

## ***Interactive comment on “Stable isotope signatures of Holocene syngenetic permafrost trace seabird presence in the Thule District (NW Greenland)” by Sebastian Wetterich et al.***

**Sebastian Wetterich et al.**

sebastian.wetterich@awi.de

Received and published: 12 September 2019

Comments on manuscript by Wetterich et al. submitted to Biogeosciences. The manuscript is well written and fairly well illustrated and the subject is suitable for Biogeosciences.

REPLY: We are grateful to referee #2 for the time and effort spent on reviewing our manuscript.

However, the authors need to refer to previous work carried out in the area. Over 30 radiocarbon ages from peat deposits below sea-bird colonies from the Thule region

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were reported by Delibrias et al. (1972) and discussed by Malaurie et al. (1972). The peat deposits were also discussed by Salomonsen (1979). The authors could also refer to a paper by Burnham et al. (2009). Malaurie et al. discussed peat accumulation rates – an issue also discussed by Wetterich et al. The oldest ages reported by Malaurie were ca. 1500 years BP. Wetterich et al. have ages going back to ca. 5000 years. I wonder if the lack of older ages is due to the sampling methods? I would assume that sea birds colonised NW Greenland already in the Early Holocene, but I agree that colonies expanded during the Late Holocene. We know from radiocarbon dating of shells of marine molluscs in the region that there was a rich marine invertebrate fauna already in the Early Holocene. And of course there are also very large sea-bird colonies in other parts of Greenland.

REPLY: We agree that Early Holocene seabird colonisation in NW Greenland is likely for some species although dated records are very rare. Arrival dates as old as in our study, with about 5.6 cal kyr BP for thick-billed murre at Appat (Saunders Island) and 4.4 cal kyr BP for little auk at Annikitsiq (north-west of Cape York), have not been reported previously for these species in the Baffin Bay region. Peat deposits on Nordvestø of the Carey Islands (also in the North Water polynya (NOW) region, likely related to Atlantic Puffin (*Fratercula arctica*) colonies, were dated to 7.1 to 5.1 cal kyr BP (Bennike et al., 2008). For this record, Outridge et al. (2016) emphasise the role of marine derived nutrients (MDN) and trace element input from seabirds for peat formation over 2000 years. A similar peat formation from Nordvestø was dated between 6.3 and 4.4 kyr BP, but it was mainly studied with focus on fossil diatom ecology and the possible relation to seabirds was not considered in the paper (Brown et al., 1994). Burnham et al. (2009) provide evidence of Gyrfalcon (*Falco rusticolus*) presence in the Thule District from at least 690-530 cal yr BP. The study by Salomonsen (1979) on seabird colony ecology was undertaken in SW Greenland in the Low Arctic Zone (as opposed to our setting in the High Arctic) and lacks therefore also the control of the North Water polynya dynamics on seabird populations that we emphasise in our study. The Nordvestø 6.3 to 4.4 kyr BP peat record mentioned above is, however, shortly discussed in

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Salomonsen (1979). Thus, considering the recommended literature, a direct comparison of our study to Bennike et al. (2008), Outridge et al. (2016), Salomonsen (1979) and Burnham et al. (2009) is not applicable, because other bird species and/or areas and/or time periods were studied. Malaurie et al. (1972) published peat formations from the Thule District related to the same bird species as in our study, but as stated by the authors they most likely did not cover the entire peat sequence at the different sites: "For strictly operational reasons, the depth of the [peat] monoliths did not exceed 82 cms. It is possible, though not certain that [...] the sampling pit could have been deepened further and that the earliest phase of peat formation could have been older [...]" (pp. 108, Malaurie et al., 1972). We have visited several of the sites sampled by Malaurie et al. (1972), and at least at Savissivik the peat layers are certainly thicker than 82 cm. Thus, the oldest dates with possible seabird control on peat accumulation from Malaurie et al. (1972)/Delibrias et al. (1972) are much younger than in our records, ranging from 1860 yr BP to 1060 yr BP. The peat accumulation rates reported by Malaurie et al. (1972) are relevant for comparison with our findings, but the results treated with caution. In detail, the little-auk-affected peat record of the site Idglolorssuit in Malaurie et al. (1972) suffers from distinct age reversals except for the uppermost and the lowermost samples and seems therefore less useful to deduce accumulation rates. The same is true for Malaurie's peat record from Savigssivik that lacks chronology. Own observations and our interpretation of the site Ivssugissok (Parker Snow Bay) in Malaurie et al. (1972) doubt its alignment to the thick-billed murre colony as stated by the authors. The thick-billed murre colony is situated at a vertical cliff that drops directly into the ocean. Please look at the map inserted below (Figure R1), where the murre colonies are indicated by blue dots. About the location of their peat site, Malaurie et al. (1972) write: "At Ivssugissok (near Cape Dudley Digges) from the first slopes north of the bay 1 km from the glacier ...". As we understand this description, they would have taken their peat sample close to the actual place name "Issuvissooq", which is just the new spelling of the place name Ivssugissok that they use, or alternatively just north of Cape Dudley Digges. Either way, this is far from the thick-billed murre colony,

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and based on our GPS-tracking of murres from this colony no murres would fly over the sites (they head directly from the colony SW to open sea and back). On the other hand, it looks like Malaurie's site could well be from inside or near a little auk colony (the red polygons on the map). In conclusion, we would re-interpret Malaurie's peat deposits at Ivssugissok as being generated by little auks, instead of thick-billed murres. There is a further complication though: Ivssugissok is an old abandoned Inuit settlement. If the peat samples were extracted close to the settlement, peat growth might also have been influenced by nutrients brought to the site by humans, at least from 1200/1400 AD and onwards. From Malaurie's publication, it appears that they extracted the samples at Ivssugissok in April. The birds do not arrive in the colonies till early/mid May, so that may be the reason why they have misinterpreted the situation. For these reasons, only the little auk colony site at Iita from Malaurie's dataset (which is also the longest record) seems appropriate to refer to, which we did as follows in section 5.1: "The spatial distribution of the polygonal peat development is related to seabird colonies. Peat records published by Malaurie et al. (1972) from a little auk colony site at Iita at the northern edge of the NOW polynya indicate continuous peat growth since 1795 cal yr BP years (Delibrias et al., 1972; calibrated using INTCAL, CALIB REV7.1.0, Stuiver and Reimer, 1993; Reimer et al., 2013) at a mean accumulation rate of 37 yr cm<sup>-1</sup> over the entire section of 52 cm. This rate is similar to the value of 38 ± 12 yr cm<sup>-1</sup> obtained from the uppermost GL3-III core zone of the Annikitisoq core dated from 2620 to 540 cal yr BP (Table 2). Malaurie et al. (1972) interpreted their data as "... the rate of growth of the peat deposits shows high degree of dependence upon local conditions ...". This is supported by the present study, which also emphasises variation in peat accumulation over time dependent on local conditions."

The authors describe some of the cores as brown moss peat. I wonder if the mosses were identified? The peat on Nordvestø consists of *Aplodon wormskioldii*, which is a most uncommon fossil species. I wonder if the other peat deposits in the Thule region are also dominated by this species? On page 10, line 35 we hear about *Polytrichastrum alpinum*, which is present in the GL3 core. Does it dominate?

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REPLY: We identified only exemplarily some on the mosses for dating issues. In this context, *Polytrichastrum alpinum* was observed in core GL3, but it remains unclear whether it dominates or not.

Page 2, line 8. How many pairs of thick-billed murre?

REPLY: Added to section 1: "The thick-billed murre population of the Thule District is estimated to approx. 225.000 breeding pairs, accounting for 68 % of the Greenlandic breeding population of the species (Merkel et al. 2014)."

Page 2, line 33 and 34. I prefer use rather than employ

REPLY: Changed accordingly.

Page 3, line 18. Please provide data on the elevation of the sites. Are the sites below or above the marine limit?

REPLY: Added to section 2: "Based on the GIMP Digital Elevation Model (Howat et al., 2014) and the geoid EGM2008, sample sites GL3 and GL3-IW at Annikitsiq are 22.1 m above mean sea level, whereas sample site SI1 on Appat is 14.2 above mean sea level. All three sites are well above the marine limit."

Page3, line 24. Please provide data on the local vegetation as you observed in the field. Grasses and sedges are much more important than rushes in the area. Not sure about dwarf shrubs at the actual sampling sites.

REPLY: Unfortunately, we did not conduct a systematic description of the current vegetation at the sample sites. We added our field observations to section 2 as follows: "In the little auk colony at Annikitsiq, the general vegetation pattern corresponded very closely to the vegetation pattern in the little auk colony of Qeqertaq (Salve Island), which is described in detail in Mosbech et al. (2018) and seems to be representative of most little auk colonies in Southern Thule without muskoxen. Thus, up high, close to the boulder scree where the little auks nest, the vegetation was dominated by foxtail grass and chickweed, whereas further down the slope, where the GL3 core

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was extracted, the vegetation solely consisted of mosses and lichens (corresponding approx. to the 150 m mark on the vegetation transect in Fig. 3 of Mosbech et al., 2018). Mosses dominated the centre of the GL3 polygon, where the coring took place, whereas the lichens dominated the surface at the periphery of the polygon (Fig. 2a-c). We observed no dwarf shrubs at Annikitsiq, and it is our general impression that dwarf shrubs are absent in areas under heavy influence of little auks. The vegetation at the sampling site at Appat was more diverse, with mosses and foxtail grass at the centre of the polygon, where the SI1 core was extracted, and a mixed community at the periphery of the polygon consisting of Arctic willow, foxtail grass, chickweed and Arctic poppy (Fig. 2e)."

Page 4, line 2. How do you know you reached bedrock? Could it be stones or boulders? From the photos it appears that both sampling sites are located in areas with thick gravel deposits.

REPLY: This concern was also raised by ref#1. We stopped drilling when we hit boulders, larger than the drill tube diameter, whose density we assume to increase at the transition between the overlying peat and the underlying bedrock. We therefore assume the lowermost (oldest) peat to be close to the bedrock surface. Thus, we almost captured the entire peat profile at the given location, although we did not probe the bedrock basement. We added the following specification to section 3.1: "Extensions were used to reach deeper deposits until the corer hit boulders, larger than the drill tube diameter, whose density increased at the transition between the peat and the underlying bedrock."

Page 5, line 4-10. More information on testacean analysis is needed. How many specimens were counted per sample? What was the sample size? It would be nice to see some testacean diagrams.

REPLY: We added the following information to section 3.4: "Samples of about 1 g (dry weight) for testacean analysis were suspended in purified water and wet-sieved

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through a 500- $\mu$ m screen.” The general agreement is that direct counting recovers from a sample only a certain fraction of species diversity. Thus, higher numbers of identified specimens per sample enlarge the probability that all species present in the assemblage are captured. However, in testacean research, this approach entails enormous effort for samples with low shell density. The standard quantity of observed individuals customary in protistology is 160 specimens, but this amount is not applicable to all fossil communities. The quantity, i.e. number of observed testacean individuals, depends on the original community species richness, on the presence of dominant species and species abundance structure, on the density of testacean organisms in soil, and on the amount of shells damaged owing to fossilisation processes. Also patchy distribution of testate amoebae reflecting habitat heterogeneity may affect the process of recovering species. In fossil samples with poor testacean density, the interpretation focuses on the ecological groups combining species with similar requirements in habitat and environmental conditions. Due to low shell densities in the studied cores, we chose this approach leading to the presentation of ecological groups in Figures 4 and 5 and cautious interpretation of these records in section 5.1. A percentage diagram seems useless due to the low count number per sample. We added the count number as Supplementary Material (Tables S1 and S2) and the following information to section 3.4: “Count numbers of testacean shells per sample were generally low (Tables S1 and S2). Thus, the interpretation is cautiously based on the ecological groups combining species with similar requirements under specific habitat and environmental conditions.”

Page 5, line 14. The succession was divided into three zones

REPLY: Changed accordingly.

Page 5, line 28. Is there only one testacean assemblage in the whole core?

REPLY: Changed to “testacean record” while the differing species assemblages along the core are described further down the ms text.

Page 7, line 3-4. Intense deglaciation occurred in the Early Holocene, long before the

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Holocene Thermal Maximum – due to abrupt warming at the Younger Dryas-Holocene transition. With respect to the deglaciation chronology see Bennike & Björck (2002).

REPLY: Changed accordingly to: “The abrupt warming at the Younger Dryas-Holocene transition promoted intense deglaciation in Arctic Canada and Greenland (Briner et al., 2016) and left large parts of the northern Baffin Bay coastlines free of glacial ice from the Early Holocene (Bennicke and Björck, 2002).”

Page 7, line 5 9.9 and 9.2 kyr BP – not yr BP!

REPLY: Changed accordingly.

Page 7, line 3-8. According to the compilation by Bennike & Björck (2002) the two study sites were deglaciated before 10 cal. kyr BP

REPLY: We appreciate the literature recommendation of Bennike & Björck (2002). Indeed, Bennike & Björck (2002) present radiocarbon dates of Early Holocene deglaciation from the Wolstenholme Fjord area of 10.6 and 11.2 cal kyr BP. We therefore added the following statement to section 5.1: “Early Holocene deglaciation of the Wolstenholme Fjord area was dated to 11.2 and 10.6 cal kyr BP (Bennike and Björck, 2002). Radiocarbon-dated marine bivalves in raised marine deposits on Appat although at a different location as our study site show ages between about 9.9 and 9.2 cal kyr BP (Farnsworth et al., 2018) in agreement with modelled deglaciation data for the Greenland ice sheet according to which both Appat and Annikitsiq became ice free around 10 to 9 cal kyr BP (Lecavalier et al., 2014).”.

Page 11, line 23. I think the main difference is the number of little auks compared with thick-billed murre. Also the different nesting places as mentioned by the authors.

REPLY: Agree. We added the following statement to section 5.2 to capture this point: “The difference in peat accumulation rates between the sites might relate to the different colony sizes, the little auk colony being much larger than the thick-billed murre colony, as well as to the different preferences of the two bird species with regard to

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location of breeding sites.”

References to our replies Bennike, O., Björck, S.: Chronology of the last recession of the Greenland Ice Sheet, *Journal of Quaternary Science*, 17, 211-217, 2002. Bennike, O., Goodsite, M., Heinemeier, J.: Palaeoecology of Holocene peat deposits from Nordvestø, north-west Greenland, *Journal of Paleolimnology*, 40, 557-565, 2008, DOI: 10.1007/s10933-007-9181-3 Brown, K.M., Douglas, M.S.V., Smol, J.P.: Siliceous microfossils in a Holocene, High Arctic peat deposit (Nordvestø, northwestern Greenland), *Canadian Journal of Botany*, 72, 208-216, 1994. Burnham, K.K., Burnham, W.A. & Newton, I.: Gyrfalcon *Falco rusticolus* post-glacial colonization and extreme long-term use of nest-sites in Greenland, *Ibis*, 151, 514-522, 2009. Delibrias, G., Guillier, M.T., Labeyrie, J.: Gif natural radiocarbon measurements VII, *Radiocarbon*, 14, 280-320, 1972. Howat, I.M., Negrete, A., Smith, B.E.: The Greenland Ice Mapping Project (GIMP) land classification and surface elevation datasets, *The Cryosphere*, 8, 1509-1518, 2014. Malaurie, J., Vasari, Y., Hyvarinen, H., Delibrias, G., Labeyrie, J.: Preliminary remarks on Holocene paleoclimates in the regions of Thule and Inglefield Land, above all since the beginning of our own era, *Acta Universitatis Ouluensis, Series A, Scientiae Rerum Naturalium* 3, *Geologica* 1, 105-136, 1972. Merkel, F.R., Labansen, A.L., Boertmann, D.M., Mosbech, A., Egevang, C., Falk, K., Linnebjerg, J.F., Frederiksen, M., Kampp, K.: Declining trends in the majority of Greenland's thick-billed murre (*Uria lomvia*) colonies 1981-2011. *Polar Biology*, 37, 1061-1071, 2014. Mosbech, A., Johansen, K.L., Davidson, T.A., Appelt, M., Grønnow, B., Cuyler, C., Lyngs, P., Flora, J.: On the crucial importance of a small bird: The ecosystem services of the little auk (*Alle alle*) population in Northwest Greenland in a long-term perspective, *Ambio*, 47(Suppl 2), 226-243, 2018. Outridge, P.M., Goodsite, M.E., Bennike, O., Rausch, N., Shoty, W.: Seabird transfer of nutrients and trace elements from the north water polynya to land during the mid-holocene warm period, Carey islands, northwest Greenland. *Arctic* 69(3), 253-265, 2016. Salomonsen, F.: Ornithological and ecological studies in southwest Greenland (59°46'–62°27'N. Lat.), *Meddelelser om Grønland*, 204(6), 1-214, 1979.

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Interactive comment on Biogeosciences Discuss., <https://doi.org/10.5194/bg-2019-71>, 2019.

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**Table S2** Table S2: Testudae specimen counts per sample from the Apsel core (S1), including an ecological indication of the different taxa

depth interval [cm bs]	zone S1	
	terrestrial	hydrobiontic
0-3	Centropages aereophila	moss-aerophilic
10-13	Centropages aereophila v. minuta	moss-hygrophilic
26-29	Centropages constricta	hydrobiontic
34-38	Centropages constricta v. minima	
52-55	Centropages sylvatica	
64-68	Centropages sylvatica v. minor	
80-84	Cyclopoides eurystoma	
88-92	Cyclopoides eurystoma v. parvula	
100-107	Triopidae cf. callida	
115-120	Triopidae linearis	
138-140	Arcella arenaria v. compressa	
146-148	Nebela linctia	
168-172	Arcella discoides var. difficilis	
176-180		
222-226		
	number of specimens	
	number of taxa	

**Fig. 3.** Table S2