–3.28 Ma at several sites in the North Atlantic (De Schepper et al., 2013; Naafs et al.,  
532 2010). In the Norwegian Sea, however, the warming is not associated with changes in  
533 Atlantic water influence, suggesting that shifts in the position of the NAC are restricted to the  
534 North Atlantic. Instead, the increase in marine and terrestrial temperatures coincides with an  
535 increase in obliquity, resulting in a strengthening of the seasonal contrast (Panitz et al., 2017).  
536 In the North Atlantic and Nordic Seas region, climatic conditions seem to be slightly colder  
537 during the mid-Piacenzian than before 3.47 Ma, as seen in colder average SSTs at Site U1313  
538 (Naafs et al., 2010), and a lower relative abundance of *Sciadopitys* pollen in the pollen  
539 assemblages of Hole 642B (Figure 6). In the Norwegian Sea, SSTs are on average only  $1^{\circ}\text{C}$   
540 lower during the mid-Piacenzian than between 3.65 and 3.45 Ma (Figure 6) (Bachem et al.,  
541 2017, 2016). An expansion of peatlands and decline in the prevalence of boreal forests in

542 northern Norway until 3.14 Ma are indicative of a cooling climate before the onset of NHG  
543 around 2.7 Ma (Panitz et al., 2016).

544 In NE Siberia, a similar pattern to the climatic changes observed at Hole 642B and Site  
545 U1313 is recorded in the relative abundance changes of trees and shrubs in the vicinity of  
546 Lake El'gygytgyn (Figure 6) (Andreev et al., 2014). While the vegetation opens around  
547 c. 3.47 Ma and c. 3.45 Ma, a pronounced decline in the relative abundance of trees and shrubs  
548 does not take place until c. 3.39 Ma. Warmer conditions establish after c. 3.28 Ma, with  
549 relative abundances of trees and shrubs accounting for >50% (Andreev et al., 2014). Changes  
550 in vegetation and climate are also recorded in northwest Africa around 3.48 Ma, with warmer  
551 and wetter conditions prevailing before and drier climatic conditions after 3.48 Ma (Leroy  
552 and Dupont, 1997). The first extensive aridification in northwest Africa at 3.26 Ma  
553 corresponds to the onset of the mid-Piacenzian, and is marked by the establishment of cool  
554 temperate conditions in Norway. The similarity between the different Northern Hemisphere  
555 records suggests that the observed climatic changes have a common forcing.

## 556 **6. Conclusions**

557 Our new high-resolution pollen record from ODP Hole 642B in the Nordic Seas enables the  
558 reconstruction of long-term climate evolution in the Norwegian Arctic during the Pliocene.  
559 The record shows multiple changes from warmer-than-present cool temperate to near-modern  
560 boreal conditions which are superimposed by a long-term cooling trend throughout the  
561 Pliocene. A comparison of vegetation changes with palaeoceanographic changes in the  
562 Nordic Sea allowed the identification of different climate forcings: shifts to a warmer-than-  
563 present Pliocene vegetation and climate with deciduous or mixed forests in northern Norway  
564 (northward shift of 4–8° latitude, average annual and July temperatures > +2–4°C and 4°C,  
565 respectively) correspond to enhanced northward heat transport via the NAC and NwAC,

566 whereas boreal vegetation and climate occurred when northward heat transport was weaker.  
567 During the Early Pliocene, we suggest that a marked decline in PARs (c. 4.65 Ma) may have  
568 been caused by oceanographic and atmospheric circulation changes. Climate model  
569 experiments suggest that pollen transport to the site may have been reduced after c. 4.65 Ma  
570 due to changes in the atmospheric circulation pattern linked to an enhanced AMOC. An  
571 increase in AMOC might have been caused by the shoaling of the CAS between 4.8 and  
572 4.2 Ma. A gradual decrease of relative abundances of *Sciadopitys* pollen over subsequent  
573 warm phases suggests a long-term cooling of climate, possibly in response to declining  
574 atmospheric CO<sub>2</sub> concentrations throughout the Pliocene. Astronomical forcing could also be  
575 identified within the vegetation record, particularly a 100-kyr cycle. However, distinct  
576 changes in vegetation and climate were linked to changes in the northward heat transport via  
577 the NAC. Our Pliocene pollen record from Hole 642B suggests that palaeogeographic and  
578 palaeoceanographic changes had a strong influence on the long-term climate evolution of  
579 Scandinavia during the Pliocene. To further understand land-sea linkages and climate forcing  
580 under warmer-than-present conditions, additional high-resolution studies along the  
581 Scandinavian coast are required, recording the spatial extent of marine and terrestrial  
582 environmental changes.

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595 **8. Declaration of interest**

596 Conflicts of interest: none.

597 **9. References**

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