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Evaluating Northern High Latitude Paleoclimate Model Results Using Paleobotanical Evidence from the Middle Cretaceous

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Abstract: Climate plays a significant role in determining the style of depositional processes at different latitudes, which in turn influences the location of hydrocarbon systems. Results of climate modelling may therefore provide important information for predicting the presence or absence of suitable hydrocarbon plays. The critical step is to validate the model results against proxy data where they are available, to determine whether the models provide realistic results. Paleoclimate proxy data are most often derived from more accessible low to mid latitude regions and are biased towards warm climate states. However, General Circulation Models (GCMs) have traditionally been biased to colder temperatures, in particular at high latitudes, struggling to maintain the high latitude regions warm enough to sustain forests that were present during greenhouse periods, such as the mid-Cretaceous (~110-90 Ma), without exaggerated warming of the equatorial regions. To

improve this approach the HadCM3L coupled atmosphere-ocean GCM, a state-of-the-art model for the long simulations required to reach an equilibrium climate, has been run for each Stage of the Cretaceous using new paleogeographic basemaps. Here, we compare the results for the Aptian (118.5 Ma) and Albian (105.8 Ma) with paleoclimate proxy data from the high northern latitudes in order to determine if the model produces viable results for this region. Paleoclimate analysis of fossil wood from conifer forests from Svalbard of Aptian-Albian age suggests that they grew in moist cool upland areas adjacent to warmer temperate lowland regions, probably with rivers and/or swamps present. Studies of conifers from the Canadian Arctic islands indicate that they grew under slightly cooler conditions than on Svalbard, similar to northern Canada today. The HadCM3L GCM results for Svalbard show that the dominant biome was evergreen taiga/montane forest with lowland temperate vegetation present during the Albian Stage possibly with an element of deciduous taiga/montane forest in the Aptian (both cold boreal forest with short hot summers according to the Köppen-Geiger classification). The modelled Mean Annual Temperature (MAT) was ~-3.7^{o}C at the sample sites with summer temperatures rising to a mean of ~18°C during the Albian. Mean Annual Precipitation (MAP) was ~571 mm. In the Canadian Arctic the model results indicate that the biomes were more mixed than on Svalbard. The Aptian biome was dominantly deciduous taiga/montane forest with temperate vegetation in low laying areas. The Albian landscape was dominated by evergreen taiga/montane forest with some elements of deciduous taiga. Both Stages were classified as cold boreal forest with short hot summers under the Köppen-Geiger classification scheme. MAT was modelled to be ~-6.5^{o}C at the sample sites with summer temperatures reaching a mean of ~13°C and MAP was ~406 mm. These results suggest that

the HadCM3L GCM, coupled with updated paleogeographic maps, can produce a good match to the climate proxy data in these difficult-to-model high latitude areas.

KEYWORDS

Aptian-Albian; Cretaceous; General Circulation Modelling; Canadian Arctic; Svalbard; Paleoclimate; Paleobotany

INTRODUCTION

Modern high latitude regions constitute some of the harshest environments for life on Earth today (Billings, 1987; Kappen, 1993; Mori et al., 2008). Since as early as the mid-nineteenth century (Lyell, 1841, 1872; Godwin-Austin, 1858, 1860; Croll, 1875; Martin, 1897; Stebbing, 1897) the mid-Cretaceous was thought of as having a similar cold climate with more recent evidence of a "cold snap" being provided for example by variations in nannofossil assemblages, oxygen isotope data and the presence of glendonites and ice rafted deposits (Francis and Frakes, 1988; Herrle et al., 2015; Jeans, 1991; Sellwood et al., 1994; Price, 1999; Mutterlose et al., 2009). However, this view has been questioned with the mid-Cretaceous having now been long viewed as a period of global warmth (Bardossy and Aleva, 1990; Chumakov et al., 1991; Vakhrameev, 1991; Herman and Spicer, 1996) extending right into the polar regions. Unusually, as well as low and mid latitudes, there is also a significant amount of paleoclimate proxy data for this time period from high-latitude regions, making it ideal for studying global climate (Dingle and Lavelle, 1998; Francis and Poole, 2002; Zhou et al., 2012).

Fossil assemblages indicate that during the Aptian-Albian polar temperatures were high enough to sustain flourishing forests at >60° latitude under conditions of elevated CO_2 (Francis and Poole, 2002; Spicer et al., 2002; Howe, 2003; Skelton, 2003; Harland et al., 2007). Some paleoclimate models have struggled to produce temperatures in the polar regions that could support these fossil forests without making the equatorial regions too hot (Barron et al., 1994; Slone and Pollard, 1998; Valdes, 2000), although progress has recently been made for other time periods (Kiel and Shields, 2005; Lunt et al., 2012; Sagoo et al., 2013). It has been suggested that polar vegetation may have been crucial for maintaining the high-latitude warmth, through feedbacks such as evapotranspiration and albedo without concomitant warming of the lower latitudes (Otto-Bliesner and Upchurch, 1997; DeConto et al., 1999a and 1999b; Osborne and Beering, 2002a; Zhou et al., 2012). Therefore, efforts have been made to improve vegetation models coupled to General Circulation Models (GCMs) (Osborne and Beerling, 2002b; Brentnall et al., 2005; Zhou et al., 2012; Loptson et al., 2014). New data are required to fully understand the geological evidence for mid-Cretaceous climate variability and proper testing of climate model outputs.

Here we determine the Aptian-Albian paleoclimatic conditions recorded in fossil wood from the Canadian Arctic (Ellesmere and Axel Heiberg islands) and Spitsbergen (Svalbard). Fossil wood is ideal for assessing paleoclimate as it is often found insitu or has been transported only a short distance from its position of growth. The dependence of trees on sufficient light levels, soil water and temperature for growth tightly constrains the climatic regime under which they grow (Woodward, 1987). As well as nearest living relative analysis it has long been shown that fossil wood (secondary xylem), records a signal of climatic conditions

under which the trees grew displayed as structural adaptations (Chaloner and Creber, 1990). The signals recorded within the wood structure include seasonality from the presence or absence of growth rings, deciduous versus evergreen habit from calculation of earlywood versus latewood in the ring markedness index calculation (Chaloner and Creber, 1990; Falcon-Lang 2000) and water supply via the presence or absence of drought ring (Fritts, 1976; Kumagai et al., 1995). In addition to these specific adaptations, general climatic conditions year on year can be accessed from measurement of the width of growth rings as an indication of annual growing conditions and productivity by using the mean sensitivity calculation (Creber and Francis, 1999; Creber and Chaloner 1985). These results are then compared to new output from the HadCM3L Ocean-Atmosphere GCM to validate the model and determine whether these high latitude forests could have been maintained under the conditions modelled.

GEOLOGICAL SETTING

The fossil wood from the Canadian Arctic used in this study was preserved within the Sverdrup Basin, Canadian Arctic. During the Hauterivian to mid-Aptian rifting and associated basaltic volcanism, a series of thick, coarse, mainly non-marine sediments of the Isachsen Formation were deposited throughout the Sverdrup Basin (Fig. 1; Patchett et al., 2004). This was followed in the mid-Aptian and Albian by a marine transgression that produced the dark laminated mudstone of the Christopher Formation (Fig. 2) in which the fossil wood was found, preserved by calcite mineralisation (Patchett et al., 2004; Fig.1 bottom). Fossil wood is present in both the Aptian (Invincible Point Member) and Albian (Macdougall Point Member) sections of the Christopher Formation.

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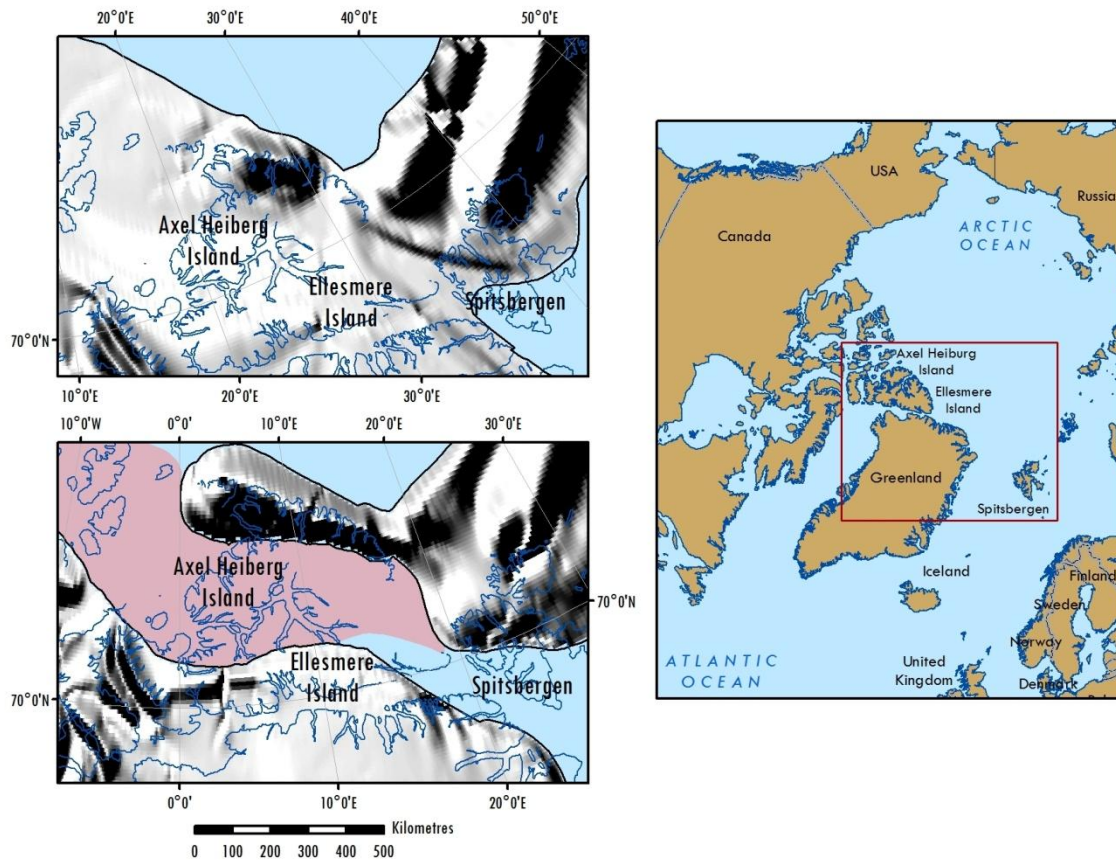
Figure 1. Present day locations shown on the right. Paleogeographic maps (left) showing the Canadian Arctic and Spitsbergen digital elevation maps (greyscale; Getech, 2011). The present day country outlines have been rotated to their palaeo-positions (blue) to allow the locations of interest to be easily identified. The paleohighstand line is shown in black.   Top: Aptian (118.5 Ma) showing the pre-rift paleogeography. Volcanism was occurring in the uplifted area to the north of Spitsbergen and rifting to the south-east at this time. Bottom: Albian (105.8 Ma) showing the marine transgression following rifting. The Sverdrup Basin shown in purple (after Goodarzi et al, 1992).
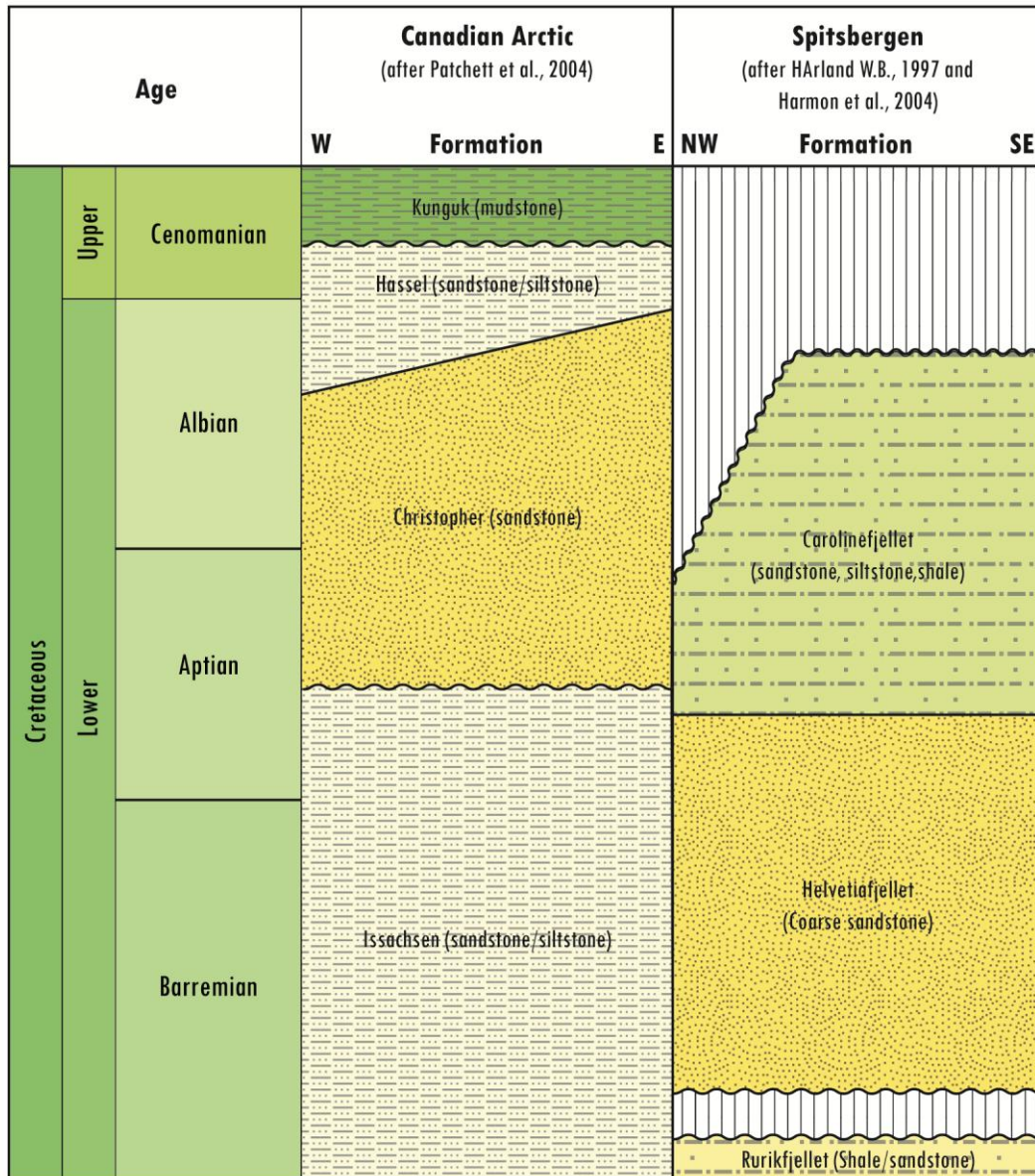
Figure 2. Stratigraphic chart showing the Barremian to Cenomanian formations in the Canadian Arctic and Spitsbergen.

During the Early Cretaceous there was a general transition from pro-delta shale through delta front to fluvial dominated sequences in the area now located south of the main island of Svalbard, Spitsbergen, (Worsley et al., 1986). Overlying these sediments, and partially laterally equivalent, are marine sandstones, siltstones and dark laminated shales of the Carolinefjellet Formation (Fig.2). These sediments suggest a relatively open marine shelf and prodelta setting that would have provided the carbonate for the formation of the

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concretions in the Innkjegla Member in which the fossil wood was found (Krajewski and Luks, 2003; Worsley et al., 1986; Fig.1).   The Carolinefjellet Formation has proved difficult to accurately date due to poor preservation of age diagnostic indictors within the sediment and the difficulty of correlating beds due to a pre-Cenozoic disconformity. However, a general Aptian-Albian age has been assigned from macrofossils (Nagy, 1970) and dinoflagellates (Århus, 1991).

MATERIALS AND METHODS

Samples of fossil wood from Svalbard were collected from the Lundstromdalen and Storknausen areas on the main island of Spitsbergen (Fig. 3). The samples from the Canadian Arctic archipelago are from Buchanan Lake (Axel Heiberg Island), Eureka and Roll Rock Valley areas (Ellesmere Island) (Fig.3). The types of wood present were identified by Harland et al. (2007).
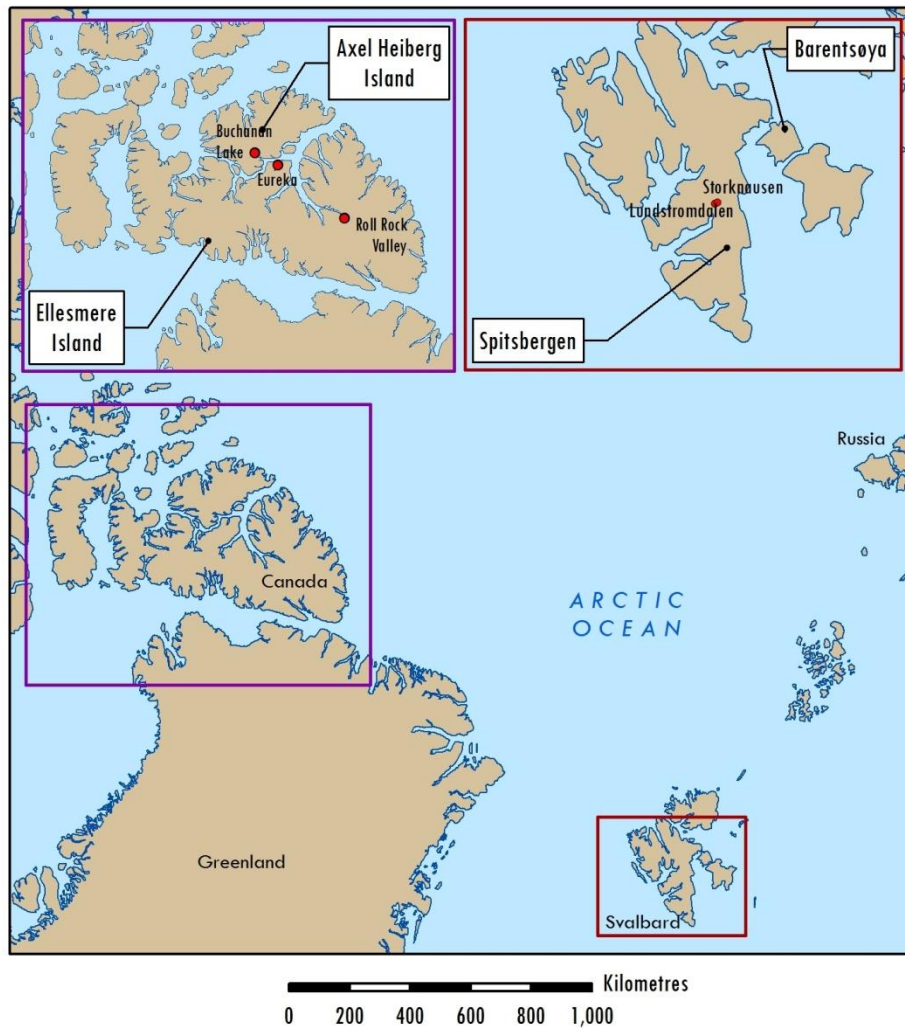
Figure 3. Present day map of the Northern Hemisphere polar region (bottom) with detailed maps of the Canadian Arctic (upper left) and Spitsbergen (upper right) showing the fossil wood sample locations (red circles).

Standard transverse thin sections were prepared for all wood samples in order to analyse the growth rings for their paleoclimate signal. The thin sections were examined under an Olympus BH-1 transmitted light binocular microscope and images captured using a Leica IM1000 imaging system. The growth rings were measured along a radial line to obtain as long a ring series as the preservation allowed. The following sets of data were collected from the wood in order to carry out in depth paleoclimate analysis:

a) The presence or absence of growth rings was noted in order to assess whether the prevailing paleoclimate was seasonal or aseasonal (Francis, 1986; Creber and Francis, 1999; Ennos, 2001). Annual growth rings tend not to occur in the tropics, although drought rings do (personal communication A.O'Dea, Smithsonian Tropical Research Institute, Panama; Creber and Francis, 1999). The presence of annual growth rings indicates that some factor in the environment induced cambial activity to slow or shut down completely. This may be the loss of leaves in winter as a carbon retention strategy halting wood growth, or the long periods of winter darkness at higher latitudes that slowed the trees metabolism.

b) The presence or absence of false rings. False rings are produced when the growing period is interrupted (Schweingruber, 1996) by drought (Fritts, 1976; Kumagai et al., 1995). False rings caused by drought tend to produce a few very small layers of cells mimicking an end-of-season boundary (Fritts, 1976; Creber and Francis, 1999). In contrast frost rings can occur that may cause physical damage such as exploded cells formed due to the expansion of ice.

c) Mean Sensitivity was determined in order to assess whether growth was consistent or variable from year to year. Annual Sensitivity shows the annual variation in growth from one year to the next and Mean Sensitivity is the average of this, indicating variability over the life of the tree (Fritts, 1976). Mean Sensitivity values fall between 0 and 2 and are calculated using the formula of Creber and Francis, (1999):

$$MS = \frac{1}{n-1} \sum_{t=1}^{t=n-1} \left| \frac{2(x_{t+1} - x_t)}{x_{t+1} + x_t} \right|$$

where x is the ring width and t is the year number of the ring, n is the number of

rings in the sequence.

Values of 0.3 to 2 indicate growth under variable climate with strongly limiting

environmental factors, especially water. Values of 0.3 or less represent growth

under equable conditions allowing production of rings with approximately constant

width year on year (Creber and Francis, 1999). In addition, values near to or over 0.4

are produced by conifers growing in semi-arid environments and low values (<0.2)

combined with narrow ring widths are produced by trees adapted to living close to

the tree line (Fritts and Schatz, 1975).

HADCM3L GENERAL CIRCULATION MODEL

The HadCM3L (HADley Centre Model version 3) coupled ocean-atmosphere General

Circulation Model (unified model Vn4.5 or UM) was developed by the Hadley Centre of the

UK Met Office in 1999 (Gordon et al., 2000). HadCM3L is a derivative of HadCM3, having a

lower resolution in the ocean (3.7 x 2.5^o as opposed to 1.25 x 1.25^o in the HadCM3). The

HadCM3 has been extensively used since it's development including in the IPCC Third,

Fourth, and Fifth Assessments and figures therein (IPCC, TAR, 2001; IPCC, AR4, 2007; IPCC,

AR5, 2013). This model has been found to compare favourably with other climate models,

as evaluated by the Coupled Model Intercomparison Project (Covey et al., 2003; IPCC, AR4, 2007; Meehl et al., 2000). The HadCM3L has also recently been used extensively in simulation of pre-Quaternary climate change (e.g. Bradshaw et al., 2012; Lunt et al., 2012; Loptson et al, 2014; Inglis et al., 2015). The model does not perform so well relative to the most recent models (AR5); however, it is comparatively efficient relative to those models and as such can be considered state-of-the-art for the long simulations required for paleoclimate studies. In this instance, the model was allowed to run for 1422 model years in order to reach equilibrium before results were averaged over the last 30 years of the simulations at a horizontal resolution of 2.5^o of latitude by 3.75^o of longitude. The results were reprocessed to a grid cell resolution of 0.5^o latitude and longitude to correspond to the resolution of the paleogeographic basemaps and interpolated to coastlines where appropriate. Our version of HadCM3L includes the Met Office Surface Exchange Scheme 2 (MOSES 2.1) tiled land-surface model that calculates the surface CO_2 fluxes associated with photosynthesis and plant respiration (Cox, 2001, Essery et al., 2001), and the TRIFFID (Top-down Representation of Interactive Foliage and Flora Including Dynamics) global vegetation dynamic model (Cox, 2001). TRIFFID simulates the distribution and productivity of broadleaf, needleaf, C_3 grass, C_4 grass and shrub vegetation types (Cox, 2001).

Boundary and initial underlying paleogeographic conditions of the model were all derived from Albian (representing 105.8 Ma) and Aptian (representing 118.5 Ma) Stage-level paleogeographic basemaps (timescale of Cohen et al, 2013; Getech, 2011). The atmospheric CO_2 was set to 1120 ppmv (4x pre-industrial), and pre-industrial values of CH_4 (760 ppbv) and N_2O (270 ppbv) and the solar constant calculated in accordance with Gough (1981). All

other variables are calculated internally by the model according to the numerical representation of the fundamental fluid dynamics and physics of the atmosphere and ocean, and the biology of the land surface. All locations discussed in the text are rotated back from their present day positions for both stages using PaleoGIS^{TM}4 (see Figs. 4, 5, 6, 7 and 8, Section 5.2), as were the Present Day international boundaries for the purposes of the discussion.

RESULTS

Paleoclimate Proxy Data

Harland et al. (2007) identified 12 morphogenera of conifer wood (*Piceoxylon*, *Pityoxylon*, *Laricioxylon*, *Protopiceoxylon*, *Palaeopiceoxylon*, *Taxodioxylon*, *Juniperoxylon*, *Protocedroxylon*, *Araucaroiopitys*, *Xenoxylon*, *Cupressinoxylon* and *Taxaceoxylon*) from 23 fossil wood specimens from the Arctic region. In addition, Ring Markedness Index studies (Falcon-Lang, 2000), of the fossil wood, measured by Harland (2005), were undertaken to determine whether the trees were deciduous or evergreen. Results indicate that these conifer forests were predominantly evergreen in nature. The forests on Spitsbergen were 85% evergreen and 15% deciduous, whilst the Canadian Arctic wood showed that these forests were 90% evergreen and 10% deciduous (Harland, 2005).

Paleoclimate was first assessed from the fossil conifers based on the climate tolerances of the nearest living relative (Nearest Living Relative analysis, NLR) identified from the wood

type observed.   Although modern conifers have a wide range of temperature tolerances this is a useful exercise to determine whether there is overlap between species to narrow the climatic window and assess whether the HadCM3L GCM results are within the tolerances identified.

On Spitsbergen the dominance of *Taxodioxylon*, resembling modern *Taxodium*, suggests that the forests were similar to those found near the coast of the southeastern USA from Louisiana to North Carolina today where *Taxodium distichum* (the Swamp Cyprus) dominates warm temperate forests in wet, swampy areas (Moore, 1982). However, modern *Taxodium* has been shown to be growing in relictual groups and its true environmental tolerances may have been more widespread. The presence of *Taxaceoxylon* (similar to modern *Taxus*) implies a cool-temperate climate with abundant rainfall (Vakhrameev, 1991). Although intolerant of severe and prolonged frost, modern *Taxus* can resist damage down to -35°C (Thomas, 2008). *Laricioxylon*, similar to modern *Larix*, can also tolerate very harsh environments (minimum -50°C), but requires temperatures between -5 and 5°C to reproduce (Vidaković, 1991). These cooler estimates are closer to those of Philippe and Thévenard (1996), who propose that the presence of *Xenoxylon* may indicate wet temperate to cool temperate conditions (Philippe et al., 2009).   The presence of *Cupressinoxylon* (similar to modern *Cupressus*) and Juniperoxylon (similar to modern *Juniperus*) in addition to the *Taxaceoxylon* and *Laricioxylon* suggest the presence of moist, cool temperate areas in the uplands with mild, sheltered warm temperate areas with rivers and/or swamps dominated by *Taxodioxylon* in the lowlands (Moore, 1982; Moss et al., 2005; Vidokovic, 1991). This fits well with the presence of an environment similar to a modern arctic mesotopographic type environmental gradient (Billings, 1987) in Svalbard

with slopes facing the prevailing wind from the north to northeast and more sheltered areas on the lee side with bogs forming at the base of slope from meltwater.

Fossil wood types and NLR analysis indicate that the conifer types present in the Canadian Arctic were similar to those found on Spitsbergen. The dominance of *Pinuxylon* with relatively narrow growth rings suggests moderate warmth, although this conifer combined with the other genera present, suggests that the samples were from cool/cold temperate upland areas that were cooler than on Spitsbergen and possibly similar to modern northern Canada today.

Frakes and Francis (1988) reported ice-rafted deposits in the Aptian-Albian of Svalbard, suggesting that there was sea ice present for at least part of the year. However, this finding has been disputed by Markwick and Rowley (1998) who suggest such erratics could have been deposited by non-glacial processes. These non-glacial processes include tree-rafting with pebbles/bolders transported within the trees and their root systems into the basin. The presence of sea ice seems too cold for Spitsbergen where *Taxodioxylon* is present in the lowlands. In addition, petrified wood has been found in the pebble-bearing Aptian Innkjegla Member of the Carolinefjellet Formation of Spitsbergen (Nagy, 1970) indicating that in this case tree rafting could have been the transportation mechanism. Harmon et al. (2004) suggest that the presence of significant amounts of plagioclase and unweathered biotite in the sandstone of the Carolinefjellet Formation does, however, indicate periodically cold conditions within the sediment-starved basin, supporting the occurrence of glendonites in this formation, which were considered to have formed in cold bottom waters ($<5^{o}$C). Modern *Taxodium* can withstand temperatures as low as -30°C therefore these conifers may have been able to survive short periods of very low temperatures in winter (Vidaković,

1991) consistent with Harmon et al's (2004) findings. However, this does not necessarily imply full glaciation or formation of sea ice. Glendonites have also been found in the Christopher Formation in the Canadian Arctic, mostly recovered from the lower part of the Formation and are concentrated in regular beds of late Aptian-early Albian age (Herrle et al., 2015). This supports NLR analysis that suggested cool to cold temperate conditions on land at that time.

All samples from Spitsbergen and the Canadian Arctic display narrow growth rings indicating that the climate was seasonal, probably with only a short growing season, followed by long periods of winter darkness.

A total of 13 ring series were obtained from the Spitsbergen samples, varying in length from 4 to 48 rings (Table 1) and width from 0.35 to 5.55mm (mean of 1.75mm; Table 1). The trees therefore seem to have had the potential for high growth rates, creating wide rings, but in some places the environment may not have been entirely favourable for rapid growth, resulting in narrower ring widths.

Specimen Nᵒ	Fossil Wood Type (Harland et al., 2007)	Nᵒ of Rings	Mean Ring Width (mm)	Min-Max Ring Width (mm)		Mean Sensitivity	Complacent (C) or Sensitive (S)
LD101	*Juniperoxylon*	6	1.04	0.47	1.89	0.56	S
LD102	*Cedroxylon*	5	5.55	4.52	6.35	0.11	C
LD105	*Piceoxylon*	13	3.21	1.90	4.45	0.24	C
LD108	*Araucariopitys*	36	1.26	0.34	2.91	0.30	C
LD120	*Protocedroxylon*	35	0.36	0.12	0.93	0.32	S
LD123	*Laricioxylon*	49	1.12	0.40	1.84	0.32	S
LD126	*Laricioxylon*	48	0.65	0.17	1.38	0.28	C
LD129	*Taxodioxylon*	16	0.86	0.23	1.35	0.34	S
LD130	*Xenoxylon*	11	2.77	1.67	4.13	0.22	C
LD131	*Taxodioxylon*	21	1.46	0.91	2.40	0.23	C
LD132	*Cupressinoxylon*	27	0.93	0.34	2.44	0.23	C
LD133	*Taxodioxylon*	12	2.11	0.84	4.26	0.36	S
SN25 4	*Taxoxylon*	20	1.40	0.57	2.63	0.29	C

Table 1 Growth ring data for Spitsbergen (Localities: LD = Lundstromdalen, SN = Storknausen).

Seven samples from Spitsbergen contain false rings that appear to have formed during the summer or early autumn (Table 2). No frost damaged cells were observed. This indicates that these trees were probably drought-stressed with the lack of water leading to the tree creating a band of small cells within one growing season that appears to falsely resemble an annual ring. Growth interruptions seem to have been rare in what was generally a constant and equable climate. The highest number of false rings in one wood specimen are in LD120, a *Protocedroxylon* wood type which has 9 false rings out of the 35 rings present. The form-genera that contain false rings are types which may have grown at higher altitudes (e.g. *Laricioxylon)* therefore false rings may have been an artifact of growth on exposed sites with steep topography and thin soils making it difficult to retain moisture. One specimen of *Taxodioxylon* containing false rings may have grown on a swampy lowland site that was susceptible to fluctuating water levels.

Specimen N[o]	Fossil Wood Type (Harland et al., 2007)	Number of False Rings	Total Number of Rings	Season False Rings Occurred
LD101	*Juniperoxylon*	1	6	Summer
LD108	*Araucariopitys*	1	36	Late Summer/Early Autumn
LD120	*Protocedroxylon*	9	35	Summer
LD123	*Laricioxylon*	1	49	Spring/Summer
LD126	*Laricioxylon*	4	48	Late Summer
LD129	*Taxodioxylon*	2	16	Late Summer/Early Autumn
SN25 4	*Taxoxylon*	3	20	Spring/Summer/Autumn

Table 2 Number of false rings present in fossil wood specimens and the season they appear in for Spitsbergen (Localities: LD = Lundstromdalen, SN = Storknausen).

Mean Sensitivity values for growth rings in fossil wood from Spitsbergen display a wide range of values from 0.11 to 0.56 with an average of 0.29, indicating that growth was mostly complacent, probably growing in stress free areas with adequate water supply (Table 1). Of the seven samples that contain false rings, four produced sensitive values (LD101, LD120, LD123 and LD129; Table 1) and three complacent values (LD108, LD126 and Sn25 4). Two samples with values >0.3 are *Taxodioxylon* (LD129 and LD133), the modern equivalent of which, *Taxodium,* can produce anomalously high Mean Sensitivity values when grown on disturbed stream-side settings (Young et al., 1993; Falcon-Lang, 2005). Two other samples (LD102 and LD123) have values >0.3 but below 0.4 (both = 0.32) and may have suffered periodic drought stress. One sample (LD101) had a high value of 0.56 suggesting that it grew in semi-arid conditions and one (LD102) had a very low value of 0.11 indicating that it may have been growing at a higher altitude.

A total of ten ring series were obtained from the Canadian Arctic samples, varying from six to 77 rings long (Table 3). The rings are narrower than those from Spitsbergen, varying in

width from 0.48 to 3.03mm (mean 1.27mm), ~27.5% narrower than those from Spitsbergen, indicating that growth was slower in this area (Table 3).

Specimen Nº	Fossil Wood Type (Harland et al., 2007)	Nº of Rings	Mean Ring Width (mm)	Min-Max Ring Width (mm)		Mean Sensitivity	Complacent (C) or Sensitive (S)
RR102	Piceoxylon	6	3.03	2.25	3.99	0.27	C
RR113	Piceoxylon	43	0.58	0.18	1.78	0.34	S
RR111	Pinuxylon	63	1.10	0.36	2.35	0.33	S
RR122	Pinuxylon	49	0.89	0.34	2.07	0.39	S
E139	Pinuxylon	49	0.48	0.14	0.99	0.23	C
E140	Pinuxylon	29	1.95	1.14	3.03	0.25	C
RR121	Cedroxylon	37	1.32	0.35	2.64	0.23	C
RR123	Cedroxylon	22	1.51	0.77	2.16	0.27	C
BL125	Palaeopiceoxylon	59	1.09	0.46	1.68	0.23	C
E137	Cupressinoxylon	77	0.71	0.22	1.56	0.19	C

Table 3 Growth ring data for the Canadian Arctic (Localities: RR= Roll Rock Valley, E = Eureka, BL = Buchanan Lake).

Five samples, 50% of the sample set (Table 4), contain false rings, even though the majority of the growth rings seem to have been produced during periods of equable conditions with adequate water supply. The majority of the false rings seem to have occurred in the spring and summer representing periods of drought (Table 4). The majority of these trees may have grown at higher altitudes than the Spitsbergen conifers, on thin, rocky soils susceptible to drought conditions.

Specimen Nº	Fossil Wood Type (Harland et al., 2007)	Number of False Rings	Total Number of Rings	Season False Rings Occurred
RR113	Piceoxylon	3	43	Spring/Summer
RR111	Pinuxylon	15	63	Spring/Summer/Autumn
RR122	Pinuxylon	5	49	Spring/Summer/Autumn
E140	Pinuxylon	2	29	Spring/Summer
BL125	Palaepiceoxylon	1	59	Spring

Table 4 Number of false rings present in fossil wood specimens and the season they appear for the Canadian Arctic (Localities: RR= Roll Rock Valley, E = Eureka, BL = Buchanan Lake).

Mean Sensitivity values for these samples range between 0.19 and 0.39 (average of 0.27), slightly lower than for Spitsbergen even though these trees had narrower rings indicating slower growth. This suggests that although growth was slow it was consistent from year to year. Of the ten samples, seven had values of 0.3 or less (RR102, E139, E140, RR121, RR123, BL125 and E137) and three had values of >0.3 (RR113, RR111 and RR122) indicating that the majority of the samples were complacent and probably grew in areas with adequate water supply for the genera present.

Taken together, the fossil growth ring and NLR analyses suggest that both sites would have had conifer forests growing under seasonal climatic conditions with adequate year round conditions for forest growth. The trees on Spitsbergen seem to have achieved moderate growth in generally moist cool upland areas with the potential to dry out quickly. Lowland areas were probably warm temperate with rivers and/or swamps that may have been susceptible to fluctuations in the water table. The conifer forests of the Canadian Arctic would have also grown under a seasonal climate which seems to have been reasonably constant and favourable for tree growth throughout the year with adequate water. This area may however have been susceptible to a more marked climatic influence with the relatively wide range of Mean Sensitivity values suggesting variable climate. The prevailing conditions were probably similar to northern Canada's boreal region today which lies between the treeless tundra of the arctic delineated by the 13°C mean July isotherm and the temperate zone to the south delineated by the 18°C mean July isotherm (Soja, et al., 2006).

HadCM3L Model

Four variables from the HadCM3L GCM that are most directly comparable with the fossil evidence were interrogated - atmospheric temperature at 1.5m above the surface (Fig. 4), total precipitation (Fig. 5), precipitation-evaporation (Fig. 6) and biomes (Fig. 7). Additionally, in order to investigate the possibility of a "cold snap" (Francis and Frakes, 1988; Herrle et al., 2015; Mutterlose et al., 2009) having occurred in the mid-Cretaceous , model results for mean annual sea ice thickness and snow depth at surface are also examined (Fig. 8).

The atmospheric temperature at 1.5m above the surface is included because this is the level at which most fauna and flora interact with the climate and most likely represents the temperatures experienced by the conifers represented by the fossils, it is also the reference height to which most proxies are calibrated. As well as Mean Annual Temperature (MAT) values, we also examined the seasonal values to identify the range of temperatures experienced by the trees at different times of the year (Fig. 4).
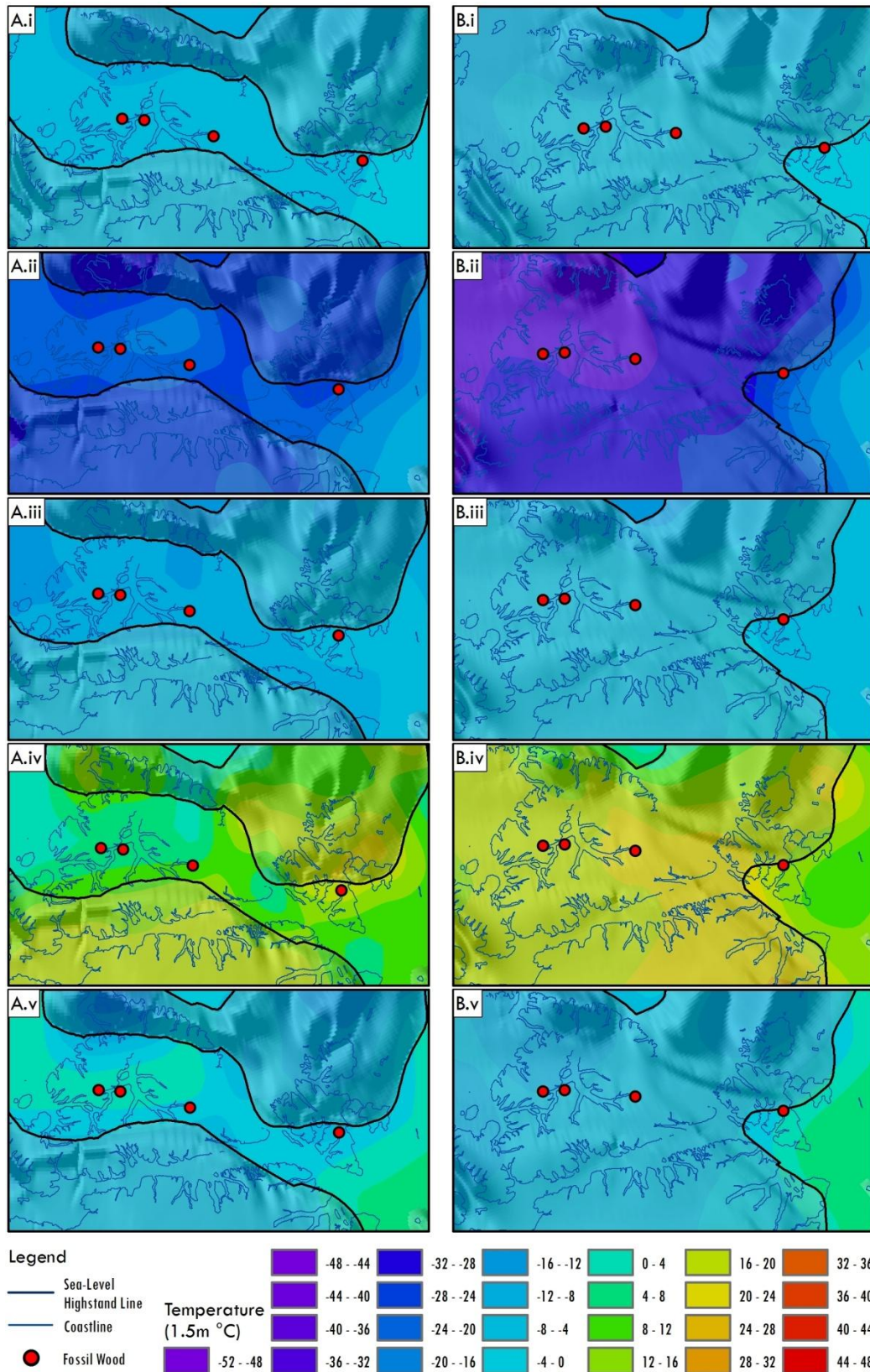
Figure 4. Atmospheric temperature model results for 1.5m above the surface given in ^{o}C **A)** Albian **B)** Aptian i) mean annual temperature, ii) mean winter temperature (December, January, February), iii) mean spring temperature (March, April, May), iv) mean summer temperature (June, July, August), and v) mean autumn temperature (September, October, November).

These model results indicate that the MAT (Fig. 4 i) in the region was similar for both the Aptian and Albian (~0 to -12°C) with the Albian being only ~1 to 2°C warmer. Both stages have sub-zero winters (Fig. 4 ii) but warm summers (Fig. 4 iv).   The winter temperatures show an overall warmer Albian than Aptian, possibly due to the maritime influence of the newly-formed rift which would have brought warmer water into the region from the south. The reverse is true for wummer temperatures, which are cooler overall during the Albian, giving this time-slice a much lower overall temperature range than the Aptian. Atmospheric temperature results from the GCM for each of the paleoclimate proxy locations and their modelled elevation are provided in Table 5. It should be noted, however, that the wood samples were not *in-situ* and probably grew on the elevated land close to their final depositional locations. These elevated areas are likely to have experienced different (cooler) climatic conditions to the lowlands/marine depositional areas in the Aptian and Albian. During the Albian, the winter temperatures at the sample sites were similar to each other (Spitsbergen ~-24°C and the Canadian Arctic ~-22°C). summer temperatures at the sample sites during the Albian were warmer for Spitsbergen (average ~18.1^{o}C) compared to the Canadian Arctic (average~7.7^{o}C) but the Canadian Arctic was warmer during the Aptian summer (average ~19.1^{o}C) compared to Spitsbergen (average ~14.9^{o}C). There was a greater difference in Aptian winter temperatures with the Canadian Arctic averaging ~-33°C and Svalbard ~-22°C. If these results are compared to recent warmest (July) and coldest (February) months recorded at Eureka Weather Station, Eureka, Ellesmere Island, Nunavut, ~ 3.3 and -38.0^{o}C respectively (mean annual temperature ~ -19.7^{o}C; Mori et al., 1998), the Present Day Arctic climate is considerably colder than indicated for the mid-Cretaceous.

| Location	Latitude/ Longitude	Model Elevation (m)		Mean Annual Temp 1.5m		Winter Temp 1.5m		Spring Temp 1.5 m		Summer Temp 1.5m		Autumn Temp 1.5m	
		Albian	Aptian	Albian	Aptian	Albian	Aptian	Albian	Aptian	Albian	Aptian	Albian	Aptian
Canadian Arctic Roll Rock Valley	81°24'14.92N/ 76°47'5.72W	-49	501	-6.16	-6.08	-23.30	-33.19	-9.57	-5.76	10.61	20.89	-2.94	-6.76
Eureka	79°59'59.97N/ 85°55'59.02W	-53	441	-5.75	-7.01	-20.32	-32.82	-10.73	-6.34	6.61	18.86	1.83	-7.78
Buchanan Lake	79°27'54.10N/ 87°43'17.93W	-102	483	-6.42	-7.33	-21.94	-32.51	-11.04	-6.65	5.81	18.18	1.49	-8.05
Average				*-6.11*	*-6.80*	*-21.85*	*-32.84*	*-10.45*	*-6.25*	*7.68*	*19.31*	*0.13*	*-7.53*
Spitsbergen Lundstromdalen	78°1'17.21N/ 17°16'47.41E	-11	-6	-4.33	-3.18	-23.88	-22.37	-6.03	-6.06	18.02	14.87	-4.34	0.82
Storknausen	78°1'36.91N/ 17°24'4.04E	-7	-6	-4.18	-3.18	-23.58	-22.37	-6.00	-6.06	18.17	14.87	-4.30	0.82
Average				*-4.26*	*-3.18*	*-23.73*	*-22.37*	*-6.02*	*-6.06*	*18.10*	*14.87*	*-4.32*	*0.82*

Table 5 The atmospheric temperature at 1.5m above the surface for paleoclimate proxy data locations spanning the Aptian and Albian stages. All temperatures given are in ^{o}C.

Total precipitation and precipitation-evaporation (P-E) from the model are examined as water availability seems to have been one of the major limiting factors for wood growth, identified as false (drought) rings (Figs. 5 & 6). The HadCM3L total precipitation is calculated as the sum of water precipitation and snow (as water equivalent) reaching the Earth's surface for each grid cell.   The general trends in total precipitation can be seen in Figure 5. As well as the mean annual total precipitation, we also examined the seasonal values to identify the range of precipitation experienced at different times of year (Fig. 5). The seasonal results also allow determination of when potential drought conditions may have occurred and whether these match the seasons in which false rings were produced in the trees (Table 4).
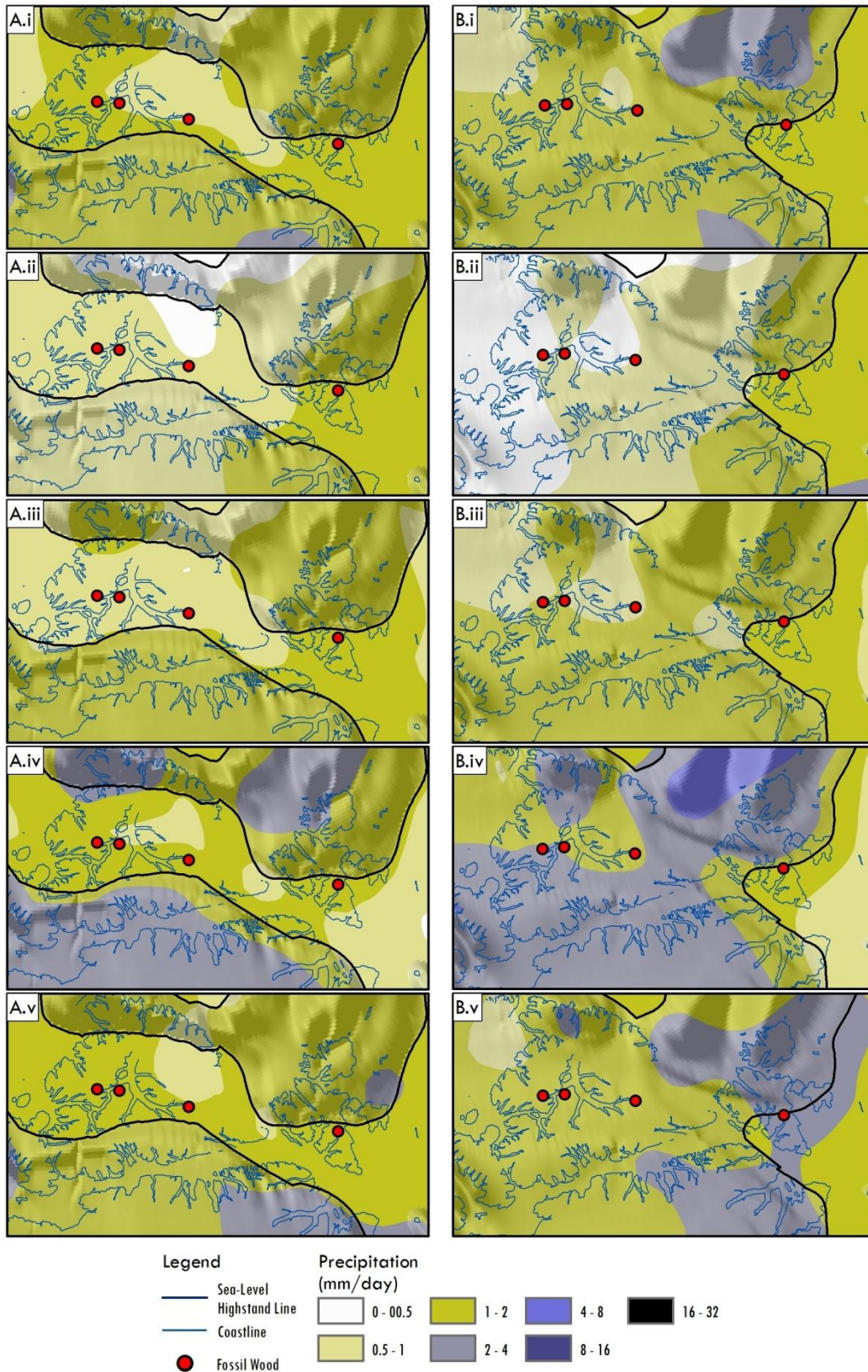
 Figure 5. Total precipitation model results given in mm/day **A)** Albian, **B)** Aptian, i) mean annual total precipitation; ii) mean winter total precipitation (December, January, February); iii) mean spring total precipitation (March, April, May); iv) mean summer total precipitation (June, July, August), and v) mean autumn total precipitation (September, October, November).

Not all of the total precipitation would have been available for uptake by the vegetation present with a proportion being removed by evaporation. We therefore also examined the modelled values of P-E to determine the likely precipitation remaining available for the vegetation to use (Fig. 6). In the HadCM3L P-E is the average total precipitation minus the average total evaporation for a given time period, thus providing a measure of aridity. Values can be positive where there is more precipitation than evaporation or negative where evaporation exceeds precipitation. Values of P-E can be greater than total precipitation where there is negative evaporation i.e. condensation which can occur if the land surface is relatively cold and the atmosphere above has high humidity. As with total precipitation in addition to mean annual P-E (Fig. 6, Ai and Bi) we also examined the seasonal variations experienced in this region (Fig. 6, Albian Aii to Av and Aptian Bii to Bv) which highlight areas particularly prone to drought at specific times of year.
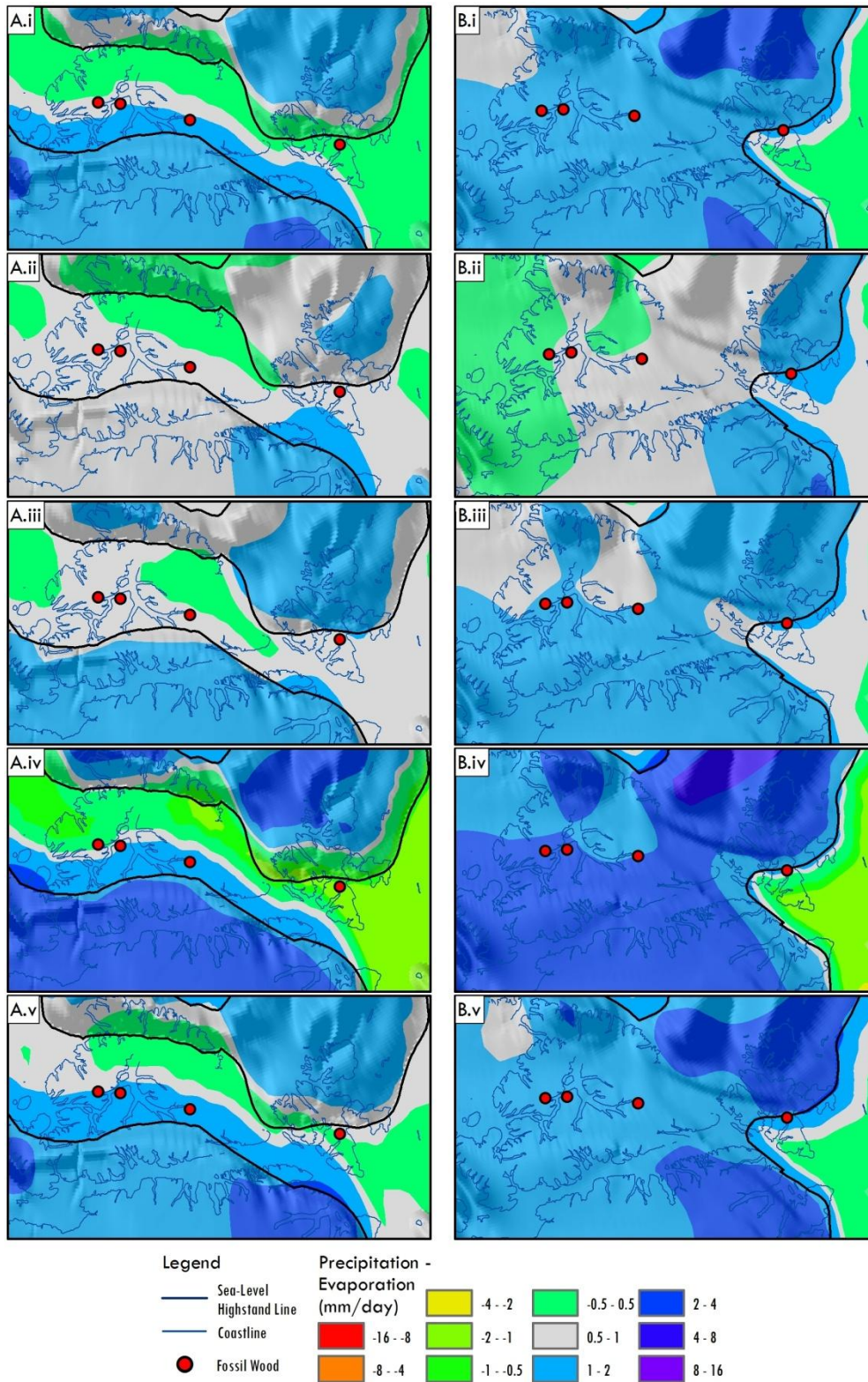
Figure 6. Precipitation-Evaporation **A)** Albian. **B)** Aptian. i) mean annual precipitation-evaporation ii) mean winter precipitation-evaporation (DJF: December, January, February) iii) mean spring precipitation-evaporation (MMA: March, April, May) iv) mean summer precipitation-evaporation (JJA: June, July, August) and v) mean autumn precipitation-evaporation (SON: September, October, November). Grey shading indicates the underlying high-resolution topography.

The general trends in total precipitation were similar in the Aptian and Albian (Fig.5). The mean annual precipitation (Fig. 5 i) is consistently low for all sites, being between ~1-2 mm/day. The general trend in the P-E values vary more between the Aptian and Albian than total precipitation with values fluctuating between -1.2 and 2.2 mm/day (Fig. 6). When this is investigated in more detail for the fossil wood locations (Tables 6) it can be seen that for both the Canadian Arctic and Spitsbergen the Aptian had slightly more average total precipitation than the Albian, although all receive < 2mm/day (Table 6). This is reflected in the average P-E values for Spitsbergen with the mean annual Aptian being significantly higher (0.89 mm/day) than the Albian (0.18 mm/day; Table 7). The Canadian Arctic is within the semi-arid zone for total precipitation for both stages (Table 6). When evaporation is allowed for (Table 7) the average values for the Canadian Arctic remain within the semi-arid zone (0.82-1.36 mm/day). Spitsbergen has slightly higher average total precipitation than the Canadian Arctic making it dry sub-humid. These higher values of total precipitation in Spitsbergen are however not reflected in the P-E values which are in the arid (<0.82 mm/day) to semi-arid zone (<1.37 but >0.82 mm/day; Table 7). There is seasonal variation in the total precipitation with the winter months being the driest (Fig. 5 ii) especially during the Aptian when, the Canadian Arctic sites are located within the arid zone. Most precipitation occurs during the summer-autumn seasons (Figs.5 iv and v), with the Spitsbergen sites receiving the highest precipitation of all sites during the autumn period (2.21mm/day; Table 6). Seasonal variations can also be seen in the P-E values (Table 7). Although most of the total precipitation occurs in summer/autumn, the summer months are the driest once evaporation is taken into account for both timeslices on Spitsbergen. The Albian summer is the only time period that produced negative values of P-E which are found at both Spitsbergen sites. The high precipitation is however retained to a greater extent

during the autumn on Spitsbergen, being 0.46 mm/day in the Albian and 1.67 mm/day in the Aptian, probably due to the lower temperatures limiting evaporation. The highest P-E values in the Canadian Arctic are found during the Aptian summer for all sites and at Storknausen on Spitsbergen which is wettest in the Aptian autumn (Table 7).

The HadCM3L model results show that the elevated source areas around the fossil wood locations would have received higher total precipitation than the sample sites during most of the year, which could have runoff to supply water into the lower-lying areas (Figure 5). However there is much more fluctuation within the P-E results between both the stages (Figure 6). During the Aptian the sample sites tend to be drier than the elevated regions when looking at the P-E whilst in the Albian the sample sites retain more moisture than some of the elevated regions to the north in the autumn and winter. The higher elevation areas show the same overall trends for both Stages in total precipitation with the winter being driest and the summer wettest. This pattern is reflected when evaporation is taken into account with the elevated areas around the sample locations retaining most precipitation during the summer although P-E values are also high in elevated regions near Spitsbergen in autumn (Fig. 6). The average winter total precipitation values modelled for elevated areas around Spitsbergen and the Canadian Arctic are ~1.6 and 0.64 mm/day respectively for the Albian and ~1.34 and 0.67 mm/day for the Aptian. These winter values are mostly lower than is received in the low-lying areas but during the summer months the higher elevation areas were much wetter than the sample locations. Spitsbergen was wetter in the summer during the Aptian (average ~2.45 mm/day) than the Albian (average ~1.69 mm/day) but the opposite was true for the Canadian Arctic (Aptian average ~2.15 mm/day; Albian average ~2.35 mm/day). This general trend of wetter summers during the

Aptian than Albian on elevated ground around Spitsbergen seems to hold true when evaporation is taken into account in the P-E results. The pattern of the Canadian Arctic summers being drier in elevate regions the Aptian however doesn't hold true for the P-E results (Fig. 6).

Location	Latitude/ Longitude	Model Elevation (m)		Mean Annual Precip mm/day		Winter Precip mm/day		Spring Precip mm/day		Summer Precip mm/day		Autumn Precip mm/day	
		Albian	Aptian	Albian	Aptian	Albian	Aptian	Albian	Aptian	Albian	Aptian	Albian	Aptian
Canadian Arctic Roll Rock Valley	81°24'14.92N/ 79°47'5.72W	-49	501	1.06	1.16	0.64	0.53	0.90	0.94	1.36	1.78	1.26	1.40
Eureka	79°59'59.97N/ 85°55'59.02W	-53	441	0.98	1.20	0.75	0.51	0.81	1.00	1.04	1.95	1.35	1.36
Buchanan Lake	79°27'54.10N/ 87°43'17.93W	-102	483	1.08	1.21	0.82	0.49	0.88	1.00	1.14	2.04	1.51	1.33
Average				*1.04*	*1.19*	*0.74*	*0.51*	*0.86*	*0.98*	*1.18*	*1.92*	*1.37*	*1.36*
Spitsbergen Lundstromdalen	78°1'17.21N/ 17°16'47.41E	-11	-6	1.45	1.66	1.32	1.45	1.36	1.30	1.27	1.57	1.84	2.21
Storknausen	78°1'36.91N/ 17°24'4.04E	-7	-6	1.49	1.66	1.34	1.45	1.38	1.30	1.31	1.57	1.86	2.21
Average				*1.47*	*1.66*	*1.33*	*1.45*	*1.37*	*1.30*	*1.29*	*1.57*	*1.85*	*2.21*

Table 6 Total precipitation for the paleoclimate proxy data locations spanning the Aptian and Albian stages. All values are mm/day.

Location	Latitude/ Longitude	Model Elevation (m)		Mean Annual Precip-Evap mm/day		Winter Precip-Evap mm/day		Spring Precip-Evap mm/day		Summer Precip-Evap mm/day		Autumn Precip - Evap mm/day	
		Albian	Aptian	Albian	Aptian	Albian	Aptian	Albian	Aptian	Albian	Aptian	Albian	Aptian
Canadian Arctic Roll Rock Valley	81°24'14.92N/ 79°47'5.72W	-49	501	0.93	1.29	0.72	0.57	0.78	1.05	1.60	2.04	1.45	1.51
Eureka	79°59'59.97N/ 85°55'59.02W	-53	441	1.01	1.33	0.73	0.54	0.71	1.10	1.13	2.21	1.33	1.46
Buchanan Lake	79°27'54.10N/ 87°43'17.93W	-102	483	0.84	1.27	0.73	0.48	0.62	1.05	0.62	2.24	1.20	1.33
Average				*0.93*	*1.30*	*0.73*	*0.53*	*0.70*	*1.07*	*1.12*	*2.16*	*1.33*	*1.43*
Spitsbergen Lundstromdalen	78°1'17.21N/ 17°16'47.41E	-11	-6	0.14	0.88	0.65	1.09	0.86	0.98	-1.24	0.24	0.41	1.22
Storknausen	78°1'36.91N/ 17°24'4.04E	-7	-6	0.22	0.89	0.65	1.09	0.86	0.98	-1.06	0.24	0.51	2.11
Average				*0.18*	*0.89*	*0.65*	*1.09*	*0.86*	*0.98*	*-1.15*	*0.24*	*0.46*	*1.67*

Table 7 Total precipitation-evaporation for the paleoclimate proxy data locations spanning the Aptian and Albian stages. All values in mm/day.

In order to allow direct comparison of the GCM results and the paleovegetation proxy data, we have run an offline vegetation model called Biome4 forced by the GCM climate, as has been done in previous pre-Quaternary climate studies (e.g. Salzmann et al, 2008). The Biome4 model is a biogeochemistry-biogeography model (Kaplan et al., 2003) for which one model run is shown. The Biome4-CO_2 results (Fig.7 i) show the biomes present as calculated by the model, with climate generated by the GCM and CO_2 set at 4* preindustrial values. We also include the Köppen classification scheme results as this scheme is more widely used within the geological community (Peel et al., 2007). This classification is based on the average annual precipitation, average monthly precipitation and average monthly temperature. The full Köppen scheme (Fig.7 ii) includes 30 climate regions (only those shown on the charts are included in the legend here, Fig. 6) based on the original Köppen-Geiger Scheme (Köppen, 1936 updated by Peel et al, 2007), plus water and H = cold, high altitude. The basic Köppen results (Fig. 7 iii) uses six letters to divide the world into six major climate regions, Tropical Rainy - A, Dry Climates - B, Warm Temperate Rainy - C, Cold Boreal Forest -D, Tundra/Polar, E and Cold (High Altitude) - H, plus water (again only those shown on the charts are included in the legend here).
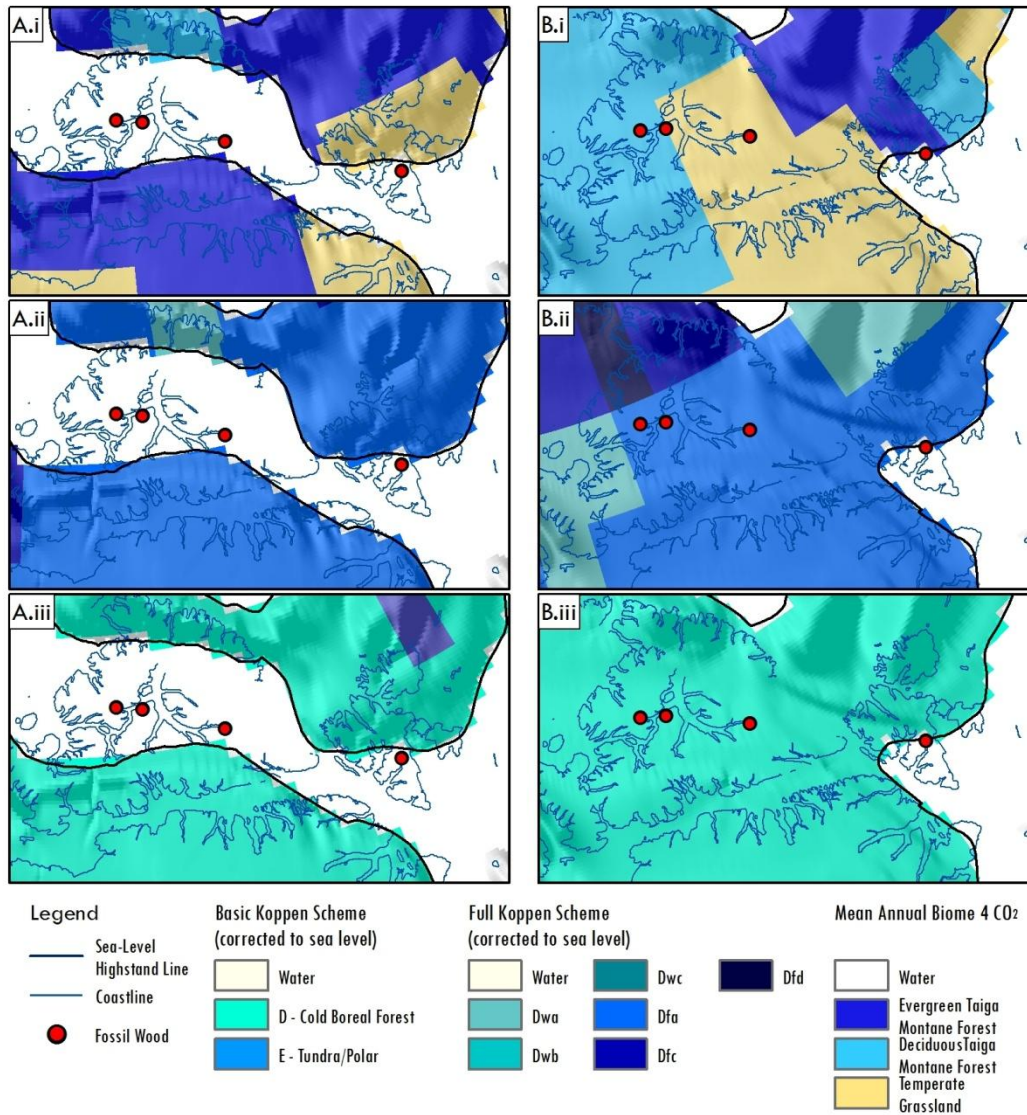
Figure 7. Biomes model results **A)** Albian. **B)** Aptian. i) Biome4 CO_2, ii) Full Köppen, iii) Basic Köppen. Full Köppen codes: Dwa = cold, dry winter, hot summer; Dwb = cold, dry winter, warm summer; Dwc = cold, dry winter, cold summer; Dfa = cold, without a dry season, hot summer; Dfc = cold, without dry season, cold summer; Dfd = cold, without dry season, very cold winter. Grey shading indicates the underlying high-resolution topography.

For the Albian, all paleoclimate proxy data locations were offshore therefore are not modelled directly, but the Biome4-CO_2 (Fig. 7 i) results show that the Spitsbergen wood locations were close to lowland temperate grassland regions and the probable elevated

source areas were evergreen taiga/montane forest (Fig. 7). It should be noted that the climate regions within the model are based on Present Day flora but grasslands had not evolved at this time (although included in the legend). Temperate grasslands, in this instance, therefore represents a unknown ground cover vegetation that tolerated similar conditions to temperate grassland today, probably something like an *Equisetum*-type low-lying vegetation. The model shows that the Canadian Arctic wood locations were surrounded by hills mostly made up of evergreen taiga/montane forest during the Albian although there may have been some deciduous taiga areas to the north. The Aptian Biome4-CO_2 model results at the Spitsbergen sample sites are close to evergreen taiga/montane forest areas although some elements of deciduous taiga and temperate grassland may have also been present. In contrast the models show that during the Aptian of the Canadian Arctic the Ellesmere Island sites were located on temperate grassland with Roll Rock Valley close to both evergreen and deciduous taiga and Eureka very close to deciduous taiga. The Buchanan Lake sample site was in an area of deciduous taiga with temperate grassland close by.

The Full Köppen charts (Fig. 7 ii) for both the Aptian and Albian show that the paleoclimate proxy sites were close to or within areas that were cold, without a dry season and with hot summers (Dfa on Fig. 7). These areas may have had a microthermal environment with average temperature above 10°C in the warmest month and coldest month equal to or less than 0°C. Modern equivalents usually occur in the interiors of continents and on their upper east coasts, normally north of 40° North latitude. This classification suggests significant precipitation in all seasons and the warmest month average temperature above 22°C with

at least 4 months averaging above 10°C. The westernmost sites (Buchanan Lake and

Eureka) may have also contained elements from areas with colder summers (Dfc on Fig.7 ii)

and/or extremely severe winters (Dfd on Fig. 7 ii) during the Aptian. These westernmost

sites may also have included wood brought in from areas with dry winters and hot summers

(≥22°C; Dwa on Fig. 7 ii) in the Albian. The Basic Köppen charts show all areas within the

cold boreal forest zone D (Fig. 7 iii).

Both Albian and Aptian model results of mean annual sea ice thickness (Fig. 8 A i and B i)

indicate that sea ice was present for at least part of the year. The ice appears to have

remained relatively thin, being less than 1m thick. Further investigation shows that during

the Albian the sea ice formed in the area of interest in the winter and spring before

shrinking back to cover a smaller region further north in the summer with only small patches

remaining in offshore Russian Federation areas by the autumn. During the Aptian sea ice

was present during the winter and spring but melted from the Spitsbergen area by summer,

although it remained in the Canadian Arctic. The sea ice melted completely by autumn from

this region, remaining only around the current site of the far northeast of Russia.

The models indicate that snow was present at the surface during the Aptian and Albian (Fig.

8). Despite the low temperatures the snowfall was relatively low, being less than

0.1mm/day in most areas with small patches up to 0.4 mm/day. This was probably due to

the atmosphere being dynamically stable, with sinking cold air from the Polar regions

preventing precipitation due to decreased capacity to carry water vapour. The general

trend shows that the sea ice thickness was similar for both Stages, there was less snowfall

onshore during the Albian (Fig. 8). Seasonal charts indicate that during both the Albian and

Aptian the vast majority of this snow fell in the winter and spring, no snow remained in the summer and only very small patches were present in the Canadian Arctic in autumn.
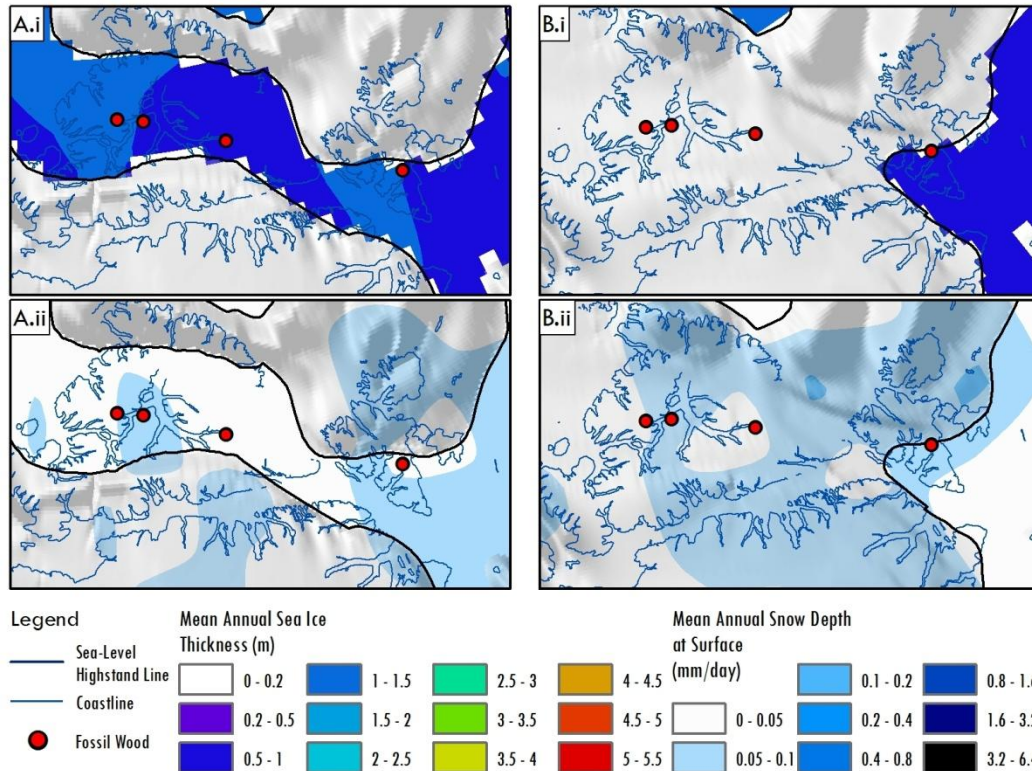
Figure 8. A) Albian. **B)** Aptian. i) mean annual sea ice thickness in m; ii) mean annual snow depth at surface in mm/day. This is the amount of snow expressed as water equivalent. Precipitation is considered to fall as snow when the temperature of the lowest atmospheric level falls below 273 Kelvin (-0.15 $^{\circ}$C) (ii). Grey shading indicates the underlying high-resolution topography.

DATA-MODEL COMPARISON

In this section we compare paleoclimate data from the analysis of fossil conifer wood from the Northern Hemisphere Arctic region (Spitsbergen, Ellesmere Island and Axel Heiberg Island (Fig. 3)) with the outputs from the HadCM3L GCM. It should be noted that the nearest living relatives of the conifers examined within this study have wide temperature tolerance ranges and the model-data comparison is carried out with this in mind.

Seasonality and Temperature

The seasonality shown by the growth rings within the fossil wood is reflected in the atmospheric temperature from HadCM3L (Fig. 4), which shows a marked difference between summer and winter temperatures. The modelled temperatures initially seem to be too cold for forests to survive in these regions, with the Canadian Arctic experiencing the lowest winter average temperature of ~-34°C. However, modern vascular plants such as evergreen conifer species are highly tolerant of freezing to -40°C or lower so long as they have favourable summer conditions (Kappen, 1993). Modern *Taxus* can survive temperatures of -35°C (Thomas, 2008) and *Larix* down to -50°C (Vidaković, 1991), at least for part of the year. Even the lowland swamp dwelling genus *Taxodium* is able to survive temperatures of -30°C (Vidaković, 1991) therefore it's fossil equivalent *Taxodioxylon* on Spitsbergen could probably have survived the temperatures produced by the model (average winter minimum temperature ~-28°C).

Consistency of Growing Season and Water Supply

The Mean Sensitivity analysis of the fossil wood indicates that there was mostly adequate water supply for consistent growth. There are some samples that produce a sensitive signal and/or false rings, suggesting that there were periods or areas that experience harsher climatic conditions for at least part of the year. The lower growth rates shown in the tree rings in the Canadian Arctic samples compared to the Spitsbergen samples support the modelled precipitation results which indicate that conditions were less favourable here than on Spitsbergen.   The low precipitation and temperature that occurred in the model over the

winter would have made it the most likely period to have stressed the trees into producing

drought rings. However, conifers can still uptake water under snow in the winter (Kappen,

1993) which reduces water stress and there may have been high water levels remaining

under the snow cover. The trees would then have had a check to their growth in the spring

as ground water levels fell and temperatures began to rise which is seen in the Canadian

Arctic where most of the false rings observed in the spring wood.   Precipitation increased in

the summer months and it would be expected that the trees would have had adequate

water for normal complacent growth in most areas. However, these may have also grown

on exposed sites with steep topography, little or no ground cover vegetation and thin soils,

making it difficult to retain moisture during warm periods as seen in the Canadian Arctic

where drought rings also occur in the summer wood. The P-E results indicate that this

region was prone to arid conditions during parts of year making any site susceptible to

producing drought formed false rings particularly in the Aptian winter and at Buchanan Lake

during the Albian spring and summer. False rings in the Spitsbergen samples occur mostly in

summer although some are also present in early autumn and spring. As with the Canadian

Arctic, the false ring production seen in the wood in spring supports the low precipitation

seen in the winter and spring periods within the HadCM3L results. The summer and autumn

months have relatively high precipitation in the models for this region, which is in

agreement with the complacent conditions suggested by the Mean Sensitivity analysis of

the fossil wood.   However the P-E results indicate that evaporation was extremely high

during the summer months during both Stages and in the Albian exceeded precipitation

which would have led to drought conditions. Most of the genera that produced false rings

in this area are those which are likely to have grown in exposed drought-prone sites as in

the Canadian Arctic (*Laricioxylon* and *Juniperoxylon*). The low lying regions probably

retained water in the water table because *Xenoxylon* is thought to have preferred wet

conditions (Philippe et al., 2009) and the sample from Spitsbergen does not contain false

rings. However, there is also a *Taxodioxylon* sample containing false rings a tree type which

is thought to have preferred lowland, moist, swampy sites. This may have produced false

rings due the site of growth being in a disturbed area with fluctuating water availability. The

Taxaceoxylon containing false rings may have been struggling to produce normal growth

during the warm summer months as the modern equivalent prefers cool temperate

conditions.

Biomes

The environmental setting suggested by the fossil wood, for the Aptian of Spitsbergen

indicates that the area was a moist cool upland next to warm temperate lowlands. The

Biome4-CO_2 (Fig. 7 i) model results are close to this interpretation with the sample sites

being near to an area of evergreen taiga/montane forest with both deciduous

taiga/montane forest and temperate grassland biomes adjacent to it. The fossil wood

indicates that the forests were 85% evergreen and 15% deciduous, in agreement with the

forest composition suggested by the GCM. Although the results of the HadCM3L for the

Albian are similar to those for the Aptian, they do not include a deciduous taiga/montane

forest element, making them close to the fossil wood sample composition from the lower

part of the mid-Cretaceous Carolinefjellet Formation. The Canadian Arctic Biome4-CO_2

model results, as expected, provide a better fit to the fossil wood data for the Albian than

the Aptian. For both Stages the models show that montane forest was present (deciduous

and evergreen taiga) but the Aptian has a much higher proportion of deciduous taiga and

also contains temperate grassland areas which are not reflected in the fossil flora. The NLR

analysis suggests a cool/cold temperate environment, possibly similar to northern Canada

today, with the fossil wood indicating that the forests were predominantly evergreen (90%).

The Aptian model results suggest that all the trees would have been deciduous in the

Buchanan Lake and Eureka locations but these sites contained wood with only evergreen

signal. This evergreen signal matches more closely the Albian GCM results in that they show

predominantly evergreen taiga/montane forest with a much smaller element of deciduous

taiga/montane forest to the north.

The model results of the full Köppen classification also produce a reasonable fit to the

paleoclimate indicated by the fossil wood. Both stages are predominantly modelled as Dfa

which is defined as cold microthermal with average temperature above 10°C in the warmest

months and coldest months equal to or less than 0°C (Fig. 7ii; Peel et al., 2007) which meets

the requirements of the fossil genera. This result also suggests that there was no dry

season. The models indicate an area of Köppens Dwa during the Albian, close to the

western sites of Buchanan Lake and Eureka. This classification is also cold but with dry

winters (driest winter month average precipitation less than one-tenth wettest summer

month average precipitation). The warmest month average temperature is given as >22°C in

this classification (Peel et al., 2007). This is in accordance with the drought rings produced

by the samples from this area but not within those from further east in Roll Rock Valley and

on Spitsbergen. However, during the Aptian Roll Rock Valley and Spitsbergen were slightly

closer to areas of Dwa which may have contributed the samples displaying false rings. The

Canadian Arctic sites were also close to areas of Dfc and Dfd Köppen classification during

the Aptian. These classifications are defined as being cold with no dry season and cold

summers (Dfc) and cold, without a dry season and very cold in winter (<-38; Dfd) (Peel et al,

2007). The Basic Köppen classification suggests that all the sample areas were within the

cold boreal forest zone. This matches reasonably well with the Canadian Arctic samples

which are thought to have been growing in an areas with a similar climate to northern

Canada today which is predominantly boreal, although probably too cold for the

Spitsbergen trees.

The climate model results support the occurrence of seasonally cold conditions in the high

latitudes during the mid-Cretaceous (Mutterlose et al., 2009), rather than fully glacial

conditions. This seasonal cold allows for the formation of glendonites which require the

temperature to be <5°C (Harmon et al., 2004; Herrle et al., 2015). However, the modelled

sea ice suggests it may not have been thick enough or present long enough to allow for the

deposition of ice rafted deposits (Francis and Frakes, 1988, Markwick and Rowley, 1998).

CONCLUSIONS

The widespread occurrence of high latitude mid-Cretaceous (Albian-Aptian) forests makes

them a valuable tool for assessing the prevailing conditions at the time of growth and for

validating climate simulations from GCMs.

Fossil wood analysis suggests that the forests were predominantly evergreen, growing under seasonal and generally favourable climatic conditions for constant growth.   Most of the trees appear to have had adequate water throughout the year but Spitsbergen may have had the potential to dry out quickly.

The modelled temperature and precipitation from the HadCM3L GCM also indicate a seasonal climate with cold winters and warm summers. Modelled precipitation indicates that the winter was probably drier than the summer for both sites. However, evaporation was much higher in the summer leaving less available precipitation for plant uptake than in the winter. Elevated areas received higher precipitation, producing runoff which supplied water to lower-lying areas and led to periodic water stress in the elevated areas. The HadCM3L Biome4 model suggests that all proxy sample sites on Spitsbergen were close to lowland temperate grassland with elevated areas of evergreen taiga/montane forest during the Albian. The Canadian Arctic wood sites were also close to evergreen taiga/montane forest areas during the Albian with some deciduous taiga as a possible additional source area in the west of the area. The basic Köppen Classification suggests the entire area was covered by cold boreal forest during the mid Cretaceous. The full Köppen Classification indicates that the region was cold with no dry seasons and hot summers although western areas may have had elements of colder summers and extreme winters during the Aptian and dry winters with hot summers in the Albian. Model results of sea ice thickness indicate that sea ice was present during the winter and spring and continued into the summer in the Canadian Arctic during the Aptian.

The results from the HadCM3L GCM produces climatic conditions that could have supported the forests identified in the fossil wood from the high northern latitudes during the Aptian-Albian. In addition the results indicate that there were no permanent ice sheets present at this time. This suggests that the model produces climatic conditions consistent with the survival of the forests indicated in these previously difficult-to-model high latitude regions.

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