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Mid-Pliocene shifts in ocean overturning circulation and the onset of Quaternary-style climates*

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Abstract

A major tipping point of Earth's history occurred during the mid-Pliocene: the onset of major Northern Hemisphere Glaciation (NHG) and pronounced, Quaternary-style cycles of glacial-to-interglacial climates, that contrast with more uniform climates over most of the preceding Cenozoic, that and continue until today. The severe deterioration of climate occurred in three steps between 3.2 Ma (warm MIS K3) and 2.7 Ma (glacial MIS G6/4). Various models and paleoceanographic records (intercalibrated using orbital age control) suggest clear linkages between the onset of NHG and three steps in the final closure of the Central American Seaways (CAS), deduced from rising salinity differences between Caribbean and East Pacific. Each closing event led to enhanced North Atlantic meridional overturning circulation and strengthened the poleward transport of salt and heat (warmings of +2–3°C). Also, the closing resulted in a slight rise in the poleward atmospheric moisture transport to northwestern Eurasia, which led to enhanced precipitation and fluvial run-off, lower sea surface salinity (SSS), and increased sea-ice cover in the Arctic Ocean, hence promoting albedo and the build-up of continental ice sheets. Most important, the closing of CAS led to greater steric height of the North Pacific and thus doubled the low-saline Arctic Throughflow from the Bering Strait to the East Greenland Current (EGC). Accordingly, Labrador Sea IODP Site 1307 displays an abrupt but irreversible EGC cooling of 6°C and freshening by ~1 psu from 3.16–3.00 Ma, right after the first but still reversible attempt of closing the CAS.

1 Introduction – links to present concerns about future climate?

At first glance, the mid-Piocene onset of major Northern Hemisphere Glaciation and Quaternary-style climates, in particular the build-up of a continent-wide ice sheet on Greenland, seems to be a fairly academic question. However, this event may be linked to burning, unresolved questions on the Earth's uncertain future climate change.

A broad spectrum of model intercomparison data (Huybrechts et al., 2004) show that the present trend of global warming will induce both a modest increase in precipitation and an annual temperature rise by up to 8°C in Greenland over the 21st century, two processes that counteract in their role for ice formation on Greenland. To test these opposed forcings Huybrechts et al. (2004) ran a duplicate model experiment, using the ECHAM-4 and HadAM3 models (Fig. 1). Results from both experiments agree that the present greenhouse warming will lead to ice growth over most parts of Central Greenland (up to 2 cm/yr ice gain), whereas massive ice melt will occur along the West Greenland margin and in the far northeastern corner (up to 100 cm/yr and more). In the models the melting volume outweighs growth and therefore, a volume loss of Greenland ice is predicted for the 21st century. However, the magnitude of this melting is highly uncertain, ranging from an equivalent of 2 to 7 cm (in contrast to an overall gain of ice mass, predicted for Antarctica; Huybrechts et al., 2004). This test resulted in the burning question, how sensitive is the Greenland ice sheet to a warming climate. Alley et al. (2005) tried to answer the question and argued for the possibility of rapid and major ice loss and significant global sea level rise. Much of the answer may depend on the orders of magnitude of the competing poleward heat and moisture transports reaching the northern North Atlantic and Eurasia.

It is the objective of this study to test a potential analogue case in the Late Neogene, the onset of Quaternary-style climates with the formation of Major Northern Hemisphere glaciation (NHG) approximately 3.0–2.7 Ma. This event is clearly revealed as a major tipping point in the long-term benthic oxygen isotope (δ^{18}O) record of the Cenozoic (Zachos et al., 2001) and as a somewhat more gradual transition on top of some distinct steps of abrupt change in the millennial-scale resolution stacked benthic δ^{18}O record LR04 of Lisiecki and Raymo (2005) (Fig. 2).

At the beginning of this paper we shortly discuss the pros and cons of various hypotheses that try to explain the potential forcings controlling the onset of Major NHG in the mid-Pliocene. In this context we stress the term “major”, because minor, regional ice sheets in the Northern Hemisphere, in particular on Greenland have already been registered since the Late Eocene (Eldrett et al., 2007) and in particular, since the Late

Miocene as recently summarized in Paleoceanography (vol. 23/3) and by DeConto et al. (2008). However, a massive rise in the discharge of ice rafted debris (IRD) to ambient seas suggests that full glaciation was only reached near 3.0–2.7 Ma, as first outlined by Shackleton et al. (1984) and displayed in detail further below. The main target of this paper is to summarize some recent lines of evidence (Bartoli et al., 2005, 2006, 2009) that suggest direct links between the final closure of the Central American Seaways (CAS), more precisely that of Panama, and various follow-up processes in the North Atlantic, the atmosphere, and elsewhere, that may have triggered changes in poleward heat and moisture transports and finally, have been responsible for the onset of full glaciation on Greenland and for the numerous and gradually intensifying Quaternary-style glaciations in Eurasia and Laurentia.

2 Conceptual models that try to explain the onset of major NHG

Cane and Molnar (2001) first proposed the gradual closure of the Indonesian Seaways near 4 Ma as forcing important to set the stage for the onset of Quaternary-style climates. More precisely, they suggested that the (poorly dated) northward plate-tectonic shift and volcanic build-up of the (previously little known) small, elongate island Halmahera northwest of New Guinea finally barred the West Pacific Warm Pool from warming the Indonesian Throughflow subsequently fed by cooler subsurface waters from the subtropical Northern Pacific (Fig. 3). On the other hand, the near-surface heat export from the West Pacific Warm Pool then was diverted to the northwestern Pacific. However, the Halmahera event occurred approximately one million years prior to the actual onset of major NHG (~3.2–2.7 Ma) and thus cannot adequately explain this turning point in climate history.

Changes in orbital forcing of climate form a further potential mechanism to initiate the onset of major NHG, first proposed by Maslin et al. (1995, 1996) and recently by several authors such as Ravelo et al. (2006). Indeed, the amplitudes of orbital obliquity cycles increased significantly ~3.0–2.5 Ma. This trend closely paralleled the major increase in global ice volume as recorded by the benthic δ18O signal (Fig. 2). However, the increase in amplitudes of obliquity cycles were reversible (at 2.25–1.8 Ma; Laskar et al., 2004), whereas the onset of major NHG was not or only to a minor degree and thus cannot be properly explained.

Huybers and Molnar (2007) established a more sophisticated approach to test the potential influence of orbital forcing on the onset of major NHG. They calculated the number of positive-degree days (PDD) for North America >50° N, obtained by applying temperature perturbations at high latitudes, expected to result from tropical anomalies and orbital variations (Fig. 4b). After ~4.2 Ma the PDD number decreased gradually down to a lowstand that persisted after ~1.8 Ma. This trend preceded the start of long-term cooling of sea surface temperatures (SST) in the eastern equatorial Pacific (Lawrence et al., 2006) by ~0.5 My (Fig. 4a). Likewise, it led the build-up of major NHG by more than 1 My (Fig. 4c). This time span requires an extremely long-lasting internal memory effect in the climate system, difficult to conceive, thus leading the authors to the honest conclusion: “Understanding the puzzle of what caused the eastern equatorial Pacific to cool off on a timescale too long to invoke the atmosphere-ocean-cryosphere system by itself now appears all the more pressing.”

Recently, Lunt et al. (2008) made a strong argument that a decline in Pliocene atmospheric CO_2 levels from 400 to 280 ppmv may have controlled the onset of major NHG (Fig. 5). This decline won’t affect precipitation patterns over Greenland and the ambient sea regions but trigger a significant decrease of surface tempeatures by 2–3°C all over Greenland, thus triggering major ice growth – as to be expected from predicting a negative greenhouse effect.

The main problem of this model study are the sedimentary records published so far, which hardly show any evidence for an atmospheric CO_2 drop as postulated for the mid-Pliocene. The two reconstructions cited (Kürschner et al., 1996; Raymo et al., 1996) do not display the postulated long-term shift in CO_2 coeval with the onset of major NHG, moreover, they show a range of uncertainty exceeding more than ±100 ppmv, that is much larger than the shift investigated, and finally, short-term trends that contradict

each other. On the other hand, a Cenozoic CO_2 record established by Pagani et al., 2005 and De Conto et al., 2008, just revealed the contrary, a fairly constant “pre-industrial” CO_2 level near 280–320 ppmv persisting over the last 25 My. Also, the cited records do not display a potential 400-ky cycle in atmospheric CO_2, which may be expected as implication of various planktic δ^{13}C records of low-latitude ocean surface waters (Wang et al., 2004) and may also play an important role for climate change, little recognized yet. Finally and most important, in case we would identify indeed sound evidence for the postulated unique and abrupt CO_2 drop, the open question on the ultimate forcing for the onset of major NHG was just postponed one step further back. That is, we needed to solve the problem, which change in global carbon reservoirs, in particular those in the ocean, may have triggered a fairly abrupt and long-lasting drop in atmospheric CO_2 during the mid-Pliocene? Possibly, the final closure of the CAS, which triggered major changes in Atlantic Meridional Overturning Circulation (MOC), may have formed a mechanism suitable to induce the postulated but not yet identified major CO_2 drop. For example, foraminiferal δ^{11}B and alkenone-based records (Foster et al., 2008) suggest various short-term and marked ups and downs in mid Pliocene $p\mathrm{CO}_2$. Apparently they were coeval with the short-term closings and re-openings of CAS shown further below, but finally summed up to a long-term decline of ~100 ppm.

3 Models and concepts on the final closure of the Panamaian Isthmus and implications for global climate change

The final closure of Central American Seaways (CAS) presents the most recent plate-tectonic change of ocean configuration in geological history, an uplift process resulting from the subduction of the Galapagos aseismic ridge (Meschede and Barckhausen, 2002). Weyl (1968) and there-after Keigwin (1982) first proposed this event as potential forcing for the onset of major NHG and Quaternary-style climates. On the basis of diverging nannofossil communities Kameo and Sato (2000) first succeeded to pin down the final closure of CAS to an age close to 2.76 Ma (marine isotope stage (MIS) G6;

equal to 2.73 Ma on the revised timescale LR04; Lisiecki and Raymo, 2005), a timing that indeed comes close to the onset of major NHG as first derived by Shackleton et al. (1984).

Maier-Reimer et al. (1990) first employed an ocean general circulation model (O-GCM) to simulate the potential impact of the closure of CAS on ocean circulation. Accordingly, the closure stopped the incursion of Pacific lower-salinity surface waters diluting West Atlantic surface water salinity (SSS), thus inducing a profound rise in poleward heat and salt transport and in turn, in Atlantic MOC. Later-on, a number of more sophisticated GCM tests basically confirmed these results (e.g., Murdock et al., 1997; Mikolajewicz et al., 1997; Prange and Schulz, 2004; Klocker et al., 2005; Schneider and Schmittner, 2006; Lunt et al., 2007, 2008). Schneider and Schmittner (2006) (Fig. 6) focussed on testing the role of four subsequent Panamaian sill depths from −2000 up to zero m on adjacent sub-SSS and sea surface temperature (SST) distributions. Different from previous concepts (Haug et al., 2001) they found Pacific-to-Atlantic sub-SSS contrasts at 50–125 m water depth, which did not respond with any noteworthy rise to the closure of intermediate waters from 2000 to 700–500 m water depth. At sill depths of 300 to 250 m only one third, at 130 m sill depth, however, already two thirds of the final sub-SSS contrasts (i.e., 1.2 psu) were established (Fig. 7). Accordingly, it was only the closing of the last 250–130 m depth of the Panamaian gateways, that finally was crucial in triggering major changes in Atlantic MOC.

Driscoll and Haug (1998) first conceived the implications of an enhanced North Atlantic MOC for the onset of major NHG (Fig. 8). Their "Panama Hypothesis" tries to reconcile the effects of two actually counteracting forcings, increased poleward heat and moisture transports for the build-up of a continent-wide ice sheet on Greenland. Driscoll and Haug postulated that stronger heating of the northern North Atlantic will result (1) in enhanced evaporation and moisture transport via the westerlies to northwestern Eurasia, as also displayed by the model of Lunt et al. (2007), (2) in much increased river discharge from Siberia to the Arctic Ocean, in turn leading to (3) more sea ice formation and (4) more Arctic albedo, and therefore, to (5) more favorable conditions for the growth of Northern Hemisphere ice sheets.

On the basis of their fully coupled, fully dynamic ocean-atmosphere models Klocker et al. (2005) and later Lunt et al. (2007) indeed confirmed that the closure of Panamaian Seaways provided the warming expected for the North Atlantic (Fig. 9), more intense Atlantic thermohaline circulation, and enhanced precipitation over Greenland and the Northern Hemisphere continents. However, they found that these forcings may be to small by an order of magnitude to produce the observed major ice sheet growth which marked the onset of major NHG and Quaternary-style climates. Though we wonder, whether sea ice-based albedo effects were sufficiently considered in the ice model of Lunt et al. (2008). Recently Molnar (2008) published harsh critiques on the proposed linkages between closing CAS and the onset of Quaternary-style Ice Age climates, arguments that need to be compared with the records presented below.

4 Sediment records on the final closure of CAS

Most of the model-predicted rise in SSS differences between the Caribbean and the eastern Equatorial Pacific forms a clear record of the closure of the Panama Seaways over the last 250–300 m water depth (Figs. 6 and 7). A range of rising SSS differences closely similar to the modelled anomalies was obtained from calculating the anomaly record between millennial-scale mid-Pliocene SSS records from Ocean Drilling Program (ODP) sites 999 and 1241 drilled to the northeast and southwest of the Panama Isthmus (Fig. 10; Steph et al., 2006; Groeneveld et al., 2006, 2008; Tiedemann et al., 2007). These SSS differences remained close to zero until ~4 Ma. First but still reversible events of rising SSS differences occurred near 3.75 Ma and 3.5–3.3 Ma, then reaching up to 0.5 psu and more; at 3.16 Ma they first reached 0.8–1.0 psu. These short precursor events of a major shallowing and/or closure of the Panama seaways may in part record short-term volcano-tectonic events, in part orbital ice and sea level cycles. In contrast, largely irreversible SSS contrasts of 0.4–0.9 and 1.0–1.3 psu were found after 2.95 Ma and at 2.5 Ma, respectively, values that came close to the model-predicted maximum anomalies in SSS. The latter two events reflect the two-step final closure of the shelf seaway induced by the uplift of the Panama Isthmus, a forcing this time stronger than any ongoing overlapping orbital sea level fluctuations also seen in the record of Fig. 10. Land-based evidence from Panama likewise documents the first full closure of the seaway near 2.85 Ma (Coates et al., 2004, and personal communication, 2004).

In contrast to objections of Molnar (2008) we conclude that initially still reversible, however, after 2.95 Ma irreversible steps in closing the CAS are well defined in terms of age by means of rising SSS differences between the S. W. Caribbean and eastern Equatorial Pacific (Fig. 10) and consistent with land-based evidence.

Model-based evidence suggests that the final closure of the CAS necessarily led to two counteracting climatic forcings with an opposed effect on high-latitude glaciations, similar to the opposed forcings on modern Greenland ice (Fig. 1; Huybrechts et al., 2004). (a) An increased poleward heat transport implied enhanced glacial melt (Fig. 9), whereas (b) an increased poleward transport of atmospheric moisture to northern Eurasia induced a freshening of the Arctic ocean and enhanced snow and ice accumulation, in particular at perennial temperatures below zero centigrade. In the following, we display sediment records from the northern North Atlantic that provide independent evidence of the two opposed processes and their potential links to a coeval and/or slightly delayed onset of NHG.

5 North Atlantic sediment records of the onset of major NHG

The onset of major NHG is best documented at ODP Site 907 to the east of Greenland and the East Greenland and East Iceland Currents (Figs. 11 and 12), a position ideal to monitor the discharge of ice rafted debris (IRD) of icebergs coming from northeast Greenland and the Arctic ocean. A second IRD record measured at Site 1307 (Fig. 11; Bartoli et al., 2009) also includes IRD originating from mountain glaciers calving nearby in southeast Greenland up to the extended Scoresby Sound. Accordingly, IRD changes

at Site 907 (Jansen et al., 2000; Bartoli et al., 2005) may best display the long-term and major trends in the evolution of NHG, whereas IRD of Site 1307 near the southern tip of Greenland may add interesting aspects with regard to the East Greenland Current (EGC) and short-term orbital-scale climate oscillations.

IRD abundances at Site 907 (Fig. 12) already suggest some kind of causal link between the build-up of major NHG on Northern Greenland and the final changes in CAS aperture, in harmony with the model of Driscoll and Haug (1998). The suite of changes in IRD 3.4–2.6 Ma follow with great detail and a persisting lag of ∼40 ky a closely similar suite of distinct steps in the evolution of CAS (Fig. 12). For example, SSS contrasts between East Pacific and Caribbean document a first full closure at 3.24–3.16 Ma, a subsequent suite of three short re-openings and minor closings 3.13–2.97, and a final closure 2.96–2.87 Ma. Each of these events was followed directly by distinct ups and downs in IRD abundance (on an exponential scale), and a final IRD extreme at MIS G10, 2.82 Ma. However, this match of two records does not provide yet the evidence actually necessary to conclude on the origin of major NHG (in harmony with doubts of Molnar, 2008). Certainly, the persistent lag of changes in IRD abundance demonstrates (a) significant memory effects in the climate system, and (b) that the oscillations in the build-up and melt of continental ice volume and resulting eustatic sea level variations cannot have controlled primarily the closing events of the CAS, but viceversa, that the CAS events have somehow controlled variations in IRD.

The IRD record from IODP Site 1307 (Fig. 12) appears less straightforward for correlations with the closings of CAS because of multiple potential IRD sources – and two competing age models (Bartoli et al., 2009). Using the (more likely) age model 2, IRD showed a medium-high IRD peak during the eminent glacial precursor stage M2, 3.33–3.24 Ma, but increased more strongly only from 3.16–3.05 Ma, right after the first full closure of CAS (MIS KM3-KM2). After a subsequent minor abundance drop, IRD formed a plateau at high level, starting with the major re-opening of CAS near 3.0 Ma and ending with a further major increase 2.7–2.66 Ma.

6 Sediment records showing increased poleward heat transport and enhanced MOC in the North Atlantic

After each major closing event of CAS we found evidence – with hardly any phase lag – for an increased poleward North Atlantic heat transport recorded at two different sediment profiles obtained from the eastern and central North Atlantic (Figs. 3 and 11; Bartoli et al., 2005). At both sites lines enveloping short-term interglacial (Mg/Ca-based) SST maxima likewise display a distinct temperature rise by 2°–3°C coeval with two major closing events of CAS, and viceversa, subsequent drops in maximum temperature, which are linked to renewed openings of the seaways. Accordingly, mid-Pliocene changes of poleward ocean heat transport linked to both the North Atlantic and Irminger Currents appear indeed closely related to the final closing and re-opening of CAS, as predicted by model simulations.

Each warming of the North Atlantic Current matched an increase in sea surface salinity by 0.2–0.4 psu (as inferred from paired planktic δ^{18}O and Mg/Ca-based SST values; Bartoli et al., 2005). Accordingly, each closing of CAS and in particular, the major event 2.95–2.82 Ma resulted in significantly intensified convection of deepwater in the Nordic Seas. The result of stronger overturning circulation (MOC) is suggested by a long-term temperature drop (−1.5° and −2°C), a slight salinity rise, and increase in density (benthic δ^{18}O values) of North Atlantic Deep Water at Sites 609 and 610 (Fig. 13). These trends paralleled clearly the twofold major (exponential) rise in IRD at Site 907, that depicts the onset of major Northern Hemisphere Glaciation and Quaternary-style climates, in particular around 2.93–2.82 Ma, when high IRD contents started to persist. The coeval changes suggest a causal linkage between enhanced MOC and the build-up of continental ice sheets.

7 Sediment records of increased poleward freshwater transport

Model simulations (Lunt et al., 2007; Prange and Schulz, 2004; Schneider and Schmittner, 2006) suggest that the closure of Panamaian Seaways led to increased precipitation, in particular over East Greenland, the northeastern North Atlantic, and western and central Europe (Fig. 9b), and fairly minor, all over the Northern Hemisphere. Today, the East Greenland Current (EGC) and its low sea surface salinity (SSS) of 32–33 psu and temperatures near 0°C provide a summary record of the outflow of low-saline surface waters from the Arctic Ocean into the northwestern North Atlantic. Thus IODP Site 1307 drilled near to the southern tip of Greenland (Fig. 11; Bartoli et al., 2009) occupies an ideal location for monitoring past changes in the EGC and its source region, the Arctic Ocean, including potential events of mid-Pliocene freshening and cooling to test the "Panama Hypothesis".

As soon as a full closure of Panamaian Seaways had been completed for a first time near 3.17 Ma (although then still reversible) the sediment record of Site 1307 indeed shows a significant change in the composition of EGC waters near 3.16–3.02 Ma (Fig. 14; Bartoli et al., 2009). Both SST maxima and minima started to decrease by 6°C in parallel with SSS oscillations that dropped by ∼1‰ $\delta^{18}O_w$ equal to 2 psu. This immense change in sea surface density exceeds by far any model expections of enhanced poleward atmospheric moisture transport. The freshening of the EGC led necessarily to enhanced stratification of the northwestern North Atlantic and reduced stability of Atlantic MOC and introduced a new, "Quaternary" regime of EGC, which was traced at Site 1307 at least until 2.7 Ma (Bartoli et al., 2009).

The great freshening of the EGC, in turn, is an immediate record of Arctic sea surface conditions, hence provides indirect but important evidence for a coeval substantial expansion of perennial sea ice and enhanced albedo in the Arctic Ocean, the condition crucial for promoting the onset of major NHG as result of the full closure of CAS. Our evidence appears in harmony with early diatom records (Herman, 1974, in Stein, 2008) and opposed to various low-resolution records (Darby et al., 2008; Frank et al., 2008) that suggest a much earlier date for the onset of perennial sea ice in the Arctic Ocean.

Obviously the mid-Pliocene increase of poleward freshwater transport has overcompensated by far the coeval effect of enhanced poleward heat transport. However, the question as to where the freshwater flow of the EGC has actually originated remains unsolved. Although GCM models show that the closure of CAS indeed implied a modest rise in poleward atmospheric moisture transport in the northern Hemisphere, this increase appears too modest for generating the major freshening found for the EGC and climatic changes such as the onset of major glacification on Greenland (Lunt et al., 2007, 2008).

Thus we need a substantial further forcing to explain the striking SST/SSS decrease near MIS KM3 to G21. A recent model study now suggests a suitable mechanism not yet considered (Fig. 15; Prange unpubl.). It shows that the full closing of CAS led to an increased steric height of the North Pacific and in turn, a straight doubling of the low-saline Arctic Throughflow (∼1 Sv today) from the North Pacific through the Bering Strait up to a strongly intensified EGC, when assuming a Holocene sea level stand. Unfortunately, no SST and SSS records have been established yet in the subarctic North Pacific for the interval 3.16–3.0 Ma. Nevertheless, two planktic $delta^{18}$O records of *G. bulloides* and *Neogloboquadrina pachyderma* (s and d) independently record a 1-permil 18O decrease from 2.85 to 2.74 Ma (Maslin et al., 1995). It either reflects a 4°C local warming or, more likely, a transient 2-psu freshening of surface waters over 100 k.y. prior to the final step during the onset of NHG at MIS G6-G4. However, the global δ^{18}O reference record LR04 (Fig. 2) indicates mid-Pliocene interglacial and in part, even cold-stage sea level stands (except for MIS G20) that were up to 30–40 m higher than today. Accordingly, the aperture of the Bering Strait near ∼3.15 Ma may have been much wider and in turn, the increase in Bering Strait throughflow even larger. On the other hand, one may assume that the Bering Strait valley, today roughly 50 m deep, was gradually deepened by erosion with each emergence due to repetetive eustatic sea level lowerings which marked the 60 glacial stages of the last 3 m.y. In this case the model-based conclusion on a doubling of the throughflow appears more real-

istic. Possibly, the enhanced throughflow may be also reflected by increased advection of Pacific, in particular siliceous plankton.

Once low temperatures and low salinity of the EGC had been established, this current led to robust thermal isolation of East Greenland from the poleward heat transport further east through the North Atlantic and Norwegian Currents. Since this time the EGC formed a barrier important to promote the growth of continental ice (however, this feature is difficult to assess by any low-resolution GCM). The Greenland continental ice sheet, once established, strengthened the Greenland High and in particular, northerly winds along its eastern margin (cf. Toniazzo et al., 2004). In turn, the enhanced winds again strengthened the EGC flow. This positive feedback, a kind of memory effect, may have been crucial in keeping the low-salinity and cold regime of the EGC going over interglacial stages K1, G21, and G19, when the CAS was shortly re-opened until the renewed and final closure after 2.95 Ma (Fig. 14), when both effects (closed CAS and pronounced northerly winds along the East Greenland coast) were strong enough to drive a vigorous, similar to present-day EGC that pushes the polar front across Site 1307.

In summary we may conclude that the final linkage between the full closure of CAS and the onset of major NHG was accomplished through a significantly strengthened low-saline Bering Strait and Arctic Throughflow hitherto overseen. The effects of this flow were far more substantial than the atmospheric poleward moisture transport and have clearly overcompensated the effects of enhanced poleward heat transport in the North Atlantic likewise resulting from the final closing of CAS. Once a major Greenland ice sheet had been established near 3.18–3.12 Ma and in particular, after 2.9 Ma, it formed together with the outlined secondary feedback mechanisms an ongoing nucleus for Quaternary-style climates recorded by Quaternary-style glaciations persisting in the Northern Hemisphere over the last 2.8–3.0 Ma.

Finally, it turns out that the outlined mid-Pliocene buildup of major NHG definitively does not form any analogue for a better understanding of the present and future evolution of the Greenland ice sheet as result of “Global Warming” in the northern North

Atlantic. Whereas the modern warming is induced by increased atmospheric CO_2, that is particularly effective at high latitudes, the mid-Pliocene warming of the North Atlantic was linked to enhanced Atlantic MOC and the closing of equatorial seaways, forcings that were overcompensated by a significantly intensified cold Arctic Throughflow, in addition to the enhanced atmospheric poleward moisture transport. We have no reason to expect any analogue case of these ocean-driven changes in mid-Pliocene climate for the near future.

8 Conclusions

- Sediment records from the northern North Atlantic show that the final closing of Panamaian Seaways has led to the model-predicted increase in poleward heat transport and Atlantic MOC first near 3.25–3.15, later-on at 3.00–2.85 Ma.
- As result of the full closure of Panamian Seaways the poleward flux of atmospheric moisture increased noteworthy and more important, the flow of low-saline and cold surface waters from the North Pacific through the Bering Strait and Arctic Ocean was doubled. Together these two freshwater fluxes have overcompensated the increased heat transport thereby inducing a dramatic cooling and freshening of the EGC, a substantial expansion of perennial Arctic sea ice and albedo ~3.2–3.0 Ma, and in turn, the onset of major northern Hemisphere glaciation, first culminating near 2.82 Ma (MIS G10).
- Cooling and freshening of the EGC led to a positive feedback, the thermal isolation of Greenland from increased poleward heat transport, thus further promoting a persistent glaciation of Greenland and NHG.
- The onset of NHG and the Quaternary is no analogue for today: increased atmospheric pCO_2 is warming high latitudes in particular, thus leading to an enhanced melt of the ice on Greenland, whereas the mid-Pliocene formation of the

full Greenland ice sheet was mainly induced by enhanced poleward freshwater transport and Arctic Throughflow, then compensating for a warming that mainly affected the temperate (Sites 609 and 610) and subpolar North Atlantic (Site 984).

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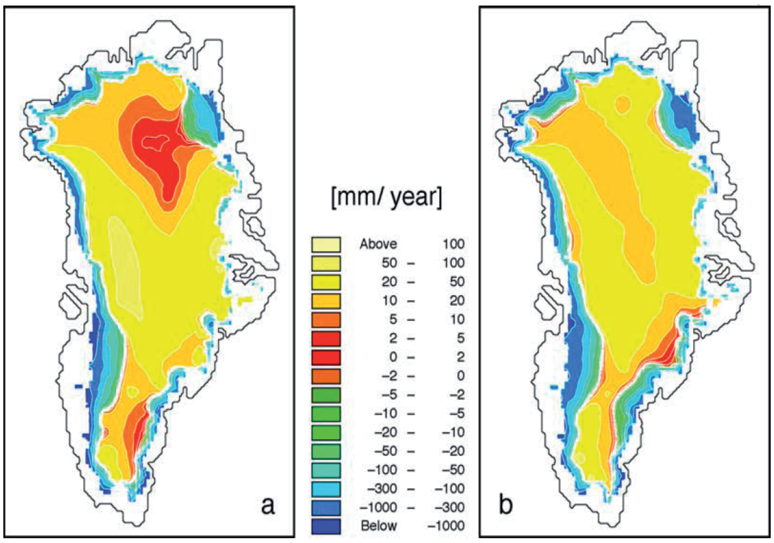


Fig. 1. Huybrechts' (2004) model of potential future variations in ice thickness on Greenland, modelled using the ECHAM4 **(a)** and HadAM3H **(b)** models.

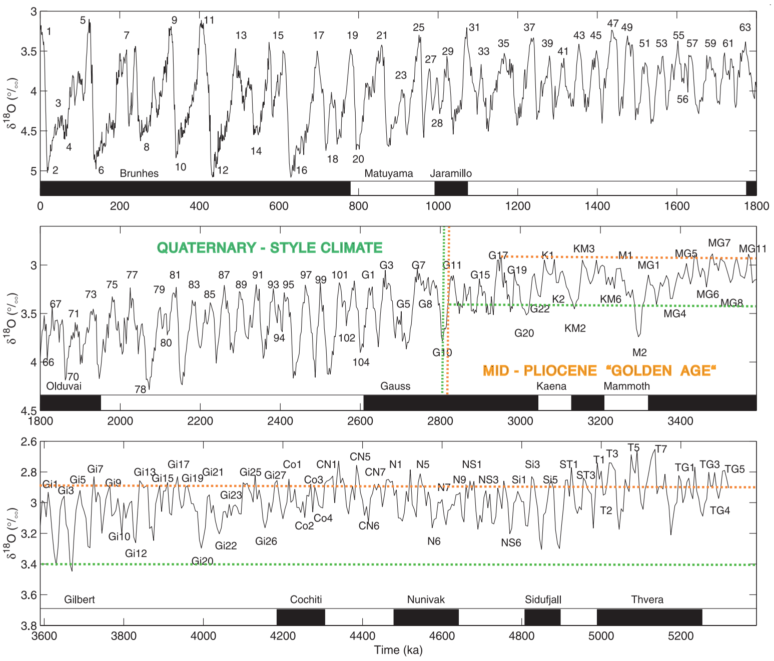


Fig. 2. "LR04" benthic δ^{18}O record of global ice volume changes over the last 5 m.y. (Lisiecki and Raymo, 2005; modified): Transition from the mid-Pliocene "Golden Age" (2.9–3.4‰) to Quaternary-style climates near 3.0–2.8 Ma. Note the expanded vertical scale at >3.6 Ma. The "Golden Age" represents a state of small-scale and fairly uniform climate oscillations that continued since 4.0 Ma, subsequent to a further 0.2–0.3‰ increase of cold δ^{18}O excursions only near 4.2–4.0 Ma in the middle Early Pliocene. Numbers are marine isotope stages (MIS).

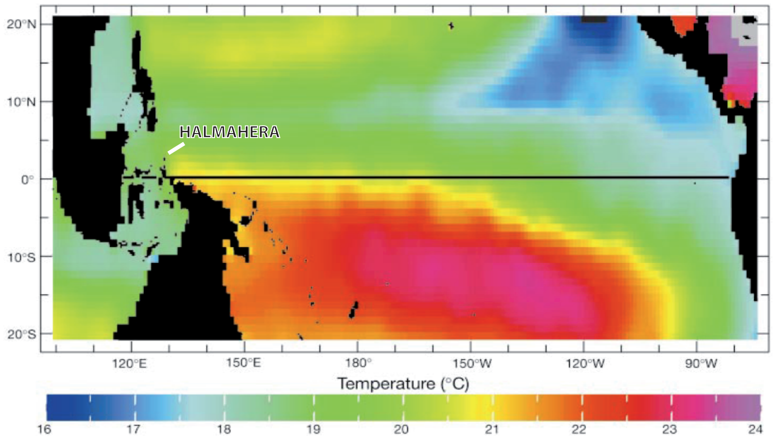


Fig. 3. Location of the island of Halmahera, today preventing the WPWP from flowing into the Indonesian Throughflow (Cane and Molnar, 2001; modified).

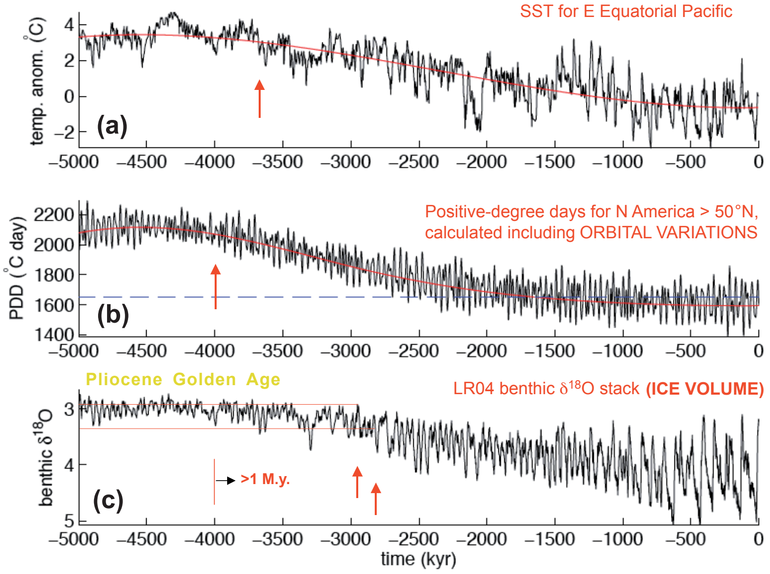


Fig. 4. Model of Huybers and Molnar (2007; suppl.) on North America's "Positive Degree Days" (PDD), East Pacific cooling, and δ^{18}O record of growth of global ice volume over the last 5 m.y.

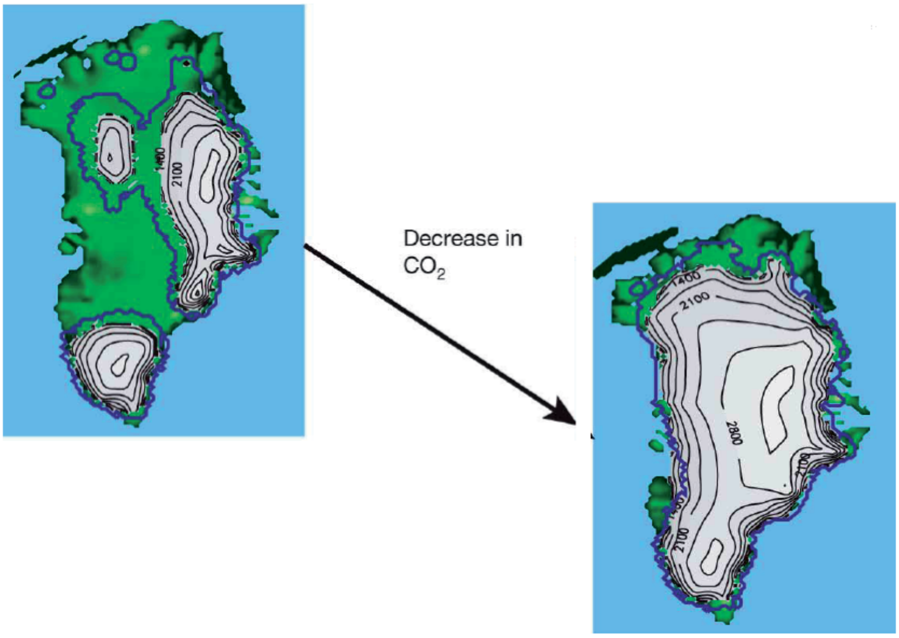


Fig. 5. Growth of Greenland ice sheet, induced by decline in atmospheric CO$_2$ from 400 to 280 ppmv (model of Lunt et al., 2008; modified).

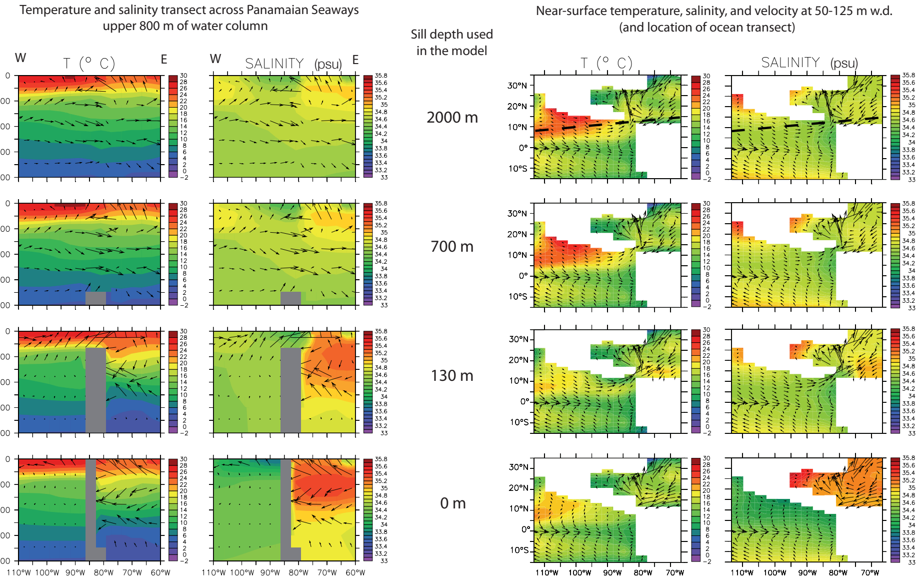


Fig. 6. Impact of shoaling of Panamaian Seaways on Caribbean and equatorial east Pacific upper ocean water mass signatures in a high-diffusion (HD) experiment with the UVic-ESCM model (Schneider and Schmittner, 2006).

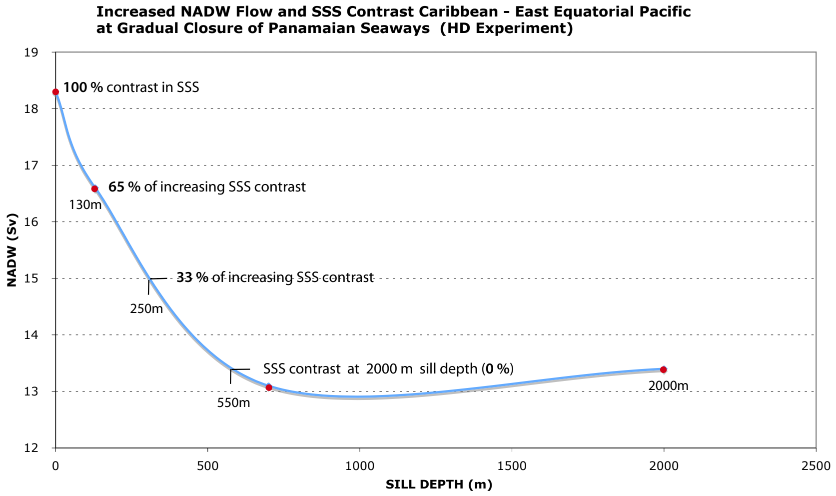


Fig. 7. Increase in NADW flow and East-Pacific-to-Caribbean subsurface salinity contrasts (at 50–125 m w.d.) during the final closure of the Panamian Seaways (based on HD model of Schneider and Schmittner, 2006).

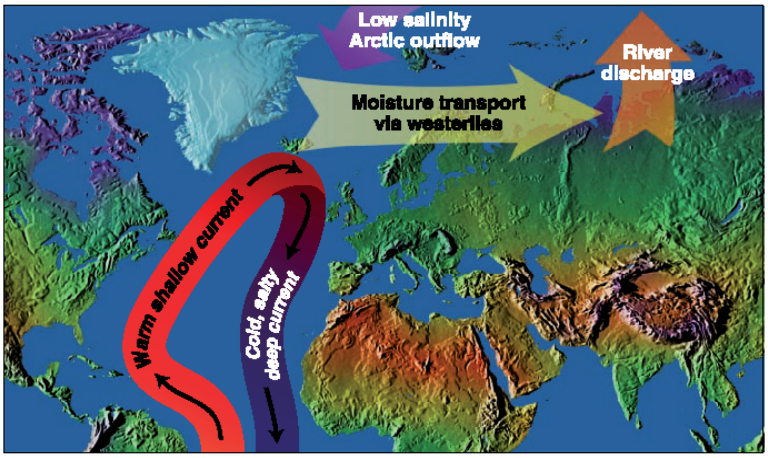
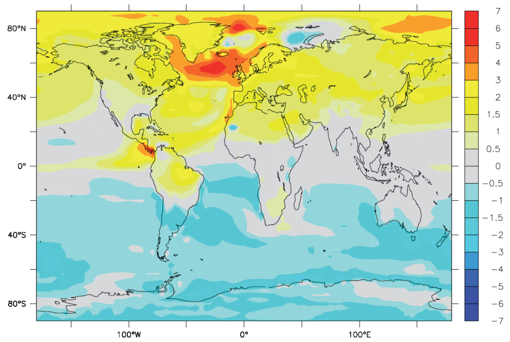


Fig. 8. Driscoll and Haug (1998) model on "Panama Hypothesis". As result of closing CAS the poleward transport of heat with the North Atlantic Current is intensified, inducing enhanced evaporation in the North Atlantic and in turn, a rise of poleward atmospheric moisture transport and finally, a freshening of the Arctic Ocean, sea ice formation, and enhanced albedo.

(a) Surface temperature change, Closed Seaway - Open Seaway (K)



(b) Precipitation change, Closed Seaway - Open Seaway (mm/day)

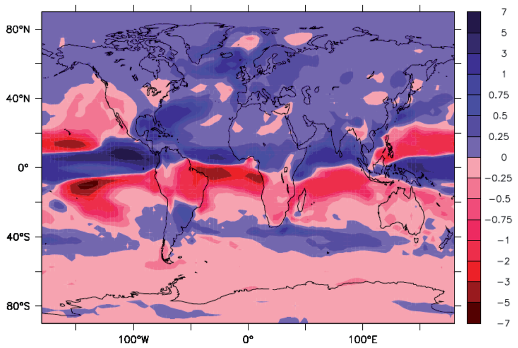


Fig. 9. Changes in surface temperatures **(a)** and precipitation **(b)**, comparing Closed Panamaian Seaways with Open Seaways (model experiments of Lunt et al., 2007).

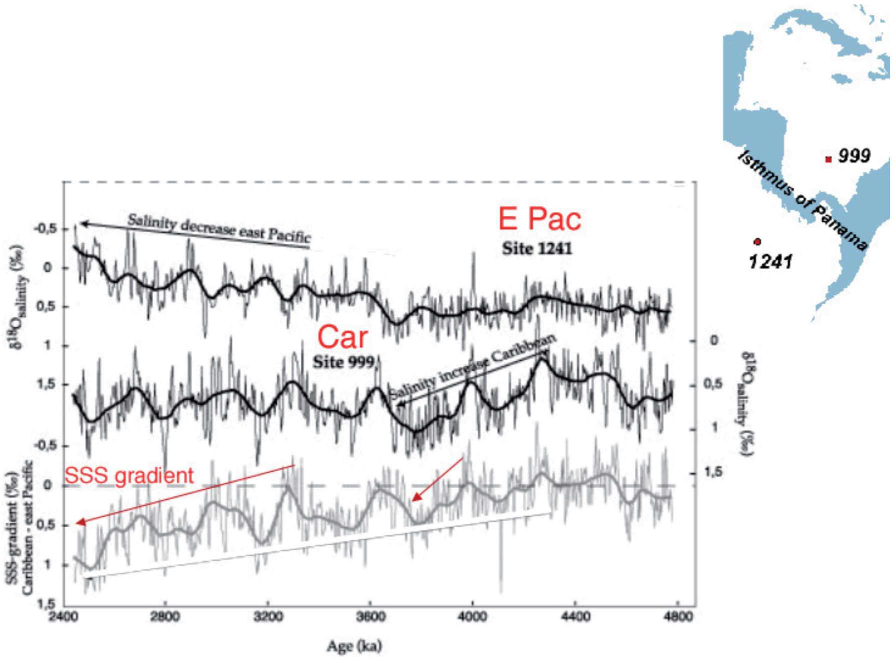


Fig. 10. Increasing SSS gradient between Caribbean (CAR) and eastern Equatorial Pacific (E Pac), reconstructed from $\delta^{18}O$ and Mg/Ca-based SST values of *Globigerinoides sacculifer*, a species growing at ~50–100 m water depth (Steph et al., 2006; Groeneveld et al., 2006). A $\delta^{18}O$ gradient of 0.6‰ is set equal to a SSS gradient of 1.2 psu that approximately corresponds to a full closing of CAS, following the gradients shown in Fig. 6. Age scales tuned to LR04 (Lisiecki and Raymo, 2005), slightly modified by Tiedemann et al. (2007).

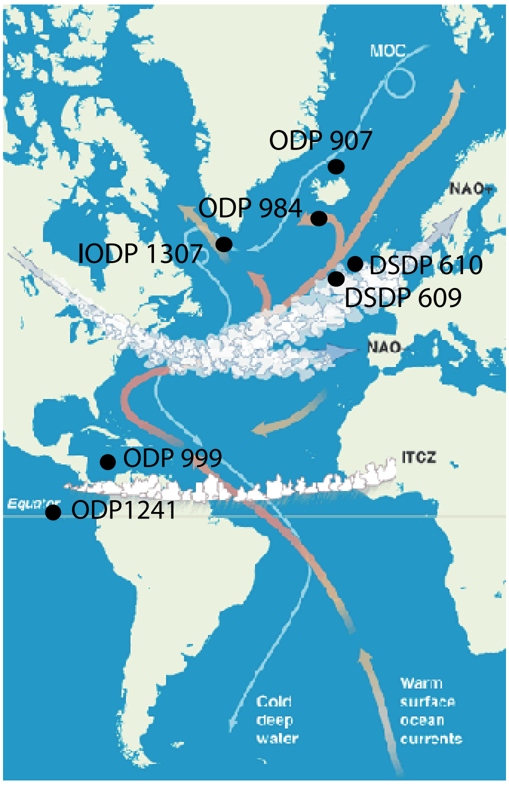


Fig. 11. DSDP, ODP, IODP site locations and surface currents in the North Atlantic.

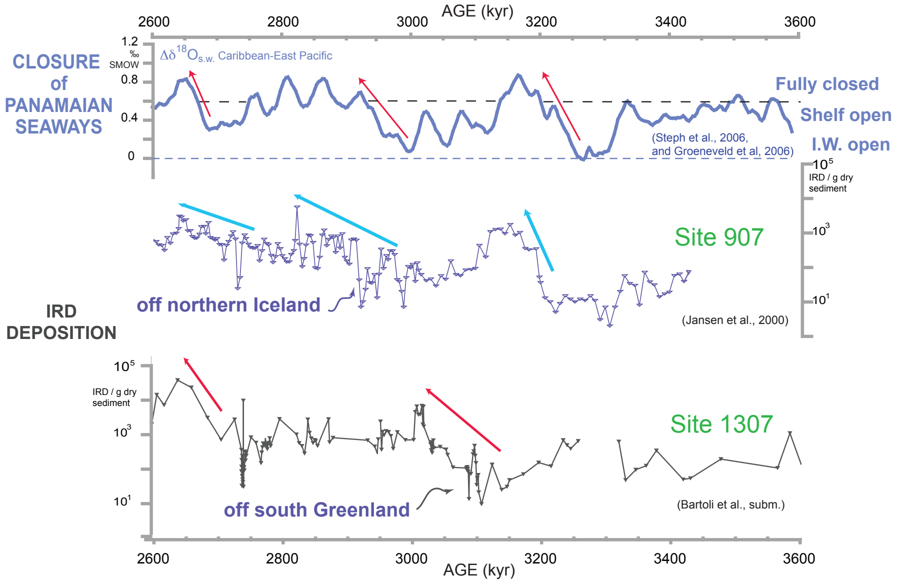


Fig. 12. Closure of CAS (record inverted from Fig. 10) and IRD abundance at ODP Site 907 (Bartoli et al., 2005; age model of Jansen et al., 2000, modified by Lacasse et al., 2002) and IODP Site 1307 (age model 2 of Bartoli et al., 2009), where the great IRD increase 3.15–3.0 Ma matches a major freshening of the EGC, shown in Fig. 13.

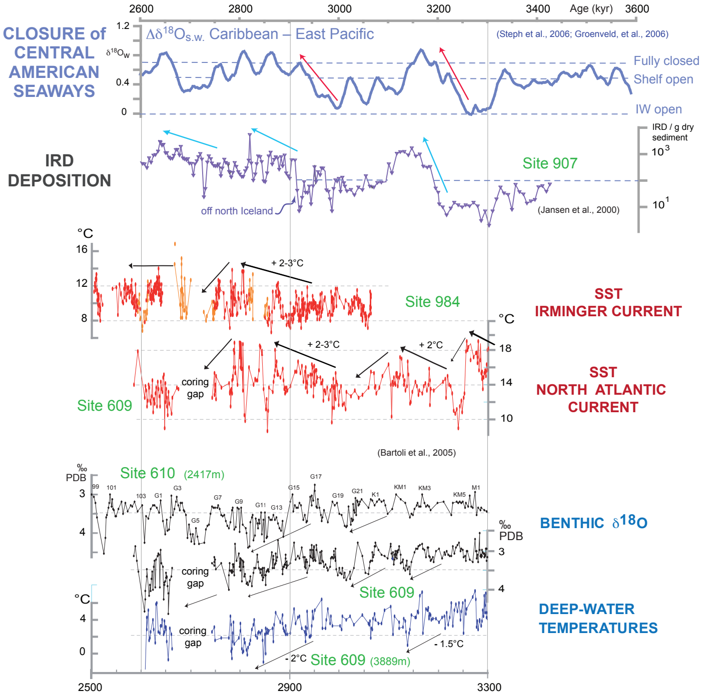


Fig. 13. Closing of CAS (record inverted from Fig. 10), IRD abundance at Site 907, warming of northern North Atlantic (Mg/Ca-based SST records from ODP Sites 609 and 984), and increased Atlantic MOC deduced from a drop in Mg/Ca-based bottom water temperatures (BWT) at ODP Site 609 and increased benthic δ^{18}O values at ODP Sites 609 and 610 (Bartoli et al., 2005; Kleiven et al., 2002). Age scales tuned to LR04 (Lisiecki and Raymo, 2005). Small letters and numbers (101–M1) label marine isotope stages (MIS).

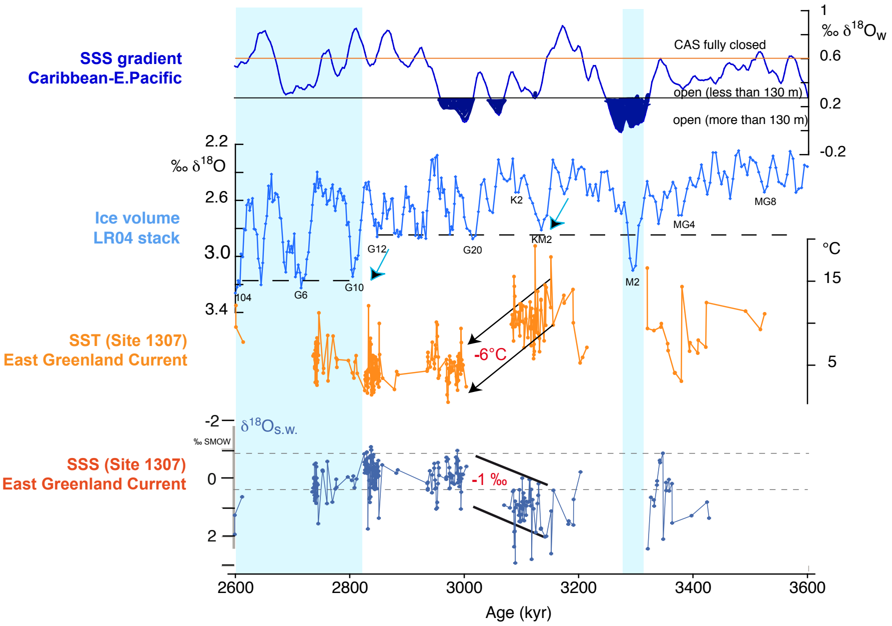


Fig. 14. Major temperature and salinity drops in the EGC at IODP Site 307, 3.15–3.0 Ma (age model 2 of Bartoli et al., 2009; modified), versus the final closing history of CAS (record inverted from Fig. 10), and benthic δ^{18}O stacked record LR04 (Lisiecki and Raymo, 2005). Age scales tuned to LR04 (Lisiecki and Raymo, 2005). Small letters and numbers (104–MG8) label marine isotope stages (MIS).

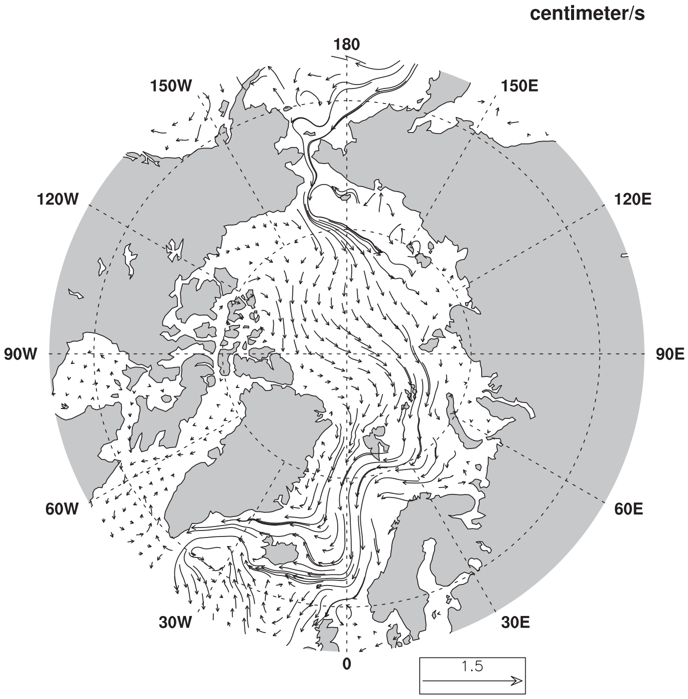


Fig. 15. Increased (doubled) flow rate of low-saline surface water through the Bering and Fram straits ("Arctic Throughflow") as result of closing CAS and increased steric height in the northern North Pacific, modelled for modern sea level stand using the NCAR Community Climate System Model, version CCSM2/T31x3a (Prange, 2008). For detailed description of the experimental set-up see Steph et al. (2006).