“From the Freezer to the Frying Pan: Trying to Understand the Wackier Climates of Ancient Earth.”

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This talk is a freak-show exhibition of the wackiest climates Earth has ever known. There have been very warm climates with extremely uniform latitudinal temperature distributions that are difficult to understand, and climates so cold that the entire ocean may have frozen over!!! Sometimes global climate has reorganized from glacial-like conditions to present-like conditions in about a decade!!! Yikes! I will talk about how we get data about these ancient and mysterious climates (including the glorious and notorious woolly mammoth turd proxy!) and the tools we use to try to understand them. These wacky climates deserve study not only because they are so incredible, but also because studying them helps us improve climate models, because they forced important advances in the evolution of life, and because they may represent analogs to some of the exoplanets that are continually being discovered. I have included some important figures from the talk below with explanations.

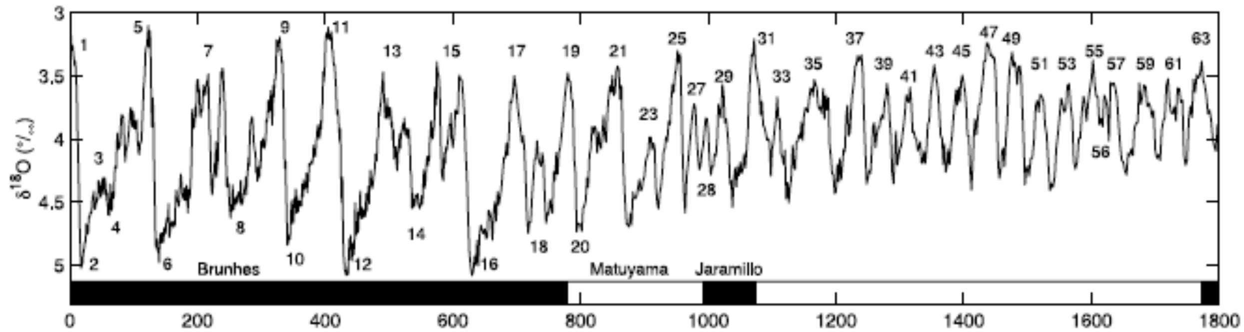

Figure 1: This figure from Lisiecki and Raymo (2005) shows the deviations in the oxygen 18 isotopic record ($\delta^{18}O$) preserved in the calcium carbonate shells of foraminifera (tiny protists) that live deep in the ocean. The scale on the x-axis is thousands of years before present. The ^{18}O content of sea water increases when large ice sheets develop on land because lighter isotopes evaporate preferably from the water surface. There is an additional temperature fractionation effect when the foraminifera form their shells such that the ^{18}O content is higher when the temperature is colder. Therefore higher values of $\delta^{18}O$ (notice the y-axis is inverted) indicate colder conditions with more ice (ice ages). For the past ~800,000 years we have had a large glacial cycle roughly every 100,000 years, but before that we had a smaller one roughly every 40,000 years. Amazingly, we do not understand in detail how these cycles work and why the timescale changed.

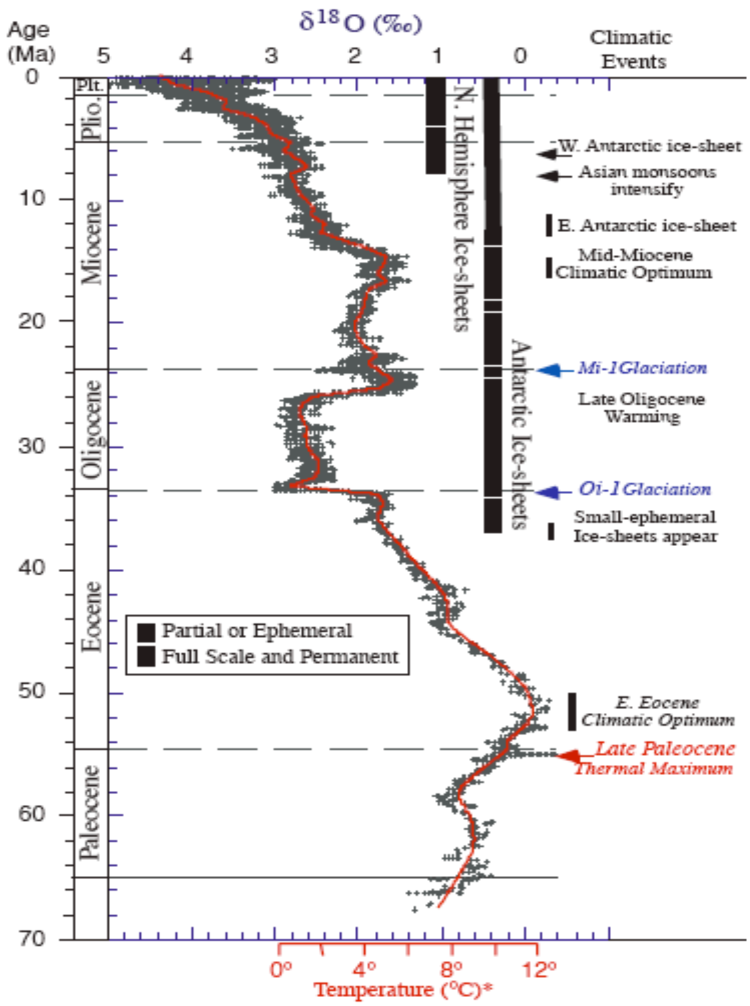

Figure 2: This is the famous $\delta^{18}O$ curve of Zachos et al. (2001). It is an extension of the curve in Figure 1 further back in time. Notice that the y-axis is in millions of years! It is hard to extend such foraminiferal records back much further than is shown here because most older ocean crust has been subducted into the mantle. The most important thing to notice here is that the climate has cooled over the past 50 million years as the climate transitioned from an "equable climate" to a "glacial climate". This cooling has been mostly gradual, although there have been some rapid changes. Notice that the first ice sheets grew on Antarctica about 35 million years ago. Before this $\delta^{18}O$ is a proxy for deep ocean temperature only (since the ice sheet effect is removed), and the temperature scale is given in red at the bottom of the plot. The spike in the curve labeled "Late Paleocene Thermal Maximum" is very important (we now refer to this as the Paleocene-Eocene Thermal Maximum or PETM). The temperature rose about 5K globally in some 10,000 years or less. We know from independent analysis of carbon isotopes that this was caused by a very large injection of carbon dioxide into the atmosphere. Therefore the PETM represents an analog to our current global experiment and is being studied intensively.

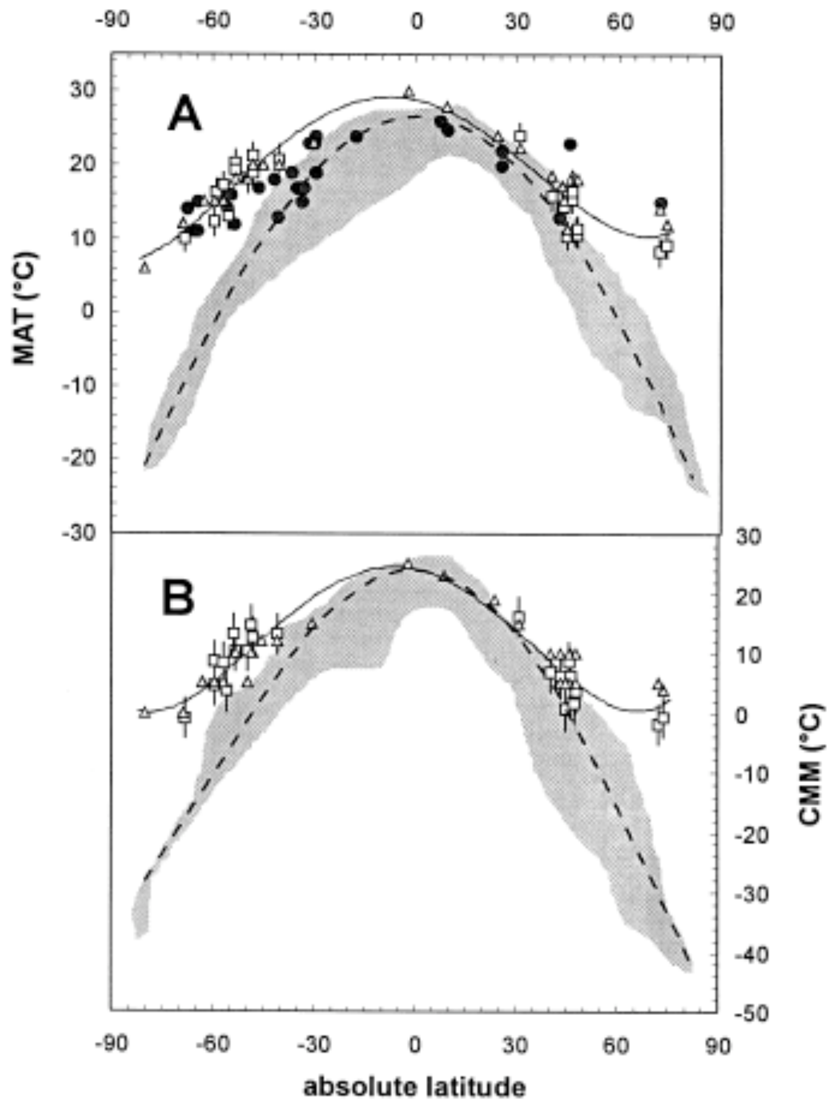

Figure 3: This plot from Greenwood and Wing (1995) shows the mean annual temperature (MAT) and the cold month mean temperature (CMM) as a function of latitude for the present climate (grey area) and for the Eocene, a period of equable climate about 50 million years ago (various other symbols). The data for the Eocene were acquired in a variety of ways, some of which I will explain in the talk. Notice that tropical temperatures are roughly the same as modern, but the high latitudes are much warmer, particularly during the winter. It is very difficult to get global climate models, which represent the embodiment of our understanding of climate, to warm enough at high latitudes without also warming the tropics. I proposed a convective cloud positive feedback on high-latitude climate which I will explain in the lecture to explain the discrepancy between models and data. Some newer models in which this feedback activates appear to be able to explain the data better.

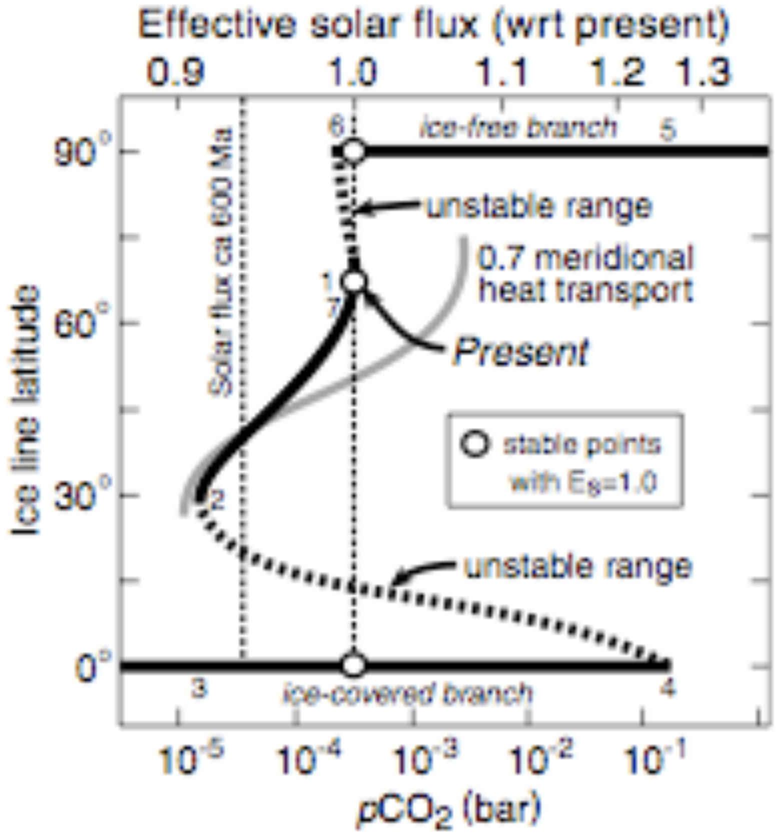

Figure 4: This is a bifurcation diagram produced by a simple climate model that is relevant for the Snowball Earth events that may have happened a few times in Earth history, most recently about 600 million years ago. The x-axis is the CO_2 concentration as a fraction of the current atmospheric pressure (the modern value is about $4x10^{-4}$) and the y-axis is the latitude to which ice extends (90 degrees means there's no ice and 0 degrees means you're in a Snowball). The solid lines are stable states of the global climate and the dotted lines are unstable states that define the zones of attraction of the stable states. There are some other lines on the diagram that are less important. The present climate is marked "present" in the diagram. In this model we could also be in an ice-free climate or a Snowball at the current CO_2 concentration. This is a sign of the nonlinear behavior of the climate system, in this case caused by the "ice-albedo feedback." There is currently a vigorous debate about whether Snowballs ever happened. If one did happen, there must be a way to escape from a Snowball, since we're not in one now. However, it has been difficult to cause Snowball terminations in climate models (this point is a bit more nuanced than this, ask me if you're interested). I proposed that dust aerosol during Snowballs could provide the extra warming that gets you out of them. A current analog to this process is the global dust storms on Mars.

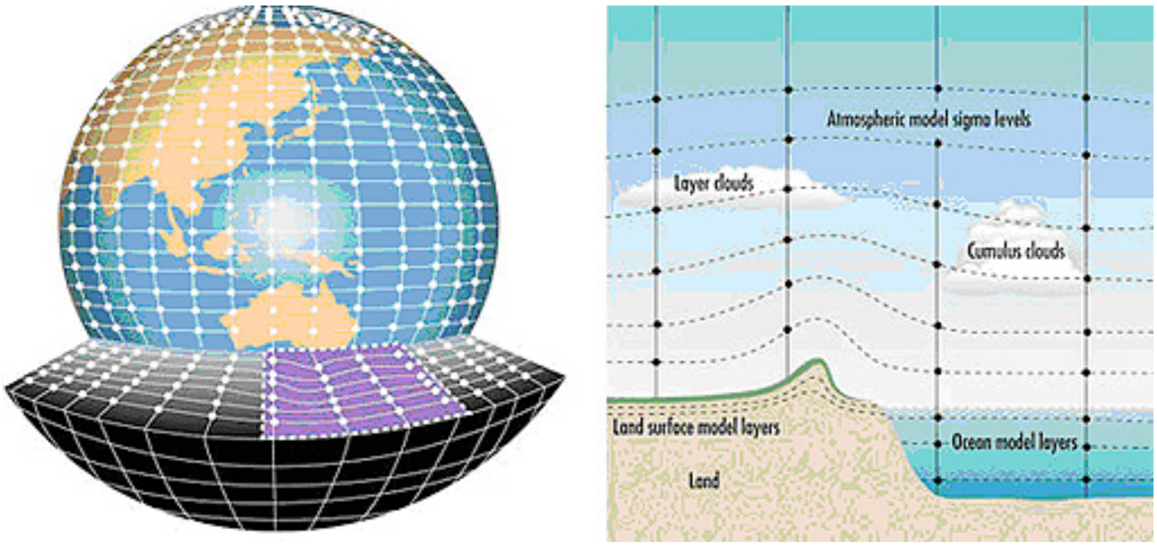

Figure 5: This is a schematic diagram of a global climate model. Global climate models solve the partial differential equations that describe the flow of a fluid (oceans and atmosphere) on a rapidly rotating sphere and the equations of radiative transfer. The gridboxes in a state-of-the-art climate model are typically about 100 km by 100 km and there are about 20-30 vertical levels (the speed of current supercomputers limits how fine we can make the resolution). Clearly there are many processes that occur on too small a scale for a global climate model to resolve, most importantly cloud processes. Such sub-grid-scale processes must be parameterized in terms of grid-scale variables such as temperature, humidity, pressure, etc. These parameterizations are essentially interpolations based on measurements in the current climate. When a global climate model has difficulty reproducing a wacky ancient climate, the sub-grid-scale parameterizations are a good place to look when you try to understand why. They are also the main source of uncertainty in our forecasts of future climate.