associated with ice-core evidence for changing conditions over Greenland.

The origin of millennial-scale climate variability is unclear. The finding of millennial-scale oscillations during the Holocene, in the absence of large ice sheets, rules out ice sheet instability as the primary cause. The interplay between the primary Milankovitch frequencies may account for climate variability at longer suborbital cycles, between 12,000 and 6,000 years (*8*), but it is unlikely that they are responsible for climate cycles of 1000 to 2000 years. Others suggest that variations in solar output may drive these climate oscillations. Bond *et al.* and Mayeski *et al.* favor an ocean-atmosphere mechanism but do not rule out primary forcing by external processes.

In the modern North Atlantic, the process of cooling surface water to form deep water, or convective overturn, provides roughly one-third as much heat as is directly contributed by the sun (*9*). Thus, variations in convective overturn can dramatically influence regional climate (see figure). Broecker introduced the concept of a "salt oscillator"—essentially controlled by the balance between fresh water delivered by melting ice and salt removed from the surface by the export of saline deep waters from the North Atlantic—to explain millennial climate oscillations during glacial times (*1*). Heat released during convective overturn may have promoted the melting of the ice sheets fringing the North Atlantic, delivering fresh water to the surface ocean. Consequently, the density of the surface waters would decrease, eventually to the point where conditions were no longer favorable for deep-water formation. As a result of the reduced heat released in the process of convective overturn, less ice would melt, salinity would rise, and eventually the system would resume the convective phase of the salt oscillator. Marine evidence of linked surface and deep-water variability during glacial and deglacial millennial oscillations is consistent with this hypothesis (*10*).

The recent finding of millennial climate oscillations in the Holocene, when large ice sheets did not surround the North Atlantic, may require modification of the "salt oscillator" hypothesis, but it by no means requires its

UPDATE: PLANETARY SCIENCE

The Early Mars Climate Question Heats Up

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Recently, Sagan and Chyba (*1*) threw a new log on the smoldering question of early Mars' climate by suggesting that reduced greenhouse gases such as CH_4 and NH_3 might have helped to warm early Mars enough to maintain liquid water on its surface. The greenhouse effect of gaseous CO_2 and H_2O alone had been shown to not be up to the task (*2*). Now, in this issue on page 1273, Forget and Pierrehumbert (*3*) suggest that a CO_2-H_2O atmosphere could indeed have kept early Mars warm—if it was filled with CO_2 ice clouds. Clouds of CO_2 ice differ from water or water ice (cirrus) clouds in that they tend to scatter upwelling infrared radiation instead of absorbing and reradiating it. Thus, they form a partially reflecting layer in the infrared, just as both CO_2 and H_2O clouds do in the visible. Crystals of CO_2 ice are expected to be large (10 to 100 mm diameter), however, which means that they should scatter radiation at thermal infrared wavelengths more effectively than they scatter visible and near-infrared radiation. This variation in reflectivity, combined with the fact that the clouds are expected to form in the upper martian troposphere and not near the planet's surface, allows them to produce a strong warming effect.

In less than 6 months, the number of plausible mechanisms for keeping early Mars warm has gone from zero to two. The idea of CO_2 ice clouds may be more plausible than the CH_4 and NH_3 idea, as calculations indicate that a biological CH_4 source would probably be needed to make it work on its own (*4*). The cloud warming mechanism is complicated, however, because the amount of surface warming depends on such details as particle size, cloud height, cloud optical depth, and fractional cloud cover. These factors, in turn, depend on the details of the atmospheric circulation. As all meteorologists are aware, the realistic simulation of clouds in atmospheric general circulation models is a tricky and still largely unsolved problem for modern Earth, not to mention early Mars. The calculations for Mars point the way to a possible solution to the early Mars climate problem, but it would be a mistake to conclude that the issue is resolved.

Indeed, the hardest part of the early Mars climate problem is understanding what the climate of early Mars was really like. Ever since the Viking mission 20 years ago, a debate has raged as to how warm the martian paleoclimate must have been to form the observed surface features. Some researchers have suggested that the climate was essentially Earth-like, whereas others maintain that the global mean surface temperature was always well below freezing. Progress may be on the horizon in the form of the Mars Global Surveyor spacecraft now orbiting the planet, which should begin returning useful data sometime next spring. The combination of instruments on board, especially the high-resolution camera and the thermal emission spectrometer (which can be used to deduce mineralogy), will hopefully allow better understanding of the climatic conditions under which the martian surface features formed.

The other interesting conclusion from the Forget and Pierrehumbert report is that their calculations imply that the habitable zones around other stars may be significantly wider than thought (*5*). This is good news for ET (extraterrestrial life) enthusiasts because it increases the likelihood that life, including possibly intelligent life, exists outside our own solar system. This question is also one on which progress could conceivably be made in the not-too-distant future: NASA and ESA (the European Space Agency) have tentative plans to construct large space-based interferometers that could return infrared spectra of extrasolar planet atmospheres. It has been argued, quite reasonably, that the signature of the 9.6-μm-wavelength ozone band (which, in turn, implies the presence of photosynthetically produced O_2) could be taken as evidence for extraterrestrial life (*6*). Although such a mission is probably at least 15 to 20 years in the future, the calculations on CO_2 clouds and their effect on planetary climates provide additional reason for hoping that it might meet with success.

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