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Influence of Bering Strait flow and North Atlantic circulation on glacial sea-level changes

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Sea-level fluctuations of about 20–30 m occurred throughout the last glacial period. These fluctuations seem to have been derived primarily from changes in the volume of Northern Hemisphere ice sheets[1-3], and cannot be attributed solely to ice melt caused by varying solar radiation[4]. Here we use a fully coupled climate model to show that the transport of relatively fresh Pacific water into the North Atlantic Ocean was limited when lower sea level restricted or closed the Bering Strait, resulting in saltier North Atlantic surface waters. This invigorated deep convection in the North Atlantic Ocean, strengthening meridional overturning circulation and northward heat transport in our model, which consequently promoted melting of ice sheets in North America and Europe. Our simulations show that the associated sea-level rise led to a reopening of the Bering Strait; the flux of relatively fresh water into the North Atlantic Ocean muted meridional overturning circulation and led to cooling and ice-sheet advance in the Northern Hemisphere. We conclude that the repetition of this cycle could produce the sea-level changes that have been observed throughout the last glacial cycle.

Over the past million years, Earth's climate has experienced quasi-regular cold and warm cycles. These are glacial–interglacial cycles, related to variations of the amount of solar radiation reaching the Earth in each season owing to changes of Earth's orbit[4] (Fig. 1). If the winter snow survives the following summer at 65° N, it increases the reflectivity of the Earth's surface to the incoming solar radiation. In this case, ice sheets can then form over successive years owing to positive albedo feedback processes, leading to a new ice age[5–7]. The last glacial cycle started about 116 thousand years before present[8] (kyr BP). As the climate entered the glacial period, ice-volume equivalent sea-level (ESL, also known as eustatic sea-level or global mean sea-level) dropped owing to the growth of shelf- and continent-based ice sheets[9]. However, significant oscillations appear in the ESL record from the earliest stage of the glaciation to the Last Glacial Maximum.

The cause of the ESL fluctuations remains enigmatic. They could be related to boreal summer solar radiation changes associated with the oscillations of the general precession of the equinoxes and the longitude of perihelion. However, when ESL started to rise after the early minima (for example, at about 112 and 94 kyr BP, Fig. 1), the amount of solar radiation reaching the Earth in boreal summer at 65° N was still at a minimum, much below the mean of the past 130 kyr. Thus, solar radiation changes cannot be the sole reason why the ESL started to increase at those times, instead of continuing to decrease. This suggests that some internal process, or processes, within Earth's climate system may have contributed to these ESL changes. An important internal mechanism that can modulate Earth's climate is the variation of the oceanic meridional overturning circulation (MOC) in the North Atlantic Ocean, which has a crucial role in the redistribution of heat and fresh water globally[10,11]. The MOC pulls warm surface water from the rest of the oceans to the subpolar North Atlantic, where this water descends in the far north to form cold, deep water, then completes the loop by flowing southward at depth. Pronounced changes in this circulation have been shown to characterize past abrupt climate change events[12–16] and may also have an essential role for future climate change[11,17,18].

The Bering Strait is a shallow and narrow strait between Siberia and Alaska with a present depth of about 50 m. At present, every second, about 800-thousand cubic metres of relatively fresh North Pacific water is transported through this Strait into the Arctic[19], and subsequently into the North Atlantic, affecting the upper ocean stratification and thus the strength of deep ocean convection and MOC (refs 20–22), and hence also global climate[22,23]. As shown in Fig. 1c, a prediction of the relative sea-level (RSL; for details see Supplementary Information) shows that the Bering Strait was nearly closed on several occasions between the onset of the glacial cycle and about 70 kyr BP, severely restricting the Pacific–Arctic flow. This suggests a potential causal relationship in which the nearly closed Strait may have had a role in modulating the MOC, ice-sheet stability and subsequent ESL.

Here we use a state-of-art fully coupled climate model—the Community Climate System Model version 3 (ref. 24) (see Supplementary Information)—to demonstrate that the Bering Strait could indeed have had an important role in ESL variations during the last glacial period. Two pairs of experiments are carried out, one pair with the North American ice sheets and one pair without. Within each pair, all conditions are identical except that one has an open Bering Strait, and the other a closed Bering Strait. We used the solar radiation[25,26], atmospheric CO_2 (ref. 27) and methane[28] concentration, and ice-sheet condition of 112 kyr BP (see Supplementary Information).

When the Bering Strait is closed, the fresher North Pacific water is no longer transported into the Arctic and subsequently into the North Atlantic (Fig. 2). This leads to a saltier subpolar North Atlantic, a less stratified water column there, enhanced deep convection and a more vigorous MOC (a 13% increase, Fig. 2, Supplementary Fig. S1a). This strengthened MOC induces

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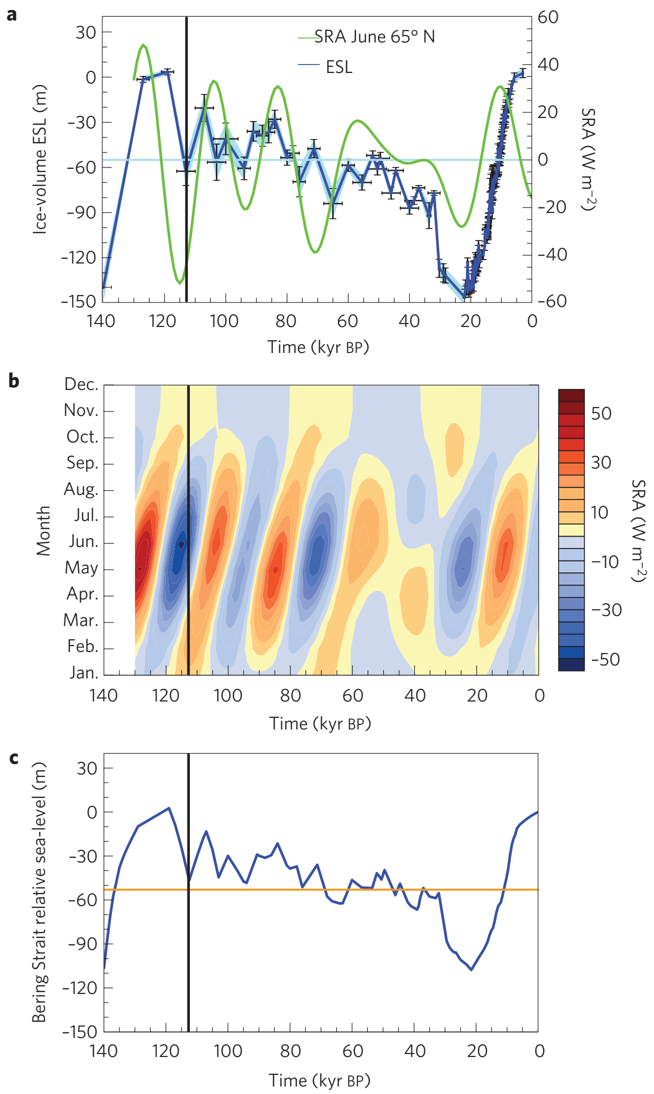

Figure 1 | Sea-level and solar-radiation variations. **a**, Ice-volume ESL (ref. 9) and solar-radiation anomaly (SRA) at 65° N in June[25,26]. The bars give the error range on ESL age and magnitude, and the shading provides the estimated error envelope. **b**, Monthly SRA at 65° N. **c**, Predicted RSL in the Bering Strait region (blue line); the orange line shows the present-day Bering Strait depth. RSL below this line indicates a subaerial Bering Strait. SRA is relative to the mean of the past 130 kyr. The vertical black line in each part indicates the ESL minima at 112 kyr BP.

global-scale changes of the meridional redistribution of heat and fresh water. First, more heat is transported from the rest of the world ocean into the Atlantic, resulting in an increase of the northward meridional heat transport (MHT) at all latitudes in the Atlantic. At 24° N, for example, this increase is 11%. Second, in the Pacific, the northward MHT is reduced by 15% at 24° N and the southward MHT is increased by 18% at 30° S. Meanwhile, the blocking of the Bering Strait also leads to a freshwater gain in the North Pacific (Supplementary Fig. S1a), producing a 43% increase of the southward freshwater transport at 40° N (Fig. 2).

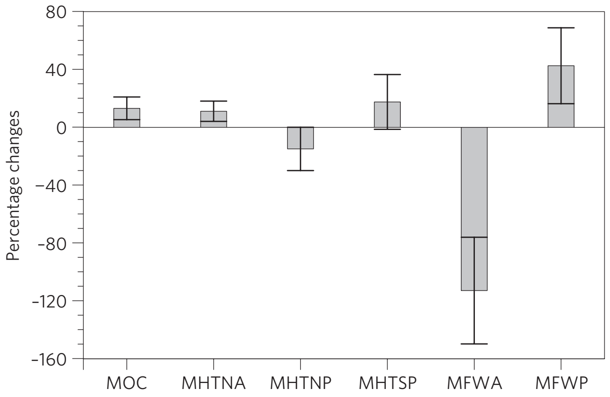

Figure 2 | Changes of the oceanic meridional circulation and associated transports. Percentage changes of the MOC, northward Atlantic (MHTNA) and Pacific (MHTNP) meridional heat transport at 24° N, southward Pacific MHT at 30° S (MHTSP), southward meridional freshwater transport from the Arctic to the Atlantic (MFWA) and southward Pacific meridional freshwater transport at 40° N (MFWP) between the closed Bering Strait simulation and the open Bering Strait simulation. The vertical bars indicate ±1 s.d. of the last 300-year segment of the open Bering Strait simulation with North American ice sheets.

The impact of these MOC-related changes on surface climate is shown in Supplementary Fig. S1. In the Northern Hemisphere, the increased MHT in the North Atlantic leads to an annual mean warming of up to 1.5 °C in northeast North America, including Greenland, the North Atlantic, the mid-latitude Eurasian continent and the Arctic, but a cooling of up to 1.5 °C in the North Pacific. A slight warming in the tropical/subtropical Indo-Pacific oceans results from elevated southward MHT. A small warming also occurs in parts of Antarctica. Associated with these temperature changes, the total precipitation is reduced in most parts of North America (Supplementary Fig. S1c), which would reduce the snow accumulation there. Seasonally (Fig. 3), the daily maximum temperature shows warm anomalies of a few tenths of a degree centigrade in the south and northeast edges of the North American ice sheets in spring, summer and autumn when the Bering Strait is closed. In winter, the warming appears mainly at the east edge of the North American ice sheets. The warming is evident during all seasons at the southern tip of Greenland.

The warming signal located between the ice-sheet boundary and the 0 °C line, as well as the region just north of the zero degree line, indicates an increased melting of the ice sheets when the Bering Strait is closed. In the boreal spring and summer seasons, this increased ice-sheet melting caused by the enhanced MOC could trigger an initial destabilization of the ice sheets. A calculation of the positive degree days[29] in the melting season shows that by closing the Bering Strait, the number of the positive degree days increases in southern and eastern parts of the North American ice sheets and the whole Greenland ice sheet (Fig. 4a). The mean annual increase is 12.2 degree days averaged over these ice sheets, resulting in an increased ice-sheet melting of 0.085 m yr^{-1}. In addition, the area mean precipitation averaged over these same ice sheets is reduced by about 0.027 m yr^{-1}, although some regions show an increased rainfall (Fig. 4b). This gives an annual loss of mean ice-sheet height of 0.112 m. This induced extra positive degree days, and the reduced precipitation would be felt by these ice sheets for thousands of years (for example, for ∼5,000 years) resulting in a thinning of the North American and Greenland ice sheets by about 560 m. This would cause a drastic shrinkage of these ice sheets and lead to a global sea-level rise of ∼33 m, a comparable magnitude as observed.

At the same time, this increased ice-sheet melting would lower the surface albedo, reduce the reflection of the solar radiation back to space and warm the planet, leading to a positive albedo–climate feedback and enhanced ice-sheet melting. This would enhance the ice-sheet retreat over subsequent years. The increased meltwater flowing into the ocean would produce an ESL rise. Then, as ESL rises, the reopening of the Bering Strait would lead to a resumed transport of fresher Pacific waters into the Atlantic, which would weaken the MOC and cool the North Atlantic region. This would

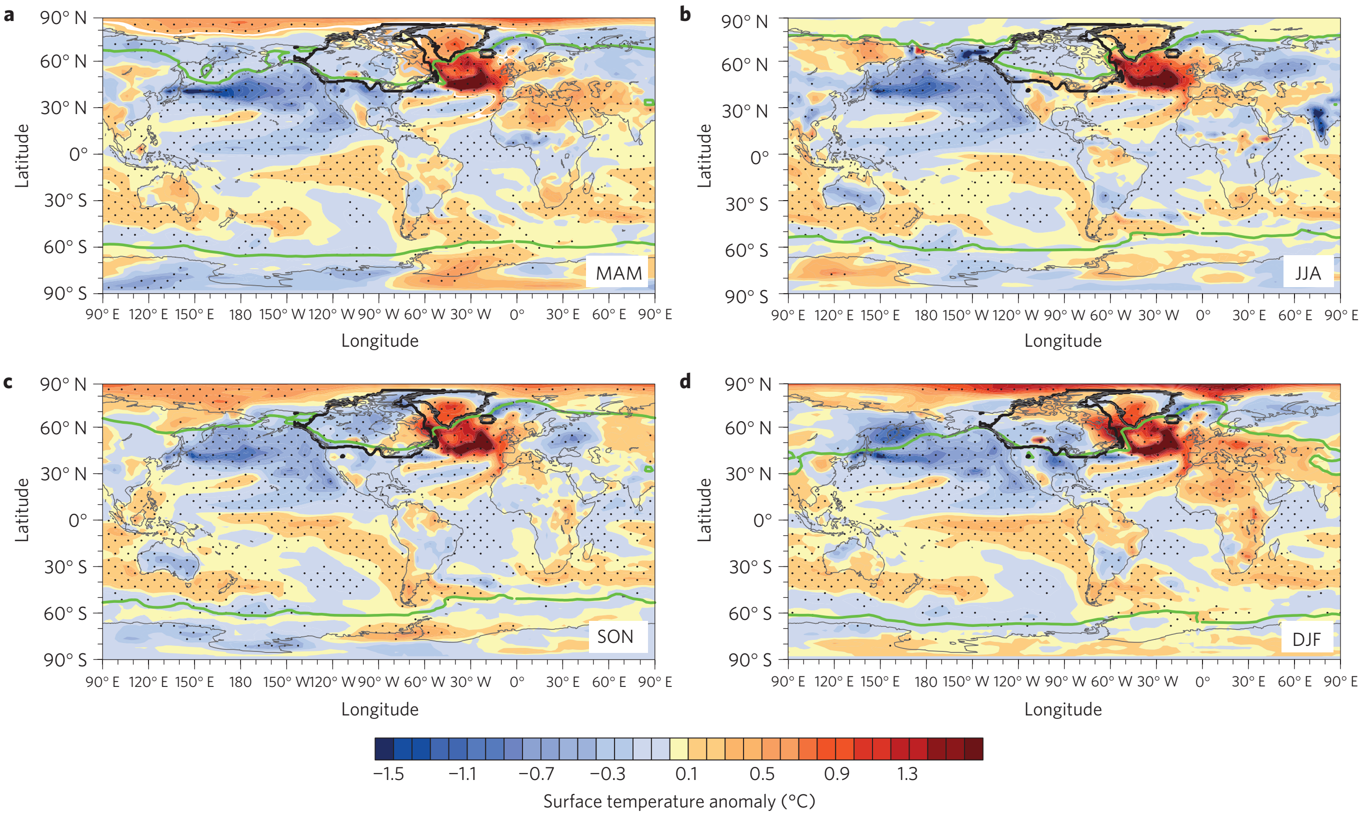

Figure 3 | Seasonal mean daily maximum surface temperature anomaly produced by closure of the Bering Strait. a–d, The seasonal mean of March, April and May (**a**), June, July and August (**b**), September, October and November (**c**) and December, January and February (**d**). Stippling indicates that anomalies are significant at greater than the 95% level based on a Student's *t*-test. The dark solid line defines the boundary of the ice sheets, and the solid green line is the 0 °C contour line in the open Bering Strait simulation. The ice-sheet size here is a bit larger than other estimates (see Supplementary Information).

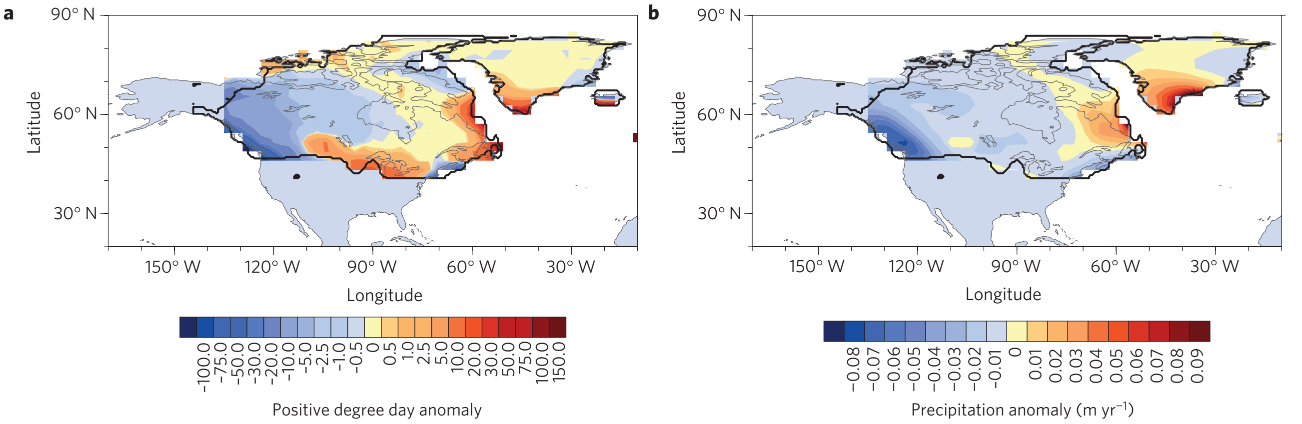

Figure 4 | Annual positive degree day and precipitation anomaly. a, The anomaly of the annual positive degree days between the closed and open Bering Strait simulations. **b**, The same as in **a**, but for precipitation. The dark solid line defines the boundary of the ice sheets.

cause the climate to cool, the ice sheets to build up and ESL to drop, eventually leading again to a closed Bering Strait, and so on, resulting in the observed ESL oscillations with a period of about 20 kyr from 116 to 75 kyr BP.

Sensitivity simulations with the North American ice sheets removed and replaced with lower-albedo vegetations show that the warming signal described above is more than doubled (see Supplementary Figs S2,S3). This result gives a measure of the large albedo–climate feedback processes owing to the retreat of the ice sheet and the growth of the vegetation, thereby further supporting our proposed feedback mechanism.

It is worth noting that from about 75 to 34 kyr BP, as the global climate cooled, the ESL also trended downward but still oscillated as it did from 116 kyr to 75 kyr BP. During the same period, the predicted RSL at the Bering Strait varied between open and just closed states of the strait with no obvious downward trend (Fig. 1a,c). This indicates that whenever the Bering Strait was closed, the corresponding changes of the MOC and the Northern Hemisphere climate would induce a melting of the ice sheets and a subsequent ESL rise. After 34 kyr BP, when the reduction of solar radiation by ice-albedo feedback made global climate cold enough to compensate for the Northern Hemisphere warming induced by an enhancement of the MOC caused by the closed Bering Strait, the ice sheets continuously grew, leading to a sharp decrease of the ESL. During this period, the global climate cooled until the Last Glacial Maximum.

As the rise of the boreal summer solar radiation above the mean of the past 130 kyr lags the ESL rise, solar radiation changes alone cannot explain the timing of the ESL oscillations observed at the beginning of the last glacial. However, these early ESL minima were all characterized by a closed—or nearly closed—Bering Strait. We propose and demonstrate that this nearly closed Bering Strait had an important role, leading to the ESL rise after those minima through modulation of the MOC strength. We show that the subsequent surface climate changes and the associated albedo–climate feedback processes provide the necessary conditions to initialize the melting of the ice sheets and produce an ESL rise.

The opening of the Bering Strait may also have wider implications on climate. For example, a recent study[23] suggests that abrupt climate change events evident in the Greenland ice core record between 70 and 11 kyr BP (ref. 30) may be related to the closing of the Bering Strait. Although the Bering Strait itself may not directly control the surface climate change, the effect of the strait on the transport of the fresh Pacific water into the Arctic and North Atlantic does influence the MOC strength, and consequently can modulate Earth's climate. Therefore, climate changes and the Bering Strait may well have been intimately linked throughout the Late Pleistocene ice age.

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Author contributions

A.H. led the project and did the simulations and the major analyses, G.A.M., B.L.O.-B. and W.H. helped with the experiment design and data analysis, C.W., K.L. and J.X.M. provided the sea-level and ice-sheet data, M.-F.L. contributed the solar radiation data, and N.R. helped to set the simulations. All authors contributed extensively to writing the paper and analysing the results.

Additional information

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