roughly similar to the stellar mass density of the star bursting population at similar redshifts (*11*). Determining how common these massive, possibly evolved, galaxies are will require deeper and wider near-infrared imaging and spectroscopic surveys that are just now becoming feasible.

Massive galaxies may also not be easily visible or identifiable in optical or near-infrared surveys because of high amounts of light extinction by dust. In the past decade, a large population of bright galaxies emitting submillimeter radiation were found at redshifts $z > 2$ that are potential precursors of contemporary massive galaxies (*14*).

These galaxies were discovered in deep submillimeter surveys that sample rest-frame far-infrared radiation, which originates from dust grains heated by photons from massive young stars. The dust in these galaxies absorbs energetic photons, and it is not clear how much light from stars in these galaxies should be seen. However, the internal kinematics of these systems, based on the velocity width of the CO emission line, suggests that they are massive galaxies (*15*).

It is not yet known whether these systems represent a phase of evolution that relates to galaxies chosen in ultraviolet-selected and near-infrared–selected samples. In addition to understanding when massive galaxies formed, astronomers are also investigating how this formation occurred. If we assume that we are not missing a large population of massive galaxies at high redshift, the higher number density of these systems at lower redshifts suggests that massive galaxies must have formed gradually through time.

How does this formation occur? There are several possibilities, including major mergers between galaxies of similar mass to build larger galaxies, minor mergers of smaller satellites, and the accretion of intergalactic gas that is converted to stars. Understanding which of these modes is responsible for forming massive galaxies is a fundamental problem that is just now being addressed.

Perhaps the most popular explanation is that the most massive galaxies formed through multiple major merger events. Major galaxy mergers are in fact a prediction of the Cold Dark Matter cosmology and are predicted to occur in simulations of galaxy formation (*1*). But understanding and tracing the extent of major mergers in the early universe is difficult. Recently it was shown that high-resolution Hubble Space Telescope imaging can enable us to determine the formation modes of galaxies. Specifically, we can identify systems undergoing major mergers by their peculiar and distorted structures. Within the Hubble Deep Field North, the merger rate and history have been traced in detail as a function of galaxy luminosity and stellar mass (*16*). Galaxies undergoing the most merging at high redshift, $z > 2$, are the most luminous and massive galaxies (see the figure). By tracing the merger history for the most massive galaxies, it appears that very few mergers occur in massive galaxies at lower redshifts (*16*). This is consistent with finding massive evolved galaxies at modest redshifts (*12*) and is in direct conflict with the predictions of Cold Dark Matter models. On the basis of these observations, it appears that massive galaxies did not form rapidly early in the universe, as in the traditional early monolithic collapse picture, but neither are they forming gradually throughout time, as in Cold Dark Matter simulations.

However, it is still not clear how the merging ultraviolet bright systems at $z \sim 2.5$ relate to the submillimeter and near-infrared selected galaxies found at similar redshifts. It is likely that these represent various phases of galaxy evolution whose time scales are still unknown. It is also likely that the environment of galaxies is an important factor in their evolution (*13*), such that those in denser areas are forming earlier than galaxies in lower density environments. Little is understood of this effect at high redshift, but future deep-infrared surveys should address this problem in the coming years.

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OCEAN SCIENCE

Global Warming and the Next Ice Age

Andrew J. Weaver and Claude Hillaire-Marcel

A popular idea in the media, exemplified by the soon-to-be-released movie *The Day After Tomorrow*, is that human-induced global warming will cause another ice age. But where did this idea come from? Several recent magazine articles (*1*–*3*) report that abrupt climate change was prevalent in the recent geological history of Earth and that there was some early, albeit controversial, evidence from the last interglacial—thought to be slightly warmer than preindustrial times (*4*)—that abrupt climate change was the norm (*5*). Consequently, the articles postulate a sequence of events that goes something like this: If global warming were to boost the hydrological cycle, enhanced freshwater discharge into the North Atlantic would shut down the AMO (Atlantic Meridional Overturning), the North Atlantic component of global ocean overturning circulation. This would result in downstream cooling over Europe, leading to the slow growth of glaciers and the onset of the next ice age.

This view prevails in the popular press despite a relatively solid understanding of glacial inception and growth. What glacier formation and growth require is, of course, a change in seasonal incoming solar radiation (warmer winters and colder summers) associated with changes in Earth's axial tilt, its longitude of perihelion, and the precession of its elliptical orbit around the Sun. These small changes must then be amplified by feedback from reflected light associated with enhanced snow/ice cover, vegetation associated with the expansion of tundra, and greenhouse gases associated with the uptake (not release) of carbon dioxide and methane.

Several modeling studies provide outputs to support this progression. These studies show that with elevated levels of carbon dioxide, such as those that exist to-

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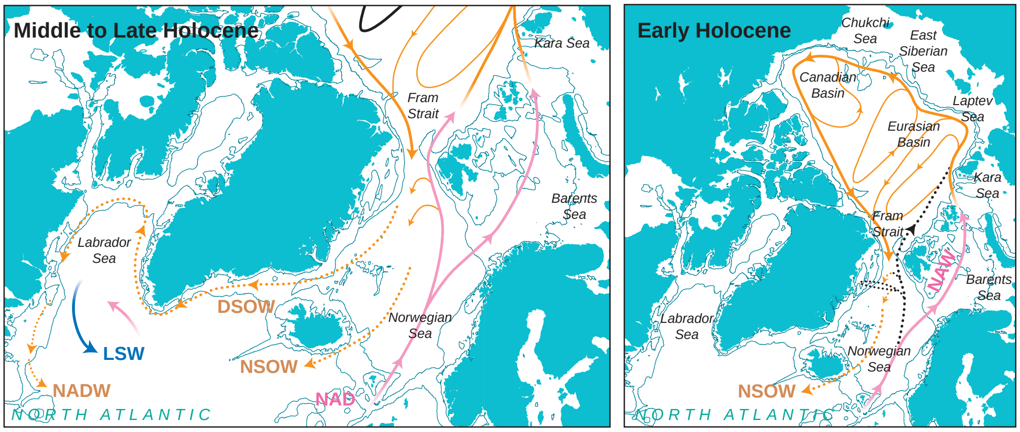
day, no permanent snow can exist over land in August (as temperatures are too warm), a necessary prerequisite for the growth of glaciers in the Northern Hemisphere [e.g., (*6*)]. These same models show that if the AMO were to be artificially shut down, there would be regions of substantial cooling in and around the North Atlantic. Berger and Loutre (*7*) specifically noted that "most CO_2 scenarios led to an exceptionally long interglacial from 5000 years before the present to 50,000 years from now . . . with the next glacial maximum in 100,000 years. Only for CO_2 concentrations less than 220 ppmv was an early entrance into glaciation simulated." They further argued that the next glaciation would be unlikely to occur for another 50,000 years.



Going with the flow. The behavior of the Atlantic thermohaline circulation (AMO) during the Middle and Late (Modern) Holocene (**left**) and the Early Holocene (**right**). Intermediate or deep water masses are orange; the incoming North Atlantic warm and saline water mass (NAW) is red. Cold and dilute surface currents evacuating Arctic fresh waters westward are not shown (that is, East and West Greenland Current, Labrador Current). Note the strong opposition between a high-salinity northeast North Atlantic and a low-salinity northwest North Atlantic. Maximum outflow of Norwegian Sea Overflow Water (NSOW) occurred during the early Holocene, whereas Denmark Strait Overflow Water (DSOW) peaked during the mid-Holocene and Labrador Sea Water (LSW) formation reached a maximum during the late Holocene. This east-west temporal shift is linked to increasing density of surface waters westward. Under the condition of increasing freshwater fluxes from the Arctic, the most sensitive sector of deep-intermediate formation would thus be the Labrador Sea, as also indicated by recent modeling experiments [for example, (*11*, *16*)]. The NAW pathway in the Arctic is from (*17*). NAD, North Atlantic Drift.

Although most paleoclimatologists would agree that the past is unlikely to provide true analogs of the future, past climate synopses are valuable for confronting the results of modeling experiments or for illustrating global warming. A reduction of the AMO due to a global warming–induced increase in freshwater supplies to the North Atlantic is often discussed in relation to a short event that occurred some 8200 years ago (8.2 ka). During this event, one of the largest glacial lakes of the Laurentide Ice Sheet, Lake Ojibway, drained into the North Atlantic through Hudson Strait, quickly releasing enormous quantities of fresh water (*8*). However, to our knowledge, unequivocal evidence that this event resulted in a substantial reduction of the AMO has not yet been obtained. Notably, the Western Boundary UnderCurrent (WBUC)—which carries North Atlantic Deep Water masses (originating from the Norwegian and Greenland seas) along the continental slopes of Greenland and eastern North America—apparently remained unchanged during this episode [for example, (*9*)]. Because we cannot possibly foresee increases in freshwater inputs to the North Atlantic that could approach the magnitude of the Lake Ojibway discharge peak (the present Arctic river cumulative discharge rate is about two orders of magnitude lower), and because the effect of this event on the AMO is still unclear, further reference to the 8.2-ka event with respect to a reduction of the AMO in the near future seems irrelevant (also see letter by Broecker, page 388 of this issue).

Unquestionable evidence for a substantial reduction of AMO has been found only for intervals such as the Last Glacial Maximum (LGM) and some short, particularly cold, intervals of the last ice ages (such as those during Heinrich events). During these time periods, vast ice sheets occupied the Northern Hemisphere, providing a large freshwater source to the North Atlantic through either the dispersal of huge quantities of icebergs (Heinrich events) or the direct release of meltwater into the most critical sector associated with the AMO—the northeast Atlantic. On the other hand, the most critical site with respect to sensitivity to enhanced freshwater supplies from the Arctic has been, and would be, the Labrador Sea (*10*). Indeed, convection could stop there in response to global warming, as demonstrated by recent modeling experiments, apparently without any major effect on the overall rate of AMO (*11*). Worthy of mention is the fact that the strong east-west salinity gradient of the North Atlantic, with more saline waters eastward, seems a robust and permanent feature that was maintained even during the Last Glacial Maximum, when the rate of AMO was considerably reduced (*12*).

A clear picture of the North Atlantic under high freshwater supply rates arises from its recent history. High freshwater supplies may indeed impede convection in the Labrador Sea because of their routing along western North Atlantic margins, but this would result in an increased eastward branch of AMO (see the figure). Further indication for such behavior is found in records of the Last Interglacial Interval. Relatively dilute surface water existed in the Labrador Sea, preventing intermediate water formation. However, a high-velocity WBUC existed throughout the whole period, indicating a high AMO along the "eastern route" (*10*).

The observed rate of global sea level rise during the 20th century is estimated to be in the range 1.0 to 2.2 mm/year (*3*). If one makes the clearly incorrect assumption that the entire maximum rate of observed sea level rise is a consequence of fresh water being added to the North Atlantic between 50° and 70°N, then this equates to a rate of freshwater forcing of 0.022 Sv (2.2×10^4 m^3 s^{-1}). This rate in itself is certainly too small to cause a major shutdown of the AMO, although it may be large enough to cause cessation of convection in the Labrador Sea [for example, (*6*)].

It is certainly true that if the AMO were to become inactive, substantial short-term cooling would result in western Europe, especially during the winter. However, it is important to emphasize that not a single coupled model assessed by the 2001 IPCC Working Group I on Climate Change Science (*4*) predicted a collapse in the AMO during the 21st century. Even in those models where the AMO was found to weaken during the 21st century, there would still be warming over Europe due to the radiative forcing associated with increased levels of greenhouse gases.

Models that eventually lead to a collapse of the AMO under global warming conditions typically fall into two categories: (i) flux-adjusted coupled general circulation models, and (ii) intermediate-complexity models with zonally averaged ocean components. Both suites of models are known to be more sensitive to freshwater perturbations. In the first class of models, a small perturbation away from the present climate leads to large systematic errors in the salinity fields (as large flux adjustments are applied) that then build up to cause dramatic AMO transitions. In the second class of models, the convection and sinking of water masses are coupled (there is no horizontal structure). In contrast, newer non–flux-adjusted models find a more stable AMO under future conditions of climate change (*11*, *13*, *14*).

Even the recent observations of freshening in the North Atlantic (*15*) (a reduction of salinity due to the addition of freshwater) appear to be consistent with the projections of perhaps the most sophisticated non–flux-adjusted model (*11*). Ironically, this model suggests that such freshening is associated with an increased AMO (*16*). This same model proposes that it is only Labrador Sea Water formation that is susceptible to collapse in response to global warming.

In light of the paleoclimate record and our understanding of the contemporary climate system, it is safe to say that global warming will not lead to the onset of a new ice age. These same records suggest that it is highly unlikely that global warming will lead to a widespread collapse of the AMO—despite the appealing possibility raised in two recent studies (*18*, *19*)—although it is possible that deep convection in the Labrador Sea will cease. Such an event would have much more minor consequences on the climate downstream over Europe.

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ECOLOGY

How “Virgin” Is Virgin Rainforest?

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Conservation biologists increasingly use the term “wild nature” rather than “high biodiversity” to identify blocks of biodiverse habitats that have been relatively undisturbed by human activity (*1*). Their preference for this term is driven by frustration that vast swathes of biodiverse habitats continue to be lost at unprecedented rates while biologists argue about which “currency” is best for measuring the value of biodiversity—genetics, species, family, rarity, endemicity—and which regions should be selected for conservation efforts. This is especially true for the tropical rainforests which, according to current estimates, are disappearing at a rate of ~6 million ha per year (*2*). Alongside these depressing rates of destruction, evidence has started to emerge from archaeological and paleoecological investigations that many of these so-called “virgin” rainforest blocks might not be as pristine as originally thought and have in fact undergone substantial prehistoric modification. The implications of such studies for understanding the resilience and recovery of tropical rainforests following human disturbance are far-reaching and should not be overlooked by conservation biologists.

The three largest undisturbed rainforest blocks are in the Amazon basin, lowland Congo basin, and the Indo-Malay region of Southeast Asia (see the figure). Yet a number of case studies in each of these regions now suggest that prehistoric human activities were far more extensive than originally thought. In the Amazon basin, for example, recent studies indicate that regions with the most fertile soils in the lowland rainforest are those with “terra preta” soils (*3*). Formation of these soils is attributed to prehistoric burning and agricultural activities from around 2500 years ago, and in central Amazonia, estimates suggest that terra preta soils cover up to 50,000 ha. In addition, emerging archaeological evidence from the Upper Xingu region of Brazil indicates extensive late prehistoric settlements dating between ~1250 to ~1600 A.D., covering regions up to 40 to 80 ha, and supporting populations between 6 and 12.5 persons per km^2 (*4*). These were complex regional settlements indicating intensive management and development of the landscape and resulting in large-scale transformation of the forest to agricultural land and parkland. Interestingly, abandonment of the land following catastrophic depopulation between 1600 and 1700 A.D. resulted in extensive reforestation in many areas. The Upper Xingu region of Brazil now comprises the largest contiguous tract of tropical forest in the southern peripheries of the Amazon.

A combination of archaeological and paleoecological studies reveals a similar story in the lowland Congo basin. Here, there have been extensive finds of stone tools, oil palm nuts, charcoal horizons (subsoil layers of charcoal), banana phytoliths (silica bodies found in plants that are preserved in sediments and permit identification of the source plant), and pottery fragments (*5*, *6*). These discoveries have led to the conclusion that much of this region underwent extensive habitation, clearance, and cultivation beginning ~3000 years ago and ending ~1600 years ago, following a population crash. In western central Africa there is also archaeological evidence for iron-working furnaces dating from ~650 B.C.—another activity that would have had a serious impact on the forest through the extraction of wood for charcoal production and smelting. A population crash in the fifth century A.D. resulted in abandonment of the land and widespread forest regeneration throughout these regions (*7*). Many forest types resulting from this former human occupation are still to be found in the lowland Congo basin. In some areas, often considered “virgin,” the forests may still be undergoing a process of secondary succession (*8*).

There is even earlier evidence of prehistoric modification of the tropical rainforest in the Indo-Malay rainforest block. This dis-

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