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Let's first talk about examples of what we generally think of as forcing of the climate system. One of the cleanest examples of forcing is changing solar constant. We'll talk about evidence that the solar constant is not quite constant.

Changes in the character of the Earth's orbit around the sun, and its spin around its own rotation axis, changing concentrations of non-interactive greenhouse gases-- well, most greenhouse gases are interactive on long enough time scales, but on shorter time scales, some of them can be regarded as fairly passive. Volcanoes, in particular aerosols put into the atmosphere by volcanoes, can be regarded as a forcing of the climate system. Man-made aerosols-- such as sulfate aerosols, changes in land use which changes the albedo of the surface, and the availability of water to the atmosphere. These are all examples of climate forcing.

Let's begin by talking about the effect on climate of variations in the Earth's rotation, and in its orbit about the sun. Back in the early part of the 20th century, the Serbian mathematician Milutin Milankovic proposed that periodic variations in the Earth's orbital characteristics were the ultimate cause of the great glacial cycles that the Earth has experienced over the last three million years or so.

Let's talk about these so-called Milankovic cycles. Here's a diagram showing the orbit of the earth about the sun. That orbit is, of course, elliptical, not circular. But the degree of ellipticity varies with time over a period of about 100,000 years or so.

We also have variations in the rotation axis. The tilt of the rotation axis with respect to the plane about which it orbits the sun is called the obliquity. And the obliquity varies on time scales of some tens of thousands of years.

And the Earth's rotation axis also precesses like a top, which changes the amount of radiation received between the two hemispheres. When we look at the effects of these variations on solar radiation, we see some interesting signals.

So this particular graph, which runs from right to left-- starting a million years ago and going to the present-- so this is 1,000 kilo-years ago, or one million years ago, going to the present here. At the top is the orbital forcing due to the precession of the Earth's rotation axis, which has three periods of about

1922 and 24,000 years each. So there are relatively fast changes in solar radiation.

The second curve is the oscillation of the obliquity of the Earth's rotation axis with respect to the ecliptic. That has a period of about 41,000 years. And then the oscillation in the degree of eccentricity, which has time scales of about 95,000, 125,000, and 400,000 years here.

Now, we put that all together. We can calculate, for example, the total amount of insolation coming into the top of the atmosphere at a particular latitude. This yellow curve here shows the amount of radiation coming in integrated over the summer at 65 degrees North latitude, reflecting the periods that you see in precession, obliquity and eccentricity.

Now naturally, these oscillations in precession, obliquity, and eccentricity are consequences of orbital mechanics-- and in particular, the influence of moon and other planets on the Earth's rotation and orbit.

What Milankovic speculated on was that these changes-- particularly the changes that influence high-latitude solar forcing-- might be behind ice ages. And the bottom curve shows a proxy for the ice volume on the planet going back a million years, as well.

What do these changes in orbital forcings have to do with the ice ages? Well, it turns out a lot. And here is an interesting graph that shows fairly strong evidence that it is indeed these changes in orbital forcing that are the root cause of the glacial cycles over the last three million years or so.

This graph, which in this case runs from left to right, begins about one million years ago going up to the present. It shows two very different quantities. The red curve that you see here-- whose value you read off the left-hand axis-- is the total amount of sunlight received at high northern latitudes integrated over the summer time. And that is expressed in giga-joules per square meter.

The second curve-- the black curve-- is the time rate of change of ice volume as deduced from the ratio of the two isotopes of oxygen in deep sea sediments. So this is a direct measure of the ice volume on the planet. And you can see that there's a strong correlation between the time rate of change of ice volume as represented by the delta O-18 in the deep sea cores, and the amount of solar radiation coming into high latitudes.

So that when there's relatively little radiation coming into high latitudes, the ice volume tends to be increasing, and vice versa. The strong correlation between these curves is pretty strong evidence that it indeed is the orbital forcing that's ultimately responsible for the great glacial cycles on the planet.

Next we'll talk about the influence of variations in the sun itself.