The 4.2 ka BP event in the northern North Atlantic.

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In the northern North Atlantic, the 4.2 ka BP event is evident in lake, bog, marine, glacial, speleothem and tree ring cores with extensive, coherent, and high resolution proxy data for abrupt century-scale alterations of temperature and precipitation. These records extend across the northern North Atlantic, 1900 kms northeast to southwest, from Spitzbergen, Svalbard to Agassiz Ice Cap, Ellesmere Island, including Sweden, Norway, Denmark, Faroe Islands, Iceland and adjacent seas, and Greenland. Adjacent region, high resolution proxy data in Europe and North America provide synchronous and similar records. The proposed article by Bradley and Bakke (cp-2018-162, in review), however, ignores the relevant data from Svalbard, Sweden, Norway, Denmark, Faroe Islands, Iceland, Nordic Seas, Greenland and Ellesmere Island.

In Figure 1, a) - b) are Greenland Ice Sheet Total mass balance and ice volume experiments 5 and 6 from Nielsen et al, 2017 that present an abrupt ca 200 year warming event beginning at ca 4.3 ka BP. This melt spike is synchronous with c), the modelled 4 degree SST cooling spike in the Northwest Atlantic, ca. 4.3-4.1 ka BP (Klus et al, 2017) and with the abrupt NGRIP ca. 5 degree K warm spike ca. 4.5-3.9 ka BP (Gkinis et al, 2014). In d), the Agassiz, Ellesmere Island and Renland, Greenland ice core temperature spike is 3-stage, beginning at 4290 BP, reaching its apogee at 4150 BP, returning to baseline at 3990 BP, and descending to pre-event levels at 3790 BP (Vinther et al., 2009). The sudden GISP2, Greenland temperature spike (Kobashi et al, 2017), although less well-defined, conforms to this event. These six key North Atlantic high resolution and modeled data are summarized in e), which presents the remarkable congruence of the Lake Hajeren, Svalbard, sediment core and the Agassiz, Ellesmere Island ice core. The Lake Hajeren neo-glaciation spike, recognized in minerogenic / glacigenic indicators TDBD (dry bulk density) and Ti/Loss on Ignition z-scores from core HAP0212, extends from ca. 4250 BP to ca. 4100/4050 BP, a calibrated radiocarbon interpolation across two hundred years (van der Bilt et al, 2015). The synchronous Agassiz ice core melt spike extends from ca. 4250 – 3950 BP, with an error of ca. 20 years (Fisher et al, 2012; Lecavalier et al., 2017).

In summary, the Lake Hajeren, Spitsbergen, Svalbard cold glaciation event was synchronous with the Ellesmere Island Agassiz ice core warm melt event 1900 kms distant across the span of Island and adjacent seas and Greenland. The same relationship obtains with the NGRIP warm event (Gkinis et al, 2014) and the modeled Northwest Atlantic Sea Surface Temperature event (Klus et al, 2018): in the northern North Atlantic, cold lake and sea events were synchronous with warm, elevation-corrected, glacier events that extend as far west as Mount Logan, Yukon (Fisher et al, 20128). This curious, highly resolved, 4.2 ka BP event situation has not been discussed previously and there exist neither proximate nor ultimate explanations for it.

Svalbard

The congeries of five relevant lake sediment studies on Svalbard utilizes a variety of paleoclimate proxies, of which the most sensitive display a clear 4.2 ka BP abrupt cooling event. Chironimid analyses from Lake Svartvatnet (Luoto et al., 2017) and a leaf wax study at Lake Hakluytvatnet (Balascio et al., 2018) show no evidence for 4.2 ka BP climate events. In Lake Hakluytvatnet, one study indicates a spike of “increased run off intensity” representing significant sea ice alterations, and a spike in XRF Si/Ti suggests decreased lake productivity “reflecting milder and wetter (i.e., more maritime conditions)” between 4200 and 3700 BP (Gjerde et al, 2018); these are, however, only indirect climate proxies. Definitively, the alkenone paleothermometry at both Lake Hakluyvatnet and Lake Hajeren (van der Bilt et al 2018) are supported significantly by the minerogenic/glacigenic indicators at Lake Hajeren (van der Bilt et al., 2015). A two-step Holocene cooling is defined, “with transitions between ~7.8-7 ka cal. BP and after ~4.4-4.3 ka cal. BP”. The abrupt transition after 4.4-4.3 cal ka BP is “best captured by a 2 degree C temperature decrease between ~4.4-4.3 and 4.2 cal ka BP… with short-lived glacier re-growth in the catchment around 4.25 ka cal. BP” that extended to ca. 4.05 cal. BP (van der Bilt et al 2018).

For the Svalbard 4.2 ka BP event proxies, Bradley and Bakke cite van der Bilt et al., 2015 Lake Hajeren, whereas there are five lake studies from Svalbard. For Lake Hakluytvatnet, Gjerde et al., 2018 is misrepresented, while van der Bilt et al., 2018 for Lake Hajeren and Lake Hakluytvatnet is not mentioned.

Sweden

Adjacent regions’ paleoclimate proxies display similar cold and wet 4.2 ka BP events. Four such records are in Sweden. At Lake Igelsjön, southern Sweden, a lake sediment core revealed “marked and coherent depletions in ^{18}O and ^{13}C at ca 4000 cal BP” (Hammarlund et al, 2003). At Lake Trehörningen, in southwest Sweden, the lake sediment pollen analysis indicates that the warm temperate tree taxa, Tilia (Linden) and Ulmus (Elm), decline beginning at 4K cal yr BP, due to a “a predominantly climatic retreat” (Antonsson and Seppa 2007). In central Sweden, moisture sensitive Scots pines (Pinus sylvestris L.), bog-preserved logs sampled from small lakes, define annual resolution lower lake-levels 2400–2200 BC and 2100–1800 BC (Gunnarsson 2008). Similarly, at Åbuamossen, southern Sweden, a 1561-year tree-ring width chronology was developed from 159 Scots pines. The earliest of three main wet-shifts here is precisely dated 2150-2100 BC, and likely “related to the to the stepwise Mid- to Late Holocene climate transition, during which the condition changed from relatively warm and dry towards cold and moist in the northern hemisphere “(Edvardsson 2016). Synchronous dying off phases during increasingly wet conditions are recorded at Venner Moor, Germany (Eckstein et al., 2010).

None of these Swedish 4.2 ka BP event proxies are mentioned by Bradley and Bakke.

Norway

Four proxies record the 4.2 ka BP event in Norway. At Søylegrotta, northern Norway, calibration of the isotope record from speleothem sample SG93 defines the 3-stage 4.2 ka BP cooling event that began at 4220 BP to 4035 BP with an abrupt temperature increase from 2.8 deg C to 4.6 deg C, i.e., 1.8 deg C in 185 years. This was followed 4035-3730 BP by an abrupt temperature decrease from 4.6 deg C to 1.6 deg C, i.e., 3 deg C cooling across 305 years, and a third stage temperature rise to 3 deg C by 3600 BP (Lauritzen and Lundberg 1999). The second proxy event, also in northern Norway, is a distinct glacier advance reconstructed between 4420 ± 45 and 4300 ± 40 cal. yr BP at Leirdalsbreen that “is suggested to indicate the start of the Neoglaciation at Høgtuva,” (Jansen, et al, 2016). The third Norway proxy is the synchronous glacial advance observed at Austre Okstindbreen, with a dry bulk density spike at 4.2 ka BP, “an event arguably global in scope” (Bakke et al., 2010). The fourth proxy comprises the two lakes at Lofoten Islands that show abrupt transitions to wetter conditions at 4.3 ka BP, as indicated by radiocarbon dated macrofossils, dry bulk density, and sedimentation rates (Balascio and Bradley 2012).

Bradley and Bakke do not mention the Leidalsbreen glacier advance, the Austre Okstindsbreen glacial advance, nor the Lotoften Islands abrupt transitions to wetter conditions. They claim, ll. 228, for Scandinavia, “A review of more than 20 papers shows that none of them indicate any abrupt anomalous change in glacier extent connected to a perturbation of climate around 4.2 ka.” Their examination of the terrestrial evidence concludes, ll. 236, “they all reflect the general decrease in summer insolation over the northern hemisphere and no abrupt transition close to 4.2ka B.P.”

Denmark

Synchronous with the Swedish and Norwegian proxy data, the recently retrieved sedimentary sequence at Filsø, a coastal wetland in western Denmark, indicates an intense, large scale aeolian sand influx at unit III: “a sharp transition to a 15 cm-thick bed of dune-sand which was dated to 4100 ± 200 B.P. and undoubtedly corresponds to the period of enhanced aeolian activity and intense dune movement identified for the same period along the entire western coast of Denmark” (Goslin et al 2018). This Filsø storm period, ca. 4400-3800 BP, may be related to the synchronous northward shift of the Azores Front (Repschläger, et al., 2017).

Bradley and Bakke do not mention the Filsø sediment core.

Faroe Islands

There are three reports of the 4.2 ka BP event from the Faroe Islands. Sediment cores at Streymoy's Lake Starvatn and Sandoy's Lake Lykkjuvøtn have a Zone 4 that begins abruptly at 4200 cal yr BP, according to high resolution radiocarbon dating, with decreases in biogenic silica and increases in sand grains flux, that indicate increase in lake ice and windiness (Andresen et al 2006). Second, a piston core from the Faroe east shelf, previously studied with radiocarbon dates and sedimentation rates, indicates the lowest SST from 4000 BP based on the distribution of planktic and benthic foraminifera, accumulation rates, $\delta^{18}O$ values and calculated temperatures and salinities (Rassmussen, et al., 2010). Third, studies of three Faroese lakes that deployed XRF data, organic matter (TOC and TN), magnetic susceptibility and $\delta^{13}C$ values indicate cooling from 4190 ka BP as judged by higher accumulation rates/increased soil erosion "due to increased influence of e.g., freeze/thaw cycles and thus colder climate" (Olsen et al., 2010).

The possible relationship of these Faroese 4.2 ka BP cooling events to the Hekla 4 eruption (Wastegård, et al., 2018), remains uncertain because the radiocarbon dates (Pilcher et al., 1995) and varve counts (Dörfler et al., 2012) suggest the eruption may have preceded or followed upon the 4.2 ka BP event, but unlikely because "the short residence time of stratospheric sulfate aerosols precludes a lasting influence on the regional energy balance from a single eruption" (Miller et al., 2012:13).

Bradley and Bakke do not mention the three reports of 4.2 ka BP proxy events from the Faroe Islands.

Iceland

The statistical analysis of seven Iceland lake sediment cores documents “episodic glacier expansion between 4.5 and 4.0 ka” (b2k), but “the prominent step toward cooling at 4.5-4.0 ka is statistically indistinguishable from the ~4.2 ka event, and coincides with Hekla 4 (H4), one of the largest explosive eruptions of the Holocene in Iceland” (Giersdóttir et al., 2019). However, “the proxy records from at least these two lakes [SKR and TRK] provide unequivocal evidence for cooling at these times unrelated to tephra-induced soil erosion” (Giersdottir et al 2019). Remarkably, at 4.25 ka BP, the high resolution $\delta^{13}C$ spike recorded at Lake Haukadalsvatn, west Iceland (Giersdottir, et al., 2013) is precisely congruent with the high resolution neo-glaciation DBD spike recorded at Lake Hajeren, Svalbard (van der Bilt et al., 2015).

The low resolution regional marine core temperature variability at this time in the northern North Atlantic is noteworthy (Orme et al., 2018: Fig. 7).The Iceland cryosphere expansion is, however, synchronous with cooling events observed at eight high resolution Nordic Seas marine cores:

(1) core MD99-2322 Kangerlussuaq Trough on the east Greenland margin with a CaCO3 spike dated at exceptionally high resolution at 4.2-3.8 ka BP (Stoner et al, 2007: Fig. 11);

(2) core MD99-2269 taken from the Húnaflóaáll Trough on the north Iceland shelf, with a synchronous high resolution CaCO3 spike (Stoner et al, 2007: Fig. 2); both MD99-2322 and MD99-2269 spikes likely from coccolith and formanifera production at surface water cooling (Giraudeau et al, 2004);

(3) core MD99-2275 from the shelf of north Iceland providing the 320 diatom sample based SST record, with dating constrained by 15 tephra markers, and recording an abrupt ca. 1 deg C cooling ca. 4200-3800 BP (Jiang et al., 2015);

(4) core MD99-2275, the high resolution chronology marine core off north Iceland, displaying a precipitous alkenone paleothermometry measured 1.6 deg C drop at 4.29 ka BP, followed by a 2.5 deg C drop at 4.16 ka BP that extended for 100 years, and then returned to pre-event levels at 4.0 ka BP. (Jalali et al., 2018);

(5) core MD99-2269 off the North Icelandic Shelf where the biomarker IP_{25}-based sea ice reconstruction "reached its mean value for the entire record at ca 5 cal ka BP, before increasing, continuously, ca 4.3 cal ka BP, broadly in line with the onset of Neoglaciation as seen in some other proxy records (Cabedo-Sanz et al., 2016);

(6) core MD99-2269 off north Iceland recording substantial East Greenland and East Iceland Current changes recorded at ca. 4 ka BP based on diatoms and sediment physical proxies (Moros et al., 2006).

(7) core DS97-2P with an abrupt, 3-stage spike in foraminifera Mg/Ca-derived temperature ca. 4.4 -3.9 ka BP cold event and Sub-Arctic Front alteration at Reykjanes Ridge, south of Iceland at (Moros et al., 2012);

(8) core DA12-11/2-GC01from the south Iceland basin providing the diatom-based SST reconstruction with a pronounced SST cooling from ca. 4 – 2 ka BP, with warmer temperatures prior to 4 ka BP and after 2 ka BP (Orme et al., 2018);

Bradley and Bakke do not mention the abrupt cooling events (1), (2), (3), (4), (5), (6), (7) and conclude ll.119 "None of these [paleoceanographic] records show evidence of an unusual anomaly at 4.2ka B.P.", and ll. 127-128 that their "review of paleoceanographic studies ...provides no evidence for a significant change in major oceanographic conditions that could be linked to the 4.2ka B.P. climate anomaly seen elsewhere."

Greenland lakes, east and west

In eastern Greenland, three lake sediment cores record the abrupt 4.2 ka BP event. At Lake Kulusuk, "at 4.1 ka BP , a sharp increase in XRF- and MS-inferred minerogenic content and decrease in organic matter content indicate the glaciers once again grew large enough to contribute minerogenic material to the lake. The regrowth of the Kulusuk glaciers represents the lowering of the regional snowline" (Balascio et al, 2015). Synchronous hydrologic changes occurred at nearby Flower Valley Lake, where "after 4.1 ka, there is a decrease in evaporative enrichment of the lake water. There is also an abrupt transition to more variable sedimentation marked by sharp increases in magnetic susceptibility, C/N, $\delta^{13}C$, and the concentration of long-chain n-alkanes, showing periodic delivery of terrestrial organic matter and clastic sediment to the lake" (Balascio et al., 2013). Synchronously, the physical and geochemical analyses at Ymer Lake, Ammassalik Island, southeast Greenland, demonstrate a "quiescent Holocene climatic optimum," followed by "Neoglacial cooling, lengthening lake ice cover and shifting wind patterns [that] prompted in-lake avalanching of sediments from 4.2 cal. ka BP onwards" (van der Bilt et al., 2018).

Bradley and Bakke mention Kulusuk, Ymer and Flower Valley lakes, but summarize the Lake Kulusuk 4.1 ka BP event, ll. 158-160, as "a short-lived 'event' at around that time … but this appears to be simply part of the overall deterioration in climate that led to ice growth across the region. There is currently no evidence for a more widespread glacial advance at 4.2ka B.P."

In West Greenland eight lakes have been studied. Jakobshavn region lakes were studied with LOI and MS measurements as well as chironomid-based temperature reconstructions. "Gradual, insolation-driven millennial-scale temperature trends… were punctuated by several abrupt climate changes, including a major transient event recorded in all five lakes between 4.3 and 3.2 ka," with a "significant drop in summer temperatures ~ 4.0 ka BP" (Axford et al., 2013). Earlier, at Braya Sø and Lake E lake organic carbon percentage and LOI spikes at 4.2 ka -3.9 ka BP were identified (D'Andrea et al., 2011). The Lake Lucy record, bolstered with bulk sediment radiocarbon dates, suggests that the western GrIS margin was "near its current margin until ~4.2 cal ka BP, at which time the ice margin retreated behind Lake Lucy's topographic threshold. The timing of this transition is marked by a steep rise in regional temperatures recorded in the Kangerlussuaq temperature record" (Young and Briner 2015; D'Andrea, et al., 2011)

Bradley and Bakke do not mention the eight west Greenland lakes 4.2 ka BP event proxies.

Greenland and Ellesmere glaciers

In contradistinction to the Swedish, Norwegian, Danish, Faroe Islands, Iceland, and Greenland lacustrine, marine, speleothem, and tree ring data, there are the four glacial core data from Greenland and Ellesmere Island, reviewed from Figure 1:

a-b) Greenland ice sheet total mass balance exhibits a uniquely abrupt 500 Gt/yr reduction at ca 4.5 ka BP and a bounce back at 4.2 ka BP, accompanied by an ice volume reduction in the modeled glacial data (Nielsen et al., 2017);

c) synchronously, NGRIP temperature experienced an abrupt 6.5 deg K degree warm spike at 4.52 – 3.92 ka BP (Gkinis et al., 2014), while SST modeled in the Northwest Atlantic plummeted 4 deg C (Klus et al., 2018). GISP 2 temperature crashed, then rose 2 deg C at ca 4.3 ka BP, while Agassiz and Renland temperatures jumped 2.5 deg C (Vinther et al., 2009);

d) the very high resolution Agassiz, Ellesmere Island 35% melt record (Fisher et al., 2012) congruent with the Lake Hajeren, Svalbard neo-glaciation proxy that spiked five-fold at 4.2 - 4.0 ka BP (van der Bilt, et al., 2015).

Bradley and Bakke, however, claim:

(1) ll. 170-172 “Ice cores from Greenland provide records of past climate variations from oxygen isotopes, glaciochemistry and physical characteristics, which are broadly consistent with those from coastal lake sediments.”
(2) ll. 188, the GrIS 4.2 ka BP event was plausibly a “short-lived cooling event, a consequence of the massive eruption of Hekla (in Iceland) at ~4.2 ka BP.”
(3) Figure 3 is GISP2 temperature record, when it is the Agassiz/Renland temperature record (Vinther et al, 2009).
(4) ll. 197 “In summary, there is no compelling evidence for a distinct climatic anomaly at 4.2ka B.P. in ice cores from Greenland.”

Linkages

The linkages of these northern North Atlantic 4.2 ka BP events are both extensive and high resolution. The Greenland and Agassiz melt record is synchronous with the 4.2 ka BP event Mt Logan, Yukon ice core melt record, the highest magnitude Holocene event there in the past 4200 years (Fisher et al., 2012), that is in turn linked to especially prominent variations from 4.2 ka BP in the Kuroshio Current, ultimate source of the Yukon westerlies, at the Pulleniatina Event (Zheng et al., 2016), and is precisely synchronous with the Mawmluh Cave record (Berkelhammer et al., 2012). Synchronous, as well, are adjacent 4.2 ka BP North American aridification event records that stretch from the northwest (Cartier et al., 2018) to the northeast (Newby et al., 2014), to Brazil (Soares Cruz et al., 2019), along Andean South America (e.g., Baker et al, 2009; Schimpf et al., 2011) and to Antarctica (Peck 2015).

The Scandinavian cold and wet records are synchronous with adjacent high resolution Alpine records (e.g., Fohlmeister et al, 2012a, 2012b) and the Urals (Baker et al., 2018), and the adjacent high resolution Mediterranean and West Asian ice cave and speleothem records that extend from Spain (Sancho et al., 2018), Greece (Finne et al 2017), the Levant (Cheng et al., 2015), Iran (Carolin et al., 2019), to the Indian Monsoon domains in the Indian subcontinent (Berkelhammer et al., 2012; Kathayat et al., 2018), and to the East Asian Monsoon domains (e.g., Zhang et al., 2018) and Africa, north to south (e.g., Ruan et al., 2016; Chase et al., 2015) as well. In summary, the northern North Atlantic paleoclimate proxies for the global 4.2 ka BP event comprise high resolution data useful for its eventual global explanation. At this juncture, the authors could 1) test the possible mechanisms by which the northern North Atlantic, with its extensive, coherent, and high resolution records, was disconnected from the global climate system at 4.2 ka BP, or 2) test the possible mechanisms by which it was connected.

Conclusion

A recent synthesis for the Arctic concluded that “acceleration of cooling ca. 4.2 ka is uncommon, with a notable (but nonsignificant) peak in cooling onset probability around that time found only in Greenland” (McKay et al 2018). That conclusion, however, was derived from a 2014 compilation (Sundquist et al., 2014) with few updates, and is both out-of-date and erroneous. The Bradley and Bakke “Northern North Atlantic” article that is proposed for CP, concludes ll. 243-

244, 248-251, that “A review of paleoceanographic and terrestrial paleoclimatic data from around the northern North Atlantic reveals no compelling evidence for a significant climatic anomaly at ~4.2ka B.P….Although a few records do show a distinct anomaly around 4.2ka B.P. (associated with a glacial advance), this is not widespread and we interpret it as a local signal of the overall climatic deterioration that characterized the late Holocene.”

Bradley and Bakke ignore, however, the 4.2 ka BP event data from Svalbard, Sweden, Norway, Denmark, Faroes Islands, Iceland, west Greenland, and the relevant Nordic Seas marine core data, and misrepresent the elevation-corrected Greenland Ice Sheet data, the Agassiz ice core data, and the coincidence of northern North Atlantic 4.2 ka BP event glacial melt and lake cooling.

In summary, the proposed article (a) ignores most of the data reviewed here for the 4.2 ka BP event in the northern North Atlantic, (b) misrepresents data in the few cases that are discussed, and (c) fails to identify the regionally coherent feature of the 4.2 ka BP event in the northern North Atlantic: abrupt lacustrine, marine and terrestrial cooling synchronous with elevation-corrected abrupt glacial warm events, as represented in Figure 1. The Bradley and Bakke proposed article does not approach the consensual standards for science publication.

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