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HOLOCENE BOND CYCLES: REAL OR IMAGINARY?

H. Wanner, J. Bütikofer: *Holocene Bond Cycles: real or imaginary?* – Geografie–Sborník ČGS, 113, 4, pp. 338–350 (2008). – During the Holocene (last 12,000 years) nine cold relapses were observed mainly in the North Atlantic Ocean area and its surroundings. Based on the pioneering studies by Bond et al. (1997, 2001) these events are called Bond Cycles and thought to be the Holocene equivalents of the Pleistocene Dansgaard-Oeschger cycles. The first event was the Younger Dryas (~12,000 BP; Broecker 2006), the last one was the Little Ice Age (AD 1350–1860; Grove 1988). A number of trigger mechanisms is discussed (see Table 1), but a theory for the Bond Cycles does not exist. Based on spectral analyses of both, forcing factors and climatological time series, we argue that one single process did likely not cause the Holocene cooling events. It is conceivable that the early Holocene coolings were triggered by meltwater pulses. However, the late Holocene events (e.g., the Little Ice Age) were rather caused by a combination of different trigger mechanisms. In every case it has to be taken in mind that natural variability was also playing a decisive role.

KEY WORDS: Holocene – Bond Cycles – spectral analysis – triggering processes – Little Ice Age

Introduction

The Holocene epoch, commonly considered as the recent interglacial, has sustained the growth and development of modern society. Nevertheless, the knowledge about global climate variability during this period is surprisingly sparse (Mayewski et al. 2004, Wanner et al. 2008). The Holocene climate can be considered in three main phases or time periods (Nesje and Dahl 1993, Marchal et al. 2002). The first includes the Preboreal and Boreal chronozones and lasted from about 11.6 to 9 kyr BP. The second phase, the Hypsithermal, which includes the relatively warm Atlantic chronozone, covers the period between about 9 and circa 5.7 kyr BP. In earlier papers it is also called “Altithermal” or “Holocene climate optimum”. The third phase, including the Subboreal and Subatlantic chronozones, lasted from 5.7 to 0 kyr BP, and is called Neoglacial because it is characterized by several cold relapses with remarkable glacier advances in different areas of the globe. In their pioneering overview Denton and Karlén (1973) showed that the whole Holocene experienced alternating intervals of glacier advances (600–900 yr in duration) and retreats (lasting up to 1750 yr) but, according to their studies, the strongest advances occurred during the Neoglacial around 200–350, 2800 and 5300 cal yr BP (calendar years before present). The authors concluded that the solar activity was a possible trigger for these fluctuations. Observations in the northern (e.g. Dansgaard et al. 1993) and southern mid- to high-latitudes indicate that the climate during the Holocene was rather stationary. In contrast, proxy based reconstructions show that strong

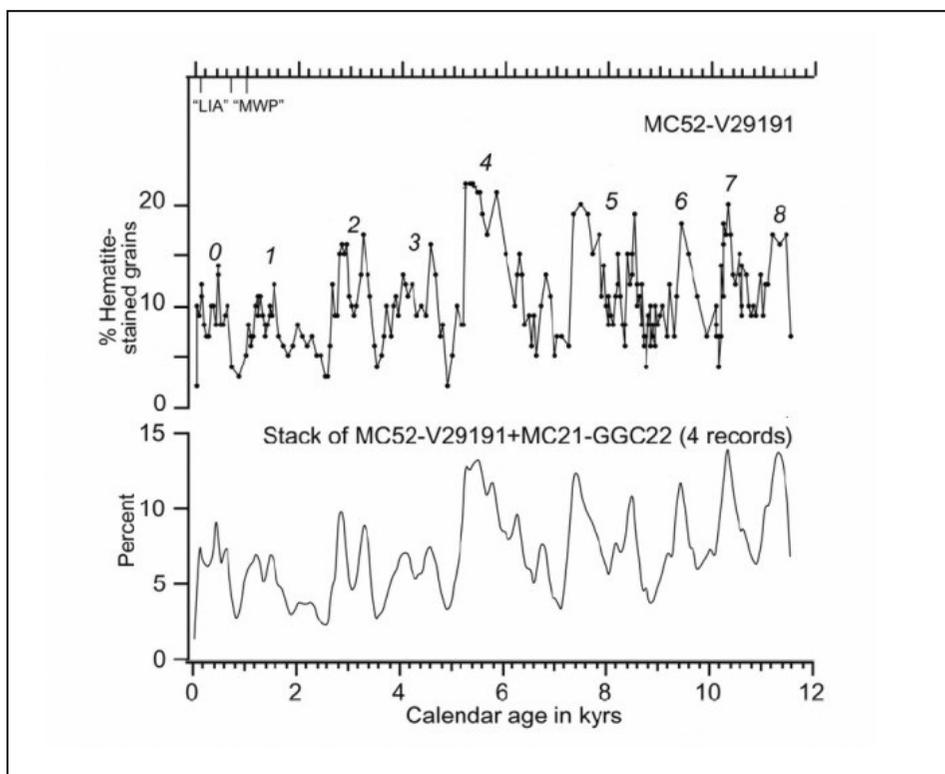


Fig. 1 – Holocene records of drift-ice as percentage variations in petrologic tracers. Upper panel: Hematite stained grains in % in two cores from the same location. Lower panel: Stack of four records at different locations. Bond et al. 1999, modified.

hydrological or circulation changes took place in the tropics and subtropics (Gasse 2000).

A larger progress in the understanding of Holocene climate variability was made by combining specific proxy data and climate models. One of the important insights of the COHMAP (Cooperative Holocene Mapping Project) was that the orbitally induced increase in solar insolation in summer between 12,000 and 6,000 cal years BP enhanced the thermal contrast between land and sea, and thus induced stronger summer monsoons generating a more humid climate in subtropical Africa as well as in west and central Asia (COHMAP Members 1988, Wright et al. 1993). These results were confirmed by the recent simulations of PMIP, the Paleoclimate Modeling Intercomparison Project (Braconnot et al. 2007).

Mainly triggered by the early studies of Denton and Karlén (1973) as well as the debate about the transition from the Medieval Warm Period (MWP) or Epoch to the Little Ice Age (LIA), several studies concentrated on the question whether the centuries or even millennia long climate variations during the Holocene were cyclic or not (O'Brien et al. 1995). The discussion was strongly stimulated by the investigations of Bond et al. (1997, 2001) who, mainly based on petrologic tracers of drift-ice in the North Atlantic (NA), postulated a “1500 year” cycle that is supposed to have persisted throughout the Holocene. These cycles were thought to be the Holocene

Table 1 – Schematic overview on 28 papers discussing the phenomenon of the Bond Cycles (Abbreviations: AO Arctic Oscillation, IOM Indian Ocean Monsoon, IRD Ice Rafted Debris, ISOW Iceland-Scotland Overflow Water, ITCZ Intertropical Convergence Zone, MOC Meridional Overturning Circulation, NADW North Atlantic Deep Water, NAO North Atlantic Oscillation, ODP Ocean Drilling Program, SST Sea Surface Temperature, THC Thermohaline Circulation).

Reference	Location	Data source(s)/parameters	Correlation with bond cycle(s)	Reported spectral peaks/length of cycle(s)	Possible mechanism
O'Brien et al. 1995	Greenland (GISP2)	Sea salt, terrestrial dust from ice core	Yes (with cycles 0, 2, 4, 5, 8)	Quasi 2600-year cycles	Enhanced meridional circulation (atmosphere)
Bianchi and McCave 1999	South Iceland basin	Sortable silt mean size	Yes (with cycles 0–6)	~1500-year periodicity	Changes in deep-water flow
Chapman and Shackleton 2000	North Atlantic off Iceland	Ocean sediment core (lightness, ^{13}C , CaCO_3 content)	Yes (with cycles 2, 5, 6, 7)	Several spectral peaks (e.g. 1650, 1000, 550 years)	Cycles possibly driven by variation in solar activity (with consequences for THC fluctuations)
de Menocal et al. 2000	Off Cap Blanc, Mauretania	Ocean sediment core (SST, $\delta^{18}\text{O}$, terrigenous (eolian) fraction)	Yes (with cycles 0–5, 7, 8)	About every 1500±500 years	Increased southward advection of cooler waters or enhanced regional upwelling
Jennings et al. 2002	East Greenland Shelf	Ocean sediment cores (magnetic susceptibility, $\delta^{18}\text{O}$, IRD, carbonate flux)	Yes (with cycles 1, 2, 3, 5)	–	Increased flux of polar water and sea ice (changing NAO indices?)
Fleitmann et al. 2003	Southern Oman	Stalagmite ($\delta^{18}\text{O}$)	Yes (with cycles 2–6)	Several shorter cycles	IOM monsoon precipitation responds to Bond events and to solar activity
Gupta et al. 2003	Arabian Sea	<i>G. bulloides</i> shells (southwest monsoon)	Yes (with cycles 1, 3, 4, 6, 7)	–	Bond events and weak Asian southwest monsoon (related to solar activity?)
Hong et al. 2003	Tibetan Plateau	Peat bog ($\delta^{13}\text{C}$ values in cellulose of 12 dominant plants)	Yes (with cycles 1, 3, 5, 7, 8)	–	Thermohaline circulation decreases, SSTs decrease in the North Atlantic and increase in the Indian Ocean, monsoon weakens
Hu et al. 2003	Arolik Lake (south-western Alaska)	Lake sediment (BSi, OC, ON, pollen, $\delta^{18}\text{OSi}$, $\delta\text{D}_{\text{PA}}$)	Yes (with cycles 3, 4, 6, 7, 8)	Several spectral peaks (e.g. 590, 950 years)	Possible sun-ocean-climate link
Niggemann et al. 2003	Sauerland (Germany)	Calcitic stalagmite ($\delta^{18}\text{O}$; indicator for paleohumidity)	Yes (mainly cycles 1 and 2)	1450 years and minor peaks	Lower solar activity was probably accompanied by drier climate in Northern Europe
Oppo et al. 2003	Northeastern Atlantic Ocean	Benthic foraminifera ($\delta^{18}\text{O}$, $\delta^{13}\text{C}$)	Yes (with cycles 2, 4, 5, 6)	Millennial oscillation of $\delta^{13}\text{C}$	Enhanced and reduced NADW contribution
Risebrobakken et al. 2003	Eastern Norwegian Sea	Ocean sediment cores (^{14}C , $\delta^{18}\text{O}$)	Yes (with cycles 0, 2, 4, 6, 7)	No evidence for a clear cyclic behaviour, weak evidence for an 81-year cycle	Stronger westerlies during early to mid-Holocene gave rise to an eastward migration of subsurface Arctic water, no response to solar activity
Yu et al. 2003	Continental western Canada	Fen peat record (ash-free bulk density; indicates moisture)	Yes (with cycles 0–5)	Broad band (mean: 1785 years)	Wet periods correlate with warm periods in the North Atlantic (response to solar activity?)
Hall et al. 2004	Subpolar North Atlantic	Two ocean sediment cores (silt mean size, $\delta^{13}\text{C}$)	Yes (with cycles 0–3, 5, 6)	Broad band of quasiperiodic variability	Link between the ISOW and the surface component of the MOC
Baker et al. 2005	Lake Titicaca (South America)	Sedimentary organic matter ($\delta^{13}\text{C}$; humidity and lake level)	Yes (with cycles 1, 2, 4, 5)	Several spectral peaks (e.g. 434–454 years)	Wet conditions on the Altiplano appear to be associated with cold conditions (Bond events) in the North Atlantic
Russell and Johnson 2005	Lake Edward (Uganda/Congo)	Sediment cores (% Mg, Mg/Ca)	Yes (with cycles 0, 1)	Enhanced power at ~725 years	Droughts in equatorial Africa occur during both, cold and warm events in the North Atlantic area, due to N-S-displacement of the ITCZ
Gupta et al. 2005	North-western Arabian Sea	ODP core (% of <i>G. bulloides</i>)	Yes (with cycles 0–7)	Several significant peaks (e.g. at 1550, 152, 114, 83 years)	Monsoon minima coincide with low sunspot numbers and increased advection of drift ice in the North Atlantic
Turney et al. 2005	Northern Ireland	> 750 oak tree ring chronologies from bog and lake sites	Yes (with cycles 0, 2, 4, 5)	Broad band of variability, dominant cyclicity of ~800 years	Trees collapse due to dryness during Bond events, but no responses to changes in solar activity

Reference	Location	Data source(s)/parameters	Correlation with bond cycle(s)	Reported spectral peaks/length of cycle(s)	Possible mechanism
Wang et al. 2005	Dongge Cave (southern China)	Stalagmite ($\delta^{18}\text{O}$: monsoon precipitation)	Yes (with cycles 0–5)	1 to 5 centuries long, peaks at 159 and 206 years	Correlation with ice rafted debris in North Atlantic (influence of solar activity?)
Willard et al. 2005	Chesapeake Bay (E North America)	Pollen from sediment core (winter temperature)	Yes (mainly cycle 1 and 5)	1429, 282, 177, 148 years	Cold events in the North Atlantic are also effective in E North America
Lamy et al. 2006	Black Sea / Gulf of Aqaba	Three sediment cores inferring hydroclimatic changes (clay layer frequency, $\delta^{18}\text{O}$, terrigenous sand accumulation rate)	Partly	Cycles of ~800 and ~500 years	AO/NAO-like atmospheric variability, likely originating from solar output changes, plays a dominating role for hydroclimatic changes in the study area
Moros et al. 2006	Area off north Iceland	Phase analyses of mineralogical quartz and quartz/ plagioclase ratio	Partly	1300 years, 75–80 years	Late Holocene trend in drift ice: Increasing in the cold East Greenland Current, decreasing in warmer North Atlantic Drift
Viau et al. 2006	North America	752 pollen records from terrestrial sediments (July temperature)	Yes (with cycles 0–2, 5)	Periodicity of circa 1150 years	Possibly solar forcing?
Yu, Y. et al. 2006	Hexi Corridor (northwest China)	Lake sediment core, loess-paleosol (MS, CaCO_3 , GS, SCR)	Yes (with cycles 0, 2, 5, 7, 8)	–	Southward expansion of northern polar vortex (NAO-), El Niño like patterns, strongly weakened Asian summer monsoon
Allen et al. 2007	Finnmark, Norway	Lake sediment cores (^{14}C ages, pollen, temperature and humidity measures, organic content)	Yes (e.g. cycles 0, 1, 5)	Several spectral peaks (e.g. 1808/09, 1639/45, 1064, 767, 348–411, 279–312, 188 years)	Complex interaction between oceanic and atmospheric circulation, solar and tidal variability
Bendle, Rosell-Melé 2007	North Icelandic Shelf	Alkenone indices (SST)	Yes (with cycles 0, 2)	–	No close correlation with Bond Cycles, rather with NAO dynamics
Li et al. 2007	White Lake (NE USA)	Two cores (^{14}C , terrestrial macrofossils)	Yes (with cycles 1–4)	–	Dry intervals correlate with cold periods in the North Atlantic Ocean
Mangini et al. 2007	Spannagel Cave (central European Alps)	Stalagmites ($\delta^{18}\text{O}$: winter precipitation)	Yes (with cycles 0, 2, 3, 4, 5)	–	Meteorological conditions in the European Alps respond synchronously to hydrographical changes in the North Atlantic

equivalents of the Pleistocene Dansgaard-Oeschger cycles (Alley 2005). The upper panel of Figure 1 shows the timeseries of hematite-stained grains (HSG) in form of a tied record from the MC-52 and VM29-191 cores from the same location (Bond et al. 2001). The lower panel shows a stack of four records from different locations in the North Atlantic area. The mechanistic explanation for the cyclic behaviour of these time series is that the high peaks with fresh volcanic glass from Iceland or Jan Mayen and HSG's from eastern Greenland are the result of the southward and eastward advection of cold, ice-bearing surface waters from the Nordic and Labrador Seas during cold periods (Bond et al. 1997). Bond et al. (2001) detected totally nine cold events during the Holocene, which were also interpreted as a consequence of a periodic expansion of the cold polar anticyclone and an enhanced meridional circulation (O'Brien et al 1995). The Bond Cycles are numbered from 0 to 8 (Fig. 1). They peaked around 400, 1,400, 2,800, 4,300, 5,900, 8,100, 9,400, 10,300 and 11,100 cal years BP. The shift from the MWP to the cold LIA with high HSG values is clearly visible in Figure 1 (upper panel). In the following we want to answer three questions:

– Where are Bond Cycles postulated in paleoclimate records?

- Do proxy time series show a similar spectral (cyclic) behaviour, and are the cycles synchronous?
- What are the possible processes causing Bond Cycles during the Holocene?

Where are Bond Cycles postulated in paleoclimate records?

The existence of Bond Cycles is reported for many areas of the globe (Bütikofer 2007). Table 1 shows a list of 28 scientific papers which refer to Bond Cycles. The series of papers starts with the publication of O'Brien et al. (1995), which was the main trigger for the deep sea research launched by the late Gerard Bond and his colleagues (Bond et al. 1997, 2001), and ends with several very recent papers. Not only the character of the data sources (e.g. isotopes or organic and anorganic compounds detected in ice cores, lake or ocean sediment cores, stalagmites, records from peat bogs) but also their spatial variety is considerable. With the exception of the Pacific area, Australia and Antarctica, multi-century to millennial scale ("Bond like") climate cycles in proxy data sets of almost all areas of the globe are interpreted to be associated with the Bond Cycle phenomenon. Yet, it is no surprise that the highest number was detected in the North Atlantic Ocean and its surroundings, followed by several studies from Arabia and Asia.

Do proxy time series show a similar spectral (cyclic) behaviour, and are the cycles synchronous?

The original data (Fig. 1) show that the cycles based on the HSG analysis by Bond et al. (1997) were quite regular during the Holocene, with a mean pacing of ~1500 years. Table 1 shows that correlations are reported between the proxy time series and all of the nine Holocene Bond Cycles. The mostly mentioned correlations with Bond Cycles in the 28 papers according to Table 1 are cycle 2 (~2800 years BP) and cycle 5 (~8100 years BP). In order to answer the question about the spectral behaviour and the synchronicity of the observed cycles, Figure 2 shows the significant (90% level) spectral peaks as described in the vast literature (black dots) and as determined by our time series analyses (open circles; Bütikofer 2007). The different dots and circles are plotted against the corresponding latitude of each record. No clear clustering is visible at all. The majority of the analyses is concentrated in the latitudes between the southern subtropics and the north pole. If we concentrate on the spectral peaks around 1500 years we recognize several dots/circles which are concentrated between 35 and 62° N. These are all located in the North Atlantic area.

Figure 3 shows the frequency distribution of all spectral peaks represented in Figure 2. As expected, the number of spectral peaks grows with decreasing timescale because the number of existing long proxy time series is limited. Small, (and non-significant) clusterings of spectral peaks occur at about 200, 500, 900 and 1500 years (dark bars in Fig. 3).

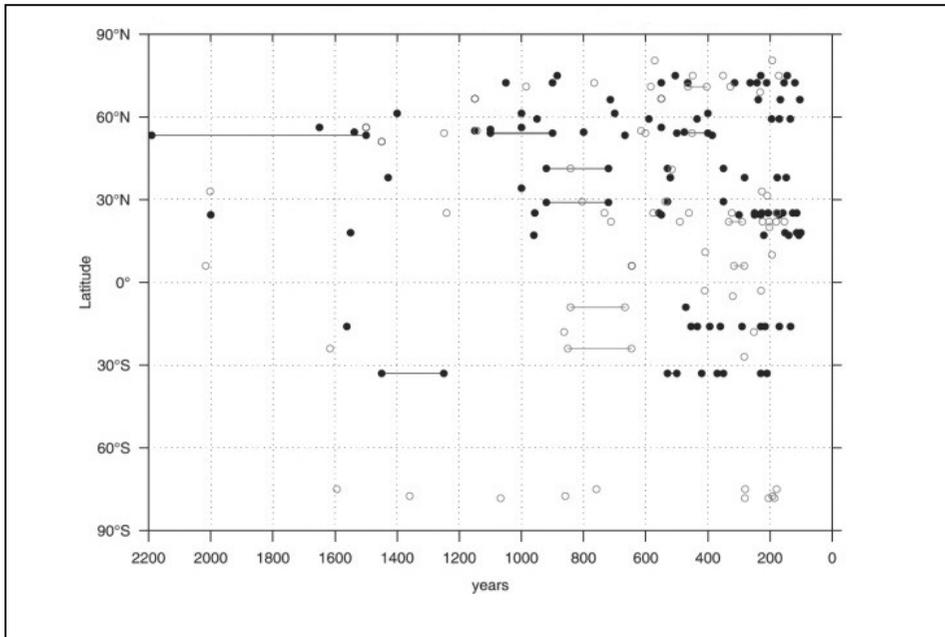


Fig. 2 – Overview of the spectral behaviour of the time series analysed by Bütikofer (2007; open circles) or of a number of referenced spectral peaks in the literature (referenced in Wanner et al. 2008; black dots). Horizontal lines represent broad peaks. The x-axis represents the times scales of the different peaks, the y-axis shows the corresponding latitude of the proxy.

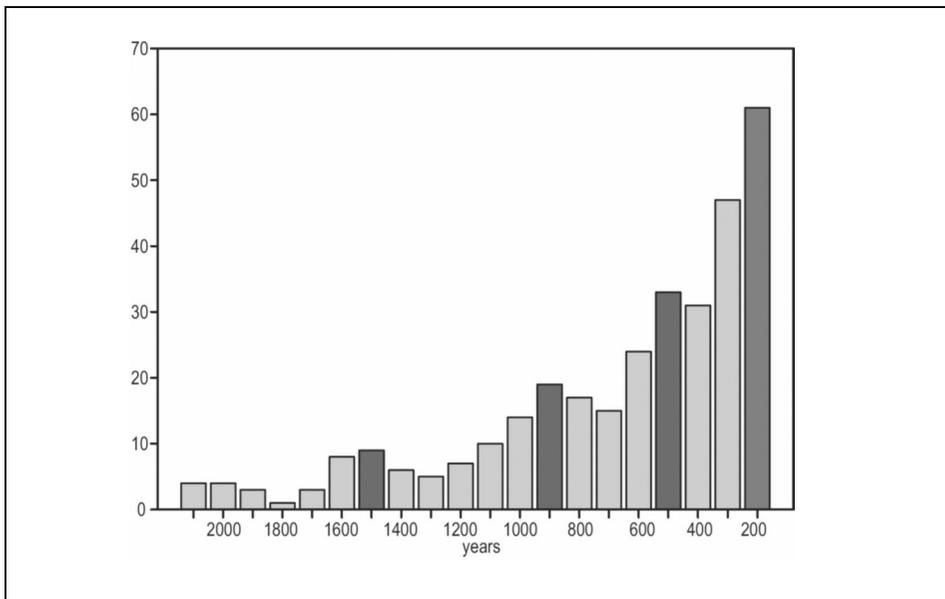


Fig. 3 – Number of all significant spectral peaks found in the timeseries represented in Figure 2. Dark grey bars mark apparently, but not significant higher frequencies.

What are the possible processes causing the Bond Cycles?

A dynamical theory explaining the formation of the Holocene Bond Cycles does not exist. Therefore it is not surprising that very different mechanisms are listed as possible triggers in the last column of Table 1.

One often applied procedure consists in the test whether the spectral peaks of selected proxy time series covary with those of the important external forcing factors or, even more simply, whether the peaks in the time series covary with the nine Bond events or not. In the latter case the authors assume that the dynamical processes which were postulated by Bond et al. (1997, 2001) are also determinant for the formation of the cycles they observed in their time series. The periodicities of the orbital forcing are far too long to be the cause for the formation of the Holocene Bond Cycles. The only option is to associate the Bond Cycles with subharmonics of the orbital forcing. One aspect which has certainly to be considered is how the decreasing mid- to late-Holocene solar insolation during boreal summer in the northern hemisphere, which caused a remarkable drop of the arctic to subarctic temperature and a massive increase of the Arctic sea ice, co-determined the multi-centennial to millennial scale climate dynamics of this area (Wanner et al. 2008).

Together with Bond et al. (2001) several authors (e.g. Chapman and Shackleton 2000, Fleitmann et al. 2003, Hu et al. 2003, Niggemann et al. 2003, Yu. et al. 2003, Gupta et al. 2005, Wang et al. 2005, Lamy et al. 2006, Viau et al. 2006, Allen et al. 2007) considered that solar forcing was the determining or at least one determining factor of their reconstructed multi-century to millennial scale climate fluctuations. Bond et al. (2001) linked their drift-ice records with the production rate of the two nuclides ^{14}C and ^{10}Be in Greenland ice cores. Both nuclides are related to solar wind and solar activity (or solar irradiance) in the sense that higher production rates are associated with a reduced solar irradiance. Bond et al. (2001) show that the Greenland ^{14}C and ^{10}Be time series match very well with their drift-ice reconstructions. This is in contradiction with Turney et al. (2005), Debret et al. (2007), and with the results of two highly resolved, 10'000 year long ^{14}C and ^{10}Be time series analyzed by the research groups of Fortunat Joos and Jürg Beer in Switzerland (Wanner et al. 2008). The latter found the most remarkable spectral peaks at 208, 510 and 710 years, and some smaller peaks at 87, 104, 150 and 350 years.

Braun et al. (2005) forced an intermediate-complexity climate model (CLIMBER-2, version 3) by periodic freshwater input into the North Atlantic in cycles of ~ 87 and ~ 210 years. Based on their findings they attribute the rather robust 1470 year cycles with the superposition of the two shorter, 87 and 210 years long cycles and conclude that the Bond Cycles of the Holocene were nonetheless triggered by solar forcing. With this statement they also support the earlier hypotheses by Bond et al. (1997, 2001) and others (Broecker 2000, Renssen et al. 2002 and 2006, Paul and Schulz 2002, Schulz et al. 2007) who demonstrated that the thermohaline circulation, namely in the North Atlantic Ocean, may have played an important role. There remains the question whether internal oscillations or external forcings in combination with feedbacks and thresholds also played an important role. Though Paul and Schulz (2002) state that internal oscillations of the meridional circulation do not rely on any external forcing, or they can draw energy of it.

There is clear evidence that the thermohaline circulation interacts with the Arctic sea ice. Bennike (2004) reports that, in northwest Greenland, surface

waters were warmer and less sea ice than at present existed from 7300 to 3700 cal yr BP. That means the sea ice started to grow after this period. In their run with the ECBilt-CLIO-VECODE model Renssen et al. (2006) showed that negative total solar irradiance (TSI) anomalies increase the probability of a local shutdown of deep convection in the Nordic Seas. This initial cooling associated with TSI reductions leads to sea-ice expansion in the area, which stratifies the water column and hampers deepwater formation.

Some authors (e.g. Briffa et al. 1998) argument that large volcanic eruptions can low summer temperatures dramatically. Robock (2000) and Fischer et al. (2006) demonstrated that one single tropical volcanic eruption leads to a climate signal which only lasts for about 2–3 years. Wanner et al. (2008) point to the fact that a higher number of large tropical volcanic eruptions has occurred during certain intervals of the last millennium, i.e. between AD 1200 and 1350 or around AD 1700 and 1800. During the last millennium these maxima of volcanic activity happened to coincide with both, low orbitally induced insolation in the Northern Hemisphere and an unusual concentration of solar activity minima (Wolf, Spörer, Maunder, Dalton) which likely led to the lowest temperatures in this area since 8000 years.

Other processes such as tidal forcing (Keeling, Whorf 1997; Berger, von Rad 2002), the influence of cosmic rays and the global electric circuit (Tinsley et al. 2007, Kirkby 2007) or changes in the Earth's magnetic field (Courillot et al. 2007) are also hold responsible for decadal to multi-century long climate fluctuations. Finally, it has to be taken in mind that forcing signals with higher frequencies might also be transformed into low frequency ones by slow reactors such as ice caps, or by internal feedbacks. In addition, some authors even express their doubt about a direct forcing of the decadal to multi-century scale cooling events. Related to the Dansgaard-Oeschger events Ditlevsen et al. (2007) vote that a detection of periodicity relies strongly on the accuracy of the dating of these events, and Wunsch (2000) states that a broad band of quasiperiodic variability rather than any kind of significant spectral peak is typical for climate records.

Conclusions

We have demonstrated that evidence for the existence of nine ~1500 years long cold or cool events during the Holocene, called Bond Cycles, exists at least in the North Atlantic area and its surroundings (Fig. 1) where such cycles were described by different authors (Table 1). A theory explaining the formation of these cycles does not exist. This fact is reflected in the long list of possible mechanisms which can trigger Bond events (Table 1). Therefore, the scepticism of different authors voting that one single factor may not be responsible for the cold relapses during the Holocene (e.g., Schulz and Paul 2002, Moros et al. 2006, Ditlevsen et al. 2007) is justifiable. Their reservations are further supported by the fact that the natural (external) forcing factors changed remarkably during the Holocene (Wanner et al. 2008). First of all, the orbitally induced summer insolation decreased strongly between 10 kyr BP and the present. This led to decreasing temperatures in the North Atlantic Ocean as well as in the northern continental areas of the Northern Hemisphere which favoured the growth of the Arctic sea ice and the strengthening of the cold polar surface anticyclone. These processes were possibly amplified during periods with a low solar activity and an

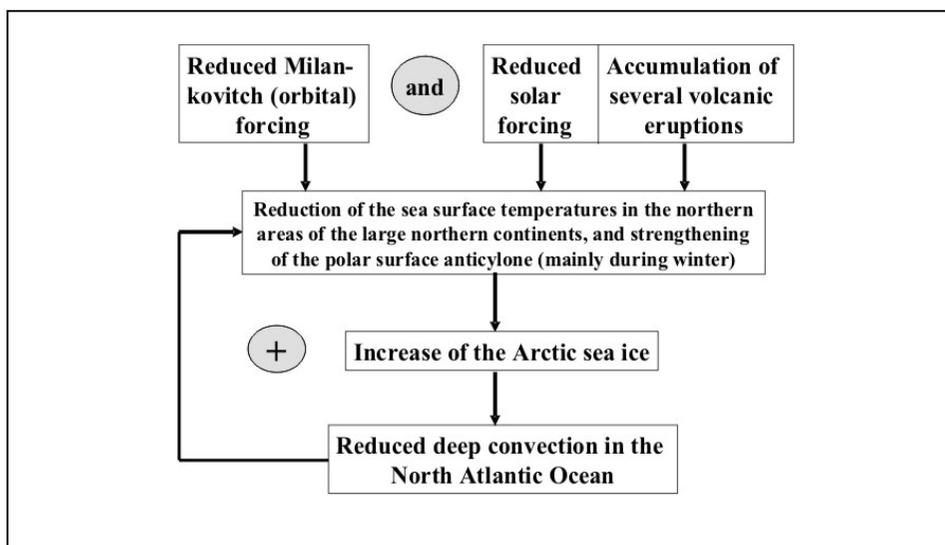


Fig. 4 – Possible mechanism for the formation of a cold event during the late Holocene (e.g., the Little Ice Age) when the summer orbital forcing in the northern hemisphere coincided with a low solar activity and accumulations of strong volcanic.

accumulation of strong, climate-relevant volcanic eruptions. This was likely the case during the period of the Neoglacial (Denton and Karlén 1973), above all during the Little Ice Age (Wanner et al. 2008).

In form of a simplified scheme Figure 4 tries to represent a possible mechanism for the formation of a cold Holocene event. If we assume that the summer orbital insolation in the Northern Hemisphere was much stronger in the early Holocene (Wanner et al. 2008) and that the Arctic sea ice was very sparse (Bennike 2004), it is indicated that cold relapses such as the 8.2 kyr event were likely triggered by strong meltwater pulses (Barber et al. 1999, Renssen et al. 2002). The late Holocene cold events (Bond events 0, 1 and 2 in Fig. 1) were rather caused by mechanisms which are shown in Figure 4. We are fully aware that this conclusion is still speculative and must be investigated with further data analyses as well as suitable model runs.

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Shrnutí

BONDOVY HOLOCÉNNÍ CYKLY: JSOU SKUTEČNÉ NEBO FIKTIVNÍ?

Na základě analýzy petrologických indikátorů z ledových ker v severním Atlantiku dokázali Bond et al. (1997, 2001), že během holocénu, tedy během posledních 12 000 let, došlo k devíti chladným obdobím. Autoři předpokládají, že tyto jevy jsou holocenními ekvivalenty pleistocenních Dansgaard-Oeschgerových cyklů a že se objevují s určitou pravidelností s délkou cyklu cca 1 500 let. Na základě literatury (tab. 1), jakož i na základě rozšířené spektrální analýzy různých proxy řad jsme ukázali, že existence takovýchto cyklů se předpokládá v mnoha oblastech světa, ale že neexistují jasné důkazy o cyklech trvajících 1 500 let. Jednotliví autoři tedy předpokládají řadu různých spouštěcích mechanismů (např. minimální sluneční aktivita, shluky silných tropických sopečných erupcí, zpětné vazby mezi termohalinní cirkulací a dynamikou arktického mořského ledu).

Domníváme se, že Bondův cyklus byl pozorován zejména v severním Atlantiku a v přilehlých oblastech (východ Spojených států, severní Afrika, Evropa a části Asie). Protože se hraniční podmínky (jako je rozsah kontinentálního zalednění, rozložení mořského ledu, množství tepla v oceánech, rozložení vegetace) během holocénu výrazně změnily, zastáváme na základě dostupných modelových studií hypotézu, že vznik těchto chladných období byl způsoben různými procesy. Soubor jevů ranného holocénu, jako mladší dryas či 8 200 let trvající chladné období, byl vyvolán spíše vodou z tající ledové pokrývky severních kontinentů. Chladná období pozdního holocénu (Bondovy jevy 0, 1 a 2 na obr. 1) byla způsobena spíše součinností různých faktorů, jako omezeného slunečního záření, souběhu několika tropických sopečných výbuchů, posílení studené arktické anticyklony a jejich interakce s dynamikou mořského ledu a termohalinní cirkulací. V průběhu přechodného období před 7 000–4 500 let byly podmínky velice složité, takže jsou potřeba nové údaje a modelové studie. Konečně bychom neměli zapomínat, že důležitou úlohu může hrát vnitřní variabilita systému (tedy kolísání severoatlantské oscilace) a že pro klimatické záznamy je typický spíše široký pás kvaziperiodické variability než jakýkoliv druh významného spektrálního vrcholu.

- Obr. 1 – Holocenní záznamy z ledových ker jako procentuální variace petrologických indikátorů. Horní panel: hematitem obalená zrna v % ve dvou jádrech ze stejné lokality. Spodní panel: soubor čtyř záznamů z různých lokalit. Podle Bonda et al. 1999, pozměněno.
- Obr. 2 – Přehled spektrálního chování časových řad analyzovaných Bütikoferem (2007; otevřené kroužky) či řady spektrálních vrcholů uváděných v literatuře (odkazy viz Wanner et al. 2008; černé tečky). Vodorovné čáry představují široké vrcholy. Osa x vyjadřuje časové měřítko různých vrcholů, osa y ukazuje příslušnou zeměpisnou šířku nepřímých (proxy) dat.
- Obr. 3 – Množství všech významných spektrálních vrcholů v časových řadách znázorněných na obrázku 2. Tmavě šedé sloupky označují zjevné, avšak nikoliv významně vyšší frekvence.
- Obr. 4 – Možný mechanismus vzniku studeného období v pozdním holocénu (např. malé doby ledové), kdy došlo k souběhu letního orbitálního působení na severní polokouli s nízkou sluneční aktivitou a řadou silných vulkanických erupcí. V obrázku shora: redukovaný Milankovič (orbitální záření), redukované sluneční záření, souběh několika sopečných výbuchů; snížení teploty mořského povrchu v severních oblastech velkých severních kontinentů a posílení polární anticyklony (zejména v zimě); nárůst arktického mořského ledu; omezená hloubková konvekce v severní části Atlantského oceánu.

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