Series

The Geoscience of Climate and Energy 2. Climate Changes at Geologic Time Scales: An Overview

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Exploration in recent decades has defined the basic outline of climate change over a range of time scales from tectonic (millions of years or more) to orbital (governed by changes in the earth's orbit around the sun over tens to hundreds of thousands of years) to suborbital variations over millennia, centuries and decades. In each case, greenhouse-gas variations appear to have played a major role.

Over tectonic time scales, potential climatic drivers include, i) changes in positions of continents; ii) elevation of plateaus and mountains; and iii) isthmus connections between land masses. During the well-defined changes of the last 50 million years, both poles experienced major cooling, marked by shifts to successively colder-adapted vegetation types and eventually the appearance of ice sheets. One index of these changes is the shifts in benthic foraminiferal $\delta^{18}O$ trends toward heavier values (colder deep-water temperatures, greater ice volume; Fig. 1).

Opening of full circum-Antarctic ocean circulation is often cited as the cause of Antarctic cooling, but simulations with general circulation models do not support this hypothesis. Instead, cooling of both poles since 50 million years ago is now widely attributed to a gradual decrease in atmospheric CO_2 concentrations. One proposed driver of this trend is reduced CO_2 delivery to the atmosphere because of a slowing of seafloor spreading rates, but reinterpretations of paleomagnetic anomalies in the northwest Pacific Ocean have now brought Cretaceous spreading rates surprisingly close to modern values. Another (still viable) proposed forcing is increased CO_2 removal by enhanced chemical weathering of silicate rock debris produced by uplift in Tibet, the Himalaya and the Andes.

Over orbital time scales, changes in Earth's climate are driven by variations in tilt (obliquity) and by eccentricity-modulated changes in precession. These orbital changes drive two major components of the climate system: ice sheets in subpolar northern latitudes, and monsoons in the tropics and subtropics. Benthic foraminiferal $\delta^{18}O$ time series in marine sediments show large ice-volume changes at orbital periods during the last 2.75 million years, but the relative amplitudes of the ice-volume changes are not well matched to those of the periods at which the orbital changes drive changes in solar radiation that reach Earth's atmosphere and alter Earth's climate (Figs 2, 3).

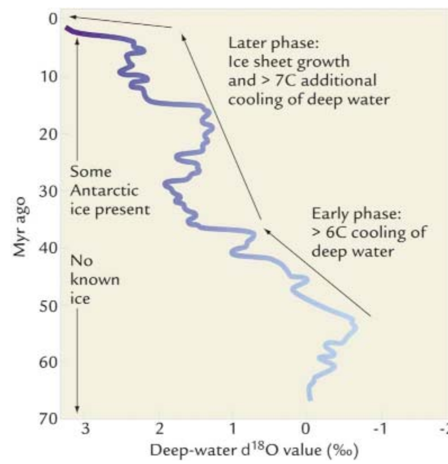

Figure 1. Benthic foraminferal $\delta^{18}O$ trend toward heavier values during the last 50 million years (from Ruddiman 2007, after Miller et al. 1987).

High-latitude insolation variations have both a substantial 23 000-year (precession) component, as well as a 41 000-year (tilt) component. In contrast, ice volume varied mainly at the 41 000-year period from 2.75 to 0.9 million years ago, and then primarily near the 100 000-year (eccentricity) period during the last 900 000 years (Figs. 2, 3). The cause of this mismatch is under active investigation. Because atmospheric CO_2 varies in close concert with ice volume (Fig. 4), greenhouse gases are a likely part of the explanation.

Variations in tropical monsoon strength over the last 15 million years are relatively well understood. Kutzbach (1981) proposed that past changes in low-latitude summer insolation at the 23 000-year period control the intensity of summer monsoons in the tropics and subtropics (Fig. 5). This mechanism is a direct amplification of the way that strong summer-season insolation (compared to weak winter

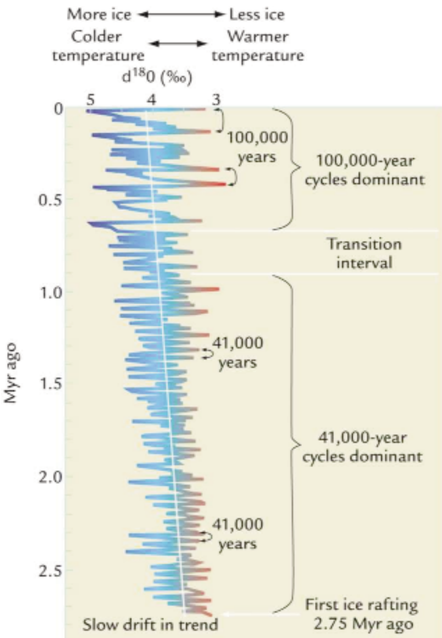

Figure 2. Variations in benthic foraminiferal $\delta^{18}O$ during the last 2.75 million years (from Ruddiman 2007, after Raymo 1994).

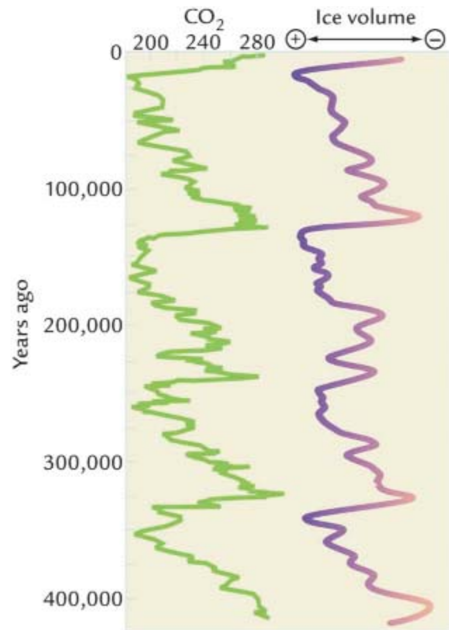

Figure 4. Close correlation of ice volume ($\delta^{18}O$) and CO_2 signals over the last 400 000 years (from Ruddiman 2007, after Petit et al. 1999).

insolation) drives modern monsoons.

Past monsoon variations are registered in a range of proxy data from the tropics, including the size of lakes and the distribution of vegetation types in discontinuous sedimentary sequences. Dramatic recent evidence for monsoon behavior comes from long calcite (speleothem) sequences accurately dated by Th/U analysis (Fig. 6). In full agreement with the Kutzbach hypothesis, large-amplitude $\delta^{18}O$ variations in cave calcite that can only reflect changes in monsoonal air masses occur at the same period (23 000 years) as insolation changes at tropical/subtropical latitudes and with the predicted mid-summer phase. These changes in the wet summer monsoon control fluxes of methane from tropical wetlands.

Large millennial-scale oscillations occurred during times when major ice sheets were present in the northern hemisphere, but they have

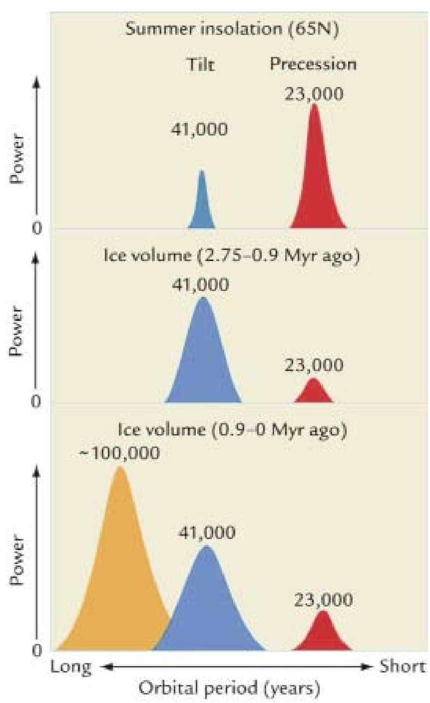

Figure 3. Schematic cartoon of mismatch in power between insolation forcing and ~ice-volume ($\delta^{18}O$) responses between 2.75-0.9 and 0.9-0 million years ago (from Ruddiman 2007).

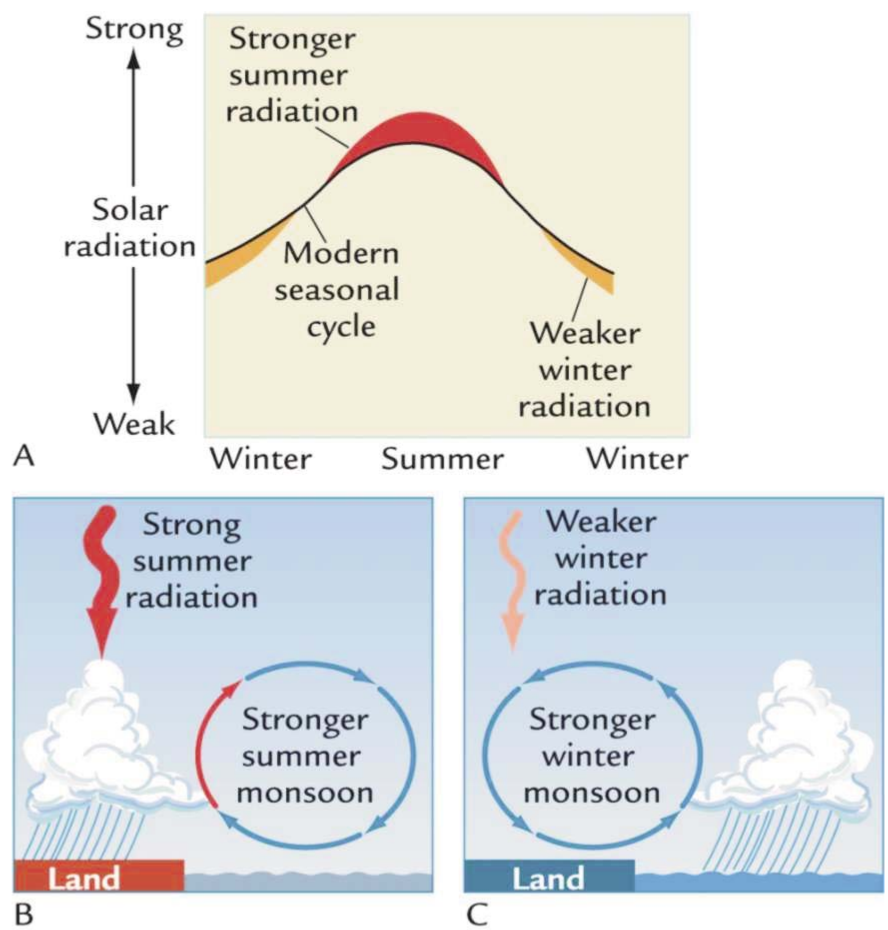

Figure 5. The strength of past monsoons has been controlled by departures of seasonal radiation forcing from modern values (from Ruddiman 2007, after Kutzbach and Webb 1991).

been much reduced in amplitude and spatial coherence during warmer interglacial climates. For the most part, these oscillations are not periodic. They appear to be a manifestation of "red-noise" interactions internal to the climate system. They probably reflect natural random variations around an average climatic state, rather than changes driven by a sustained external source.

The Holocene interval began near the end of the most recent melting of northern ice sheets in response to a summer insolation maximum 11 000 years ago, supplemented by coincident CO_2 and CH_4 maxima. A longstanding view of the climate-science community is that the Holocene remained in a naturally interglacial state because summer insolation and greenhouse-gas concentrations have not yet fallen far enough to initiate the next glacial interval. A different view (Ruddiman 2003) is that early agriculture generated sufficient amounts of CO_2 (from deforestation) and CH_4 (from rice irrigation, livestock, and biomass burning) to reverse a natural downward trend in greenhouse-gas concentrations during the millennia prior to the industrial era and instead cause a slow rise. In this view, early anthropogenic interference countered a natural cooling trend that would have caused glacial inception by now (Fig. 7).

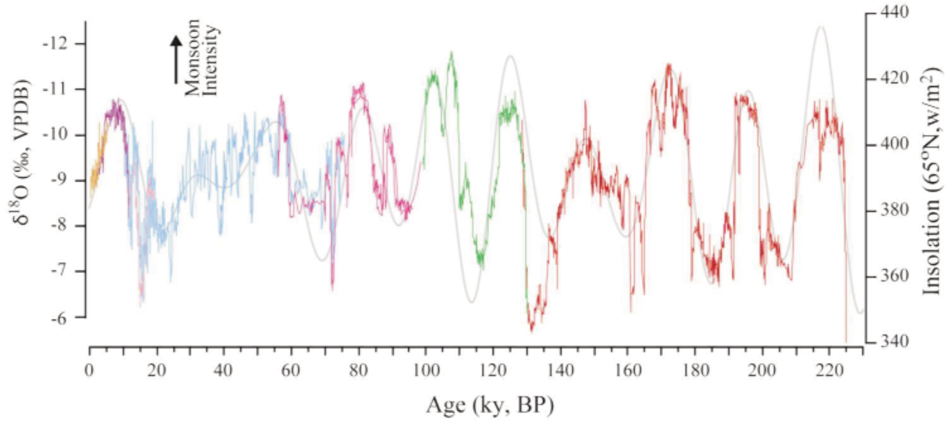

Figure 6. Long-term $\delta^{18}O$ variations (jagged coloured line) in speleothem calcite from Shangbao Cave in south-central China are dominated by a 23 000-year response that reflects mid-summer insolation at latitude 65°N (smooth grey line) (from Wang et al. 2008).

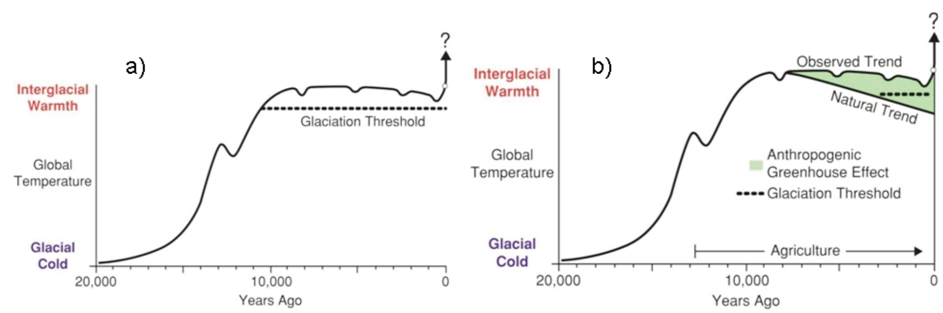

Figure 7. a) Schematic cartoon of a naturally warm Holocene, with a small (mostly polar) cooling since 8000 years ago, but not enough to cause inception of the next glaciation. b) Alternative view that early-anthropogenic CO_2 and CH_4 emissions kept climate warmer and prevented cooling and glacial inception.

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