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Climate Control Requires a Dam at the Strait of Gibraltar

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If the Mediterranean Sea continues to increase in salinity, shifting climatic patterns throughout the world may cause high-latitude areas in Canada to glaciate within the next century. The Mediterranean is starved of freshwater by human activities: most of the annual flow of the Nile River is now used for irrigation and no longer enters the sea. The sea surface evaporation losses are also increasing as the surface warms due to rising CO_2 concentrations in the atmosphere. Consequently, the Mediterranean hydrologic deficit is steadily increasing. The deficit is the difference between the larger amount of water lost by evaporation and the smaller amount received from rainfall and river inputs. The difference is made up by a two-way exchange of water with the Atlantic at Gibraltar. Barring a significant change in regional atmospheric circulation, these two human modifications of the environment will cause the salinity of the Mediterranean to increase for some time as fossil fuels are consumed.

The higher salinity will lead to a larger volume of the Mediterranean outflow at Gibraltar, which will modify high-latitude oceanic-atmospheric circulation and, in effect, initiate new glaciation. This hypothesis arises from a recent study of climate conditions and inferred circulation changes that probably triggered the last glaciation [*Johnson*, 1997]. The hypothesis will be tested in coming decades. If it is validated by the onset of ice-sheet growth in Canada and cooling in northern Europe, a partial dam at the Strait of Gibraltar could be constructed to limit the outflow and reverse the climate deterioration, thus holding off the next ice age.

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Initiation of the Last Glaciation

Although it is commonly thought that the last ice age began in Canada when diminishing Milankovitch summer insolation cooled the climate, circulation changes that increased moisture advection to ice sheets were probably more important. Frequent storms moving into Baffin Island and other areas in the presently arid Canadian subarctic more likely caused the ice age. Evidence supporting this scenario shows a warming of the northwestern Labrador Sea and Baffin Bay at the beginning of the last glaciation and warm $\delta^{18}O$ values and larger quantities of pollen in ice at the base of cores from remnant glaciers on Devon and Ellesmere Islands [*Koerner et al.*, 1988]. The increased precipitation and summer cloudiness probably triggered ice sheet growth. This view is consistent with general circulation model experiments which, lacking such details of circulation, find it difficult to simulate new ice sheets by cooling at 115,000 yr B.P. when July insolation at high latitudes was 7% lower than today.

Moreover, in Barbados and New Guinea, stratigraphy of corals with reliable ages dated by thermal ionization mass spectrometry suggests that new ice sheet growth began not later than 120,000 yr B.P., when insolation at 60°N was similar to today's values [*Johnson*, 1997].

It has been known for some time that the Labrador Sea was warmer at the start of the last glaciation. A strong northward current of Mediterranean outflow water upwelling off Ireland and Scotland [*Reid*, 1979] now appears to have been the cause of this warmth. The upwelling water is 4–5°C colder than North Atlantic Drift water moving north from the Gulf Stream, and diverts the warm Drift water westward into the Labrador Sea. The saline and initially warm Mediterranean outflow is about 0.8×10^6 m^3 s^{-1} [*Bryden and Kinder*, 1991]. Leaving Gibraltar, the water sinks and mixes with very cold water of the lower thermocline [*Price et al.*, 1993], moves northward, and enters the northern gyre. As the water approaches the shallow banks north and west of Ireland (Figure 1), it upwells.

The cold core of the outflow water mixture probably reaches the surface; it has a velocity as much as 0.01 m s^{-1} greater than surrounding North Atlantic Drift water [*Greatbatch and Xu*, 1993]. Although mixing with North Atlantic Drift water doubtless occurs, *Reid's* [1979] temperature and salinity data suggest that much of the cold outflow water passes on into the Nordic Seas.

The upwelling apparently behaves like a fluidic switch that warmed the Labrador Sea and caused Canadian ice sheet growth while cooling the Nordic Seas and northern Europe. In this conceptual model of glacial initiation, the switching is controlled by the hydrologic deficit of the Mediterranean and the resulting outflow. Thus the hydrologic deficit is a critical link in a chain of circulation and climatic factors (Figure 2) that began with low insolation, weak African monsoons, and drought in the headwaters of the Nile and culminated with new ice-sheet growth in Baffin Island and other regions in northern Canada.

Strong Milankovitch insolation in northern subtropics causes strong African monsoons, and strong insolation correlates well with high-volume discharges of the Nile. This is inferred from the records of sapropelic sediments caused by surface water stratification in the eastern Mediterranean. The most recent sapropel was formed about 8500 yr B.P. with insolation near a strong maximum and at a time of well-documented, high-volume Nile discharges [*Yan and Petit-Maire*, 1994] implying a weak outflow. When the last ice age began 120,000 years ago, however, the insolation at all latitudes was nearly the same as today, implying a similar and much smaller Nile flow and a larger hydrologic deficit and outflow. That today's climate may be close to the threshold for new glaciation may indeed be the case. Large plateau areas of Baffin Island are now covered with semipermanent snow fields that expanded during the historic Little Ice Age 150–350 years ago when cool summers and extremely severe winters were frequent in northern Europe. The cause of this cold fluctuation is not

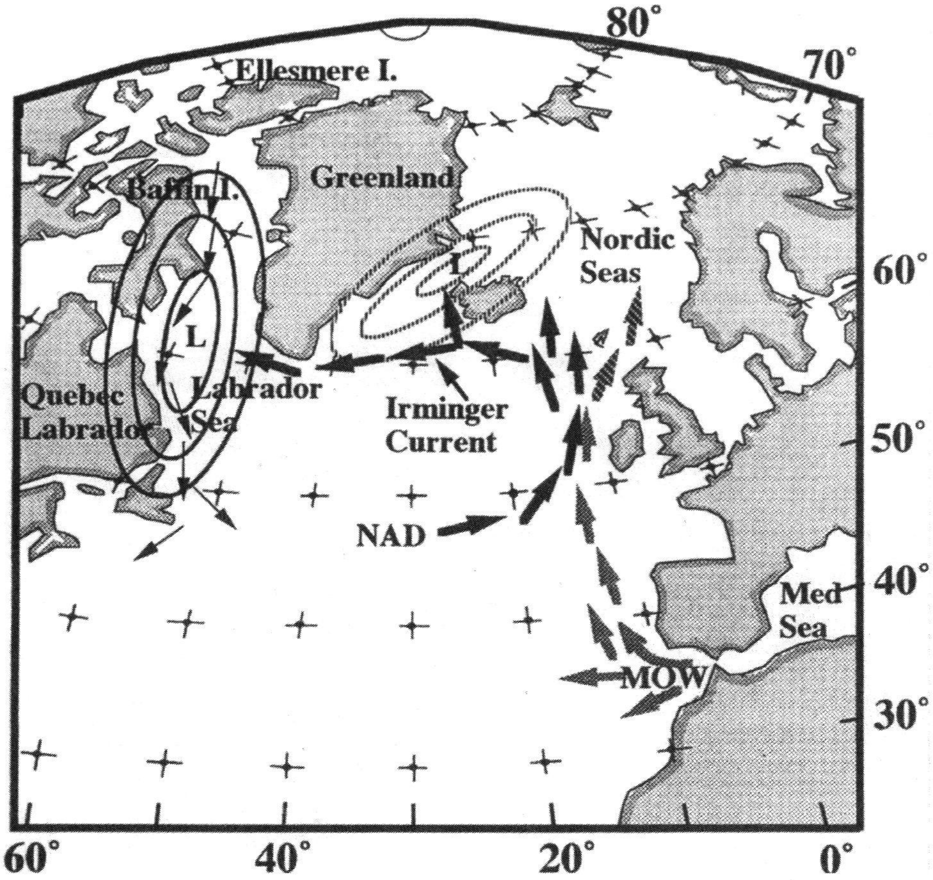

Fig. 1. Principal currents involved in the chain of proposed factors connecting the Mediterranean Sea and Canada. Approaching the Scotland-Faeroe sill, the North Atlantic Drift (heavy black arrows) that would otherwise enter the Norwegian Sea due to the coriolis effect is diverted westward by upwelling of more rapidly flowing Mediterranean outflow water (patterned arrows) from the lower thermocline. The diversion warms the Labrador Sea, enhances the Labrador Low, weakens the Iceland Low, and increases advection of moisture into the Baffin area, thus triggering new ice sheet growth. Smaller arrows indicate the cold Canadian Current. Adapted from Johnson *[1997].*

known, but it implies that a significant bias toward conditions favoring glaciation might well initiate new ice sheet growth.

Modern Ice-Age Initiation

If all the Nile flow entered the Mediterranean, the hydrologic deficit would be approximately 31,000 $m^3 s^{-1}$, estimated from Mediterranean outflow and inflow volumes and salinities at Gibraltar [*Bryden and Kinder*, 1991; *Price et al.*, 1993], river discharges, and an assumed steady state. A larger hydrologic deficit due to the loss of Nile River discharge is the main difference between today and 120,000 years B.P. in the chain of factors in Figure 2.

Ninety percent of the 2700 $m^3 s^{-1}$ average Nile flow is now diverted for irrigation and lost by evaporation. Most of the diversion has been accomplished in modern times and has increased the Mediterranean hydrologic deficit by about 8%, with half of this increase due to the Aswan High Dam. This dam was completed in 1968 and is a major source of Egyptian power [*Gasser and El-Gamal*, 1994]. It impounds the annual Nile flood water from the monsoons in Lake Nasser for power production and irrigation, thus preventing the floods from reaching the Mediterranean. The planned additional diversion of 300 $m^3 s^{-1}$ from Lake Nasser at Abu Simbel will bring the deficit increase up to 9%. The mixing time for an ideally mixed Mediterranean Sea (that is, the time needed to attain 63% of a new higher steady-state salinity after an abrupt reduction in fresh water input) is about 100 years. Consequently, most of the effect on northern North Atlantic circulation caused by the 9% increase in the deficit will be realized by the end of the next century as the salinity rises and the Mediterranean outflow increases.

If proportionality assumptions hold, 14% more warmer surface water could enter the Labrador Sea [*Johnson*, 1997] with a corresponding substitution of cold water entering the Nordic Seas. This increase may initiate new glaciation for two reasons: the last ice age was probably triggered by an inferred hydrologic deficit equal to or less than that of today, and Canadian glacial nucleation areas are now perilously close to the threshold for new ice-sheet growth, as indicated by historic expansion of snow fields on Baffin Island. Severe cooling in northern Europe and new expansion of Baffin snow fields may occur within the next few decades.

CO_2 warming would probably trigger a new ice age by increasing Mediterranean evaporation losses, independently of Nile discharge. If CO_2 warming increases the sea surface temperature by 2°C, as predicted when atmospheric CO_2 doubles in the next 70 years [*Manabe et al.*, 1994], the increase in the hydrologic deficit of 14%, as estimated from the ratio of future/present vapor pressures at the sea surfaces, would exceed the effect of Nile loss. The combined CO_2 warming and Nile loss might increase the hydrologic deficit to 23%. New ice sheet growth and a much colder Europe would then become extremely likely, and CO_2 concentrations will continue to rise.

Initiation of new ice sheet growth is of great concern because the strong positive feedback of enhanced albedo and heavier cloud cover, much like the effectiveness of cloudiness over the Greenland Ice Sheet today, might lock in the ice-age growth mode despite CO_2 warming. The ultimate consequence might be a combination of two extremes. The strong CO_2 warming of lower-latitude land and sea surfaces would nourish—by ever stronger moisture advection—rapid expansion of ice sheets in Canada and Eurasia.

A Gibraltar Dam

The diversion of North Atlantic Drift water as a function of the Mediterranean outflow is difficult to measure accurately because of the complex and fluctuating currents within the northern gyre. Quantitative verification of the fluidic switch model is therefore difficult. Nevertheless, if the conceptual model is approximately correct, a new ice age can be avoided if a partial dam is constructed on the sill across the strait 40 km west of Gibraltar (Figure 3a). By limiting the Mediterranean outflow to, for example, 20% of today's flow rate, the higher-velocity component of flow approaching the Scotland-Faeroe sill would be removed, upwelling would diminish, warm surface water now diverted to Labrador would enter the Nordic Seas, Canada would remain dry, and Europe's climate would remain mild and stable.

The reduced outflow would also reduce the risk of large-scale flooding of world coastlines if the West Antarctic Ice Sheet melts as global temperatures rise, leading to a sea level rise of 6 m [*Mercer*, 1978]. Antarctic sea ice is a strong factor in cooling the Antarctic climate [*Weyl*, 1968] and stabilizing Antarctic ice sheets. The sea-ice extent, however, depends on the higher salinity in the mid-depth Southern Ocean, which enhances

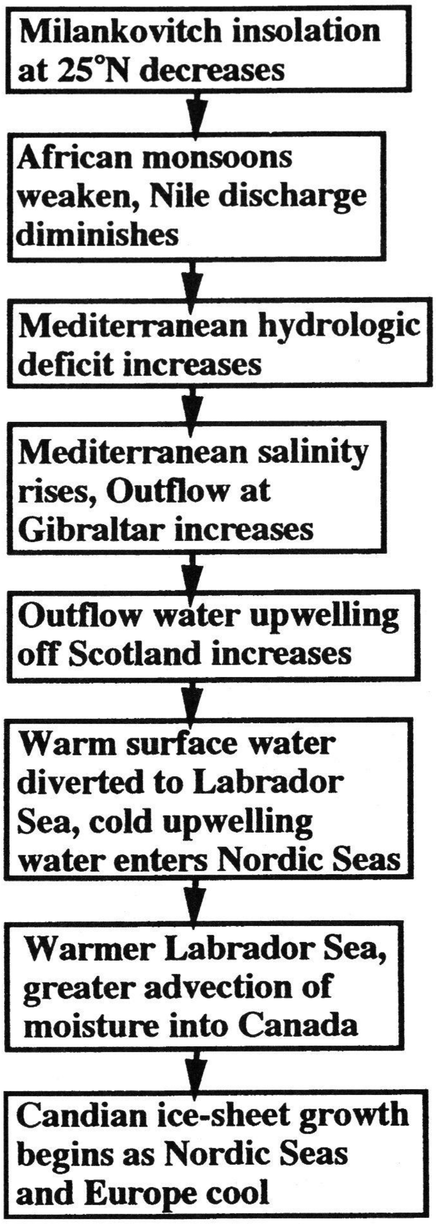

Fig. 2. Block diagram of the chain of factors in the conceptual model for initiation of the last ice age.

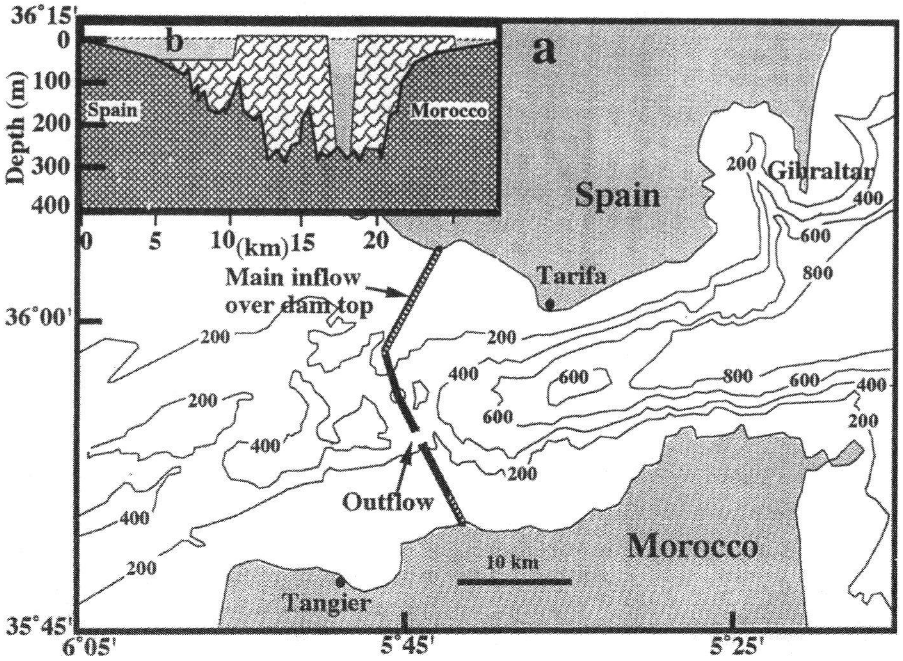

Fig. 3. a) Location of the proposed dam on the sill across the Strait of Gibraltar. The counterflow exchange of salt is greatly minimized by separating most of the surface inflow from the deeper Mediterranean outflow water entering the Atlantic. Bathymetry is in meters. Adapted from Bryden and Kinder [1991]. b) Profile of the suggested large-rock dam structure on the transect of a). Assumed angle of repose is 30°. Maximum depth on the sill is 284 m. Bridges over inflow openings (not shown) would enable transport of material to the extending faces. A bridge over the central outflow opening would complete the link between Spain and Africa. Flow modeling to attain an 80% limitation of Mediterranean outflow water in the future steady state could significantly change the opening dimension.

deep convection and heat transfer to the surface. About 25% of the excess mid-depth salt is supplied by the Mediterranean outflow and is exported via the deep Western Boundary Current. For a few hundred years after completion of the Gibraltar dam and before Mediterranean salinity reaches a new approximate steady state, this source of salt would be greatly reduced. This would tend to maintain sea-ice coverage as CO_2 warming progresses, and prevent or delay melting of the West Antarctic Ice Sheet and world coastal flooding.

The construction of the Gibraltar Dam may be both politically and technically feasible, but the scale of the dam is large, and construction would require an unprecedented effort probably over many decades. The profile of a suggested dam configuration is shown in Figure 3b. The maximum underwater height is twice that of the Great Pyramid of Egypt. If the dam has a 70-m-wide top, and if a rock material is used with a 30° angle of repose, the required volume would be 1.27 km^3, or about 420 times that of the Great Pyramid.

To minimize the eventual increase in Mediterranean salinity to a few parts per mil caused by the more restricted exchange with the Atlantic, the present counterflow entrainment of salt from the outflow into the inflow could be greatly reduced by confining the outflow to a narrow opening, possibly 1 km wide or less, with most of the inflow consisting of shallow water entering at a distance. A detailed hydrodynamic model of the flow field would be required to determine the width of the opening needed to maintain the specified flow restriction when the ultimate Mediterranean salinity and density is attained. Such a model is one of many research tasks needed in the planning of the dam.

The type of construction that the dam would require remains to be determined, but the large-rock barrier is a possibility and it would be a rust-proof and geologically permanent structure. Dam design and construction methods would need to be developed to avoid underwater debris flows of dam material while the dam is being built, and afterward under seismic stresses.

The Decision

The cost of the dam would be minor compared to the benefits of a mild climate in northern Europe and Asia and the prevention of widespread new ice sheets in Canada. However, the cost and the magnitude of the task and the associated uncertainties would probably generate controversy that might delay a decision to build the dam until the threatened climate deterioration becomes a reality in Canada and Europe. Would the dam construction then be too late ? Probably not, because the redirection of warm North Atlantic Drift into the Nordic Seas would duplicate the strong meridional North Atlantic circulation of 8000 years ago, when the outflow was smaller, the Labrador Sea was cold, and deglaciation was rapidly removing the Laurentide Ice Sheet. However, until the dam is completed and more warmer North Atlantic Drift water is again allowed to enter the Nordic Seas, cold climatic fluctuations in Europe are likely to become increasingly severe.

If a decision to build the dam is delayed, a more worrisome concern is the scarcity of petroleum supplies that will probably develop in the next century. This could lead to political or military conflicts that would increase the difficulty of organizing the broad international effort needed to carry out the project. The sooner the decision is made, the easier it will be to plan and complete the dam. The

Aswan High Dam's effect on Mediterranean salinity will trigger glaciation much more quickly than would CO_2 warming alone, thus providing a compelling motive to build the remedial dam, and quickly, while petroleum supplies are still plentiful and society is stable.

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U.S. Budget Update

First Numbers for National SCIENCE FOUNDATION, NASA

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After months of speculation about funding for science in the Fiscal Year 1998 (FY 1998) federal budget, some first figures became available in late June for the National Science Foundation and NASA— when the House of Representatives' VA, HUD, Independent Agencies Appropriations Subcommittee marked up its bill. However, details may not be known until July 8, when the full House Appropriations Committee meets to vote on the legislation. The full House is expected to vote on the appropriations the week of July 13. The Senate Appropriations Subcommittee, which has less overall money to spend, is expected to complete its work the week of July 13 also. The following information is known about the House bill.

National Science Foundation (NSF). The House VA, HUD subcommittee has recommended a 6.6 % increase in NSF's overall budget. At a time when staying even with inflation is seen as an achievement, this increase is remarkable. The administration requested a $97 million increase over this year. The subcommittee recommends an increase of $217 million to $3,487 million.

Within this overall budget is Research and Related Activities. The subcommittee recommends an increase of 4.3%, or $106 million, to $2,538 million. This is $23 million over the request. Preliminary information suggests that this additional $23 million would be used as follows.

Next Generation Internet: $13 million
Gemini Telescopes: $4 million
U.S. Mexico Foundation: $1 million
Phase out money relating to the Partnerships for Advanced Computational Infrastructure program: $5 million

The recommended budget increase for Education and Human Resources is 2.3%, or $14 million, to $633 million. This is $7 million more than the administration requested, with this additional money be used as follows.

Minority Graduate Education: $5 million
Advanced Technological Education program: $2 million

NSF lumps construction and acquisition budgets for large, expensive research facilities into the Major Research Equipment account. The subcommittee provided all of the money requested for the Polar Cap Observatory, the Laser Interferometer Gravitational Wave Observatory (LIGO), and the Millimeter Array Radio Telescope. They included significant additional funds, above the request, for the South Pole Station modernization.

The subcommittee also provided the full request for NSF's salaries and expenses account.

NASA. The subcommittee recommended an FY 1998 total budget of $13.648 billion, $148 million more than the administration requested but $61.2 million less than current year funding. The additional $148 million is distributed as follows.

Space Station: $100 million than requested
Science, Aeronautics and Technology: $48 million more than requested, mostly to be used for earmarks, with an additional $6.3 million for National Space Grant Colleges and Fellowships and an additional $5.5 million for enhancements to the space radiation science program

DoD Authorization Bills Advance in Congress

Both the House and Senate authorizing committees responsible for the Department of Defense (DoD) completed their bills for Fiscal Year 1998 (FY 1998) in June.

Authorization bills are intended to approve programs and set funding levels, although they do not provide any actual money; that is done by the appropriators. In many cases, appropriators do not follow the guidelines set by the authorizers, or authorizing legislation is not passed in time to affect the appropriation. However, defense funding is an exception; appropriators usually align their legislation closely with the authorization.

The House National Security Committee and the Senate Armed Services Committee bills vary in content. For the Research, Development, Test and Evaluation (RDT&E) account, the Senate bill is identical to President Clinton's FY 1998 request, while the House would provide more for this account. The authorization levels are specified for each service, but not broken out into the DoD research and development categories of basic research, applied research, and advanced technology development. Each amount includes test and evaluation as well as research and development. House ill specifies that of the $37.3 billion it recommends

Table 1. Budget Figures for Department of Defense Research and Development, Testing, and Evaluation (in billions of dollars)

Service	FY '97 Appropriations	FY98 Request	House Bill (H.R. 1119)	Senate Bill (S. 450)
Army	4.931	4.511	4.753	4.511
Navy	7.851	7.611	7.947	7.611
Air Force	14.069	14.451	14.660	14.451
Defense Agencies*	9.738	9.361	9.914	9.361
Total	36.589	35.934	37.274	35.934

*Defense Agencies include the Ballistic Missile Defense Organization, the Defense Advanced Research Projects Agency, and others.