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Let's now turn our attention to forcing by changing greenhouse gas content. Some greenhouse gases, like carbon dioxide, are relatively long lived, and we can think of them as forcings, at least on time scales of decades to hundreds or perhaps thousands of years. Other greenhouse gases, like water vapor, respond very quickly to climate change, and should be considered feedbacks instead.

But concentrating on the long-lived greenhouse gases, here again is a record going back to 1750 of the carbon dioxide concentration of the atmosphere based on the direct measurements from Mauna Loa beginning in 1958-- that's the blue curve on here-- and from air trapped in bubbles in ice cores-- the colored dots here-- which are consistent where they overlap, of course.

One could see that the concentration of carbon dioxide-- which was around 280 parts per million since about the end of the last Ice Age-- begins to increase at the dawn of the Industrial Age, and is increasing quite rapidly in the late 20th century, and is at 2000 up to 370 parts per million. As I'm recording this video, the concentration has just exceeded 400 parts per million.

Let's look at that in comparison to other greenhouse gases. And rather than measure their concentration in parts per million, we'll convert them into a total radiative forcing using the equations of radiative transfer. So here-- on a scale where it's meaningful to compare their greenhouse effect-- is carbon dioxide, methane, nitrous oxide in blue, and other greenhouse gases in orange-- going back to about 1850.

So you can see that the total forcing of the climate is dominated by carbon dioxide, because it's relatively plentiful. But methane is also influential. There is an effect from nitrous oxide. And some of the other greenhouse gases are influential as well.

One of those other greenhouse gases is ozone. And here are various estimates of the total radiative forcing in watts per meter squared by ozone in the troposphere-- which is given by the blue curve here-- and in the stratosphere-- which is given by the green curve. Anthropogenic activities have actually led to a decrease in stratospheric ozone, but an increase in tropospheric ozone.

In terms of the net radiative forcing, the troposphere dominates the total, as given by this red curve here. You can see that we have about-- in round numbers-- a half a watt per meter squared of total forcing by ozone, which is already somewhat larger than the forcing that we believe is pertinent to variations in solar activity, at least on the 11-year time scale.

We can look at some of these greenhouse gases going even further back in time using bubbles of gas trapped in ice cores. So here are variations in carbon dioxide at the top, and methane at the bottom, going back 20,000 years into about the period of the last glacial maximum.

Now, concentrating first on carbon dioxide, one can see here that there was an increase-- presumably natural-- of carbon dioxide from about 180 parts per million to about 280 parts per million as the last ice sheet retreated, and the climate stabilized about 7,000 years ago. So this variation is part of the natural variations of greenhouse gas content that go along with the glacial cycles.

But from about 7,000 years or so ago until not very long ago, the carbon dioxide content was fairly constant. And this upward spike you see-- which really occurred in the last 100 years or so of the record-- is the anthropogenic effect on carbon dioxide. As I mentioned a while ago, today the concentrations are just exceeding 400 parts per million.

The same character, with some differences, is shown in methane. There's a natural variation of methane, presumably going along with glacial cycles. But we also see a big upward spike in methane at the end of the record, corresponding to the anthropogenic effect.

On even longer time scales, we make some inferences about changing carbon dioxide. So this graph-- which we saw at the beginning of the course as well-- goes back 70 million years into the Cretaceous and Eocene periods. And the bars-- the vertical bars you see on here-- are various proxy estimates of carbon dioxide content-- including estimated error ranges, which of course are very large for this period of time. The middle graph shows the corresponding delta O-18 of deep sea sediments that serves as a proxy, we believe, to deep ocean temperature.

So there looks like there might be some correspondence here, but the variations we see on the time scale of tens of millions of years may be as much as a few thousand parts per million, rather than a few tens or a few hundreds of parts per million.