estimate total CO_2 emission from European estuaries (Fig. 4), which appears to be a significant percentage of the present anthropogenic CO_2 release to the atmosphere from Western Europe due to combustion [647 million tons of C in 1995 (*16*)]. A minimum estimate, calculated by applying an outer estuarine efflux of 0.01 mol m^{-2} day^{-1} to 80% of the total European estuarine surface area, yields a total European emission of 20 million tons of C per day, representing 3% of the present anthropogenic emission of CO_2 from Western Europe. It is likely that the percentage of surface area of inner estuaries is in the range of 25 to 50% and, from data presented here, we estimate the actual value to be in the range of 30 to 60 million tons of C per day, which is 5 to 10% of the present European anthropogenic emission. This percentage has been obtained for a highly industrialized area of the world; it may be higher for developing countries, where anthropogenic CO_2 emissions are lower and where significant organic carbon load results from overpopulation.

Few data are available for other estuaries in the world, but the available data shows a high degree of supersaturation (*1, 17–19*), ranging from 500 to 6000 μatm. Some data are also available for major rivers. The carbon budget of the Amazon has been studied (*20*), and it was shown that this river emits 0.17 to 0.52 mol m^{-2} day^{-1}, very similar to our flux data. Carbon dioxide levels have been measured in the Niger (*21*), and the highest values reported were ~6400 μatm, again in agreement with values reported here.

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27. $F = K\,\alpha\,\Delta P$, where F is the flux in mol m^{-2} s^{-1}, K is the exchange coefficient in m s^{-1}, α is the CO_2 solubility coefficient in mol m^{-3} atm^{-1}, and ΔP is the CO_2 gradient through the interface [$pCO_{2(water)} - pCO_{2(air)}$] in atmospheres. An exchange coefficient of 2×10^{-5} m s^{-1} (that is, 8 cm $hour^{-1}$) (*2, 22, 23*) was used for a Schmidt number Sc = 600 (*24*), which is a typical value for a moderately turbulent river (*25*).
28. Atmospheric exchanges of CO_2 were measured using the direct floating chamber method (*26*) adapted for operation in estuarine environments (*2*). The chamber was set up on a lagrangian system in order to avoid creation of turbidity due to estuarine current and to follow the same water mass. Measurements were typically carried out each 2.5 salinity step through the whole estuary. Wind speed is usually low in investigated areas (0 to 5 m s^{-1}), and the exchange coefficient K (*27*) is mainly determined by the turbulence of the water column. Calculated values of K, from measured flux and CO_2 gradient (*27*), is in good agreement with those reported for rivers (*25*). It should be pointed out that, if wind becomes predominant, actual efflux would be higher than our estimate.

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A Short Circuit in Thermohaline Circulation: A Cause for Northern Hemisphere Glaciation?

N. W. Driscoll and G. H. Haug

The cause of Northern Hemisphere glaciation about 3 million years ago remains uncertain. Closing the Panamanian Isthmus increased thermohaline circulation and enhanced moisture supply to high latitudes, but the accompanying heat would have inhibited ice growth. One possible solution is that enhanced moisture transported to Eurasia also enhanced freshwater delivery to the Arctic via Siberian rivers. Freshwater input to the Arctic would facilitate sea ice formation, increase the albedo, and isolate the high heat capacity of the ocean from the atmosphere. It would also act as a negative feedback on the efficiency of the "conveyor belt" heat pump.

Major ice sheet growth in Eurasia, Greenland, and North America is recorded by a $\delta^{18}O$ enrichment in benthic foraminifera between 3.1 and 2.5 million years ago (Ma) (*1, 2*) and by the massive appearance of ice-rafted debris in northern high-latitude oceans since 2.7 Ma (*3*). An increase in the $\delta^{18}O$ value of benthic foraminifera predominantly reflects the growth of continental ice volume. The intensification of Northern Hemisphere glaciation (NHG) finalizes the Cenozoic cooling trend, which started in the early Eocene and is marked by the first indications of ice sheets in Antarctica 36 Ma (*4*). This long-term cooling brought the climate system of Earth to a state critical for ice sheet buildup in the Northern Hemisphere. This has been the case since approximately 11 Ma, when the first and minor occurrence of ice-rafted debris in the Arctic and North Atlantic indicates the first attempts of the climate system to start a glaciation (*5*). However, the climate system failed to generate and maintain major ice sheets in the Northern Hemisphere until 2.7 Ma. Here we suggest that the closure of the Isthmus of Panama, which enhanced moisture transport to the Eurasian continent,

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increased freshwater delivery to the Arctic and led to NHG (Fig. 1).

The progressive closing of the Panamanian isthmus in the late Miocene and early Pliocene has often been linked to the major intensification of NHG that occurred between 3.2 and 2.7 Ma (*6–10*). The closure redirected Atlantic Ocean surface currents, enhanced the Gulf Stream, and thus transported warm saline surface waters to high northern latitudes. This in turn increased the formation of North Atlantic Deep Water (NADW) (*8*, *9*). Increased evaporation at high latitudes would provide additional moisture, which is a substantial requirement for ice sheet growth. This increased moisture supply led previous researchers to propose that the closing of the Panamanian isthmus caused NHG (*6*, *10*, *11*). However, the altered ocean circulation would also increase heat transport to the higher latitudes, as evidenced by a slight warming trend in the Northern Hemisphere at approximately 4.6 Ma (*9*). Enhanced Atlantic Ocean thermohaline circulation and the associated heat transport to high latitudes are thus seemingly at odds with the formation of large ice sheets in the Northern Hemisphere.

New paleoceanographic records from the Caribbean Sea [Ocean Drilling Project (ODP) Site 999] and from the Ceara Rise depth transect in the equatorial west Atlantic (ODP Sites 925 through 929) indicate that the closure began to have a major impact on intermediate and deep water circulation at 4.6 Ma (Fig. 2) (*8*, *9*). Data from the Labrador Sea (ODP Leg 105) indicate that bottom water currents and drift sedimentation increased at ~4.5 Ma (*12*), timing that is consistent with the increase in the formation of Upper North Atlantic Deep Water (UNADW) and Labrador Sea Water, as suggested by General Circulation Model simulations (*13*). The formation of UNADW reached a first maximum at 3.6 Ma and culminated during the early Pliocene Northern Hemisphere warming (*9*). Records of deep water ventilation and carbonate preservation in the north, equatorial east (ODP Sites 552, 659, and 665) (*14*, *15*), and west Atlantic (Ceara Rise depth transect, Sites 925 through 929) (*8*) below a water depth of 3000 m show that Lower North Atlantic Deep Water also increased at 4.6 Ma (*9*).

The closing of the isthmus and the consequent redirection of Atlantic surface circulation increased moisture delivery to the Eurasian continent via atmospheric transport by the westerlies. This change is recorded in drill cores recovered from Lake Baikal (*16*). Diatom abundances and assemblages, spore and pollen data, magnetic susceptibility, and sedimentological evidence indicate, as expected, that the climate was warmer in the early Pliocene and that Siberian humidity increased at ~4.5 Ma (*16*). Because most of the drainage across Siberia is to the Arctic, an increase in Eurasian moisture would enhance freshwater delivery to the Arctic (Fig. 1).

Today, the Yenisey, Lena, and Ob are the three largest Arctic rivers, respectively, in terms of annual water discharge (*17*). Because of the immense size of the drainage basin (~7.2×10^6 km^2) (*17*) and discharge volumes (nearly 10% of global river discharge annually) of the major Siberian rivers they have likely had a marked effect on Arctic circulation and salinity, as well as modulating the East Greenland and West Spitzbergen Currents (Fig. 1). These rivers of Siberia drain large regions of northern Tibet and the Tien Shan and Altai Mountains, which were high-standing regions before the Pliocene (*18*). The Verkhoyansk fold belt is a topographic barrier that has focused river discharge toward the north into the Arctic Ocean since Cretaceous time (*19*). The enhanced moisture for the region must be sourced from the west because the high Himalayas preclude northward transport of moisture from the Indian monsoons, as evidenced by the Gobi Desert (Fig. 1).

The Arctic Ocean has a surface layer of cold and relatively fresh water some tens of meters deep (*20*). The input of fresh water by fluvial systems can diminish the surface water salinity on the broad shelf regions by as much as 5 ‰ (*20*). The increased fresh water input to the Arctic would facilitate the formation of sea ice. The formation of sea ice would markedly increase the surface albedo in the high latitudes and insulate the atmosphere from the high heat capacity of the ocean. Thus, when covered with sea ice, the Arctic Ocean has the climatic attributes of a landmass. It has been estimated that there is at least three times more atmospheric cooling with bipolar ice than there would be without it (*21*).

This river input of fresh surface water from Siberia flows off and away from the shelf region (for example, the Kara and Laptev Shelves) and joins with other surface flow from the western Arctic, forming the East Greenland Current (*20*). At some level of increased export of fresh Arctic water, it would affect the efficiency of the "conveyor belt" heat pump (*22–24*). Ocean circulation models indicate that the vigor of the ocean's thermohaline circulation is rather sensitive to even small inputs of fresh water (*25*). Even small salinity anomalies appear sufficient to reduce deep water formation (*26*). In fact, the salinity anomaly observed in the northern Atlantic and the Norwegian-Greenland seas in the 1970s (*27*) has been proposed as the potential cause for reduced Greenland Sea Deep Water formation during the 1980s (*25*). Modulating the efficiency of the conveyor belt heat pump would allow for climatic cooling.

The Lake Baikal data suggest that there is little to no time lag between the closing of the isthmus and the enhanced moisture supply to the Eurasian continent via atmospheric transport by the westerlies (Fig. 1). The evident increase in the formation of NADW at ~4.6 Ma suggests that the closing of the Central American Seaway played a more dominant role and outcompeted for some time the neg-

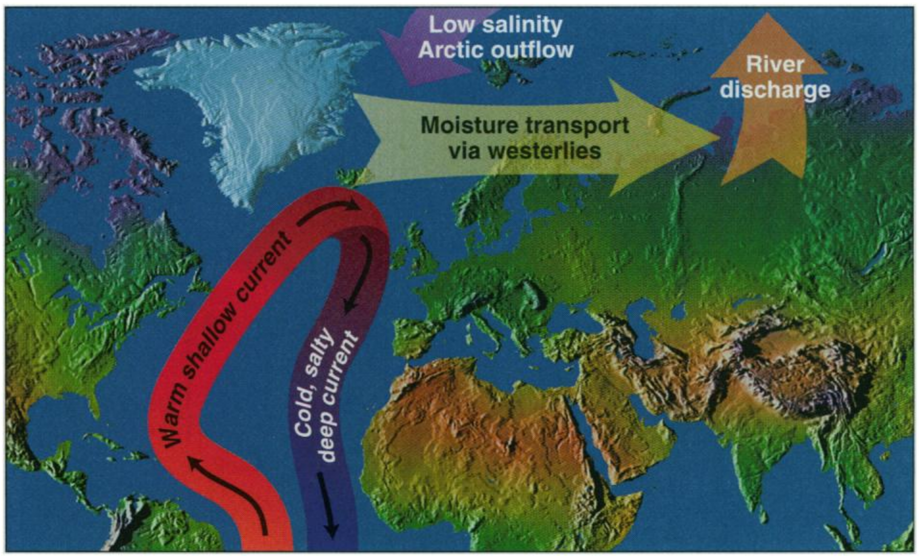

Fig. 1. A simple schematic illustrating the ocean's thermohaline circulation in the North Atlantic (*22*) and the proposed short circuit of the system through freshening of the Arctic Ocean. Increased moisture delivery to the Eurasian continent via atmospheric transport by the westerlies is shown by the yellow arrow. The consequent freshwater input from the Siberian rivers to the Arctic Ocean (orange arrow) decreases surface salinity, facilitates sea ice formation, and freshens the Arctic outflow into the North Atlantic. The fresh water diminishes the production of NADW and thus short-circuits the thermohaline circulation.

ative feedbacks associated with freshwater export from the Arctic. We suggest, however, that freshening of the North Atlantic began to modulate the strength of the thermohaline circulation and thus placed an upper limit on the amount of heat transported to high latitudes. Likewise, if the supply of fresh water exported from the Arctic decreased, then continued evaporation in the Atlantic would have further invigorated the conveyor belt circulation and transported more heat poleward, which would have inhibited ice sheet growth (*23*).

Low tilt angles in Earth's obliquity cause cold summers in the Northern Hemisphere. High-amplitude fluctuations in the obliquity set the stage to strengthen the glacial-interglacial 41,000-year cycles during the late Pliocene and early Pleistocene (*28*). A pronounced long-term minimum in obliquity amplitude fluctuations occurred between 4.5 and 3.1 Ma (*28*) (Fig. 2). The $\delta^{18}O$ records of ODP Sites 659 (*2*), 846 (*29*), and 999 (*9*) show that during this unfavorable orbital configuration there may have been several failed attempts by the climate system to start the glaciation (for example, between 4.1 to 3.9 Ma and 3.5 to 3.3 Ma). Thus, it appears that the progressive increase in obliquity amplitudes between 3.1 to 2.5 Ma was the final perturbation that tipped the scales and led to the initiation of NHG (*9*).

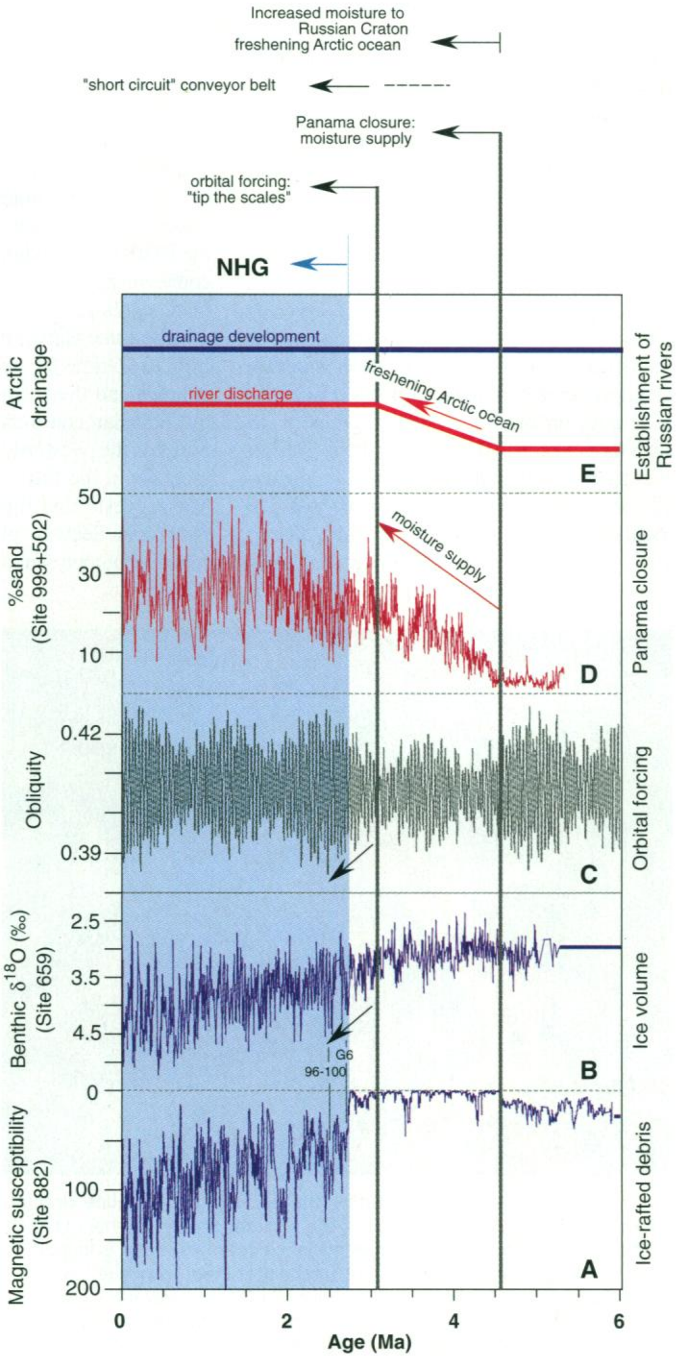

Fig. 2. Paleoceanographic proxy data indicating the onset of major NHG glaciation and the necessary preconditions. **(A)** Ice-rafted debris input to the subarctic northwest Pacific, as indicated by the increase in magnetic susceptibility at ODP Site 882 at 2.7 Ma (*3*). **(B)** Increase in ice volume between 3.1 and 2.4 Ma, as indicated by the increase in $\delta^{18}O$ (‰, per mil) from ODP Site 659 (*2*). **(C)** The increase in obliquity amplitudes between 3.1 and 2.4 Ma (low tilt angles cause cold summers) (*28*). **(D)** The increase in sand content of ODP Sites 999 (*14*) and 502 (*30*) since 4.6 Ma, indicating enhanced formation of UNADW and enhanced moisture transport to high northern latitudes. **(E)** Establishment of Siberian drainage systems. The drainage systems existed before Pliocene time (*18*) (blue line). The increased river discharge in response to enhanced moisture supply is shown by the red line. The arrows mark the Pliocene cooling trend between 3.1 and 2.5 Ma (intensification of NHG) and the major step in Panamanian isthmus closure that has altered ocean circulation since 4.6 Ma. The first major ice sheets occurred at isotope stages G6 and 96-100, which are labeled accordingly.

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