Nature Unbound II - The Dansgaard-Oeschger Cycle.

Javier. January 2017

Summary: Dansgaard-Oeschger (D-O) events are the most dramatic and frequent abrupt climate change events in the geological record. They are usually explained as the result of an Atlantic Ocean salt oscillation paced by internal variability. Available evidence however supports that they are the result of an externally paced oceanic-sea ice interaction in the Norwegian Sea. A lunisolar tidal cycle provides an unsupported yet explanatory hypothesis for the 1470 yr pacing and triggering mechanism of D-O oscillations.

Introduction

A review of the abrupt climate changes of the recent past provides a frame of reference for the current global warming. The glacial cycle was reviewed in the previous article in the series. In this article we review the abrupt changes that characterized the last glacial period. They are relevant because some scientists believe that they may be related to the millennial climate variability taking place during the Holocene, and thus would constitute part of the background to present climate change.

It was already known by palynologists early in the 20th century that pollen records showed quite abrupt climate changes reflected in vegetation changes that indicated that the end of the last glacial period was marked by alternating cold (**stadials**) and warm (**interstadials**) periods. The last two stadials were named after a tundra flower whose pollen became abundant, *Dryas octopetala*, as the Older Dryas and the Younger Dryas.

In 1972, after analyzing the isotopic composition of ice cores from Camp Century in Greenland, Willi Dansgaard reported that the last glacial period showed over 20 abrupt interstadials marked by a very intense warming (Johnsen et al. 1972). The discovery was met with indifference by a scientific community still struggling to identify Milankovitch cycles in the data, because the new abrupt changes were not found in Antarctic records. Twelve years later Hans Oeschger reported that the abrupt changes were accompanied by sudden increases in CO_2 in the Greenland ice cores (Stauffer et al. 1984). From then on the abrupt changes were known as **Dansgaard-Oeschger (D-O) events**. It was later decided that Greenland elevated CO_2 records were the result of a chemical contamination, since they did not match Antarctic CO_2 records.

Dansgaard-Oeschger oscillations.

The good temporal resolution of the GISP2 ice core, where the annual ice layers can be counted, allowed the discovery that D-O events were oscillations of a **1470 yr cycle** (Figure 18. Schulz, 2002).

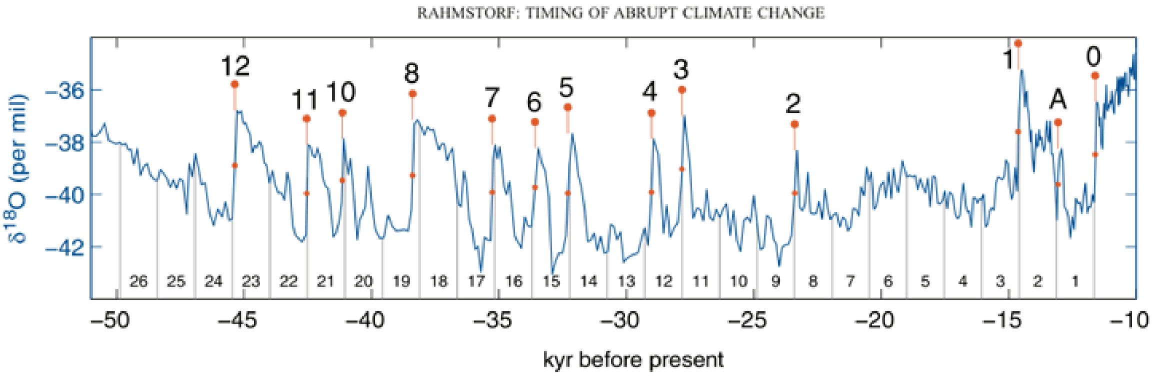

Figure 18. The Dansgaard-Oeschger cycle. Dividing the 50-10 kyr BP period in boxes of 1470 years clearly shows the periodicity of the DO cycle, that has less than 1% probability of being due to chance. The deviation for the later, best dated, oscillations from the period is of only 2%. Source: S. Rahmstorf, 2003. Geophys. Res. Lett. 30 1510-1514.

D-O oscillations are the most dramatic and frequent abrupt climate change in the geological record. In Greenland, D-O oscillations are characterized by an abrupt warming of ~ 8°C in annual average temperature from a cold stadial to a warm interstadial phase, followed by gradual cooling before a rapid return to stadial conditions. Initially they were thought to be a regional phenomena, since they were not prominently displayed in Antarctic ice core records, however evidence uncovered since shows that they display a hemispheric-wide climate effect reaching also the southern hemisphere (figure 19).

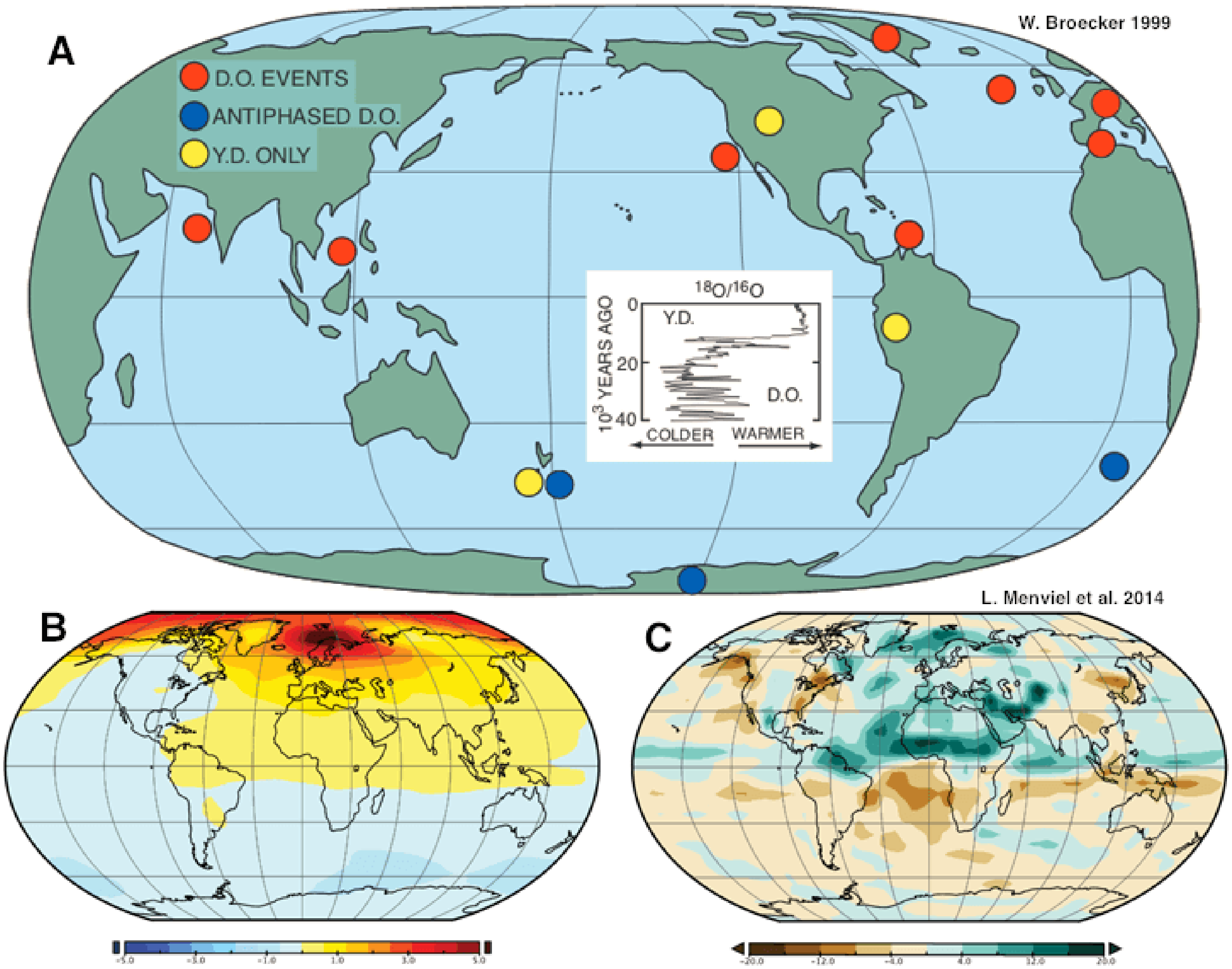

Figure 19. Widespread effects of Dansgaard-Oeschger cycle. **(A)** Warming in Greenland is coincident (red dots) with warmer wetter conditions in Europe, higher sea-surface temperatures in the western Mediterranean. increased precipitation in the Venezuelan coast, enhanced summer monsoon in the Indian Ocean, aridity in the southwestern North America and China, changes in ocean ventilation in California, increased sea temperature and productivity in the Arabian sea. Warming in Greenland is also coincident (blue dots) with anti-phased cooling in Antarctica, and the circumpolar seas. Yellow dots, places were evidence has been found for the Younger Dryas (YD). Source: W. Broecker. 1999. Updated. **(B)** Modeled changes in temperature for the stadial-interstadial transition. **(C).** Modeled changes in precipitation for the stadial-interstadial transition. Source: L. Menviel, et al. 2014.

D-O oscillations are not the only climate change taking place during the last glacial period. Temperature variability is very high (figure 20A and B), and the changes have different shapes, durations and spacing. They are sometimes separated by other intense climate changes of a different nature called Heinrich events. Lets describe those changes starting with Greenland.

With a periodicity of ~ 6,000 years (figure 20 turquoise) 1-4 kyr **Heinrich events** (HE) took place in the northern Atlantic region, causing a drop of 2-3° C from the already cold glacial climate. Sea surface temperatures in the North Atlantic dropped to what are now Arctic conditions as far south as 45°N, and were probably covered by sea ice during the winter. Almost at the end of that period, on what appears just a few decades, a huge armada of icebergs was produced from the Laurentide ice sheet, or less often from the Fennoscandian one, carrying with them huge amounts of eroded material that when the icebergs melted was deposited on the sea bed as ice rafted debris (IRD). Heinrich events are labeled H0 to H6 (figure 20), with the most recent coinciding with the Younger Dryas.

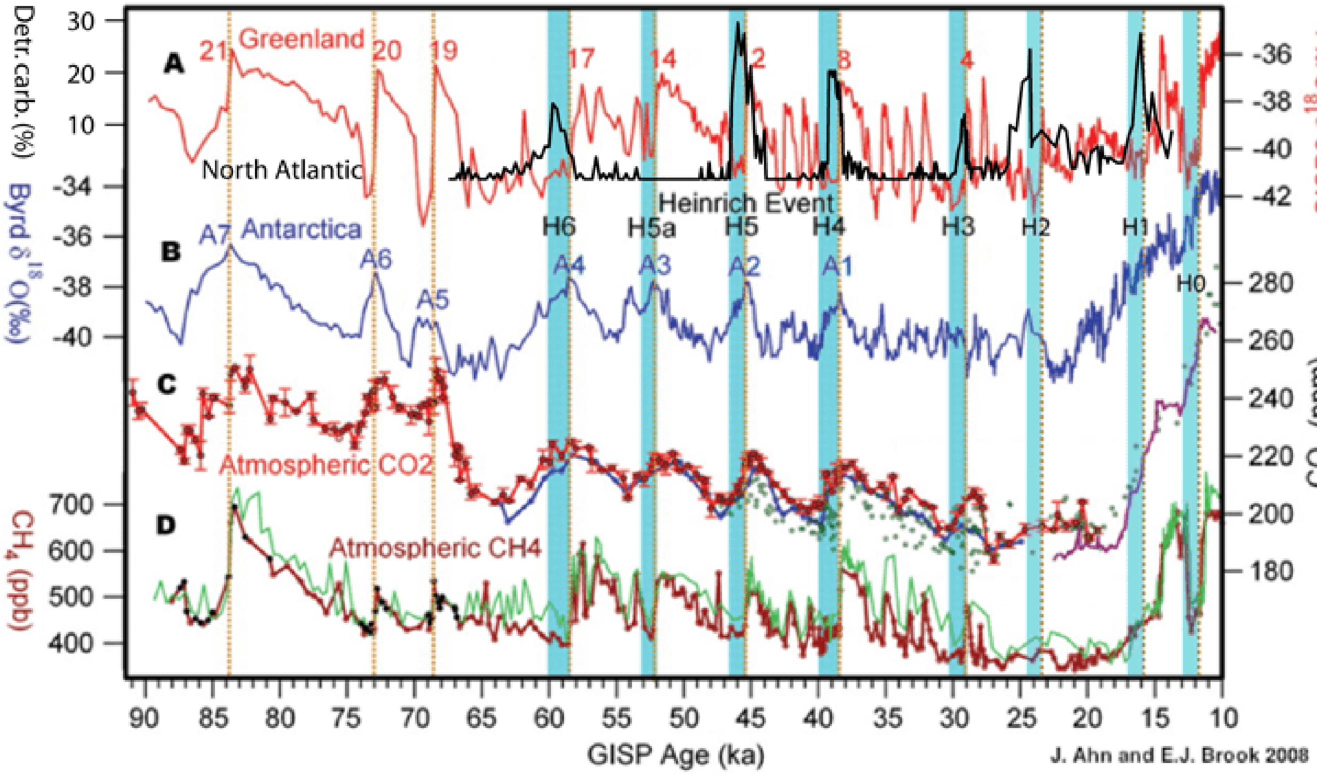

Figure 20. Chronology of climatic events for the Last Glacial Period. (A) Red, Greenland temperature proxy. Red numbers denote D-O events. Black, detrital carbonate in the North Atlantic. Black H-numbers denote Heinrich events. **(B)** Antarctica temperature proxy. A1 to A7, Antarctic warming events. **(C)** Antarctic atmospheric CO_2 concentrations. **(D)** CH_4 concentrations from Greenland (green) and Antarctica ice cores (brown). Vertical turquoise bars, timing of Heinrich events. Brown dotted lines, abrupt warming in Greenland. Source: J. Ahn, and Brook, E.J. 2008. H0 to H2 S.R. Hemming, 2004. Modified.

A Heinrich event is followed by the triggering of a D-O interstadial warming. Even if only one in four D-O oscillations is preceded by a Heinrich event, all of them appear to have been preceded by a similar albeit reduced cooling and IRD deposition in North Atlantic marine sediments. Gerard Bond suggested that Heinrich events are part of the D-O cycle (Bond et al. 1993). Since Heinrich events involve more profound cooling and much more intense ice-shelf calving we can therefore distinguish between HE D-O oscillations (numbers 1, 4, 8, 12, 14, 17) and non-HE D-O oscillations.

D-O oscillations are characterized by their asymmetric change in temperatures. They all display a very fast warming, with temperatures rising by about **8-10°C in just a few decades**, within the span of a human life time (figure 21). This warming in less than a century is followed by a slower cooling of ~ 2°C in about 200 years. From this point D-O oscillations take different paths. Some D-O oscillations will quickly drop 6-8°C into cold glacial temperatures in about 250 more years for a total span of ~500 years. Other D-O oscillations will take 500 to 800 years to complete a more irregular descent, for a total span of 800-1000 years. Finally some D-O oscillations will take more time to go back to glacial stadial baseline than the length of a cycle. In such cases new D-O oscillations are prevented from taking place until the cooling ends. One of the greatest difficulties that D-O models have to face is explaining how such a wide distribution in cycle duration matches with a precise pacing of 1470 ± 8% in the warming phase that is only 2% in the best dated more recent cycles (Rahmstorf, 2013).

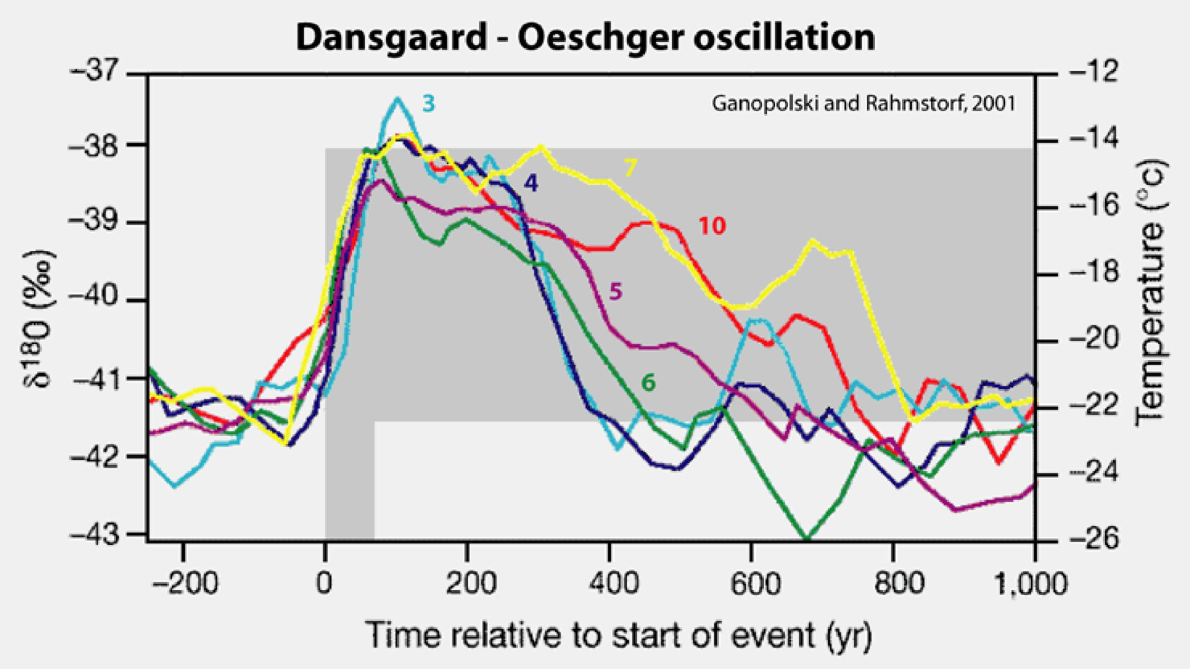

Figure 21. Time evolution of recent D-O oscillations. D-O oscillations show a very abrupt warming phase followed by a slow cooling phase. Afterwards a more abrupt temperature drop usually follows while oscillations display variable length of the last cooling phase. Source: A. Ganopolski, and Rahmstorf, S. 2001. Nature 409 153-158.

Dansgaard-Oeschger oscillations in the Antarctic record.

When studying the D-O cycle in Antarctic records it became apparent that Greenland temperature changes matched methane level changes at a global scale (figure 20). Since methane levels were skyrocketing simultaneously in both Greenland and Antarctic ice cores, this provides a precise way to align both records (Wais Divide Project Members 2015).

The alignment of Antarctic and Greenland records shows that there is an inverse temperature relation between both poles. During a D-O cold phase temperatures rise in Antarctica. This rise is especially intense if the stadial is a Heinrich event. Temperatures in Antarctica peak 220 years after the D-O transition triggers in Greenland (Wais Divide Project Members 2015; figure 22). This delay suggests an oceanic link between both poles. Afterwards temperatures go down simultaneously in both poles, but Antarctic temperatures bottom early and start to raise again in preparation for the next cycle.

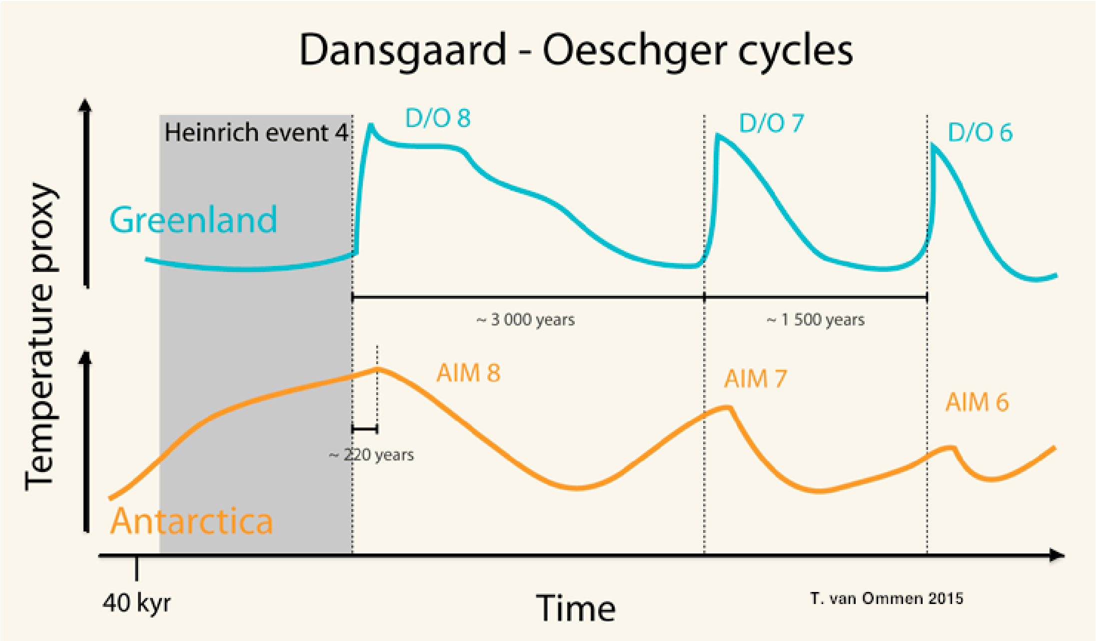

Figure 22. Cartoon of the D-O interpolar phasing of temperatures. During a Heinrich event Greenland temperatures (blue) get very cold, while they raise in Antarctica (orange). Once the abrupt warming takes place in Greenland, temperatures peak in Antarctica on average 220 years later. If the previous Antarctic warming has been very intense, as in D-O 8, the Arctic cooling can take much longer and then one or more cycle periods are skipped until temperatures are cold enough. Source: T. van Ommen, 2015. Nature 520 630–631, based on data from WAIS Divide Project Members 2015. Nature 520 661–665. Modified.

How is this temperature connection achieved? The planet receives most of the energy from the Sun through the tropical areas where part of it is radiated back. The rest of the energy that has been converted to heat has to be directed to the poles, where most of the surplus heat loss takes place radiating the energy back to space. This meridional heat transport is achieved in part through the atmosphere, that transports two thirds of the surplus heat towards higher latitudes, and in part through the oceans, where another third of the surplus heat is carried through the Meridional Overturning Circulation as warm surface currents, that return as cold deep currents once they ventilate the heat to the polar atmosphere. What makes the meridional heat transport function is the temperature gradient between the tropics and the poles.

Pacific warm waters are mostly prevented from reaching the Arctic, so the only effective connection is through the North Atlantic between Greenland and Scotland. The closure of the Panamanian Pacific-Atlantic connection converted the North Pacific Ocean into a cul-de-sac for the meridional heat transport. The South Atlantic is the only southern ocean that transports heat northward across the Equator. Therefore the Atlantic is an avenue for surface warm waters that originate in the Southern ocean and go to the Arctic ocean, returning as deep cold waters. This is the cause of the temperature connection between the poles. It has been proposed that when the Atlantic current is strong it cools the Antarctic and warms the Arctic by changing the energy budget in favor of the last, and when the Atlantic current is weak it warms the Antarctic and cools the Arctic through the opposite effect. This heat-piracy hypothesis is the basis of the **bipolar see-saw model**, that is supported by available evidence on changes of the Atlantic Meridional Overturning Current (AMOC; Stocker and Jonhsen, 2003).

The explosive growth of methane during D-O oscillations raised fears that the abrupt climate change had repeatedly triggered the hypothetical **clathrate gun** and that it could happen again in the near future. However deuterium isotopic analysis of ice core methane showed that the increase in methane was accompanied by a depletion in deuterium (Bock et al., 2010; figure 23). This depletion indicates that its origin is in deuterium poor methane from boreal wetlands, one of the main natural sources of methane, and not from deuterium rich clathrate hydrates. The increase in temperatures and precipitations associated to the D-O cycle (figure 19b and c) would be responsible for boreal wetlands expansion and CH_4 emissions.

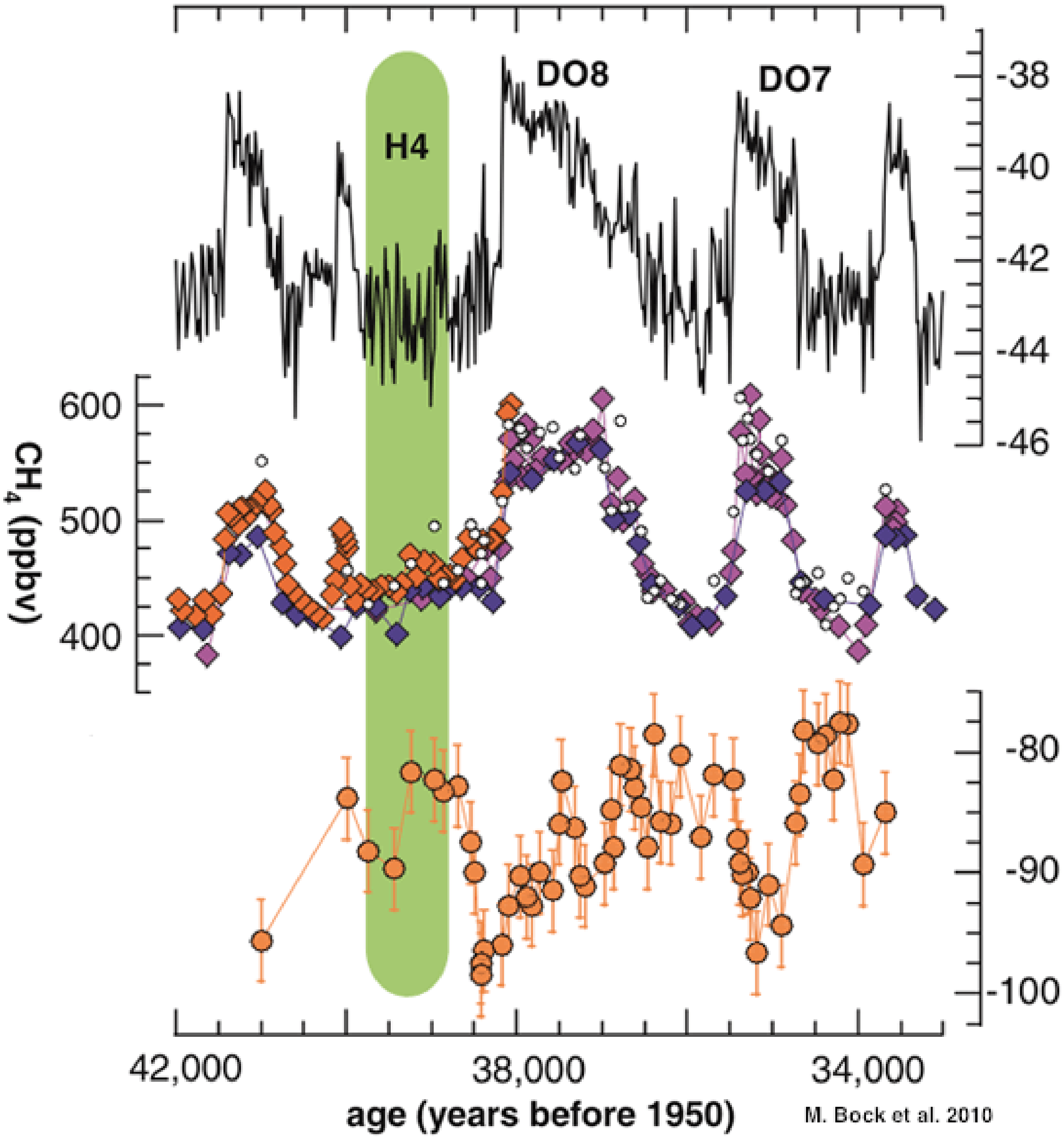

Figure 23. Methane changes and origin during D-O cycles. Top panel shows a temperature proxy from Greenland. The second panel shows CH_4 records from Greenland, GRIP (Greenland Ice Core Project) (purple diamonds), NGRIP (orange diamonds), and Antarctica EDML (blue diamonds). Deuterium $\delta D(CH_4)$ values in the bottom panel are from the NGRIP ice core (orange circles). All data sets are given on an age scale after CH_4 synchronization. The green bar indicates the Heinrich 4 event (H4). Changes in methane levels are inversely correlated to methane deuterium content, indicating a deuterium poor source, most likely boreal wetlands. Source: M. Bock, et al. 2010.

Some scientists believe CO_2 is the main agent responsible for temperature changes not only in the present, but also in the past. Curiously Antarctic ice core records do not register any contribution or response from CO_2 to the most frequent abrupt changes of the past, the D-O cycles (figure 20). CO_2 levels only increase during Heinrich events. As we have seen Heinrich events are associated to Antarctic warming while the North Atlantic region cools down several degrees and iceberg discharge is greatly enhanced. Since the Antarctic region is the only one warming during a Heinrich event, it is generally believed that the increase in CO_2 originated from enhanced CO_2 ventilation from a warming Southern Ocean (Ahn and Brook, 2014).

HE D-O and non-HE D-O oscillations display different CO_2 changes during their previous stadial cold phase (figure 24, a and b). In Antarctica this cold phase is manifested as warming for all D-O oscillations (except D-O 9; figure 24, b). However only HE D-O oscillations display an increase in CO_2. **Non-HE D-O oscillations do not show any increase at all in CO_2 levels** (figure 24, a). The contrast in the behavior of both type of events is more evident when changes in CO_2 are plotted against changes in temperature (figure 24, c). This result suggests that it is the Heinrich event cooling the North Atlantic that is causing the Southern Ocean to warm and release CO_2, and not the Antarctic warming, that is unrelated to CO_2 levels.

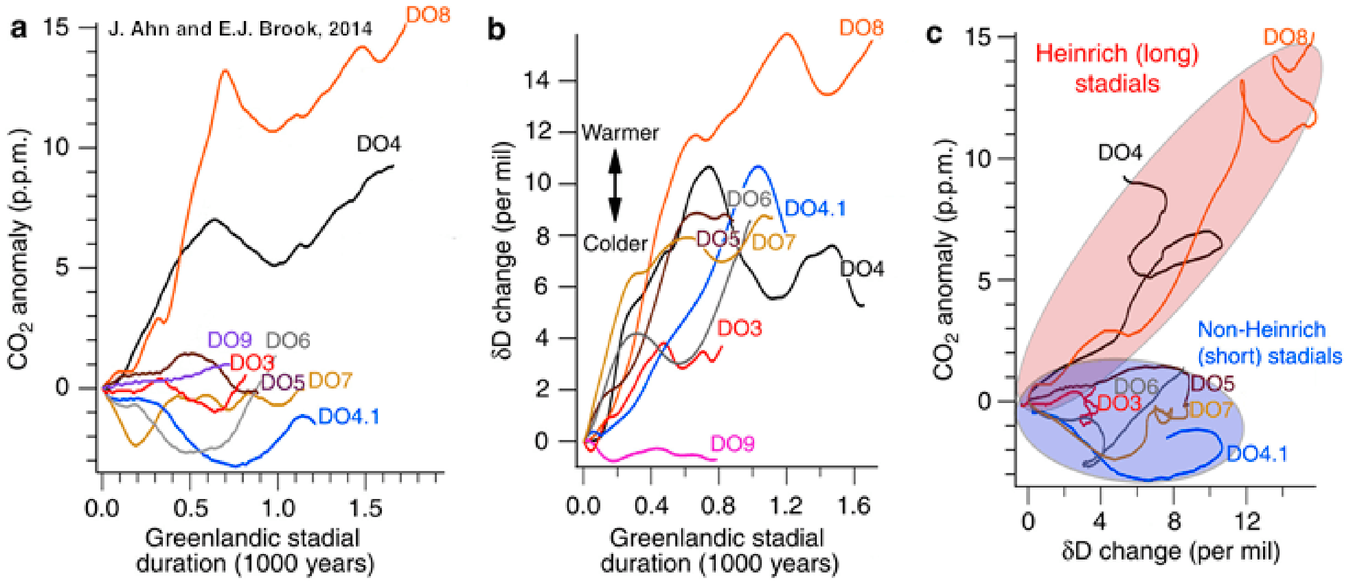

Figure 24. Time evolution of CO_2 and Antarctic temperature during Greenlandic stadials. **(a)** CO_2 change during Greenlandic stadials from Antarctic ice core records. DO numbers indicate D-O warming events at the end of stadials. **(b)** Antarctic temperature proxy record during Greenlandic stadials. **(c)** Time evolution of atmospheric CO2 versus temperature anomalies during stadials. Derived from (a,b). The pale red and blue ellipses indicate records for Heinrich (long) and non-Heinrich (short) stadials, respectively. Three hundred-year running means are used for both CO_2 and temperature proxy records. In order to remove multi-millennial changes during short Greenlandic stadials, the Siple Dome CO_2 and temperature proxy records are detrended. D-O 9 (pink in b) is not considered a true D-O oscillation by several authors (see text). Source: Ahn, J. and Brook, E.J. 2014. Nature Communications 5, Article number: 3723.

We can conclude that according to available evidence, **CO_2 plays no role at all in the most abrupt and frequent climate changes** of which we have knowledge, the D-O cycle, and that the increases in CO_2 observed in Antarctica associated to Heinrich events appear to be a consequence of Southern Ocean warming, and neither a cause or consequence of Antarctic warming. Furthermore, the increase in CO_2 during Heinrich events (of about 10 - 15 ppm) does not appear to significantly alter the rate or magnitude of the warming during the subsequent D-O oscillation (see for example that DO4, figure 24, shows a similar warming to the rest).

Conditions for Dansgaard-Oeschger cycles.

Some authors have disputed the existence of a regularly spaced D-O cycle on the basis that the oscillation distribution is not significantly different from random (Ditlevsen et al., 2007). There is obviously the difficulty in correctly dating with sufficient precision oscillations that took place so long ago and it is significant that the most recent oscillations are the ones that show a better periodicity. Additionally, the ice record that shows a more robust periodicity is GISP2, the Greenland ice core with the best temporal resolution as it allows counting of annual snow layers. Finally the abrupt climate oscillations that are part of the D-O cycle have to be properly defined. A D-O oscillation requires several signature conditions. It is highly asymmetric with rapid warming in a few decades and slow cooling over at least 200 years followed by rapid cooling over at least 200 more years for a minimum duration of 400 years. It is matched by a similar peak of methane levels of similar amplitude and duration. And it is preceded by prior Antarctic warming that peaks about 220 years after the Greenland warming peak. Most mathematical analyses fail to include this signature and thus consider peak number 9 as a D-O oscillation when it clearly is a different type of abrupt warming (see figures 18 and 24b). Abrupt warming 9 is the odd placed warming event and if eliminated from analysis, the robustness of the cyclicity is greatly increased.

Since D-O oscillations, as previously defined, are a glacial feature, they appear to be influenced by global temperatures and therefore by orbital changes. D-O cycles are suppressed at warm times of maximal obliquity at 90, 50, and 10 kyr BP and at very cold times after minimal obliquity at 65 and 20 kyr BP (figure 25). So it appears that D-O abrupt changes cannot take place when the world is warm or very cold.

Schulz et al. (1999) investigated the irregular distribution of D-O oscillations during the past 100 kyr by extracting a 1470 yr signal from GISP2 temperature proxy data using time-frequency analysis through harmonic filtering. The resulting signal (figure 25A) shows four periods of higher amplitude separated by minima at 80, 65, 50, 20 and 10 kyr BP (figure 25B arrows). Each period of higher amplitude corresponds to periods of D-O oscillations. They then noticed a strong relationship between the 1470 yr signal and variations in continental ice mass, as recorded in sea-level variations. Each of the five minima in the 1470 yr signal corresponds to an inflection point in sea level variation and four of the five take place when sea levels are above -45 m or below -90 m from present level (figure 25B). The fifth at 50 kyr BP coincides with a maximum in obliquity.

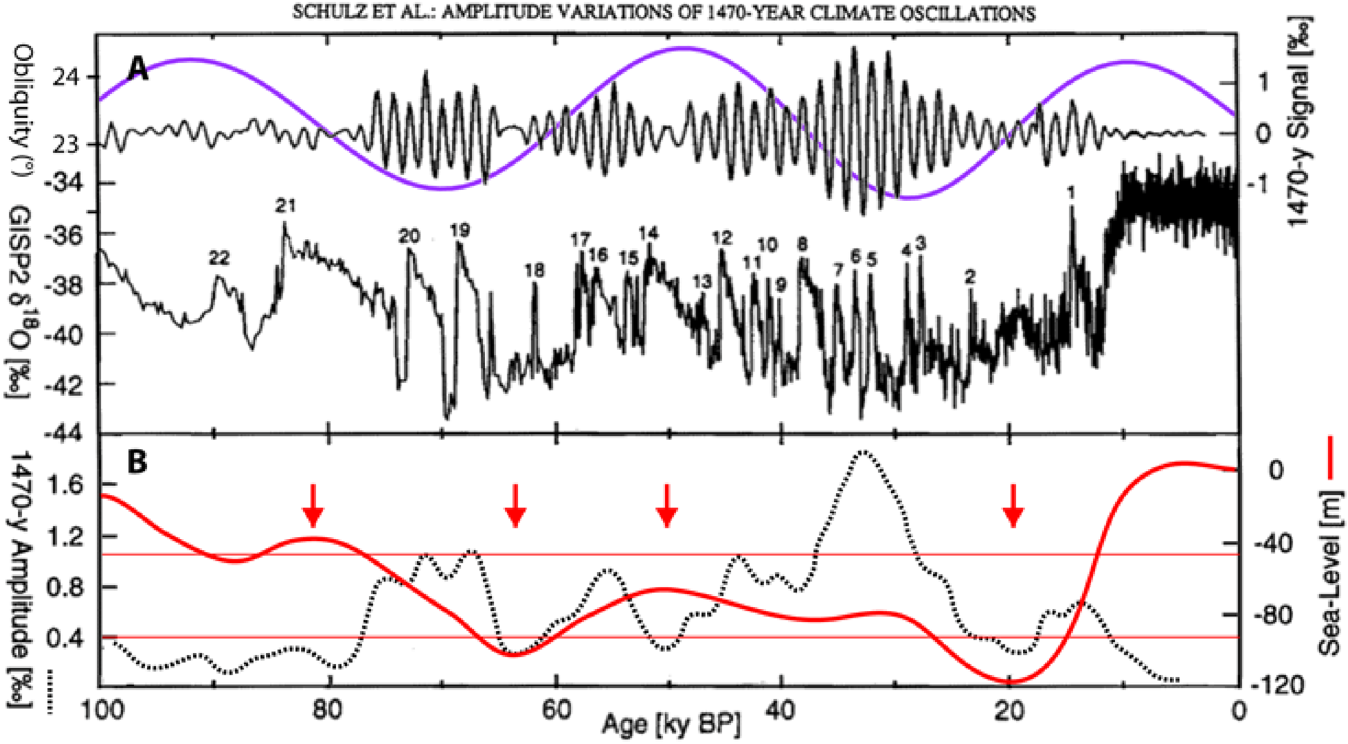

Figure 25. D-O oscillations and changes in sea levels. **(A) Top**: Temporal changes of the 1470-yr signal component in the temperature proxy record estimated by a harmonic-filtering algorithm using a sliding rectangular window of width 4 x 1470 yr. **Bottom**: Temperature proxy record from Greenland GISP2. Numbers indicate D-O oscillations. **(B)** 2000-yr smoothed amplitude of the 1470-yr signal (dashed line) and sea level (red). Amplitude increases sharply as sea level falls below -45 m and decreases when sea level falls below -90 m. Pronounced amplitude minima coincide with local minima or maxima of sea level (arrows). Source: Composite of figures 1 & 2 from M. Schulz et al. 1999. Obliquity and -90 m sea level band added.

So since the conditions for D-O oscillations can be shut down, for example during the Last Glacial Maximum, and upon being restarted they still maintain the same 1470 year pacing, this is a strong indication that **the trigger for the D-O cycle is external**, and its clock is ticking all the time. The right conditions for a D-O oscillation require the build up of extensive ice sheets over the northern continents that cause a drop in sea levels of at least 45 m. Once that happens, the bipolar see-saw must be set to warm Antarctica and cool the North polar regions. These conditions will extend the sea ice cover over ample regions of the Nordic seas and North Atlantic and produce an increase in iceberg discharge. Then the next tick of the clock will trigger a D-O cycle. Whenever those conditions are reset a new D-O oscillation might be triggered. Warming from obliquity maxima will prevent the conditions from taking place, as will a profound cooling that reduces sea levels below -90 m and produce too much ice.

Consensus Dansgaard-Oeschger cycle theory and challenges

The consensus theory on the D-O cycle was established by Wallace Broecker (Broecker et al., 1990), and is defended by one of the leading experts on abrupt climate changes, Richard Alley (Alley, 2007). It is known as **the "Salt Oscillator" hypothesis**, and it is based on oscillatory changes of the Atlantic Meridional Overturning Circulation, or AMOC, in response to fresh-water pulses due to ice melting water (melt-water pulses, MWP) being stored and released periodically from ice-sheets (figure 26).

The AMOC is controlled by warm sea surface waters of its North Atlantic Current component (NAC) becoming saltier through evaporation that takes fresh water out of the Atlantic basin, and further becoming saltier and colder through evaporation in subarctic regions until they become dense enough to sink and then turn South to constitute the cold **North Atlantic Deep Water (NADW)** component. The intensity of the NADW determines the state of the AMOC. The term Thermohaline Circulation (THC), introduces confusion as it refers only to the thermal and salt effect on the circulation, ignoring wind and tidal effects also included in AMOC, but since they are difficult to separate, it is better to refer to AMOC instead. Global conveyor and MOC (global Meridional Overturning Circulation) are interchangeable terms.

The NADW then flows southward along the bottom of the Atlantic Ocean exporting with it the excess salt, resulting in a gradual reduction in North Atlantic surface salinity over time. Furthermore, tropical heat transferred to the high-latitude North Atlantic produces ice melting and MWP that further reduce water salinity. If surface waters at the sites of deep-water formation become too fresh, then AMOC weakens or shuts off because the surface waters are not dense enough to sink. Once AMOC weakens enough or even shuts down, salt starts to accumulate again in the North Atlantic due to the absence of NADW export. According to this theory, weak AMOC conditions are associated to cold stadials (figure 27).

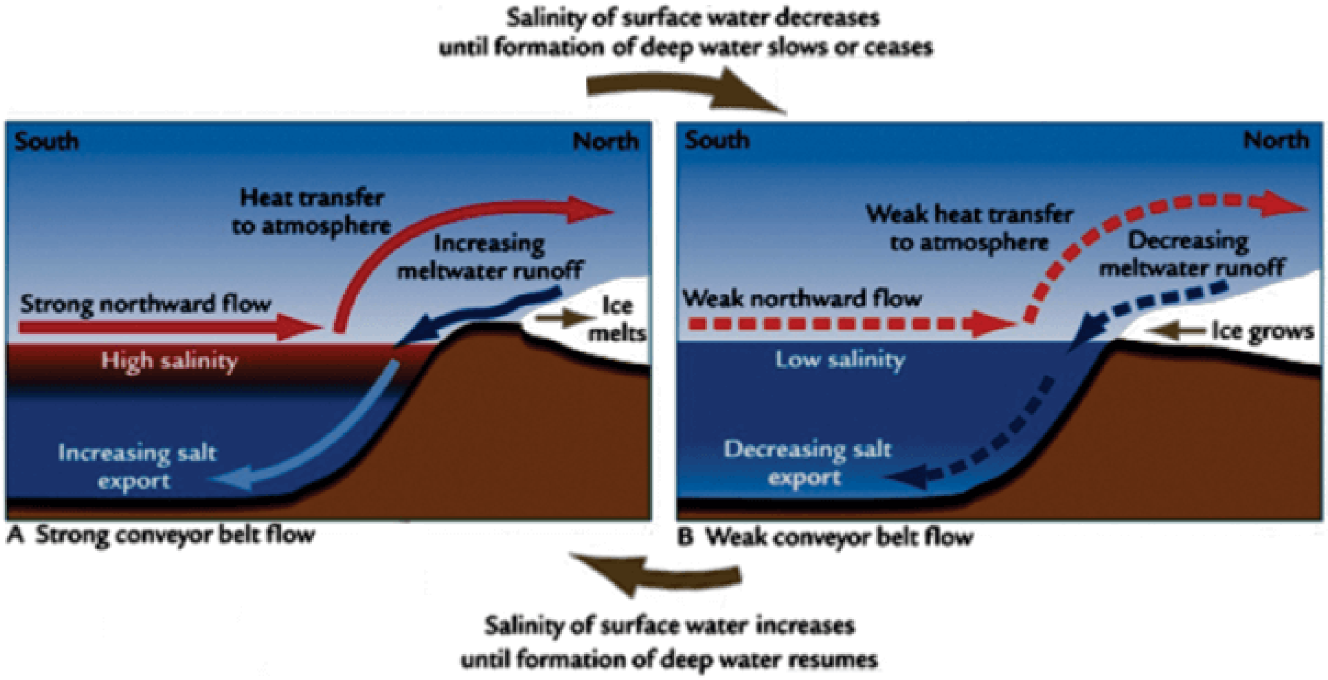

Figure 26. The salt oscillator hypothesis. **Left,** During warm interstadials, a strong AMOC transports heat northward causing the ice sheets around the North Atlantic to melt, gradually reducing surface water salinity until it no longer sinks and deep water formation ceases to form stopping NADW. Eventually, surface salinity is reduced enough to weaken AMOC, shifting the climate into a cold stadial. **Right,** During stadials, cooler conditions in the North Atlantic reduce meltwater input from the ice sheets, allowing an increase in surface salinity that eventually causes water to sink restarting NADW and causing AMOC to strengthen, returning the climate system to an interstadial. Source: Ruddiman, W.F. 2000. "Earth's Climate: Past and Future" First ed. W.H. Freeman ed.

As salt continues to accumulate in the North Atlantic during periods of reduced NADW formation, eventually surface waters at key sites of deep-water formation would become salty and dense enough again to sink, thus **restarting AMOC and causing an abrupt warming in the high-latitude North Atlantic**, triggering the warm phase of a D-O cycle.

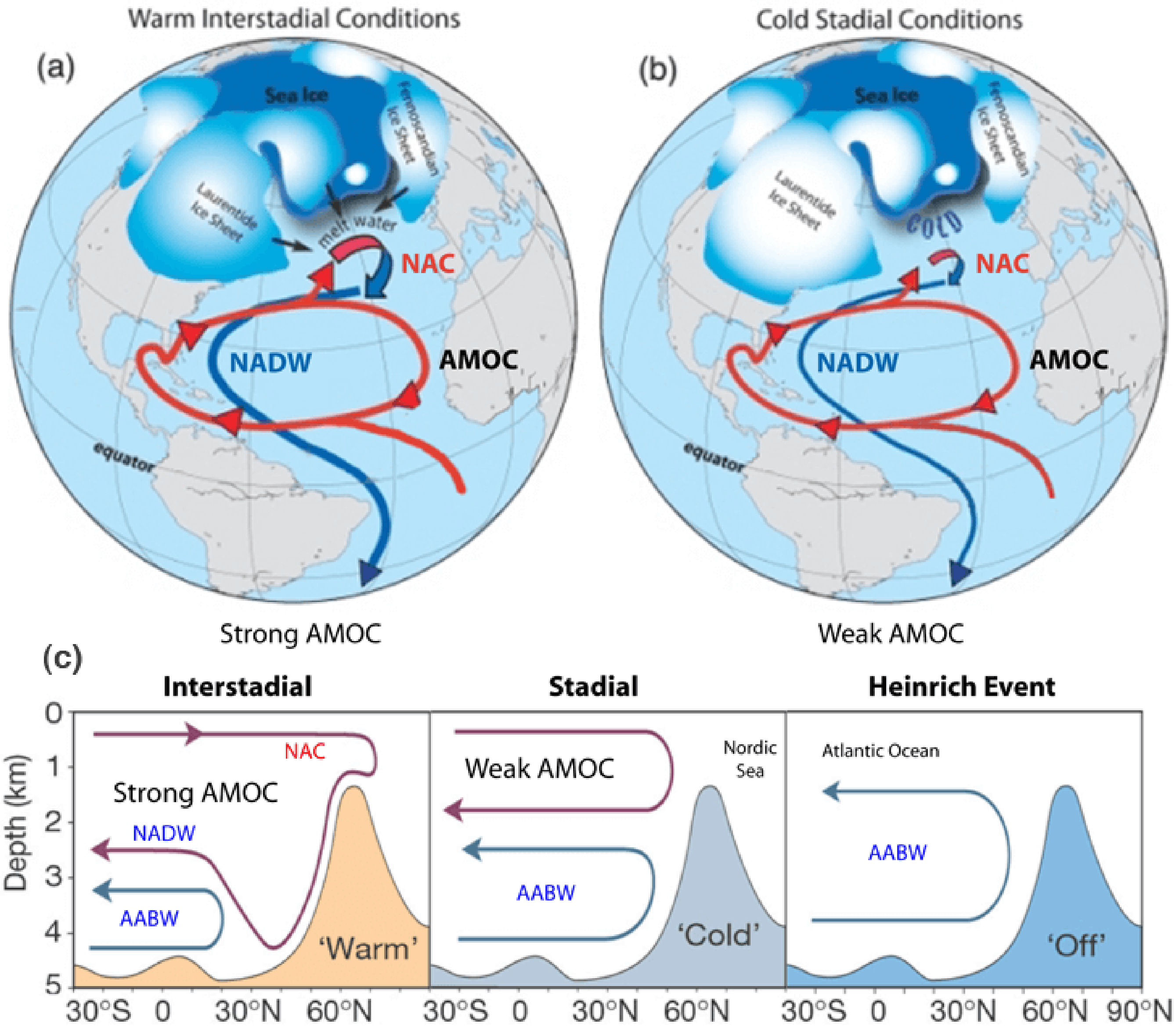

Figure 27. Mechanism of the salt oscillator hypothesis. **(a)** During warm interstadials, when AMOC is stronger, enhanced northward oceanic heat transport results in warmer conditions in the North Atlantic. Warmer conditions in the North Atlantic cause the ice sheets around the North Atlantic to melt, gradually reducing surface water salinity. Eventually, surface salinity is reduced enough to weaken AMOC, shifting the climate into a cold stadial. **(b)** During stadials, cooler conditions in the North Atlantic reduce meltwater input from the ice sheets, allowing an increase in surface salinity that eventually causes AMOC to strengthen, returning the climate system to an interstadial. Source: Schmidt, M.W. and Hertzberg, J.E. 2011. Nature Education Knowledge 3 (10):11. **(c)** Atlantic profile from 30°S to 90°N showing the underwater crest between Greenland and Scotland. Interstadial conditions show a strong AMOC capable of crossing the crest. Stadial conditions show a weakened AMOC that turns further South. During Heinrich events the AMOC collapses. Source: Rahmstorf, S. 2002. Nature 419 207-214. AMOC: Atlantic Meridional Overturning Current. NAC: North Atlantic Current. NADW: North Atlantic Deep Water. AABC: Antarctic Bottom Water.

Several studies have suggested that it only takes a small reduction in sea surface salinity to alter the rate of NADW formation, to the point that some scientists, including late Wallace Broecker and Richard Alley became worried that an increase in the hydrological cycle due to current global warming could reduce North Atlantic salinity, leading to the shut down of the AMOC causing an abrupt cooling in the near future (Broecker, 1999). They seem to forget that before the mid-Holocene transition, around 5000 yr BP, the northern Atlantic region was warmer and generally wetter than present, when the Sahara was a savanna type of environment, and the AMOC did not shut down.

The salt oscillator hypothesis has no particular explanation for the regular pacing of D-O cycles according to a 1470 year cycle. The pacing must come from the intrinsic delays in the salinity and meltwater build up and depletion, and the oceanic currents response delay for the cycle to proceed. As simply put, the pacing of a pendulum depends on its length, but climate variability is far from the regularity of simple physics.

In recent years this consensus view of D-O cycle formation through salt-oscillation has become under assault on several fronts. While several studies have questioned the occurrence of MWP at the expected time intervals, others indicate that AMOC is a lot more stable than required by the theory and even extreme MWP would not be able to destabilize it persistently.

The work of Rasmussen and Thomsen (2004), also confirmed by Dokken et al. (2013), and Ezat et al. (2015), and theoretically framed by Petersen et al. (2013; see Climate Etc. article) shows that during stadials the flux of warm water to the North Atlantic and Norwegian sea does not cease. Instead during cold stadials warm waters enter the Arctic under the sea ice at a subsurface level and thus instead of ceding the heat to the atmosphere they warm the subsurface waters below a double insulating cold water layer made of fresh superficial water and a cold and saline halocline. Thus while the atmosphere gets colder and sea ice increases, the ocean heat accumulates at the subsurface level, and no cold bottom water is produced.

Mechanistic explanation of the Dansgaard-Oeschger cycle

According to available evidence and new theories, and starting the cycle at the point during the stadial when the Antarctica starts warming, the bipolar see-saw is set to warm Antarctica and cool the north polar regions. The AMOC is then weakened and transmits less heat towards the North Atlantic. As the North Atlantic and the Arctic cool down, ice sheets expand and sea-ice increases reaching farther South (figure 28a).

As Antarctica gets warmer and the Arctic colder, the amount of warm water transmitted North starts to increase due to the enhanced equato-polar thermal gradient. This warm water produces an enhanced iceberg discharge that carries IRD to the ocean sediments, but the warm water fails to warm the higher latitudes because instead of venting the heat to the atmosphere it submerges below the ice sea where it gets layered and insulated by the halocline (figure 28b).

Every 6,100 years the Antarctic warming and the Arctic cooling are enhanced and prolonged. The temperature gradient gets much bigger and much more warm water gets moved North, where much more ice has built up, so the iceberg discharge is much higher, producing a Heinrich event (figure 28d).

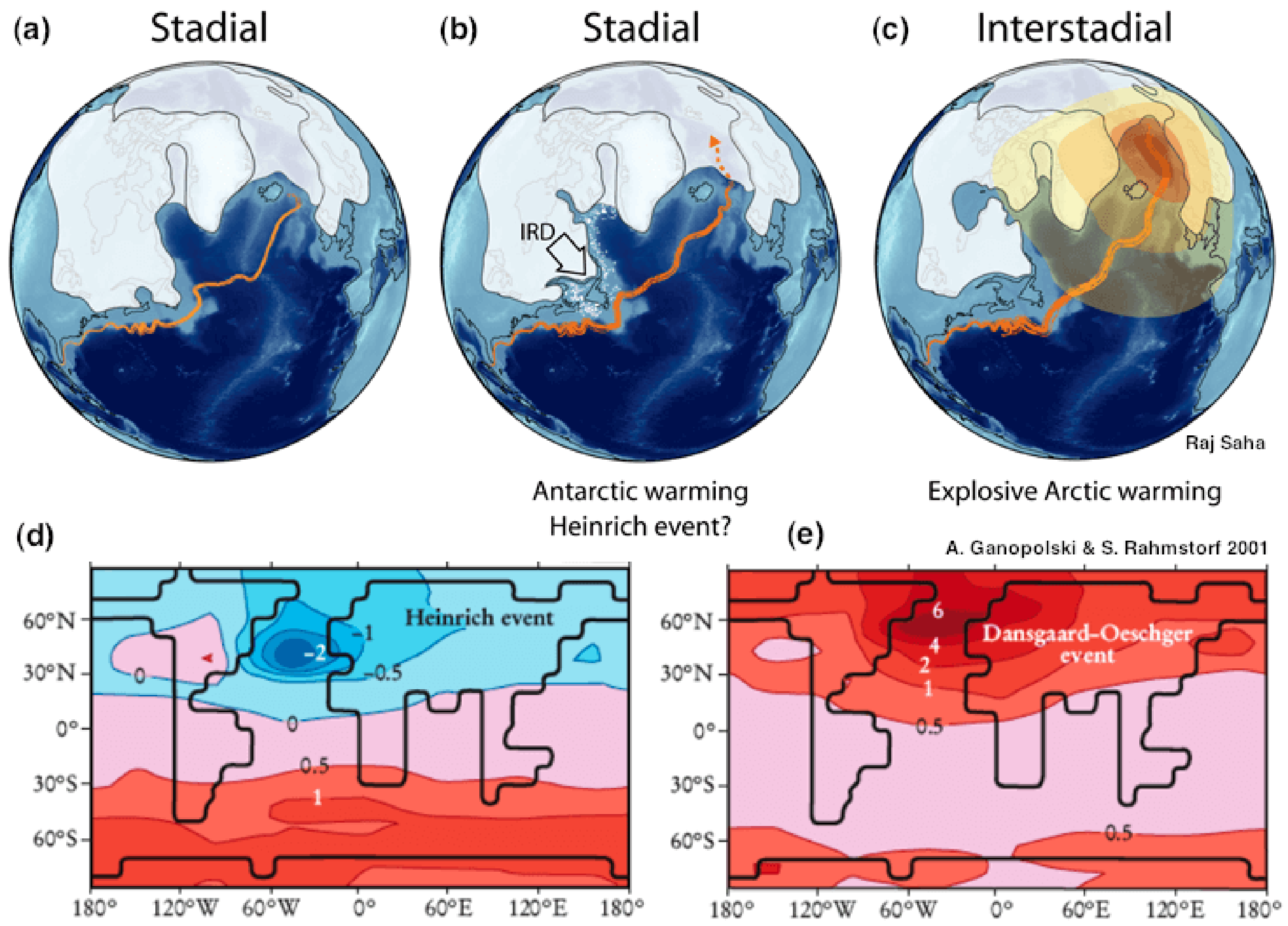

Figure 28. Mechanism of the D-O cycle. **(a)** At the beginning of the stadial the Arctic is cooling down, sea ice is growing, and surface warm water (orange) is reduced. **(b)** At the end of the stadial the Arctic cooling is maximal, Antarctica is warming, and there is an increase in the warm North Atlantic Current, that produces an increase in iceberg discharge carrying ice-rafted debris (IRD). At the Norwegian sea, warm waters sink below the ice preventing warming. From time to time this conditions are enhanced to produce a Heinrich event. **(c)** An interstadial is abruptly produced when in an explosive manner the warm water rises and melts the sea ice, transferring heat to the atmosphere. Source: Raj Saha http://math.umn.edu/~rsaha/research/DO-events.html. **(d)** Conditions during a Heinrich event as modeled. Observe the North Atlantic cooling. **(e)** Conditions during a D-O abrupt warming as modeled. Source: Ganopolski, A. and Rahmstorf, S. Nature 409 153-158.

Every 1470 (± 120) years the subsurface warm waters at high North latitudes raise to the surface and abruptly warm the atmosphere (figure 28c, e), starting the Greenlandic interstadial. This warming inverts the bipolar see-saw, so the Antarctic region starts to cool after about 200 years. As warm waters cool down they sink and form the NADW, so the higher North latitudes also start to cool. Once sea ice re-growths and the halocline forms, it insulates again the warm waters from the atmosphere and the temperature drops putting an end to the interstadial. The deep cooling of the new stadial flips again the bipolar see-saw restarting the cycle.

There is evidence from Norwegian sea sediments that have preserved the temperature stratification of the sea that changes in the sea temperature and stratification precede the abrupt atmospheric changes (Dokken et al., 2013). During the stadial phase, the planktonic foraminifera are mainly recording the temperature of cold water within, or just below, the halocline. As the stadial phase progresses, the planktonic foraminifera show an increase in temperature (Figure 29) consistent with the continuous arrival of relatively warm and salty Atlantic water below the halocline. With no possibility of venting heat to the atmosphere due to the sea ice cover, the decrease of subsurface waters density weakens the stratification that allows the halocline and sea ice cover to exist. **The transition to warm Greenlandic interstadial occurs when the stratification collapses**, at which point heat from the subsurface layer is rapidly mixed up to the surface, melting the sea ice cover (figure 30). This sudden mix-up is seen in the planktonic foraminifera proxy record as an abrupt sea temperature warming that precedes the atmospheric warming (figure 29).

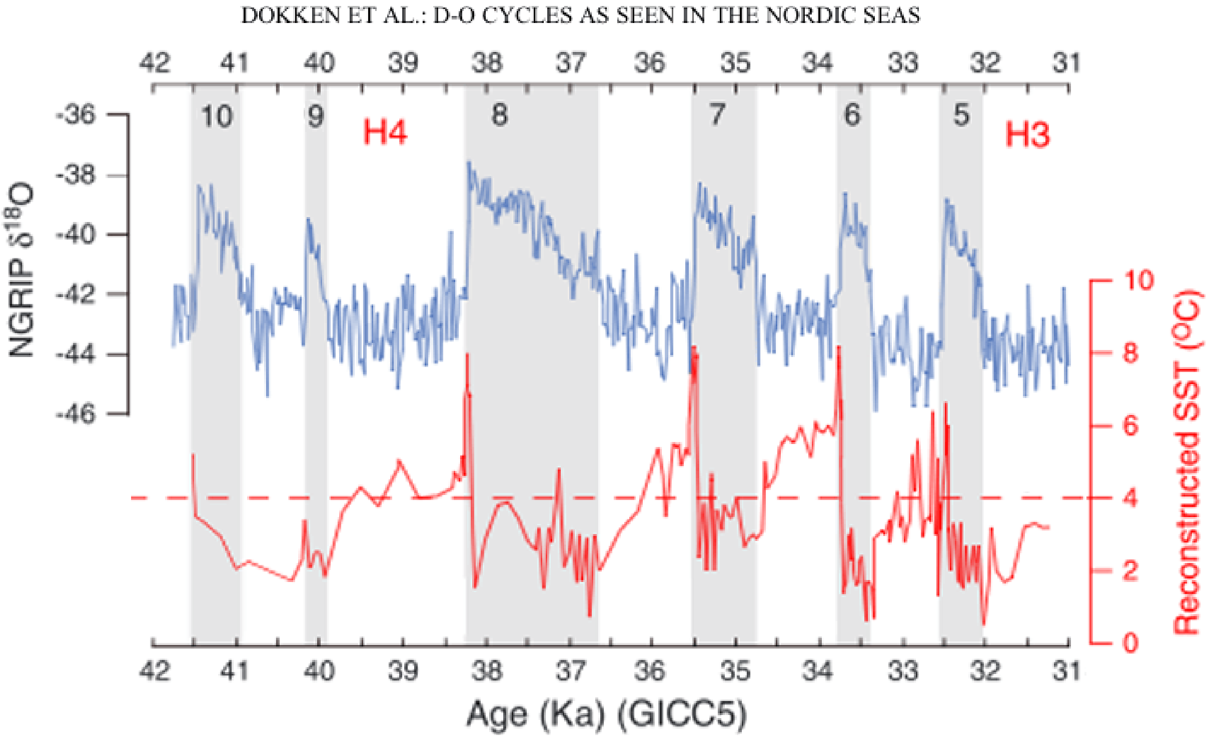

Figure 29. Subsurface temperature in the Norwegian sea. Proxy temperature records covering the period 41 to 31 kyr BP. Top panel in blue, NGRIP δ18O proxy for Greenland temperature. Bottom panel in red, sea surface reconstructed temperature (SST) based on planktonic foram assemblages. Source: T.M. Dokken et al. 2013. Paleoceanography 28 491-502.

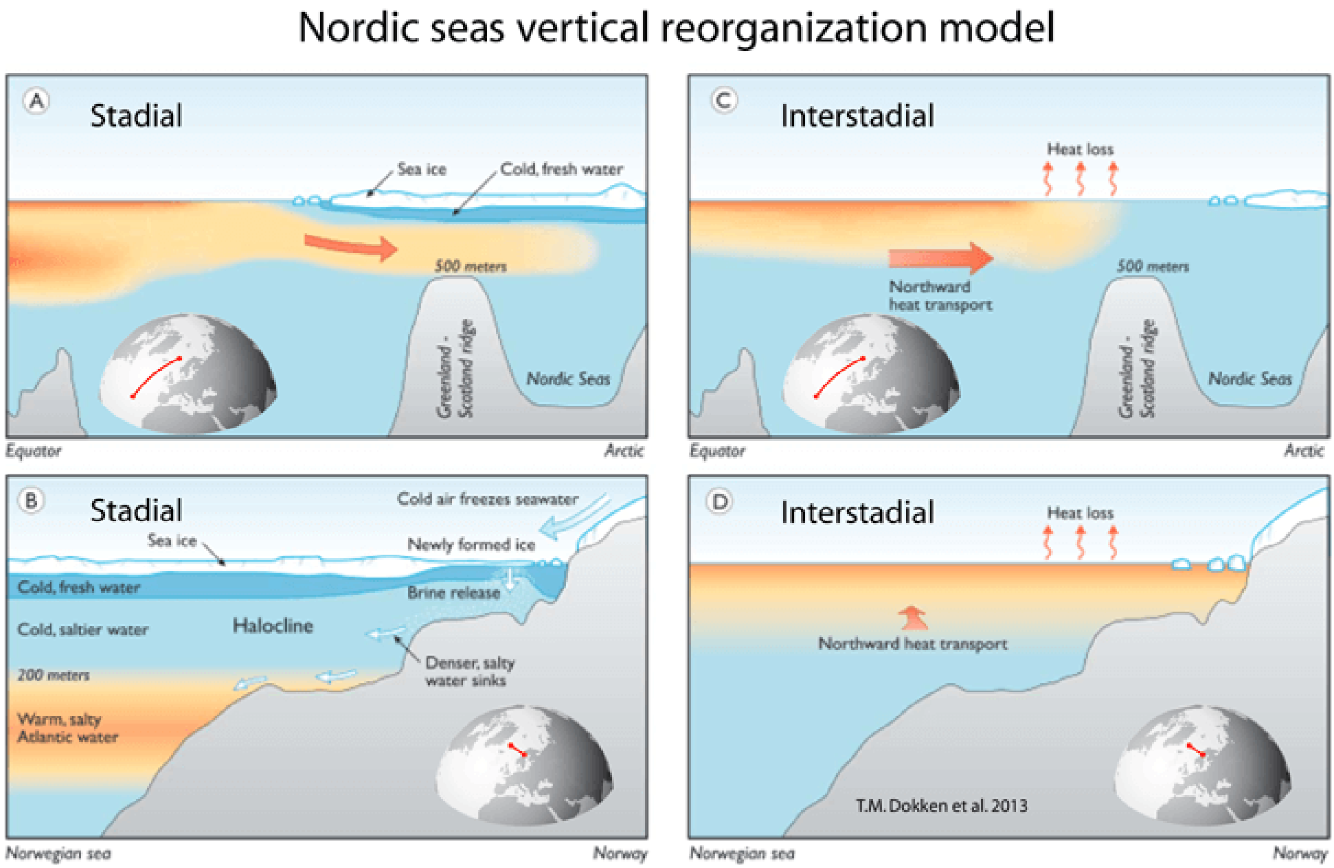

Figure 30. Norwegian sea vertical reorganization model. Schematic showing wintertime conditions in the North Atlantic and Norwegian sea during typical (left) cold stadial periods and (right) warm interstadial periods of a D-O cycle. Locations A and C show north-south sections of the North Atlantic during stadial and interstadial conditions, respectively. Locations B and D show east-west sections of the Norwegian Sea during stadial and interstadial conditions, respectively. During stadial periods warm northward Atlantic water is stratified below insulating layers of sea ice, cold fresh water and cold saltier water (A and B). At interstadial periods the stratification collapses and the warm Atlantic water reaches the surface warming the atmosphere (C and D). Source: T.M. Dokken et al. 2013. Paleoceanography 28 491-502.

Lunisolar tidal cycles as an explanation for Dansgaard-Oeschger triggering mechanism

The cause for the observed 1470 years periodicity is one of the great mysteries of paleoclimatology. Proposed explanations fall into two classes: internal variability, like oscillations in ocean circulation or ice sheet dynamics, and external forcings, like variations in the sun or orbital planetary cycles. But each explanation has shortcomings. Internal variability hypotheses have a problem explaining how such precise periodicity can be achieved given the great intrinsic variability of the involved phenomena and given the variability in the duration of D-O oscillations. Solar cycles of ~1500 years are unknown. Orbital cycles of ~1500 years are not widely accepted and the closest known lunar cycle has ~1800 years.

I have looked at most explanations for the highly regular pacing of the D-O cycle and they all come quite short. Internal factors like changes in oceanic currents or ice build up are influenced by many variable factors like wind and temperatures to expect that they are capable of producing such regularity. The same goes for the vertical reorganization of stratified Norwegian sea waters. During Heinrich events the time and amount of subsurface warm water build up is much higher, yet the pacing is maintained. Regarding external factors, the Sun looks problematic. There's no ~1,500 year solar cycle signature in the proxy records and changes in the sun luminosity are neither as precise (the sunspot cycle shows a 14% variability in pacing), nor as intense to explain the observed changes.

There are very few scientists defending a tidal origin to the pacing of D-O cycles, and curiously, Charles Keeling, the father of global CO_2 measurements since 1956 at Mauna Loa, dedicated his later years to find a tidal origin to temperature changes (Keeling and Whorf, 1997; 2000). Yet as outlandish as the tidal hypothesis sounds initially, it is uniquely capable of explaining some mechanistic features of the D-O cycle available evidence.

As with any suspect, we have to analyze if it has the means and the opportunity. Are tides capable of producing the required effect? Regular tides already have a strong effect in ocean water vertical mixing. The vertical mixing effect of tides is calculated annually at 4 Tera Watts, versus 2 TW for the wind (Keeling and Whorf, 1997). Since ocean waters are temperature stratified, vertical mixing is one of the main factors in ocean temperature changes. Moreover, tides also take place below sea ice, where they are the only factor affecting vertical mixing.

Tides also increase their power in a non-linear way according to cycles, the main one being the 18.6 years nodal cycle. Since the orbit of the Moon has an inclination of ~5° with respect to the orbit of the Earth, the nodes are the points at which the Moon crosses the ecliptic plane, and the line that joins both nodes produces a full rotation every 18.6 years. This produces alignment cycles with different periodicities, that occur when the Earth is at perigee, and the Moon is at apogee or perigee at the time of being at one of the nodes where the Moon orbit crosses the ecliptic, and with Earth the Moon and the Sun being in syzygy. Even more important that this alignment cycles, tidal strength varies with harmonic beats of tidal frequencies at longer cycles. This cycles act on a centennial scale and unlike the alignment cycles produce very high tides over a period of months or years. They have been associated with cool periods of historic times (Keeling and Whorf, 1997; figure 31).

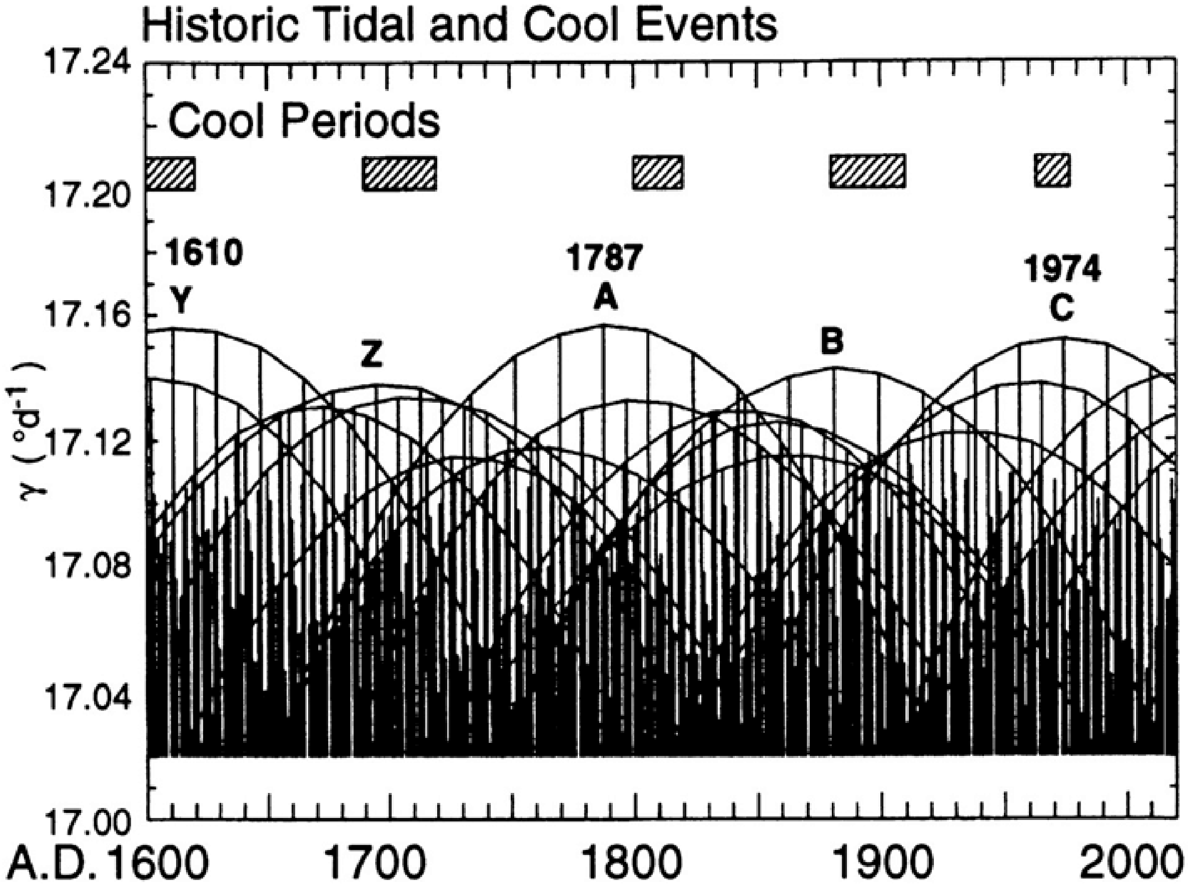

Figure 31. Timing of lunisolar tidal forcing from A.D. 1600. Each event, shown by a vertical line, gives a measure of the forcing in terms of the angular velocity of the moon, in arc degrees per day, at the time of the event. Arcs connect events of each prominent 18.03-year tidal sequence. Also plotted are times of cool episodes seen in climate data. Centennial maxima are

labeled with letters. Climactic events of the dominant sequences from 1700 and 1974 are at about 90-year intervals. Source: C.D. Keeling and T.P. Whorf, 2000. PNAS 97 3814-3819.

The strongest dominant tidal sequence of the last 200 years took place on January, 8th, 1974 (figure 31). Therefore we can check if anything unusual happened with tides around that date. According to historical records unusually high tides affected the western coasts of US and Europe on January 1974. In Western Europe the tides coupled with storms caused severe flooding in Ireland, where the severity of the damage on the 11-12th January flooding was higher than a previous hurricane "Debbie", causing the worst disaster in history for the Electricity Supply Board of Ireland (Keane and Sheahan, 1974).

In the US Fergus Wood, a researcher for the National Oceanic and Atmospheric Administration (NOAA), gave a public warning on December 26, 1973, on the upcoming very close perigee-syzygy alignment of January 8, 1974, and coastal damage was prevented by sandbagging, backfilling, and other precautionary measures. The Los Angeles Times reported on Wed., Jan. 9, 1974 (CC Ed. Part I, Page 1, Cols. 2, 3) "Giant waves pound Southland coast, undermine beach homes. Sandbag barriers erected to ward off tidal assault." (Wood, 1978). The next alignment on February 9 also caused a tidal flooding along the southern coast of England.

In Fort Denison, at Sidney Harbour, Australia, analysis of water levels since 1914 to 2009 show that the largest tidal anomaly was recorded on 26 May 1974 during the most significant oceanic storm event on the historical record. Over this timeframe some 96.8% of the measured anomalies fall within the bandwidth between -10 cm and +20 cm. The anomaly of 1974 measured 59 cm (Watson and Frazer, 2009).

Ocean tides beneath the Ross Ice Shelf in Antarctica were measured between December 1973 and February 1974 by Robinson et al. (1974), where they detected tides of about 2 meters at that time underneath the ice shelf by gravimetry.

So it is clear that unusually strong tides take place with centennial periodicities capable of exerting powerful vertical mixing even below the sea ice, thus providing a mechanism for triggering a Dansgaard-Oeschger abrupt interstadial warming. Tides were already demonstrated to enhance iceberg calving by Otto Petterssen in 1914, but tides are also sensitive to sea levels and so some researchers are showing through models that reproduce current tides, that with glacial conditions of low sea level, much bigger tides would be produced at certain areas of the world (Arbic et al., 2004; Griffiths and Peltier, 2008). These areas are located mainly in the North Atlantic region (figure 32), so the authors propose a tidal origin for Heinrich events. As tidal waves propagate, these mega tides of the glacial period would have affected the North Atlantic - Norwegian sea area where D-O cycles abrupt warming took place.

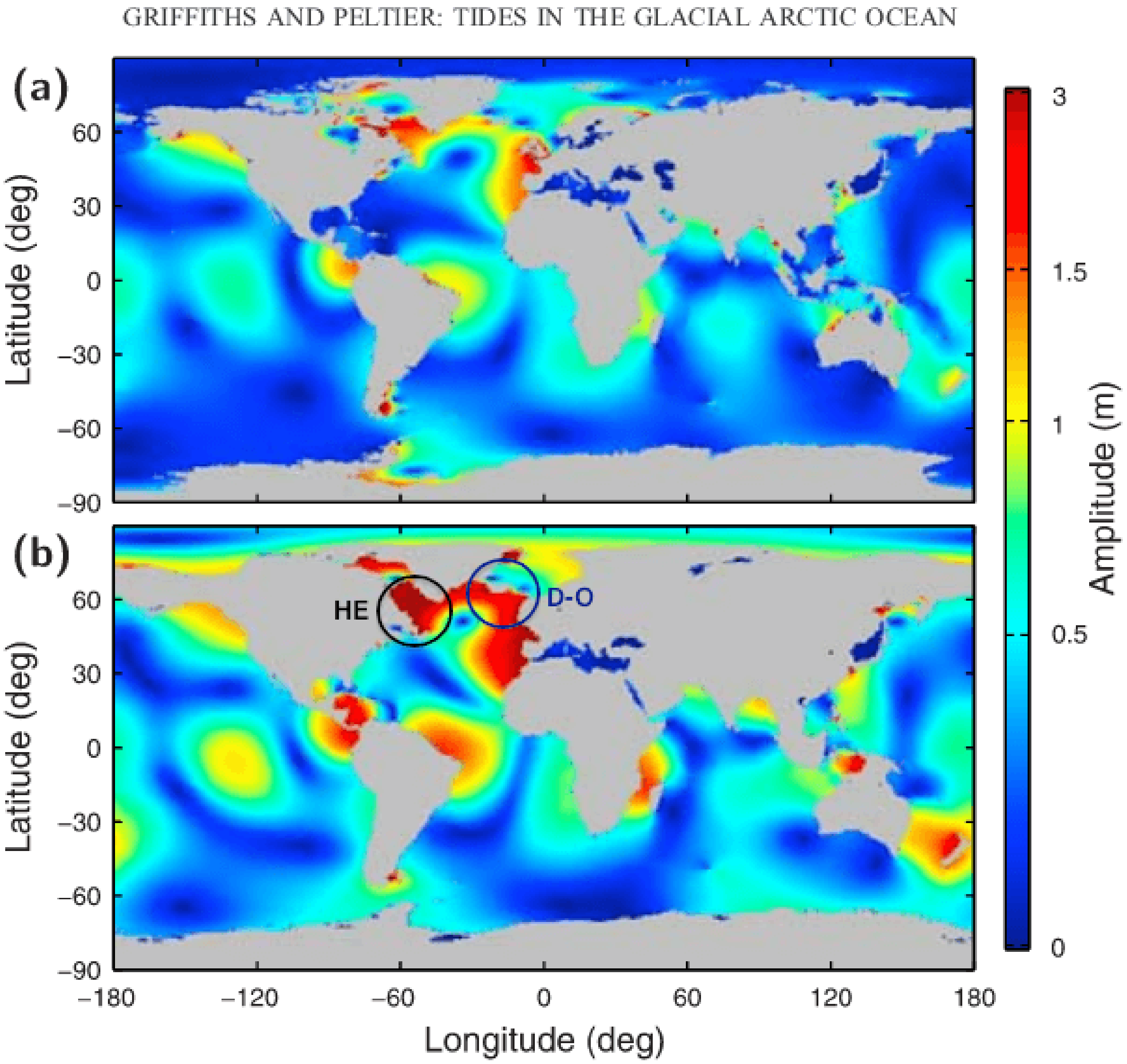

Figure 32. Ice age tidal amplitude. Tidal amplitude (m) of the principal lunar semidiurnal tide M2 at **(a)** present time and **(b)** 23 kyr BP in a hydro- dynamical model coupled to a gravitationally self-consistent (hence geographically variable) prediction of sea-level change. Between the areas with stronger tides are those producing iceberg discharges during Heinrich events (HE, black circle), and Norwegian sea area where D-O abrupt warming originates (dark blue circle). Source: S.D. Griffiths and W.R. Peltier. 2008. Geophys. Res. Let. 35 L08605.

We have seen that lunisolar tidal cycles have had the capability to have produced megatides during the glacial period, strong enough to produce intense vertical water mixing, and thus capable of explaining the triggering of D-O cycles. The tidal hypothesis is very consistent with the known requirements for D-O cycles: cold conditions that favor extensive sea-ice cover, water temperature stratification of enough differential, sea levels low enough for huge tides to be produced, but not too low as the ice cover can be too thick and stable so the tide effect is not strong enough.

The tidal hypothesis appears to have the means, does it have the opportunity? No clear 1470 yr tidal cycle is known from the data, however one can be deduced from the theory. We have already seen that the nodal precession takes place every 18.6 years. The apsidal precession, or perigee cycle is the rotation of the elliptic orbit of the Moon around the Earth every 8.85 years. By the time a nodal cycle takes place (18.6 years), two perigee cycles occur (17.7 years). This numbers are so close, that both cycles produce maximal interference every 366 years, at which point bigger tides take place. Berger et al. (2002) have proposed that the cycle of 1470 years results as a factor of 4 over the 366 years harmonic beat reflecting perhaps the requirement that the maximum tidal action occurs at a relatively narrow window during the summer season, when the sea ice is most susceptible to disruption by tides.

A lunisolar tidal cycle of millennial scale is just a hypothesis without supporting evidence for the 1470 yr pacing of the D-O cycles abrupt warming. During the Holocene the D-O cycle disappears, as it is based on low enough sea levels, extensive sea ice and temperature inversely stratified waters, with the possible participation of enhanced glacial tides. However as we will see in a future article of this series, an echo of an oceanic signal with the same periodicity resonates over the Late Holocene (Neoglacial) climate. The general features of this signal also agree well with what could be expected from a lunisolar tidal cycle during a warm interglacial: increased storminess and decreased sea-surface temperatures.

Conclusions

1) Between 90 and 12 thousand years ago Greenland proxy temperature records show more than 20 **abrupt and intense climate changes known as Dansgaard-Oeschger cycles paced according to a 1470 yr periodicity**.

2) Each D-O oscillation is preceded by North Atlantic cooling and iceberg discharges that when intense and prolonged constitute a **Heinrich event**.

3) D-O oscillations present an **asymmetric change in temperatures** with warming of 8-10°C in a few decades followed by a cooling in stages from a few centuries to a few millennia.

4) Prior to the Greenland abrupt warming, temperatures are raising in Antarctica until about 220 years after the start of Greenland warming.

5) The abrupt northern hemisphere warming **increases global methane concentrations from boreal wetlands** due to increased temperature and precipitations.

6) **CO_2 has no role during D-O cycles**, and its levels are neither cause nor consequence of the most frequent most abrupt climate changes of the past. The increase in CO_2 levels during Heinrich events does not significantly alter the rate or magnitude of the warming during the subsequent D-O oscillation.

7) **D-O cycles require sea levels between 45 and 90 m below present**, and appear to be inhibited by maximal obliquity.

8) The leading theory, the "salt oscillator hypothesis," has no explanation for the periodicity and relies on unproven melt water pulses and a contrary to evidence shut down of the Atlantic Meridional Overturning Current.

9) Challenger **D-O theory proposes the stratification of warm subsurface waters below the halocline and the sea ice** in the North Atlantic and Norwegian sea, with the abrupt warming taking place due to the collapse of this stratification.

10) Lunisolar tidal cycles provide an unsupported yet explanatory hypothesis for the 1470 yr pacing and mechanism of triggering of D-O oscillations.

Acknowledgements

I thank Andy May for reading the manuscript and improving its English.

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