A Causality Problem for Milankovitch

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The Milankovitch theory postulates that changes in incident solar radiation (insolation) in the Northern Hemisphere during summer months is responsible for driving Earth's ice ages. In 1992, Wallace Broecker wrote a comment titled "Upset for Milankovitch Theory" (1) in which he discussed what was then a troublesome new measurement. Oxygen isotope data ($\delta^{18}O$) from a cave in Nevada called Devils Hole appeared to show that the timing of the penultimate termination of the ice ages, called Termination II, was incompatible with the standard Milankovitch theory (2, 3). The data indicated a shift in $\delta^{18}O$ to interglacial values that was essentially complete by 135 thousand years ago (ka). But at this time, the Northern Hemisphere summer insolation had not yet warmed to the point at which it should have triggered anything extraordinary, let alone a glacial termination. The termination event appeared to precede its cause. We call this discrepancy the "causality problem." In Figure 1, we show the Devils Hole $\delta^{18}O$ data and the calculated July 65N insolation (based on the orbital calculations of Quinn et al. (4)).

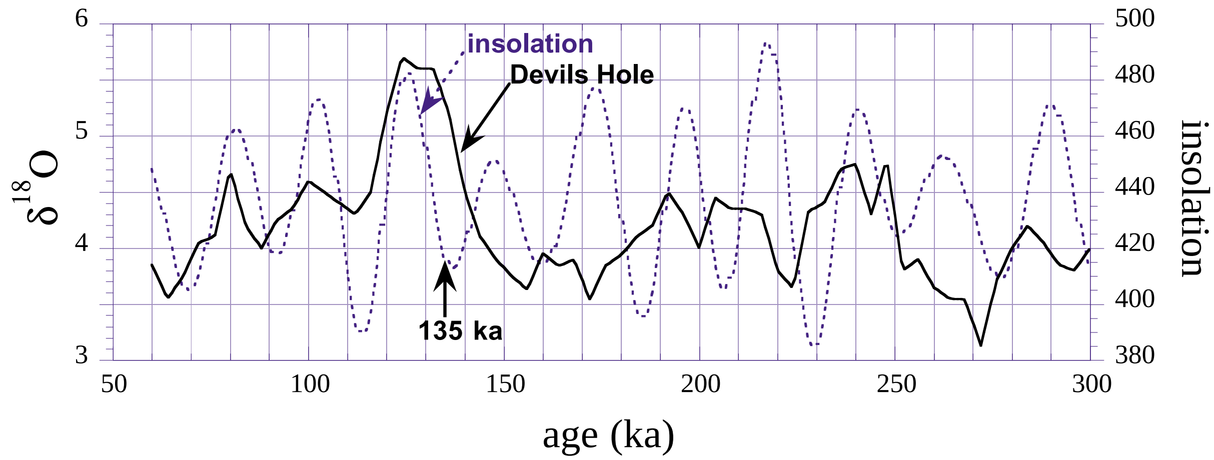

Figure 1 The "causality problem." Devils Hole $\delta^{18}O$ (a proxy for temperature and ice volume) and July 65N insolation, the driving force of the standard Milankovitch model. The rise in $\delta^{18}O$ associated with Termination II is nearly complete before the insolation begins its rise. Recent data from sediment and corals indicate the termination was virtually complete by 135 ka, in agreement with the Devils Hole results.

The Devils Hole data had not been the first to indicate a problem. As far back as 1974, Bloom et al. (5) had suggested that sea level had reached a high point, from melting glacial waters, by as early as 142 ka. Their work was based on U-Th ages of coral terraces from the Huon Peninsula in Papua New Guinea. These results were not used when Imbrie et al. (6) created the SPECMAP template, the most widely used model for explaining how insolation could drive ice age cycles. Instead, Imbrie et al. set the termination at 127 ±6 ka, based on radiometric dates from Barbados corals by Mesolella et al. (7) and Shackleton and Matthews (8). In 1991, Chen et al. (9) studied ^{238}U-^{234}U-^{230}Th ages for different coral species from two Bahamian reefs. They concluded that "the high sea level stand began possibly by 132 ky and certainly by 129 ky ago, when sea level reached ~6 meters above present mean low sea level." This was uncomfortably early for the Milankovitch theorists, but not necessarily fatal to the theory. Perhaps the ice started to melt when insolation began to rise (at about 137 ka), but that it did not turn into a full termination until the insolation proceeded upward. By 129 ka, insolation had completed about 3/4 of its rise -- comparable to Holocene levels, and was higher than it had been in the previous 40 thousand years (kyr).

But the Devils Hole chronology was based on U-Th dating, and was not easy to dismiss. Their two standard deviation uncertainties on individual measurements relevant to Termination II were less than ± 3 ka (3). Their results suggested that the termination was virtually complete before Northern Hemisphere July insolation had risen to a significantly high level.

The supporters of the Milankovitch theory suggested numerous possible faults with the Devils Hole results. A debate ensued in the literature; the most relevant references are the following (10), (11), (12), (13), (14), (15), (3), (16), (17). Most of the criticisms had substance, and they were eventually addressed by the experimenters. Their chronology was subsequently replicated using Uranium-Protactinium dating (18). Based on the additional age analysis in Winograd et al. (19), Termination II in the Devils Hole data occurred at 142 ± 3 ka – two kyr earlier than their original results. Nevertheless, virtually no one in the Milankovitch theory community seemed to change their minds. Perhaps that was a reasonable response, since there is strong evidence that insolation affects climate, seen in other records. As long as Devils Hole was unique, it could have been a fluke. It is a land-based site, and perhaps it was only recording a local climate change (although that was unlikely, based on its strong correlation with the Vostok paleotemperature time series (19)). It would have been incautious to abandon the otherwise successful Milankovitch theory based on a single data record.

But now there are other records - sea level records from opposite sides of the globe, that show the causality problem is real - and these data are not easily dismissed. In January 1999, Tezer Esat and collaborators published new results of measurements of coral terraces of the Huon Peninsula in Papua New Guinea (20). They showed that sea level rose and peaked around 135 ka, to a point close to (only ≈14 meters below) present levels. At the Fall meeting of the American Geophysical Union in San Francisco, Gideon Henderson and Niall Slowey reported new results from U-Th dates of aragonite-rich sediments from the slopes of the Bahamas (21). They had three samples spanning Termination II, and they arrived at an age of 135 ± 2.5 ka for the termination. At the same meeting, Christina Gallup and collaborators presented new U-Th and U-Pa ages of fossil corals in Barbados (22). They too found that most of the rise in sea level took place prior to the expected insolation warming. They report that sea level had risen to within 18 meters of the present level by 135.8 ± 0.8 ka.

In Figure 1, we indicate the date 135 ka with a vertical arrow. At this age, the insolation has a value of 416 calories/cm^2 per day. It had been above this level for 71 of the previous 100 kyr. There is no plausible reason to think that this low level of insolation could have triggered an ice age termination that was, by that time, essentially complete.

We conclude that the causality problem is real. Northern Hemisphere summer insolation could not have triggered Termination II; knowing whether it accurately predicts earlier terminations awaits more precise radioisotopic ages on those terminations. Is this problem fatal for the Milankovitch theory? No -- insolation successfully accounts for too much other data to throw out the theory entirely. But we were mistaken to think that climate was so one dimensional that it could be predicted by a single parameter: summer 65N insolation. Climate is more complicated than that. We *can* conclude that the standard Milankovitch insolation theory does not account for the terminations of the ice ages. That is a serious and disturbing conclusion by itself. We can conclude that models that attribute the terminations to large insolation peaks (or, equivalently, to peaks in the precession parameter), such as the recent one by Raymo (23), are incompatible with the observations.

More importantly, these new results do create practical problems for the working scientist. For example, virtually all of the published time scales used in paleoclimate are based on Northern Hemisphere summer insolation. This includes the frequently referenced time scales of SPECMAP and the low latitude stack of Bassinot et al. (24). The coral results show that these are incorrect, at least for Termination II, by five to 10 kyr or more. There is no reason to believe that they are not similarly in error at other terminations.

What can we do? Crowley and Kim (25) suggest that a more complex insolation model. A possibility that received attention at the Fall American Geophysical Union meeting is to attribute terminations to Southern Hemisphere insolation (21, 22). But if we do this we lose the explanation for the most recent ice age termination (at about 12 ka) which was previously accounted for by the increase in *Northern* Hemisphere summer insolation. Does each termination have a different cause? And the Milankovitch theory has other difficulties, such as the "Stage-11 problem" (26), that have been addressed with other ad hoc mechanisms. If we allow every discordant measurement to have its own explanation, we do not have a theory that can make predictions, and that means it really isn't a theory at all.

Even if we have no simple answer, at least we can conclude that the Milankovitch theory must not be a procrustean bed into which every observation will be forced. Different aspects of climate may have different driving forces – and some may even be unrelated to insolation (27). There is already evidence that different proxies in the same core can be measuring completely different aspects of climate. Precession, for example, is dominant in the atmospheric oxygen signal in the Vostok ice core (28), and simultaneously very small in the temperature proxy for the same core. In the sea floor, eccentricity can be strong in one proxy, and yet virtually absent in another (29). Now that we have lost the simple Milankovitch picture, we must look at the data again, as if for the first time, regard climate to be multidimensional, and be open to new ideas unbiased by our prior theoretical prejudices.

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