A Couple of Degrees

What's the big deal?

Did you ever wonder why experts are so worried about 2 or 3 degrees of warming?

You might find an answer here

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2013

A COUPLE OF DEGREES … why does it matter?

Scientists investigating the climate problem tell us it's a big deal if the world warms 2 degrees or more ... and yet if you've ever thought about this at all, it must have occurred to you there's something strange about this claim.

- It warms a lot more than this every 24 hours as night turns into day ... or even in a few minutes when the Sun appears from behind a cloud.
- People living 100 miles apart tolerate this much average temperature difference without inconvenience.
- The natural climate changed much more than this long before people came on the scene.

Earth & Moon from Space

This is the right perspective from which to contemplate the planet's temperature - and what a little bit of warming will mean.

So what's the big deal?

Why does warming 2 or 3 degrees, or even 4 or 5 matter so much?

Clearly, scientists are seeing something the rest of us aren't. But what is it? In this essay, I'm going to try and answer this genuine puzzle. To do that, we need to close some of the gap between scientific understanding of the warming planet and our ordinary intuitions. That will address one bit of the puzzle. But I suspect there's another part - and it's not about knowing things so much, but imagining them. How many of us can carry in our heads a really solid picture of the whole world, and then think about its temperature - the whole enormous thing?

Just about nobody is my guess. I'll try to make this idea easier to think about by sketching a few of the parts of this unimaginable, yet most familiar thing - our planetary home. It's the best we can do. Remember, only 24 people, the Apollo astronauts, have ever seen the Earth from afar - a jewel-like ball, hanging in the infinite blackness of space. They understood what "planet Earth" means in a way no one else can. We who stayed behind must use intimacy, rather than distance, to fill in details of how our planetary home works. For us, the concept of "Earth's temperature" must always be a bit abstract. *

Let's begin by rendering the puzzle into three related questions; then we'll examine them one at a time.

1. What is "temperature"? The concept certainly tells us something about conditions on Earth's surface; but what is really going on when the temperature changes?
2. What is meant by "Earth's mean temperature"? How do we measure it? How does it change? Temperature differences from place to place and time to time are not the same as change in the mean temperature of the whole surface. Why is that so?
3. Is present warming the same as natural climate change in the past, or different? If different, how?

If we can follow the scientists' approach to answering these, we should have a fairly good handle on the concept of global temperature and what it means to change it a couple of degrees. However, before going any further, I'd better make it clear where I stand on the issue of the climate problem - whether it's real and whether it's serious - just in case you think this is controversial.

I have been convinced for some time that the experts have diagnosed an immense ecological problem. As far as I can tell, nobody who understands the climate problem really well is unconcerned. Quite the opposite. They worry about the problem *and* the fact that all of us non-scientists aren't nearly worried enough. All the baloney you hear about it being a beat-up, or exaggerated alarmism, or an environmentalists' hoax, comes from people who have never bothered to investigate it closely (or who's prejudices prevent them) - and yes, I include certain well known professors in that group.

If you will take the trouble to follow the scientific enterprise carefully (and there are many ways to do this) you will find that its main conclusions are as solid as a rock. It is not a finished work by any means and there's still a lot to learn, but there's really not the smallest doubt about four primary claims that arise from what has been discovered:

- Current planetary warming of the climate system is rapid and severe.
- Its causes may be complex, but a big part of them, if not all, is due to human-induced changes to the atmosphere, together with human impacts on terrestrial and marine systems.
- Some of the consequences of rapid warming will be very severe - on all ecosystems and human societies.
- Because the disturbance to the climate system is so rapid and our diagnosis so late, we have to fix it now or not at all.

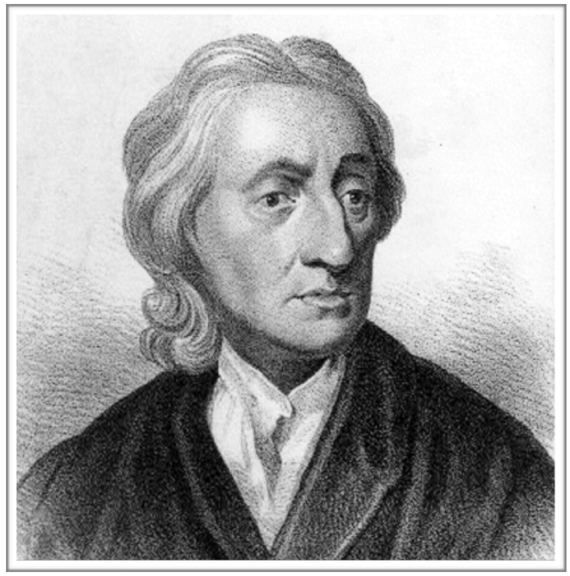
So if you have doubts and haven't yet treated them as they should be - to a confrontation with the findings of working scientists - I hope you might be persuaded by what follows. If you're just wondering what can be wrong with your intuitions about the couple of degrees, here's where I start my answer.

Temperature and heat

Since long before Aristotle, philosophers have been wondering what it is that makes things hot, and how one thing can heat another. Most of the time - almost until the twentieth century - the most common idea was a fairly intuitive one: heat was a kind of substance, like a weightless fluid that could soak into things and flow from one to another. But in the scientific era, some people figured out this couldn't be right, and located the property of heat in the movement of the constituent parts of matter. That's how we understand it today.

It's interesting to see that, although the kinetic theory of heat only makes sense with an atomic theory of matter, it's essence was understood long before we knew about atoms - just as atoms themselves were discovered by clever guesswork long ago.

Here's the philosopher John Locke, friend of Isaac Newton, in 1690:
"Heat is very brisk agitation of the insensible parts of the object, which produces in us the sensation from whence we denominate the object hot; so what in our sensation is heat, in the object is nothing but motion."



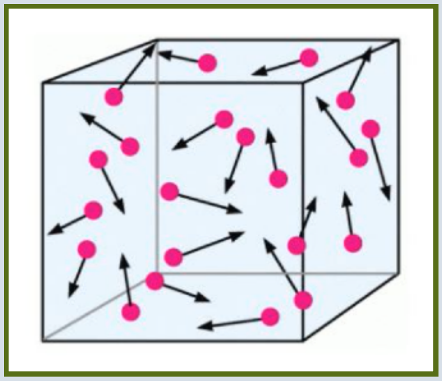
Here is physicist Richard Feynman in 1961:
"... the jiggling motion is what we represent as heat: when we increase the temperature, we increase the motion. If we heat the water, the jiggling increases and the volume between the atoms increases, and if the heating continues there comes a time when the pull between the molecules is not enough to hold them together and they ... fly apart and become separated from one another."

It turns out that all the particles of matter are ceaselessly in motion - in solids they mostly vibrate without moving around; in liquids they move a bit more, and in gases, they fly around a great deal, bumping into each other and whatever contains or contacts them. Try passing your hand quickly through the air. That soft rushing feeling is the countless molecules of the air pushing against your skin as they're displaced. When heat is applied to anything, this motion accelerates. Gas atoms or molecules fly faster and further, and solid ones vibrate quicker. Withdraw heat and they slow down - right down to an absolute limit at which motion ceases altogether (-273.15℃). Nothing can get any colder. *

So, ***heat is just the kinetic (motion) energy of the particles of matter***. One can therefore speak of its *quantity* - amounts of heat are specified as so many *Calories*, or *Joules*, or *Watts*. Strictly speaking, heat is not *equivalent* to energy; it is more accurate to think of it as the *transfer* of energy, discoverable in the motion of particles or photons.

* *SEE NOTES AT THE END*

The particles of matter are constantly in motion



Heat can be added to a population of particles in three ways:

- Radiation, when energetic photons are captured by atoms or molecules;
- Convection, when energetic particles are added to a population;
- Conduction, when kinetic energy is transferred by collisions.

In each case, the effect is to raise the ***average*** velocity of the population.

Measurement shows heat is being added to Earth's lower atmosphere at a steady rate. ***One*** of the effects of that (only one) is an average rise in the recorded temperature.

When we say the world will warm by 2 degrees, what we mean is that the layer of air close to the planet's surface, where we place our weather thermometers, will have its molecules going a bit faster, on average. Not all the time; not everywhere at once, and not year after year - but averaged over space and time. The climate system is a big, complicated thing, so you need to observe it for a couple of decades to be sure a trend like that is happening. But once you are sure you've seen the mean temperature rise, you know that heat has been added to the Earth's surface, and it is staying there.

This brings us to the idea of *temperature*, which is not a quantity of anything, but a way to measure the effect of heat on sensible, or observable things, like our skin, or a thermometer. Those effects (the sensation of heat, or rising mercury) are all due to collisions between the moving particles of matter. Dip your finger into water, and tiny gadgets embedded in your skin respond to the average velocity of the countless water molecules bouncing against them. If you stick a thermometer in, and if the glass and mercury are cooler than the water, kinetic energy transfers from the water and the mercury expands up its tube. The opposite transfer occurs if the water is colder.

Heat energy *always* moves from where it is more concentrated to where it is more diffuse. This is a fundamental fact about the universe called the second law of thermodynamics. Heat moves in such a way as to even out the temperature - just as if nature found temperature differences intolerable. That's the way things work.

It's worth pausing here to get this straight.
***Temperature is a measure of the <u>average</u> kinetic (motion) energy of a population of particles in a system* -** either particles of matter or photons - both cause the sensation of heat. It doesn't matter how many particles or how close together they are, or how heavy, or what kind. The temperature registers their average energy - basically how fast they go - that's all. To see where this leads, try this thought experiment.

Imagine a box full of air, and imagine that, with a powerful microscope you can see the individual gas molecules bouncing around, colliding with each other and the walls of their container. Now add some heat. When heat energy reaches the interior, you will see the particles speed up, traveling faster and further. The energy of their collisions will be greater, and a thermometer inside the box will show this by a rise in temperature as the molecules collide with the glass and mercury.

Now, imagine the air is nearly all pumped out, so just a few molecules remain. Repeat the experiment, and you will notice the thermometer hardly ever gets hit by an air molecule, they are so scarce. Instead, it will respond to any energy photons emitted by the walls of the box, and register *that* temperature instead.

Thinking about this tells you that temperature is a *statistical* measure - it's the average effect on a thermometer when it interacts with a large number of energetic particles. It can't actually tell us about the *quantity* of heat present, just the effect of that heat on some stuff. Yet, when you think about it, if Earth is warming, it's exactly the *quantity* of heat accumulating in the Earth's surface systems that we are interested in. So here is one source of our confusion ... we are inclined to think temperature is the same as heat. But it's not.

Temperature is not heat

You might see this clearer by asking this question: If you heated a packet of air until it warmed by 2 degrees, then applied the same amount of heat to the same volume of water, would it warm the same amount?

The answer is no. Actually, it takes about 4,000 times as much heat to do that to the water. This difference is due to what is called the *heat capacity* of substances. The way heat changes the velocity of molecules is very different from one substance to another. It just so happens that water needs a lot of heat to change its temperature, and air not nearly so much. When you think about it, this is a pretty important fact, since if the air gets warmer, you could guess that a lot of heat must be disappearing into the ocean without affecting thermometers much. And this is true. The ocean is Earth's great heat "sink". It is vast, and it holds incredible amounts of heat. Some people have suggested we would think more clearly about global warming if we called it "ocean warming" instead. *

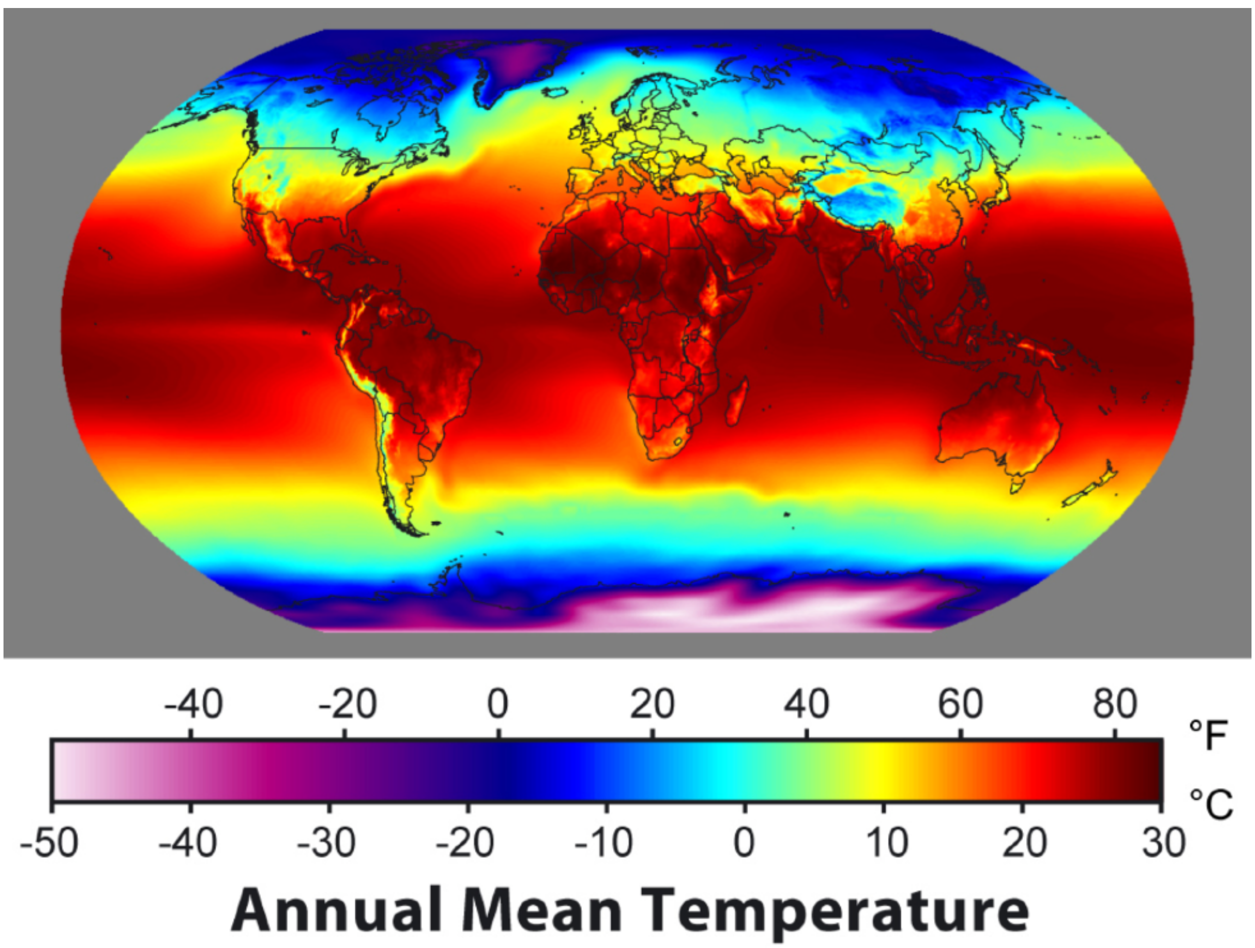
The global ocean holds most of the heat on Earth's surface.

It covers ¾ of the surface & its average depth is about 4 kilometres. It also has an enormous heat capacity. Transfer of heat to the ocean, transporting it around the ocean basins and transferring it out again - to the air, land, and ice are the real drivers of the dynamic events of the climate system.

The temperature of the world

The most concentrated chunk of energy in our solar system is, of course, the Sun. It is so much more energetic than space that it radiates a vast quantity of energy constantly in all directions. It's been doing this for more than 4 billion years and, we are told, it will keep doing it for at least another 5 billion. A little bit of this energy flood reaches Earth, 150 million kilometres away. * Just as well - otherwise our planet's surface would be nearly as cold as space because it's been cooling for so long.

What happens to the solar photons when they arrive on Earth? Some strike water in the air and are absorbed there; some reflect off clouds and never get any further; about half reach the actual surface. Some of these bounce back off shiny things like snow or desert sands, but most are absorbed by what they fall on, warming the surface. Absorbing energy just means accelerating the movements of atomic particles and molecules, so the effect is to raise surface temperature above the temperature of surrounding space (which is very cold). But that means heat must move from Earth to space. And Earth does indeed radiate to space - under normal conditions, exactly the same amount as it receives from the Sun. This normal state, where the planet is in "energy balance", keeps it's surface temperature constant. If for any reason, the energy balance is lost, the equilibrium temperature will change. Not immediately, but at some speed determined by the ways surface materials and structures conduct and distribute heat.



Distribution of heat on Earth's surface

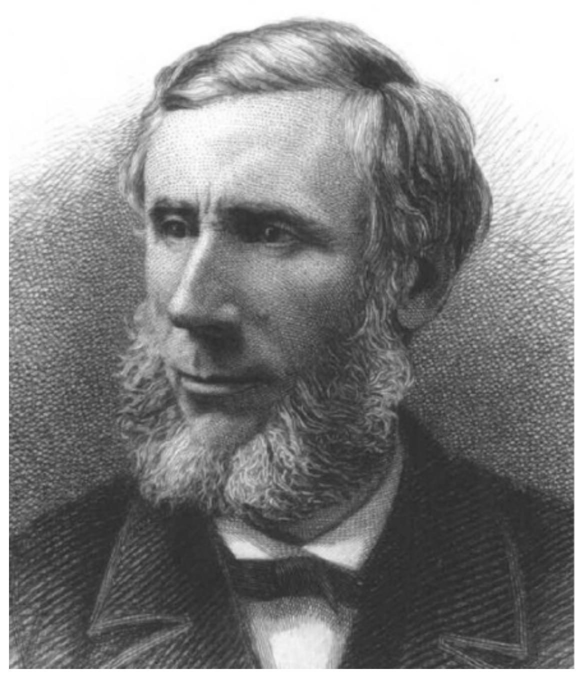
Because this pattern varies from year to year (within limits) such a map represents measurements over some length of time - typically a decade or two or three.

For example, the air absorbs heat fairly quickly, as you know if you've waited for the rising Sun to warm you up on a cool morning. We've already seen that the heat capacity of air is low. That just means it doesn't take much heat to raise the temperature. In contrast, water appears to be quite slow to warm - but that's because it's also soaking up a lot of heat. Think of this - because of their different heat capacities, all the heat that's in the whole atmosphere would fit into the top 10 feet of the ocean.

So if anything adds to Earth's energy income - say, the Sun gets brighter - the surface, which is warmed by the Sun, will see a rise in temperature. This rise will stop only when the planet's energy losses also rise to equal the income and a new balance is reached. In this way, anything at all that can affect the energy balance can also affect the surface temperature. Our knowledge of what these things are has been developing a long time.

Earth's energy balance *

It's been nearly 200 years since men of science first wondered about this fascinating subject - how Earth is warmed by the Sun - and realized there was something odd about the behaviour of heat near the planet's surface. In the 1820's, Joseph Fourier and others reasoned that if Earth radiated directly to space exactly the amount of energy it received from the Sun, the surface should be colder than it is. They figured there must be something in the air that acts a bit like a blanket, creating a warm layer next to the solid surface.

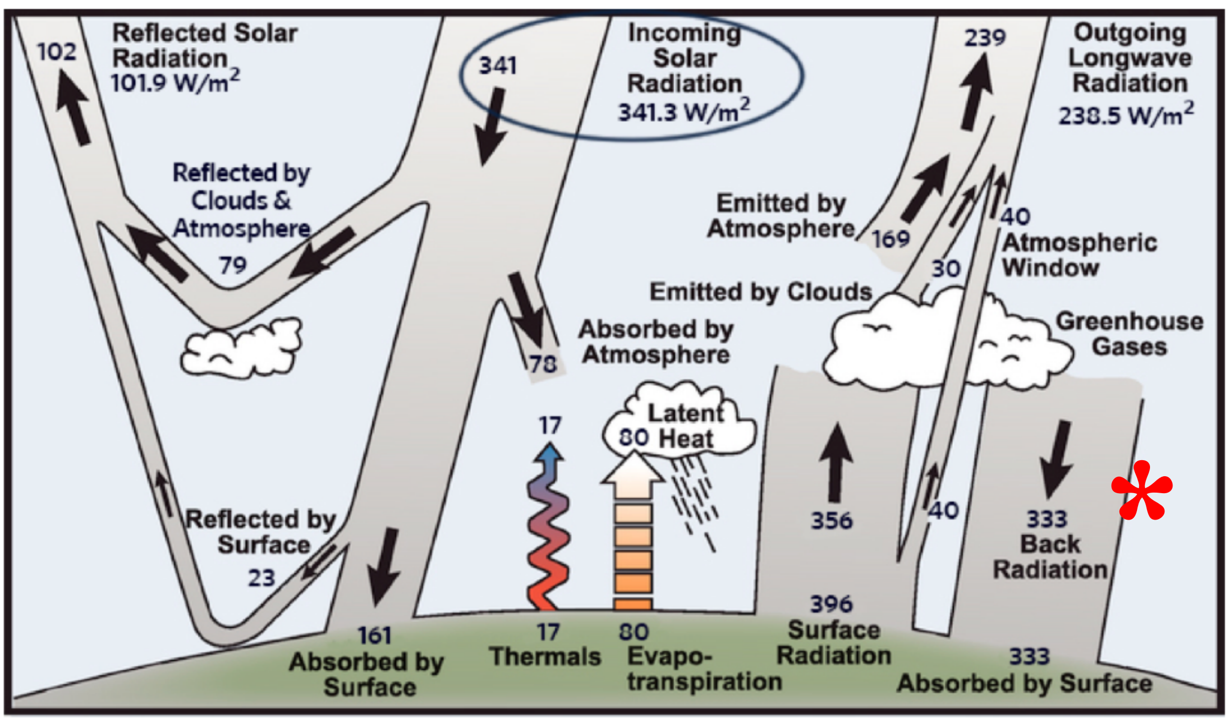


In the 1850's that something was identified by an Irish physicist, John Tyndall. The two components of the atmospheric blanket he found were water vapour (the gaseous form of water that makes about 1-5% of a typical atmospheric sample); and carbon dioxide. Both gases, he found to his surprise, exert a remarkably powerful effect on "Earth radiation", as he called it. Today, we know this as *infra-red* - wavelengths that normally interact with matter by warming it. *

What he found was that water vapour, carbon dioxide, and some other gases (but not nitrogen or oxygen, the main ingredients of the air) blocked the transmission of infra-red rays through his experimental tube, in low concentrations, with great efficiency, by absorbing the photons. In other words, the gas molecules soaked up the energy, and got warmer as a result. This was the first clear demonstration of the atmospheric "greenhouse effect", and even though he had no theory of radiation (that was only discovered later) Tyndall understood how important the effect was in the climate system on Earth.

Step by step, over the next century, all the detailed physics of the greenhouse effect were worked out (like a lot of things they turned out more complicated than first appeared). Now, however, we have a very complete understanding of these minor constituents of the air ... how they make life on Earth possible; how they regulate natural climate cycles; how their effects are connected with other parts of the surface system; and how changes in their abundance affect the climate.

Earth's Annual Energy Budget



What happens to solar energy

The numbers show quantities of energy arriving and leaving earth's surface (Watts per square metre). The big figure for "back radiation" over on the right shows how powerful the greenhouse effect is at holding Earth's radiation near the surface, warming it.

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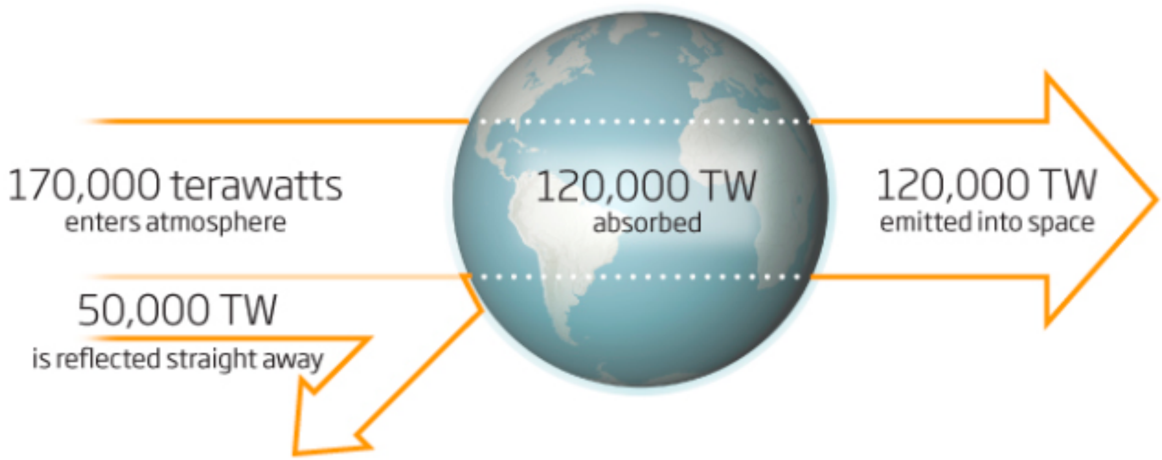
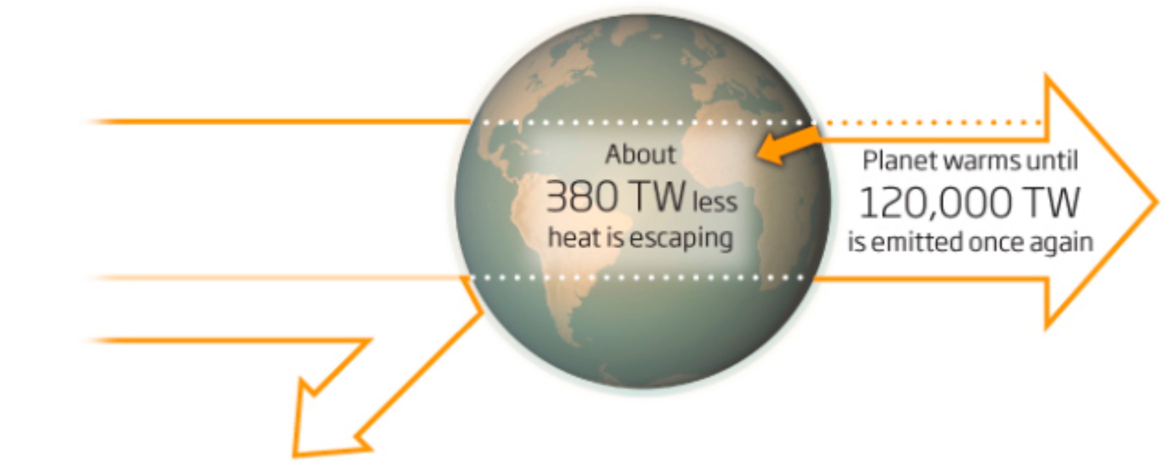
EQUILIBRIUM

For the past few thousand years before the industrial age, roughly as much heat escaped as arrived, so Earth's temperature varied little

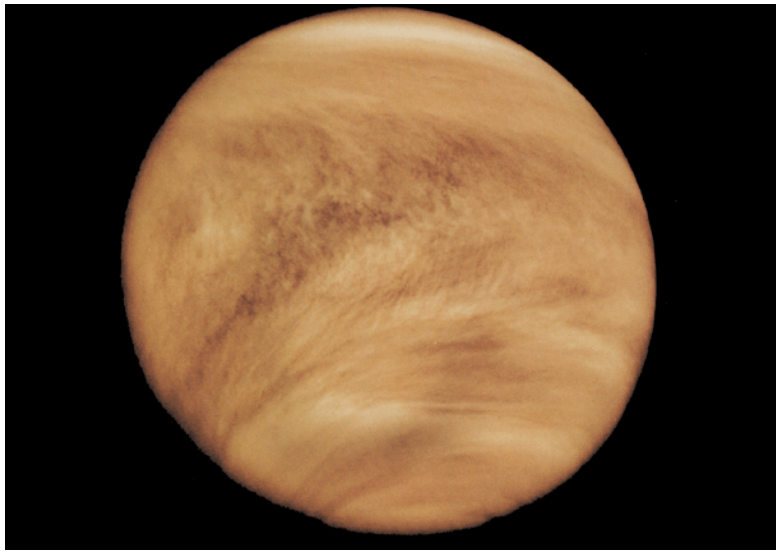


GREENHOUSE EFFECT

Now less heat is escaping, so the planet is warming. Once levels of greenhouse gases stop rising, equilibrium will eventually be established at a higher global temperature



We know, for example, that without the greenhouse effect, Earth's mean surface temperature (14℃) would be 32 degrees colder than it is - about the same as the inside of a freezer. Most, or all of the ocean would be frozen; there would probably be no life. We know that small changes in the amount of carbon dioxide in the air have rather big effects on temperature. The reason is that the amount of water held in the air (even though it is locally variable) depends on temperature - so if a carbon dioxide rise causes a bit of warming, more water enters the air, causing even more warming. This kind of thing, called an amplifying feedback, is common in the climate system. *



We know what a very massive greenhouse effect can do because that is what makes Venus the hottest planet. Its atmosphere has about 250,000 times as much carbon dioxide as Earth's, and the surface is as hot as a furnace. We know quite a bit about how Earth's greenhouse is regulated by complex interactions involving all the surface features - land, ocean, air, ice, the biosphere, and even the deep ocean and deeper parts of the crust. Study of Earth's past strongly suggests that these processes form an inherently stable system that allows surface conditions on Earth to vary within limits, but not chaotically.

Measuring Earth's temperature

Obviously, near-surface temperature on Earth varies a lot by latitude, altitude, season, geography, and also by the day-to-day variability of the climate system. It might seem impossible to take the world's temperature and get any meaningful number, but luckily we've had what we need for over a hundred years - a large network of weather stations collecting reliable records from all over the globe. Well, almost. There aren't many stations in Antarctica, for example, nor in the Sahara, or in mid-ocean. But we can fill in these gaps in various ways now, and putting all the data together, work out a mean temperature for the entire surface. This task is done by several large research Centres specializing in the analysis, and the results are very reliable and accurate. *

The historical record of global mean surface temperature

There have been reliable networks of observations over the whole globe since about 1880. That's how charts like the one below are made - by carefully collating these records, screening them for various biases and errors, and filling in missing regions. This one was made by the Goddard Institute, a research and monitoring laboratory belonging to NASA. Others, from different institutes, using slightly different techniques, agree very closely. Notice that the two hemispheres have warmed somewhat differently.

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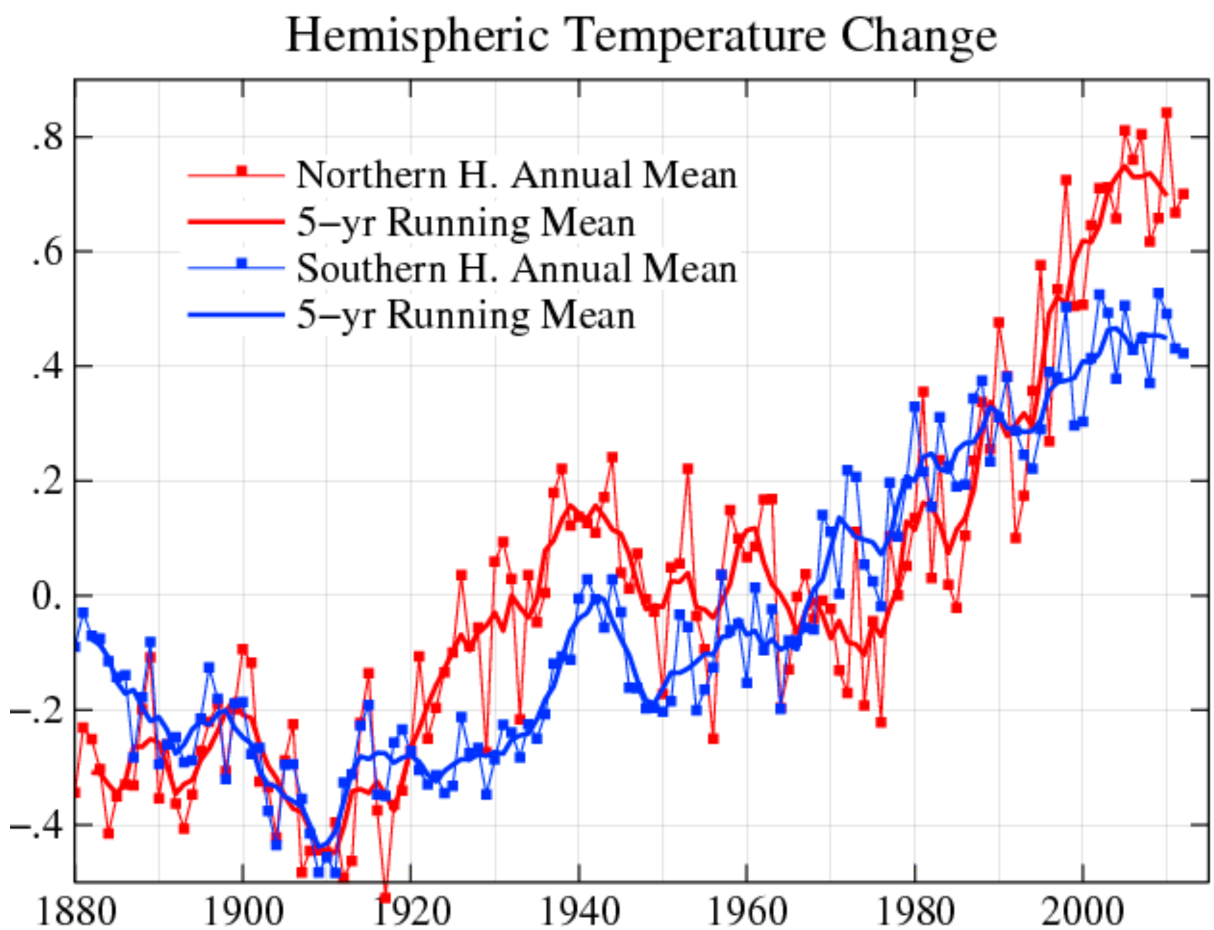
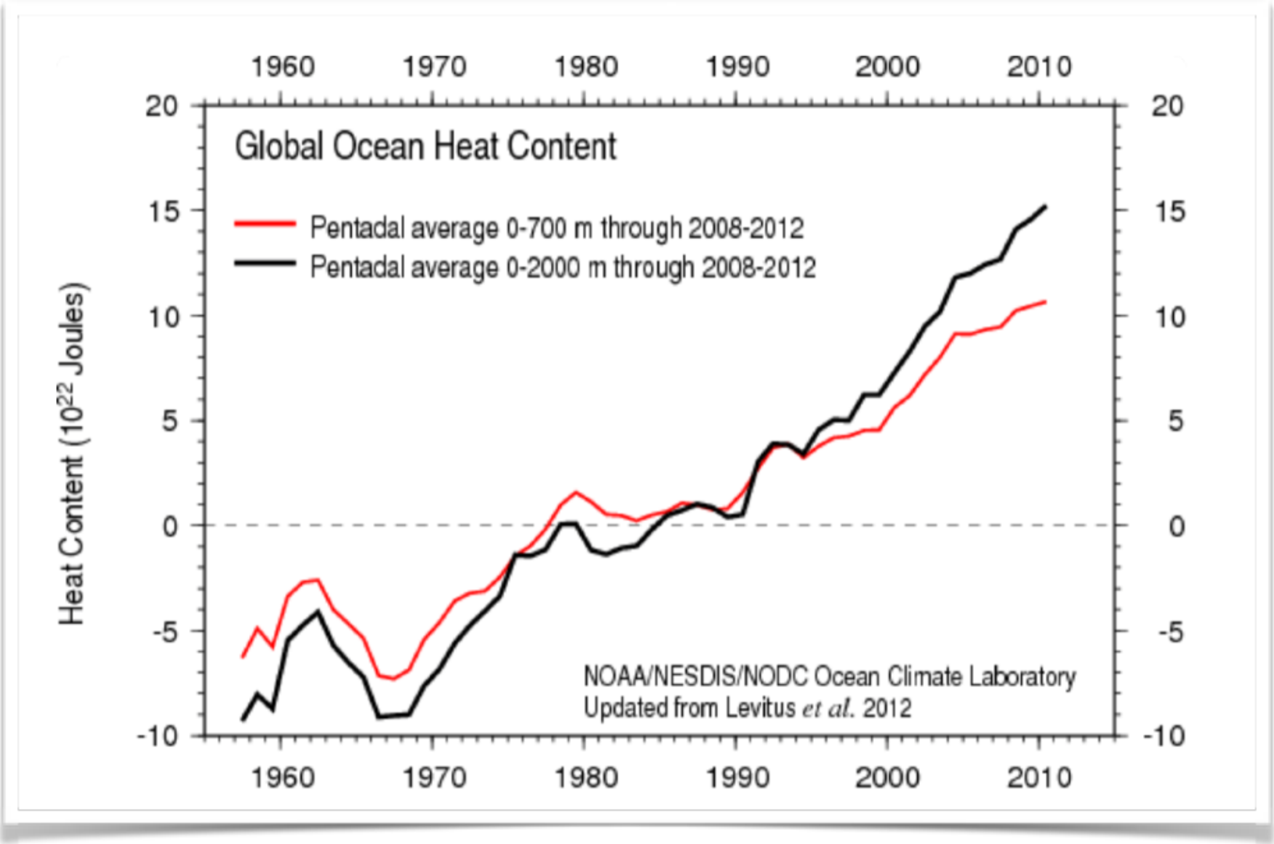


When you want to understand how the world is warming up, this is an important number to have. But it isn't everything. It doesn't tell us much about the state of the planetary energy balance - how much heat (if any) is being added or subtracted from the surface systems. We've already seen the reason - air heats and cools too quickly to be a good record of accumulating heat - and anyway, most of the heat - at least 90% of it - goes pretty smartly from the air into the ocean. So the number most often discussed - the ***global mean surface temperature***, is informative about the near-surface air, where we all live, but not so much about the really important quantity: Earth's crucial energy balance. To figure out how much heat is being added to Earth's surface systems as it warms, we need other measurements.

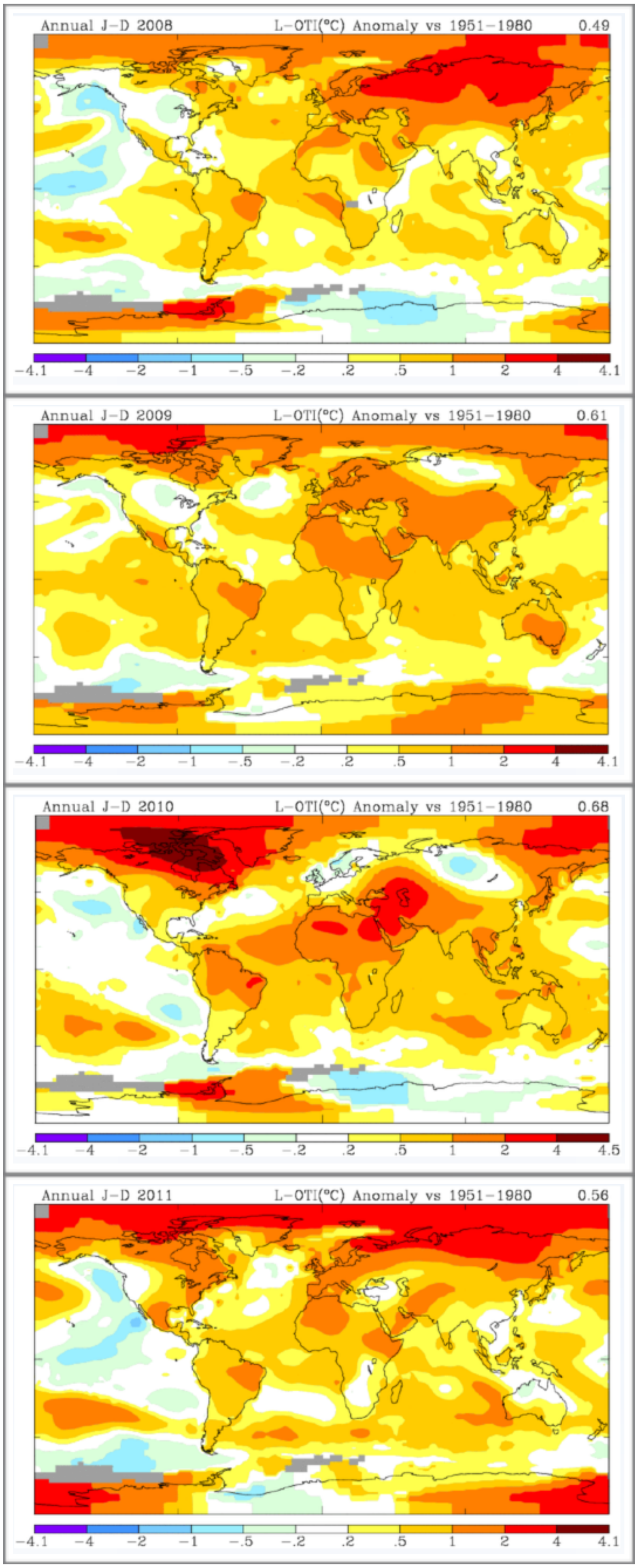
Measuring ocean heat

The number that tells us most about the state of energy balance is called *ocean heat content*. You can calculate it if you have enough observations from all the world's ocean basins, from surface to deep. For many years, oceanographers used ships to take water samples, but in the last decade, an international team has finished the deployment of the ARGO floats - sophisticated probes that travel freely in the global ocean, diving regularly to measure temperature, salinity and other things down to depths of 2,000 metres. With this data, it's possible to accurately assess the actual rate of addition of heat to the entire ocean - about 93% of the heat present on Earth's surface. *



What they show is very clear. The planet's heat reservoir is gaining at the rate of about $8X10^{21}$ Joules/year. James Hansen made this huge number more concrete by saying it is the same as adding the energy of 400,000 Hiroshima bombs every day!

Just because most greenhouse heat goes into the ocean doesn't mean it stays there. Far from it. Heat is obliged to move - remember the second law - so in time, this vast accumulated energy store will be distributed to every part of the surface; to the land, and all the things that grow there; back to the air, wherever it happens to be cooler than the ocean surface; and to the great masses of ice at both poles. This delay - the time it takes for ocean heat to spread around, raising the temperature of surface features with less heat capacity - is what makes it hard to predict when all



the consequences of warming will occur. We know they will happen, but we don't know exactly how fast, or in which order, or how each will affect the others. These very important matters are subjects of big current research programs.

Heat is not evenly spread

Greenhouse warming is created in the lower atmosphere. If it stayed there, we would have been fried long ago, but it is quite quickly transferred to the ocean surface - the layer stirred by wind and waves. The burden of heat in this layer puts it in motion. Just as hot air rises, convection in the ocean makes warm equatorial surface water flow toward the poles. Earth's rotation and winds also push it toward the west. This is how the great system of ocean currents gets its motive force - same as the wind: heated fluids *must* move, and in moving they start patterns of circulation. In the global ocean, these are shaped by the ocean basins themselves, as well as differences in density between nearby water bodies, surface winds, and pressure and temperature patterns in the atmosphere.

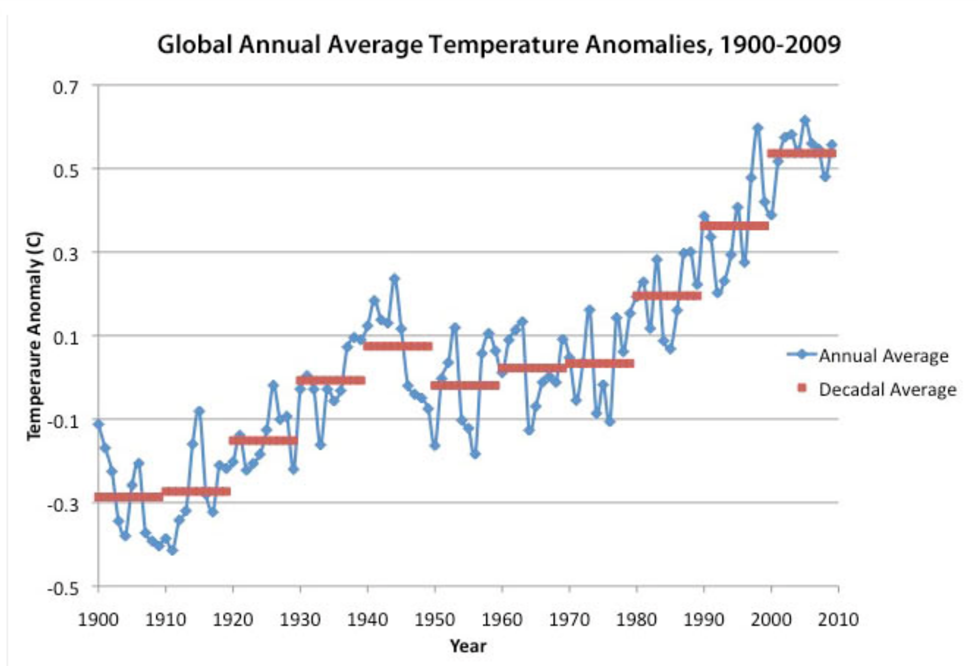
So complex a system as this has many quasi-periodic sub-systems, like the El Niño/La Nina oscillation in the Pacific, the North

Series of four consecutive years of global temperature anomalies

Showing how much the pattern of warming varies from year to year and region to region. These maps are made by GISS and updated monthly. You can examine and download them here: http://data.giss.nasa.gov/gistemp/maps/. As well as the variation, you can see some of the characteristics of greenhouse warming … land is warming more than ocean surface; the poles are warming more than the tropics - the Arctic most of all; and some cool regions of the sea-surface occur even in years of pronounced warming.

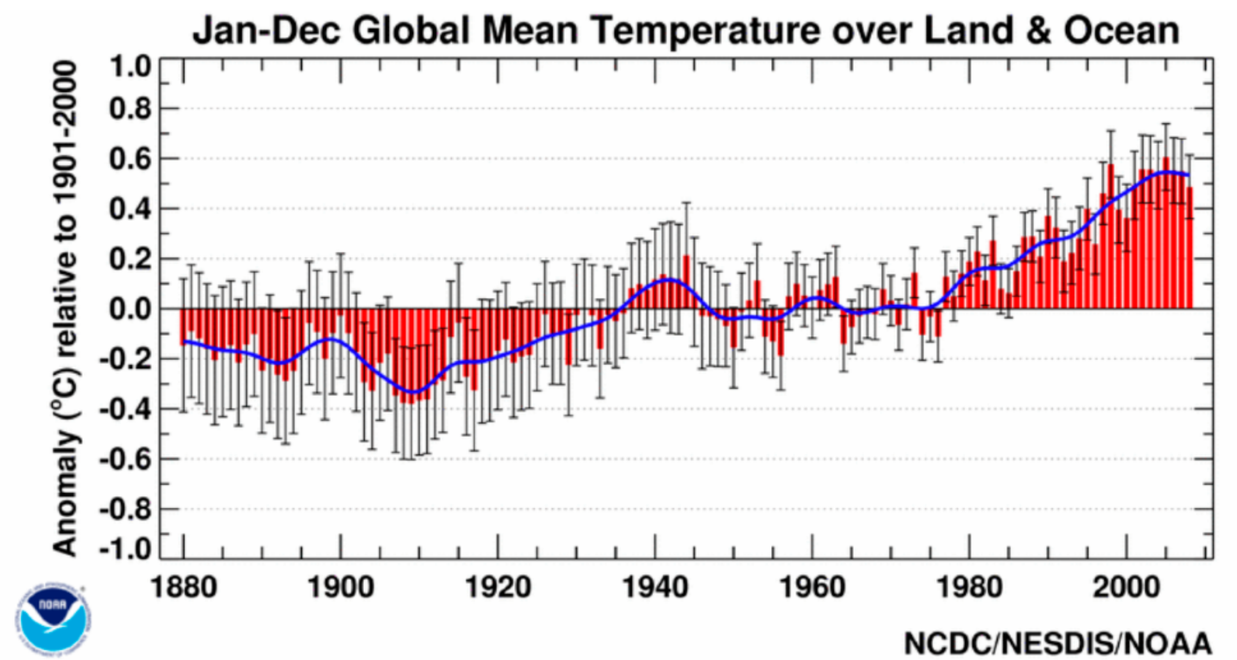
Atlantic oscillation, the Indian Ocean dipole, and many others on regional scales, large and small, in every part of the globe. As you'd expect, these patterns are mirrored in the pattern of recorded near-surface air temperature - so from year to year there are rather large variations in this record.

This means, if you want to identify a trend in the global temperature, you have to wait at least a decade - for some phenomena, even longer, up to 30 years. That's just the way things work.

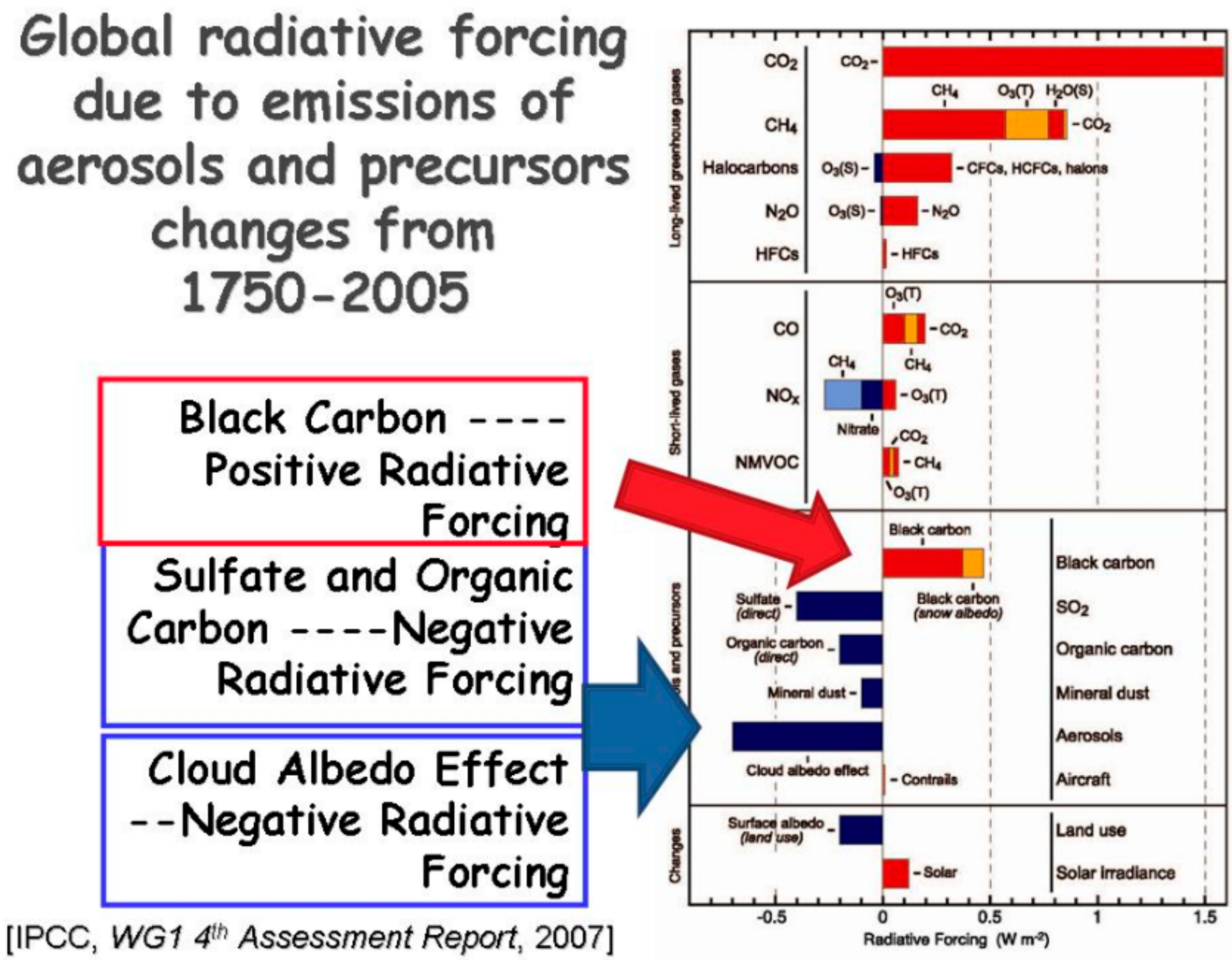


No fewer than 11 decades of no warming can be drawn onto a chart of last century's temperature. None of them mean anything, because the climate system varies too much. The only meaningful pause is the 30 year one in mid-century. Most of this was due to the big increase of man-made opaque aerosols then - cleaned up since the 1970s.

Some people have claimed that the record of global surface temperature is false because too many weather stations are sited in urban areas where they receive heat from air-conditioners, industrial heaters, roads, reflected sunlight from buildings, and so on. The extra heat, which is real enough, is known as the 'urban heat island' effect. However, the scientists who synthesize global data are very well aware of its potential bias, and have long understood how to compensate for it. There isn't the smallest doubt that the global record is as sound as you could wish. These data are routinely scrutinized by the monitoring Centres and cross checked; their methods constantly updated. *



In the graph above, you can see a two-stage warming over the last century. From about 1900 to 1940, the surface warmed 0.4℃, then there was a 30 year pause, then renewed warming of another 0.4℃ since 1975. The mean warming rate for the last four decades has been close to 0.15℃ per decade. If this continues, we will have cumulative warming of 2℃ by about 2050. It is possible the rate could change in either direction for a couple of decades, just as it did in the mid-twentieth century * - but really, the only way this can happen is if the Sun changes brightness, or the Earth changes albedo (the quantity of solar radiation reflected back to space) ... as long as we continue to increase the atmospheric greenhouse at something like the current rate. The reason, of course, is that changing the strength of the greenhouse effect forces the climate into a positive energy balance. That is simple physics. The ocean must continue absorbing extra heat, eventually redistributing it everywhere.



The main discreet influences on global temperature

Climatologists call these "forcings" - all of them are capable of changing the planet's energy balance either up or down. They have been divided into four categories:

- The major "long-lived" greenhouse gases. CO_2 is by far the most important, not just by potency, but because it lasts so long once added to the atmosphere.
- Minor greenhouse gases. Note that methane causes some reactions that augment cooling.
- Aerosols and clouds. Black "soot" absorbs radiation, causing warming; but most of the vast quantities of aerosols emitted by fires, factories, vehicles etc, increase atmospheric albedo.
- Last, the Sun. There appears to have been a tiny net positive forcing over this time.

Red forcings are positive; blue negative. Net positive forcing is now about 0.75W/m^2.

The World has warmed in the past … but not like now

Many people have a vague feeling that, because the climate system has always changed under natural causes, the present change must be similar, and pretty harmless. It is certainly true that Earth's climate has changed a lot during its long history, warming and cooling more than a couple of degrees many times. But that doesn't mean this time is the same. This is an important thing to understand, and the only way I can think of to correct this false impression is to lay out some facts about Earth's climate history, even though that will be a longish diversion. If you don't find this specially interesting, you can skip to the end.

In the last 30 years or so, we've learned an enormous amount about past climate states - how and when they changed; how much, and for what reason. This is a very active field of study with lots of major discoveries arriving every year, and plenty more to come. So how does the present look against this background? We can characterize our current problem this way: ***by mid-century there will have been a sudden injection of a couple of gigatonnes (2 billion tonnes; Gt) of fossil carbon into the atmosphere, in less than 200 years.***

Has this ever happened in Earth's history before? Not as far as we know. The closest natural analogue occurs in the historical data as a temperature spike at 55.8 million years ago - an episode now known as the Paleocene-Eocene thermal maximum (PETM). The world warmed about 6℃, possibly in two steps, over maybe 20,000 years (although the timing is still debated). The cause appears to have been the escape of a large quantity of submarine methane - at least 1.5 Gt, but quite possibly more. What provoked this is not known either. The world was already a lot warmer than it is now, with no ice at either pole. It seems to have taken about 100,000 years for things to return to normal after it was over. *

You can see at a glance how this episode was at least an order of magnitude slower than the current change - and of course there were no humans to encounter any of its effects. Much more typically, geophysical events change the climate very much slower even than this - as we shall see.

The climate system on Earth is dynamic …

Earth has been cooling gradually ever since the era of its birth, 4.5 billion years ago. It's quite cool on the outside, but there is still plenty of heat deep beneath the crust - enough to keep the crustal plates slowly moving about, and to renew and recycle their rocks and elements. This in turn, changes the position and topography of land masses and the shape of ocean basins.

The Sun heats the surface unevenly, concentrating its warmth in the tropics. That keeps the air and ocean moving, causing winds and currents. Over time, the disposition of both is altered by the slow changes in surface forms - winds deflected by mountains and deserts; currents shaped and propelled by temperature contrasts, ocean depth, salinity differences, and the opening and closing of channels. Basically, the climate on Earth is all about how the Sun's constant donation of energy is incorporated into the surface systems ... how much of it is simply reflected back to space; and how the rest is distributed between the air, sea, land, ice, and living things. Each of these parts of the planetary surface is itself a dynamic agent, changing and reacting with all the others, sometimes fast, other times very slowly. The key to understanding these processes is the idea of the planet's energy balance. Surface conditions may change it in many ways.

This is an abstract sort of way to specify how the climate system changes, and it hardly gives you a clear idea of the dynamic Earth system in action. So you can get an idea how it actually works, here are three well studied examples:

The Gulf Stream

Today, the Gulf Stream, the best known major surface ocean current, sends a large volume of warm salty water from the tropical North Atlantic toward the pole, flowing parallel to the North American continental shelf, from south to north. This water is heated in the Caribbean basin and Gulf of Mexico; evaporation makes it salty, but being warm, it is not dense enough to sink. In the region near Greenland, having cooled enough, it forms big vortices as it plunges to the bottom. Meantime, it has warmed the atmosphere of the entire North Atlantic, and hence the climate of Northern Europe.

But 5 million years ago, things were quite different. The two Americas were still separated by a seaway. Then, much of the warm water of the western Atlantic in the tropics mixed with water from the Pacific, and the Gulf Stream wasn't nearly as strong. In this way, the formation of a narrow landform, the Isthmus of panama, made a big difference to the climate of a continent on the other side of the ocean. This event, the closure of the Panama Seaway, is probably the cause of a major change in the global climate too - the one we recognize as the Pliocene/Pleistocene transition. Re-routing a large flow of ocean heat from one ocean basin to another is quite capable of influencing climate all over the world. *

 * *SEE NOTES AT THE END*

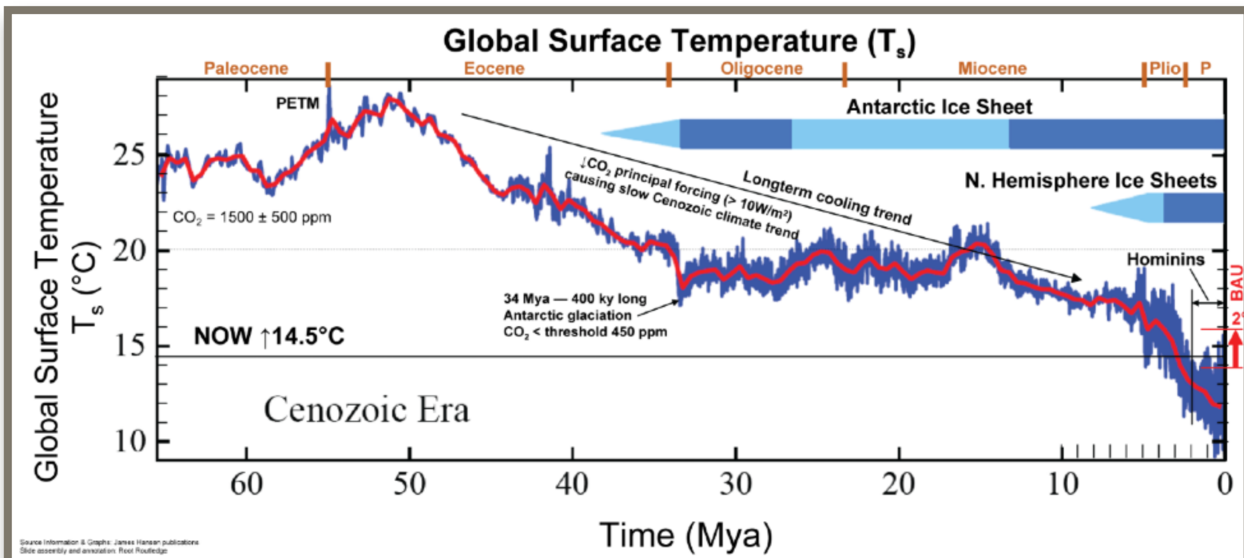
How tectonic shifts can alter ocean heat transport

Before the formation of the Isthmus of Panama, Pacific water flowed through the Panama Seaway, freshening tropical Atlantic water in the Gulf. Closure of the Seaway profoundly changed the major ocean heat current in the Atlantic, and started the major deep-water formation in the North Atlantic.

Our second example is ***the late Mesozoic warming -*** another, and longer trend discovered by studying the ancient climate - the gradual warming of the world from around 110 million years to 50 million years ago in the Eocene epoch, and then the gradual, uneven cooling ever since - easily seen on the chart below. We know such a big, slow pattern couldn't have been caused by the Sun, and there's no evidence of any change in the planet's reflectivity that could account for it, so scientists investigating this have concentrated on the greenhouse gases - the climate's main control knob.

It's pretty hard to know exactly what the atmosphere was like tens of millions of years ago, but such indirect evidence as we have suggests that CO_2 concentration rose slowly through the late Mesozoic and early Cenozoic to a peak of maybe 800-1,200 ppmv, and this peak coincided with the peak temperature at 50 million years - a feature in the record known as the *Eocene climate optimum*. It's a bit hard to say just how much warmer it was then, because the distribution of warmth between high and low latitudes seems not to have been the same as it is now - but the mean global surface temperature may have been as much as 10-12℃ warmer, and the poles warmer still. It was an ice-free world. Fossils confirm that warm-living animals and plants grew at or near the poles; the tropical seas might well have been too hot for most life.

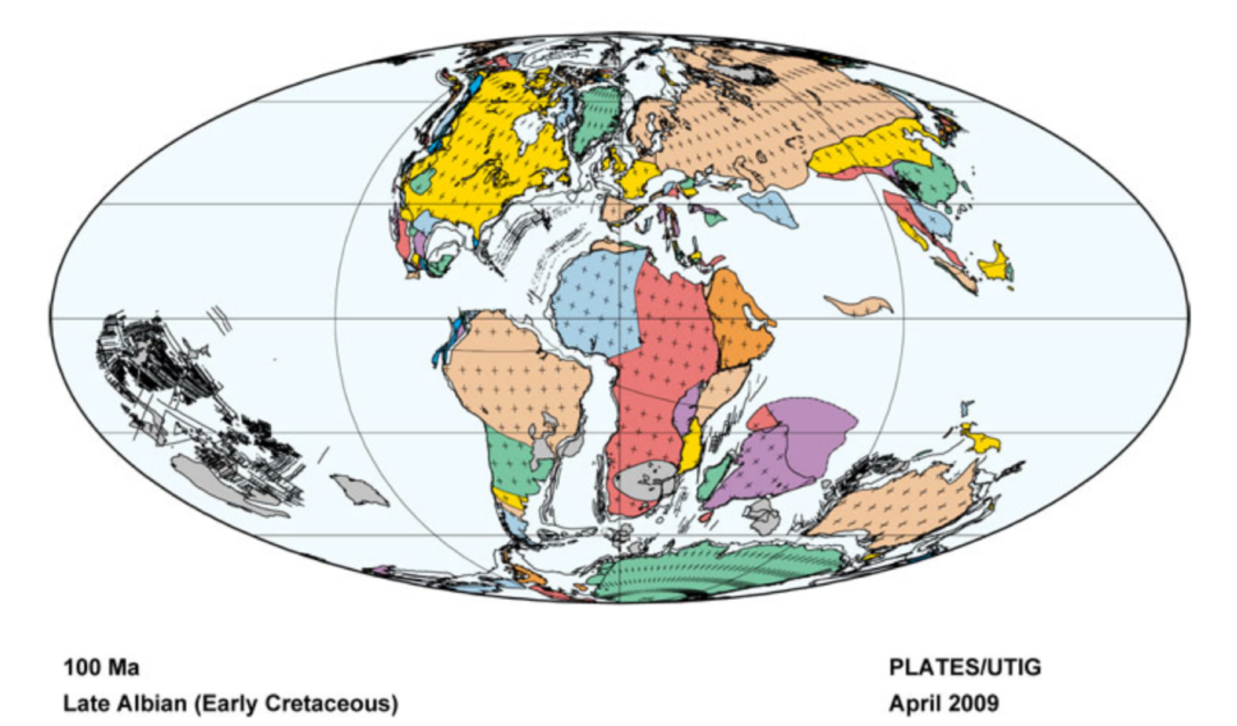
But then things turned around. By 34 million years ago, the Antarctic ice sheet had begun to form, and 14 million years ago, the world cooled steeply again; this great ice sheet grew to something like its present size, and the cooling continued right up to our own time. We know from somewhat better evidence, that CO_2 fell throughout this long cooling phase too, reaching values close to the pre-industrial concentrations around 3 million years ago. The thing is ... what could have caused such big climate events spread over so much time? *



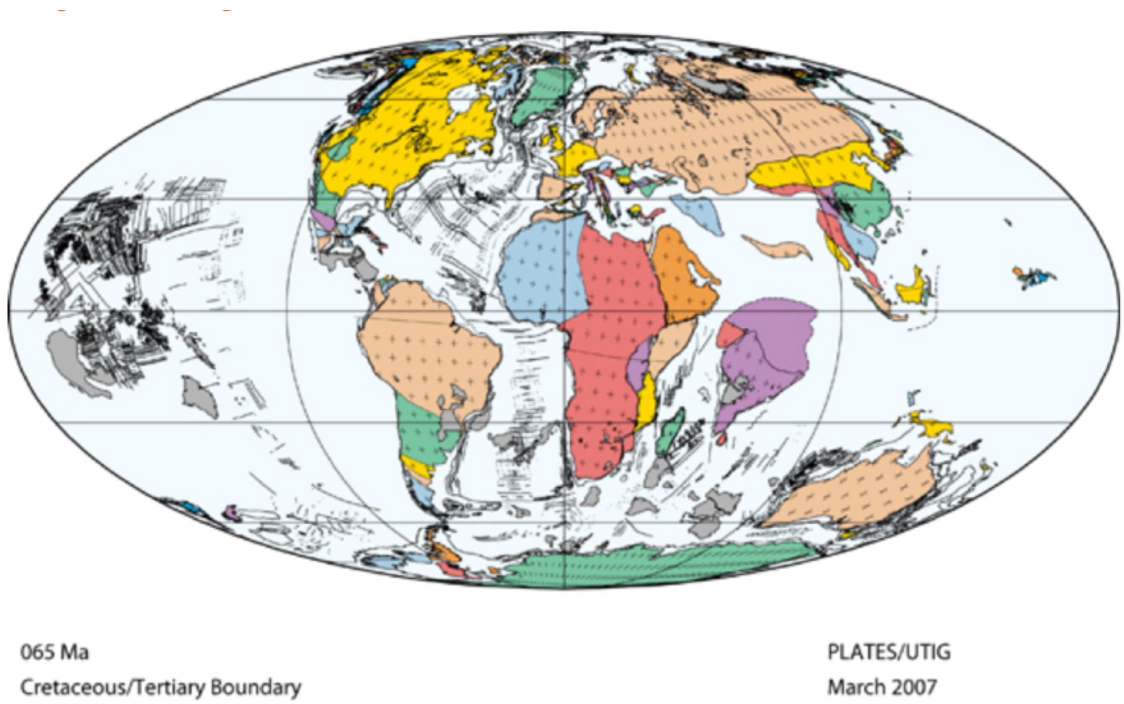
Global temperature over the last 70 million years

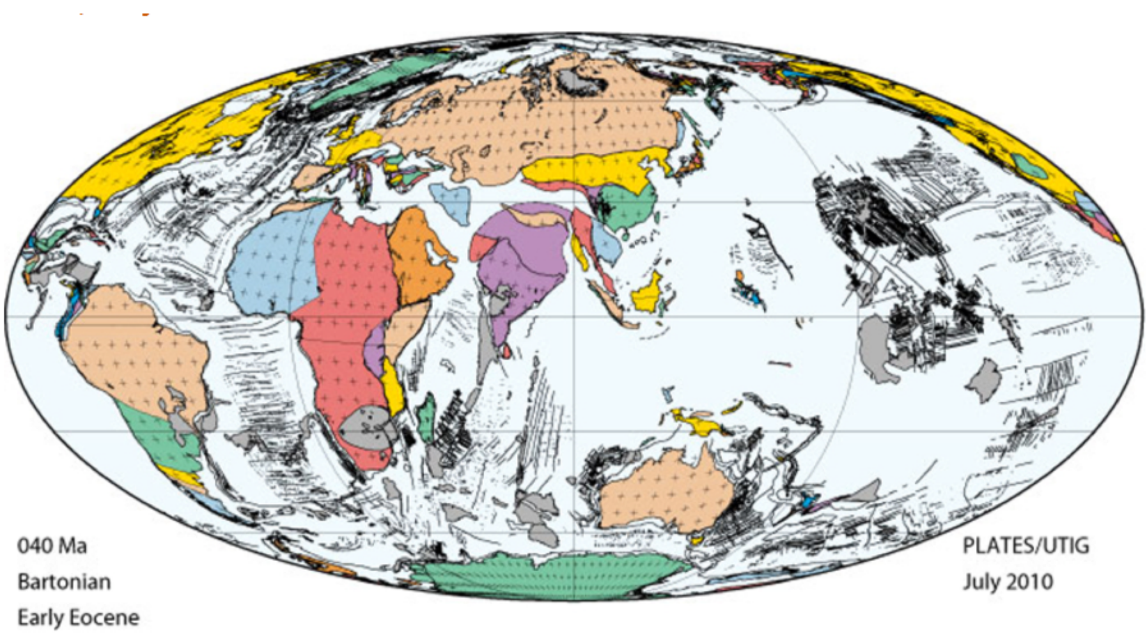
A remarkable record, first put together by Jim Zachos in 2001. The data came from ocean floor sediment cores drilled in all the ocean basins. It's worth looking carefully at the details. Notice how the long term cooling trend paused for 20 million years in the Oligocene & Miocene, and how the see-saw pattern of that time is exaggerated in our own. The world is cooler now than at any time for 50 million years … yet it would take no more than 3℃ of warming to destabilize the great Antarctic ice sheet, and start a long term rise in sea-level.

Speculation on this question has come to focus on a surprising candidate - India! How come?
Well, reconstructing plate tectonic movements has shown that the Indian sub-continent broke from the southern continent of Gondwana about 100 million years ago, then from its traveling partner, Madagascar. It then crossed the entire ocean we now call by its name before colliding with the Asian plate at just about the time of the Eocene optimum. It is an unusually thin continental plate, and it travelled quite fast - about 8 inches a year - all the while swallowing ancient ocean bed beneath its leading edge. Very old ocean floor builds thick sediment rich in carbonates, and when this material is returned to the deep crust beneath the margin of an advancing plate, heat releases large amounts of CO_2 through volcanoes erupting near the continental margin.



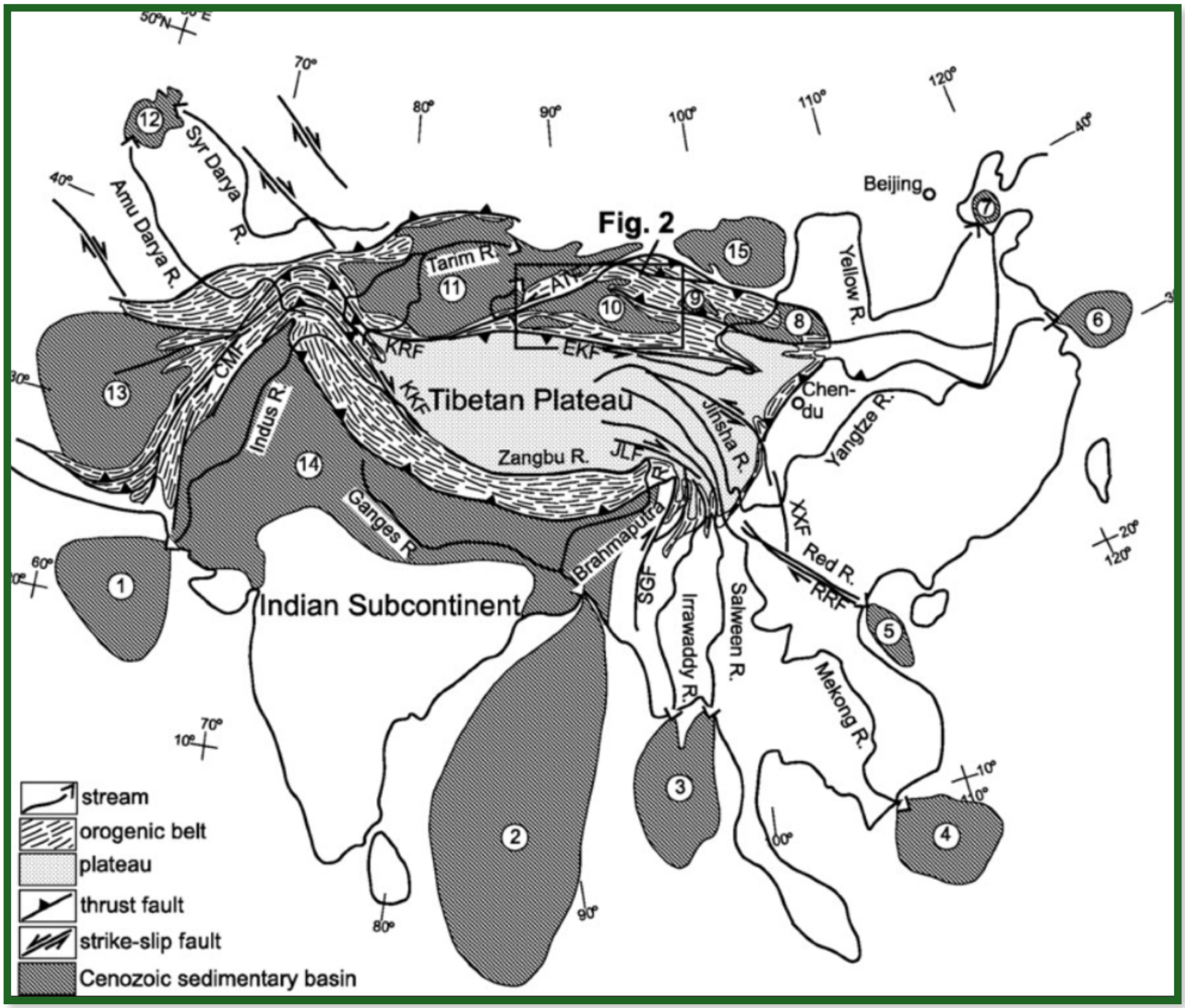
Calculations show that active volcanic outgassing, sustained over a few tens of millions of years would have produced enough gas to cause the warming ... but what caused the cooling? Well, when the smaller Indian plate ran into the big Asian plate, neither was subducted, but they both buckled, elevating what is now the biggest topographic feature on Earth - the Himalayan Range and Tibetan plateau. The volcanoes stopped. Massive quantities of new rock like this act like a sponge, soaking up atmospheric CO_2 by chemical rock weathering. The Himalayas are still rising today, so this massive sponge has been capturing the gas ever since.





How a single continental plate can change the global climate for tens of millions of years

These reconstructions of the northward drift of the Indian plate are based on solid evidence. The geophysical consequences for the climate system are the subject of continuing work, but it is widely accepted that this is the most plausible candidate for the cause of both the long greenhouse forcing peaking in the Eocene and the long cooling over the last 50 million years. Other features in the record have different explanations.



The results can be seen in the Bay of Bengal and on the Arabian side of India - the two biggest submarine fans of erosion material on earth, and the vast sediment deposits in the Indus and Ganges valleys and other Himalayan rivers. *

This story tells us a few things about the kind of stability you can find in Earth's climate system:

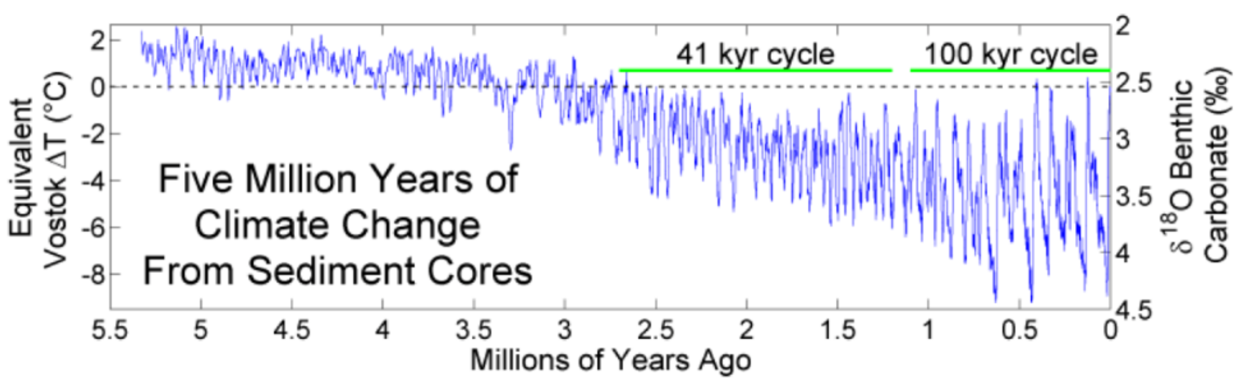
- Large changes normally happen very slowly.
- Geological processes are capable of slowly changing the strength of the greenhouse effect - in both directions. If you wait long enough, any climate forcing will tend to be reversed by another one acting as its corrective. There's nothing purposeful about this, but the system as a whole has the kind of complex stability that limits deviations from its long-term state. That can be inferred from

the fact that life has survived for so long through many vicissitudes, always reviving and playing its part in the entire scheme.

- The emission of CO_2 from volcanoes (the normal source of long-term additions to the atmosphere) has a natural antidote in the chemical weathering of rock. In the present era, these two processes are pretty much balanced, but you can see that if either one is enhanced for long enough, they can change the climate decisively by altering atmospheric composition.
- Carbon that naturally accumulates as sea-floor carbonates is cycled through the atmosphere over millions of years by volcanoes, and back to the sea via rivers. This is part of the inorganic carbon cycle. Typically, the rate of CO_2 rise due to this cause is of the order of 1 ppmv every 10,000 years (100ppmv in a million years). Compare this to the present rate of 2 ppmv per year, and you can see how very unusual the current forcing is.

A third example is something you can see in the Zachos graph at its right side - the see-saw effect of our present era - ***the Pliocene & Pleistocene - the last 5.2 million years.***

The chart below shows it magnified. There's no doubt this period of Earth's climate has been quite unlike the previous 65 million years. It's colder, and the climate is apparently oscillating more or less regularly from cold to warm and back. It looks as if this whole period has been full of dozens of ice ages, gradually becoming more severe, with the most extreme climates in the last million years. What is going on? Well, whatever it is, the first thing to say is that there must be some kind of equilibrium here. Because these cycles are repeated so often, something must be limiting the excursions in both warm and cold - some rhythmical set of causes has to be acting. But what could they be? *



Climate of the last 5 million years

This era has been nothing if not changeable … but careful study shows regularity here. The global climate has oscillated between two semi-stable states, driven by regular natural forcings

You can guess that there must be a trigger of some sort, to start each cycle, and it must be a recurring one, and there must be a reliable brake to send it into reverse. You can also see that the rhythm of these oscillations has changed in distinct steps, both in frequency and amplitude - so something must have caused those too. The search for these causes began 150 years ago, as soon as geologists recognized that Earth had experienced repeated ice-ages, and it has taken most of the time since to find a detailed answer. Here it is.

Ice ages - what causes them?

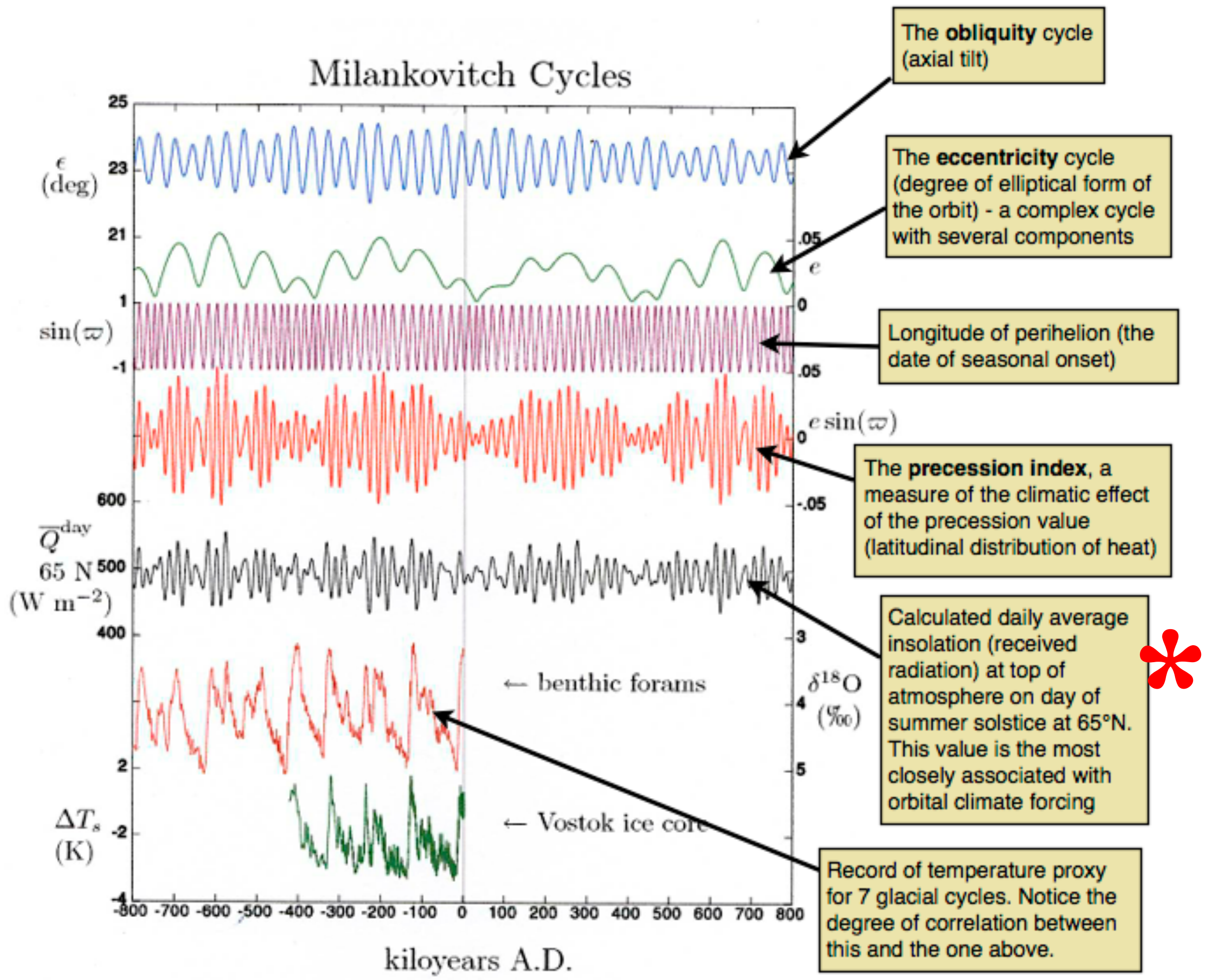
Earth orbits the Sun once a year. Its axis of rotation is inclined to the orbital plane - it leans over - at an angle of 23.44º. This is enough to cause pronounced annual seasons, because the two hemispheres take it in turn to lean toward the Sun. But the angle slowly changes a little in a regular cycle, from 22.1º to 24.5º and back again, taking 41,000 years to complete each cycle. As the angle changes, the contrast between the seasons gets stronger or weaker accordingly: maximum tilt increases the difference between summer and winter in both hemispheres.

The axis also wobbles - it describes a circle at both poles, slowly revolving, every 26,000 years. The long axis of Earth's elliptical orbit also rotates slowly, and between them, these two effects cause the dates of the seasons to advance through the calendar once every 21,000 years (about 25 minutes a year).

The orbit also changes shape fairly regularly, from elliptical to nearly circular. This effect, caused mainly by Jupiter's gravity, is complex, but the cycle works out to be approximately every 100,000 years. Right now, the orbit is near its least elliptical shape. Earth is furthest from the Sun (152,000,000 km) on July 3rd and closest (147,000,000 km) on January 3rd - so Southern Hemisphere summer gets about 7% more solar energy than the northern summer. At the other end of this cycle, when the orbit is most egg-shaped, this difference goes up to about 23%.

Scientists looking for the causes of ice-ages realized that there must be times when these cycles intersect in such a way that northern summers are cold. It would take the conjunction of three factors: the axial tilt would be near minimum; the orbit close to maximum ellipse; and northern mid-summer falls when Earth is near perihelion (furthest from the Sun). It turns out this happens about every 100,000 years - close to the frequency of the orbital ellipse cycle. This matches the frequency of ice-ages of the last 1.2 million years; before that, until the Pliocene-

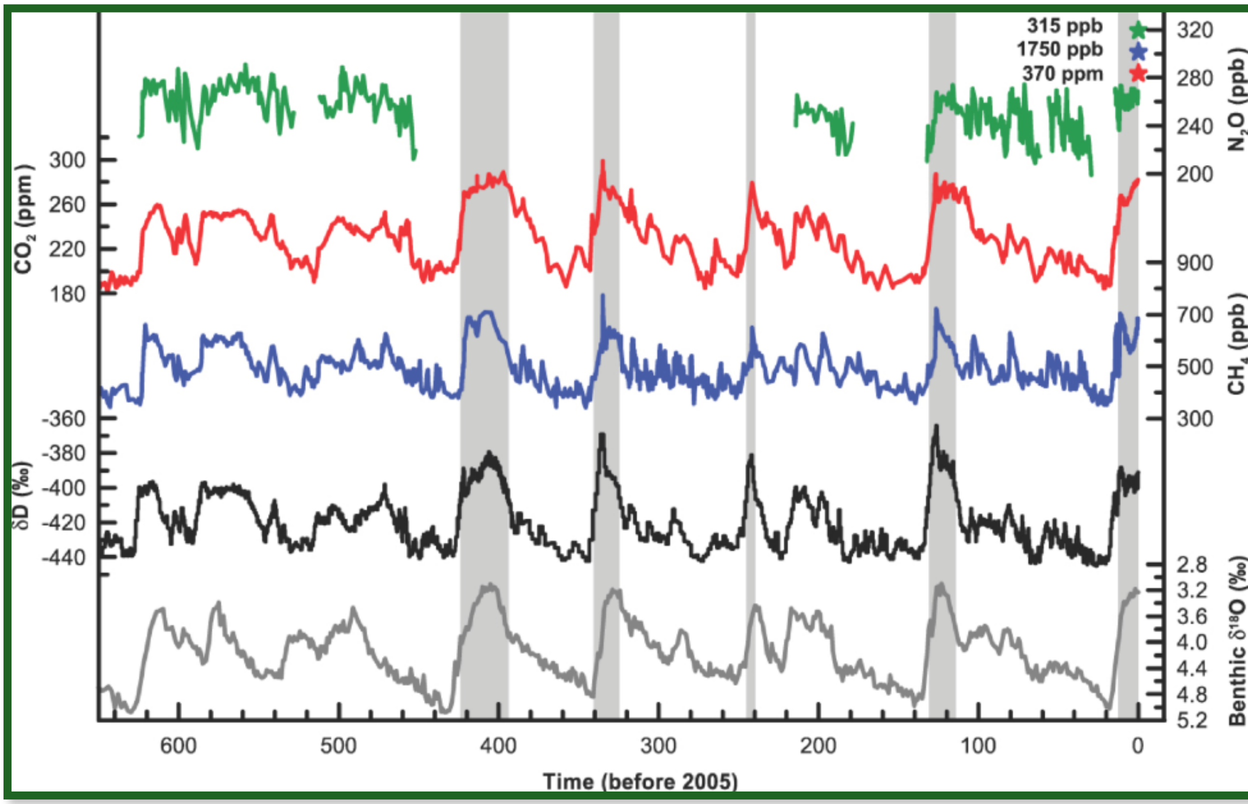
Pleistocene transition the frequency approximately matches 41,000 years, the period of the axial tilt cycle. This is called the Milankovitch theory. *



What's so special about cold summer in the northern hemisphere? Geography. The Arctic Ocean is bordered by land that receives a lot of winter snow. If it doesn't melt in summer, next winter's fall lies on top, and if this happens for long enough, a perennial ice sheet begins to grow. This has the effect of greatly increasing the albedo, making things colder. As the ocean gets colder, it dissolves more CO_2, reducing the greenhouse effect and making it colder still. After some time, the incipient ice-age is driven by falling CO_2 and the albedo feed-back, and the climate becomes colder for about 80,000 years until the massive continental ice-sheets on North America and Eurasia are destabilized by a warming trend in the orbital cycle. Once started, this phase proceeds faster, usually lasting 10-15,000 years. There is then an interval of 5-10,000 years before a new glaciation is triggered. *

In the south, cold summers merely make the Antarctic ice sheet colder. It can't grow because it already occupies the whole continent, so the orbital trigger won't work in the Southern Hemisphere.

This is a record of the last eight ice-ages, made from the longest Antarctic ice core, drilled at Dome C by the EPICA collaboration and completed in 2004. * This is what it shows:

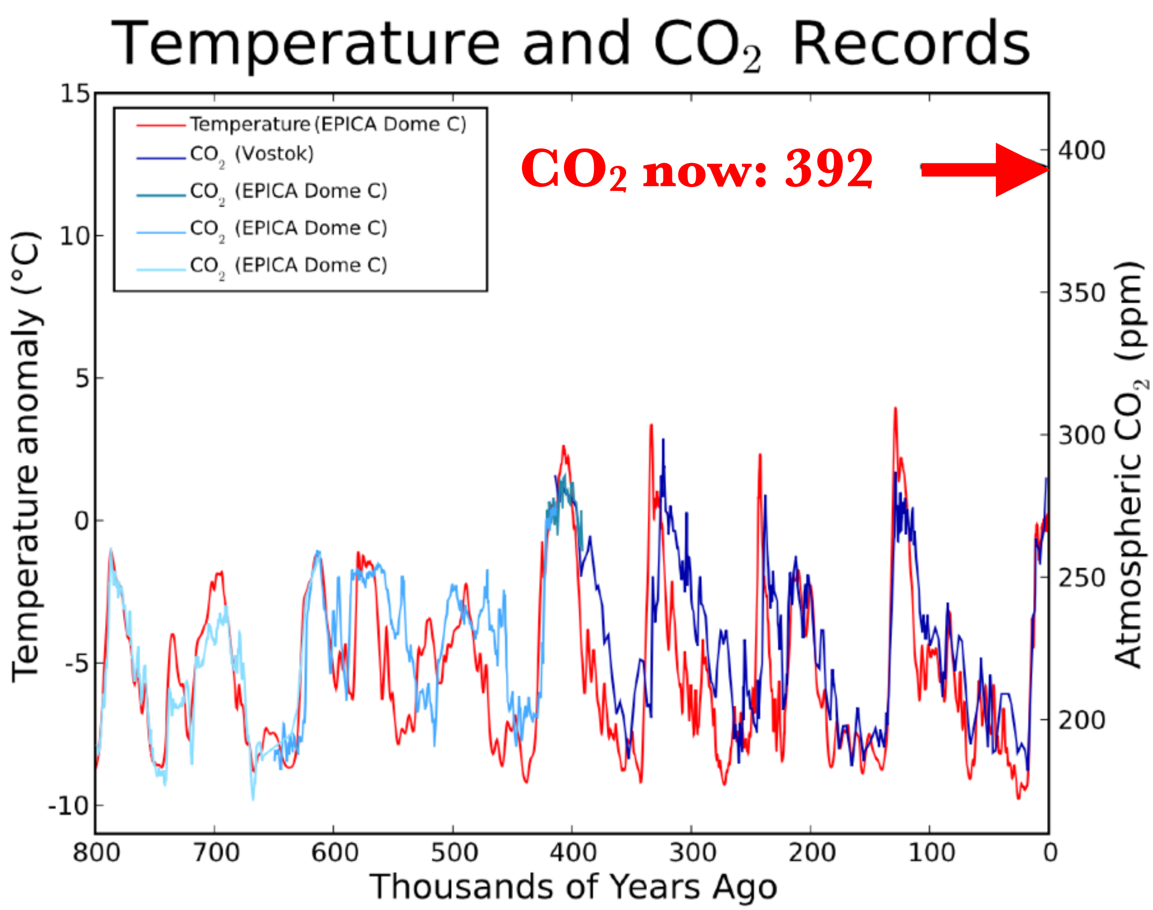


Eight glacial cycles. A remarkable record from Antarctic ice

The two bottom graphs are two different radiochemical temperature proxies; the blue one is methane; the red CO_2, and the green, nitrous oxide. Despite their importance, the coincidence between these greenhouse gas forcings and the temperature is not exact … you wouldn't expect it to be, because the climate responds *via* many complex feedbacks.

- Every 100,000 years or so, the typical pattern of glaciation can be seen - onset of cooling lasting up to 80,000 years, followed by warming over about 10,000 years, then a warm interval.

- The cycles are not identical, either in amplitude or profile (because the orbital cycles don't always intersect the same way) but the underlying rhythm is still there.
- Temperature difference between the ends of the cycle is typically 4-5℃.
- The record of the two principle greenhouse gases (measured from air bubbles trapped in the ice) shows a nearly identical pattern, strongly suggesting a causal relation between gases and temperature.
- CO_2 varies between 290 ppmv in warm interglacials, and 180 ppmv at the coldest depth of an ice-age - without exception.
- Very careful examination of these records confirms the process outlined above, in which the ice-age is initiated by a celestial trigger, then, after a century or two, driven for millennia by the greenhouse gases - in both directions.



The extraordinary rapid rise of modern CO_2

The abundance of this gas has increased 40% above its ice-age maximum in little more than a century, and continues to rise about 200 times faster than it does at the end of an ice-age.

We learn from this history:

- That in the present era (with continents and oceans in their present positions, and with global volcanic activity fairly dormant) global climate oscillates regularly between two semi-stable states - ice-ages with large growing northern ice sheets, and shorter warm interglacials.
- We are in one of those now.
- Mean surface temperature during the Pliocene and Pleistocene has been a couple of degrees colder than it is now.
- Temperatures in the early and middle Pliocene (3-5 million years ago) were sometimes a couple of degrees warmer than now.
- Four degrees warmer (early Miocene, 20 million years ago) was warm enough to melt all the northern ice and a lot of Antarctica.
- Between 4 and 5 degrees warmer and the world would be essentially ice-free. In an ice-free world, the ocean surface is 70 metres higher than it is now.

I hope this deduction of some concrete facts about the meaning of a couple of degrees strikes you as significant. If seems to me that the study of climate history is calling to us loud and clear, and only willful deafness could keep us ignorant. However, there is one more question that might have occurred to you - a pretty important one:

What is the true significance of 400 ppmv - a milestone we will pass in a couple more years?
What do we know about conditions on Earth last time CO_2 was in the range it will be during the 21st century?

We know with great precision that CO_2 has been in the glacial range (180-290 ppmv) for 820,000 years, because ice core analysis is so exact. But we don't have ice any older than this. No method for estimating atmospheric composition beyond this date is nearly as good, but some recent work provides pretty reliable estimates until about 15 million years ago. Here's what we know.

- CO_2 in the middle Pliocene (around 3 million years ago was probably close to 400 ... about where it is now - and global temperature was about 2℃ warmer. These facts are perfectly consistent with our current theoretical understanding.
- Mid-Pliocene sea-level was 15-25 m higher than now. *
- Last time CO_2 was sustained in the range 400 to 425 appears to have been the middle Miocene - 15 million years ago. *
- Global temperature in the middle Miocene was 3℃ higher.
- Polar temperatures may have been up to 8℃ warmer.

- Sea level was 25-40m higher.
- There was no northern hemisphere ice (no Greenland ice sheet), and no West Antarctic ice sheet.

On our present path, we will see annual mean CO_2 for the whole atmosphere reach 400 ppmv in May, 2016. If emissions growth doesn't change much, this will rise to 425 ppmv about a decade later. Because the addition of CO_2 is so fast, responses in the Earth system will be delayed, so we won't see all these consequences right away. But, if this is some comfort to folks living now, it is bad news for people of the future - because nothing they can do will make any difference once the gas is in the air. We know of no way to get it out again - at least not fast enough to matter. The warming will come, and it will last for at least a thousand years. If we mess around and allow CO_2 to reach 600 ppmv, as many experts think it will, our descendants will eventually have to learn to live in an ice-free world - more like the one inhabited by dinosaurs than the one humans have known. * Four degrees or so would be enough to do that. It's a big deal.

* *SEE NOTES AT THE END*

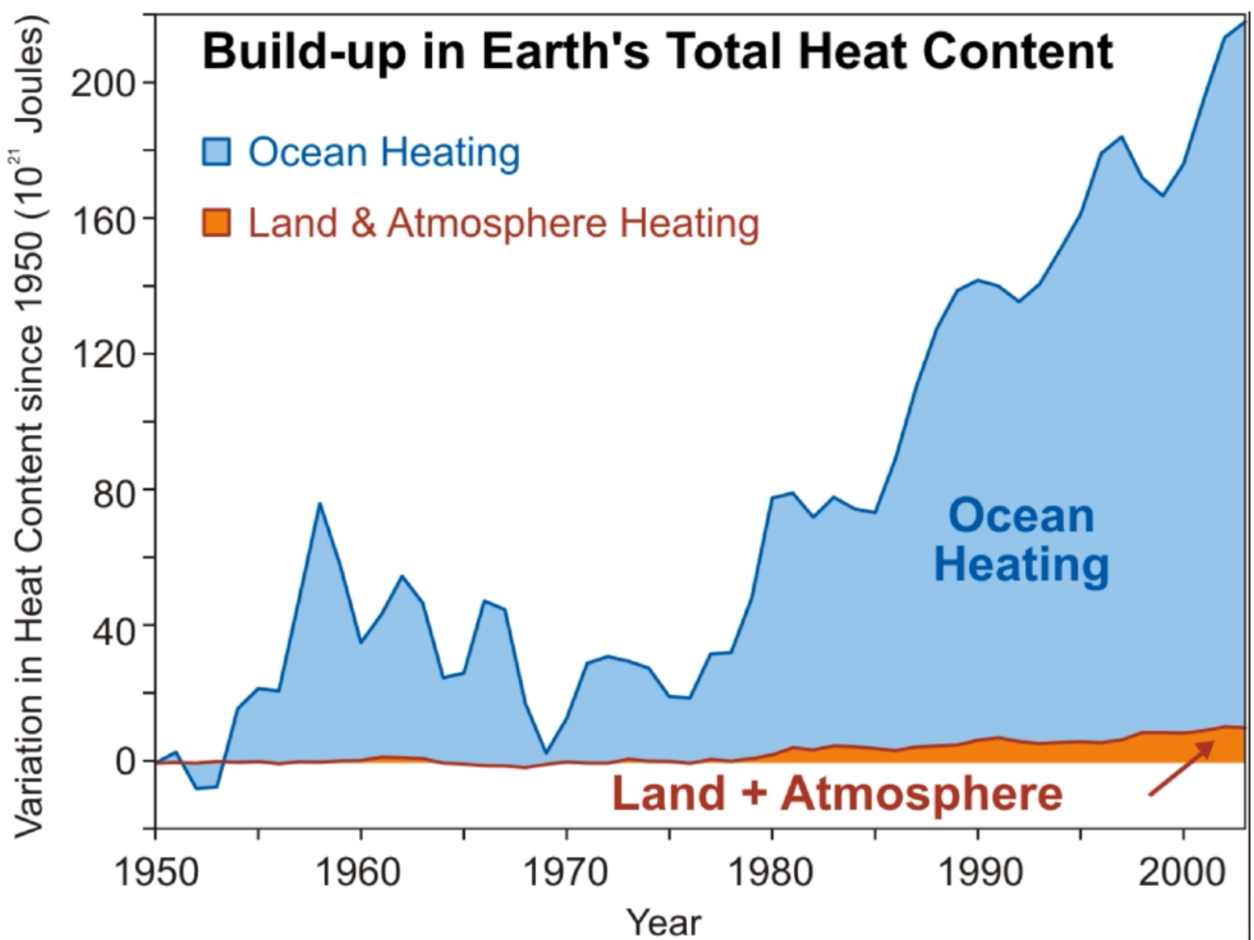
Notes *

page 3 … must always be a bit abstract … Astronauts and others' thoughts about this perspective - viewing Earth as a cosmic object - are collected here: *http://www.spacequotations.com/earth.html*
There's a short video on the same thing here:
http://www.planetarycollective.com/overview/

page 5 … nothing can get any colder … You can watch Richard Feynman discussing this here: *http://www.youtube.com/watch?v=v3pYRn5j7oI*

page 8 … ocean warming instead … This the ocean heat site of NOAA:
http://www.nodc.noaa.gov/OC5/3M_HEAT_CONTENT/

Below is a diagram from skepticalscience.com showing how the accumulating positive energy balance is distributed between ocean and the rest of the surface.



page 8 … energy flood reaches Earth, 150,000,000 kilometres away … Total radiation output of the Sun is about 63,000,000 Watts/m^2. Of this vast quantity, Earth intercepts 1,366 Watts/m^2 at its mean orbital distance of 150,000,000 km.

page 10 … Earth's energy balance … There is a short introduction to this subject here: *http://eesc.columbia.edu/courses/ees/climate/lectures/radiation/*

page 10 … interact with matter by warming it … If you are interested in the history of the discovery of global warming science, the place to go is Spencer Weart's superb site: *http://www.aip.org/history/climate/index.htm*

page 12 … common in the climate system … The proposition that carbon dioxide is the main "control knob" of Earth's climate system is supported by multiple lines of evidence and a solid century or so of confirmation. Nevertheless, the counter-claim that current warming is due instead to the Sun is a common one. Its clearest refutation is the absence of any observational facts. On the contrary, the modern satellite record of solar irradiance shows the normal 11-year cycle (0.1% variance).

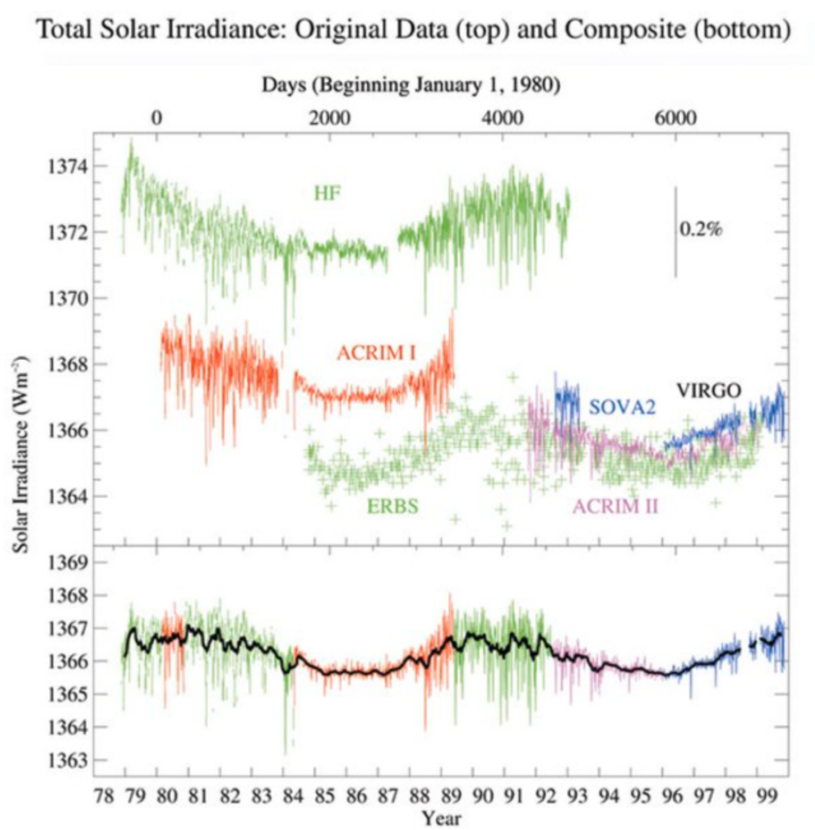


Figure 4: Measurements of solar output outside the Earth's atmosphere from six independent space-based radiometers since 1978 (top). This data has been re-calibrated and combined to produce the composite total solar irradiance graph (bottom). These graphs indicate that the sun's output varies with the 11-year sunspot cycle by about 0.1 percent. Temporary drops (few days) in output of up to 0.3 percent are the result of large sunspots passing over the visible region of the sun. The 11-year peak in sunspot numbers is accompanied by an increase in magnetic activity that causes a general rise in the radiation output. This increase in output exceeds the isolated cooling effects of the sunspots. (Data Source: NASA - SOHO)

page 13 … very reliable and accurate … You can follow the work of the Goddard Institute (GISS) one of the three leading global monitoring laboratories, here: *http://data.giss.nasa.gov/gistemp/*

page 15 … about 93% of the heat present on Earth's surface … A recently published update of the science of ocean heat content is Levitus et al, here: *ftp://ftp.nodc.noaa.gov/pub/data.nodc/woa/PUBLICATIONS/grlheat12.pdf*

Notably, the authors say:
"The global linear trend of OHC2000 is ***$0.43x10^{22}$ J yr^{-1} for 1955-2010*** which corresponds to a total increase in heat content of ***$24.0±1.9x10^{22}$ J*** …
"We have estimated an increase of $24x10^{22}$ J representing a volume mean warming of 0.09°C of the 0-2000m layer of the World Ocean. If this heat were instantly transferred to the lower 10 km of the global atmosphere it would result in a volume mean warming of this atmospheric layer by approximately ***36°C (65°F)***."

page 18 … their methods constantly updated … The idea that the urban heat island effect is seriously distorting the global mean temperature record persists, despite any number of detailed refutations. Here is a short summary answering most of the common fallacies: *http://www.realclimate.org/index.php/archives/2007/07/no-man-is-an-urban-heat-island/*

page 18 … just as it did in the mid-twentieth century … This 30 year halt in twentieth century warming has been much studied. There is now a strong consensus that reduced solar irradiance was a minor factor, but the dominant one was the escalating production of opaque aerosols from rapidly growing industrial economies in the post-war decades. Air pollution controls, which came in the 1970s to all the offending Nations, appear to have caused the warming to resume.

It is often pointed out that, if similar measures were to arrive in the big newly industrializing countries - specially China & India - we could expect warming to accelerate appreciably. The total negative forcing due to atmospheric aerosols today is estimated to be about enough to negate all the positive forcing of atmospheric methane … about 0.7 W/m2.

page 20 … return to normal after it was over … The PETM has received a lot of study. There is a good Wikipedia article here: *http://en.wikipedia.org/wiki/Paleocene–Eocene_Thermal_Maximum*

page 21 … capable of influencing climate all over the world … While it is indisputable that the closure of the Panama Seaway had major geophysical consequences, studies have so far failed to pin them down very precisely. There are problems with the timing of the closure - obviously it took place over several millions of years, yet the climate effects seem to have occurred in discreet steps. It is clear that the formation of the northern polar ice cap coincided with this event, and no other plausible explanation has been forthcoming; and there is direct evidence for the altered condition of the Gulf Stream at that time.

Here are two papers that provide somewhat different conclusions:
http://www.rci.rutgers.edu/~jdwright/MarGeol/Haug.pdf
http://homepages.see.leeds.ac.uk/~earamh/Files/PAGES_Pliocene/Key%20references/Luntetal2008.pdf

page 23 … what could have caused such big climate events spread over so much time? … Richard Zachos in 2001 made the first synthesis of oceanographic studies of sea-floor sediment, designed to provide a proxy record of global surface temperature for the whole Cenozoic era. His result has become an icon of paleoclimatology - a spectacular insight into the behaviour of the climate system over tens of millions of years, and a fruitful stimulus for lots of further work. Each and every feature of this record requires its own causative explanation. These have been sought (and found) in many disciplines, with great benefit to the study of climate history and much else.
The original paper is here: *ftp://ocean.ims.metu.edu.tr/pub/iklim/ecoclimate/science/686.pdf*

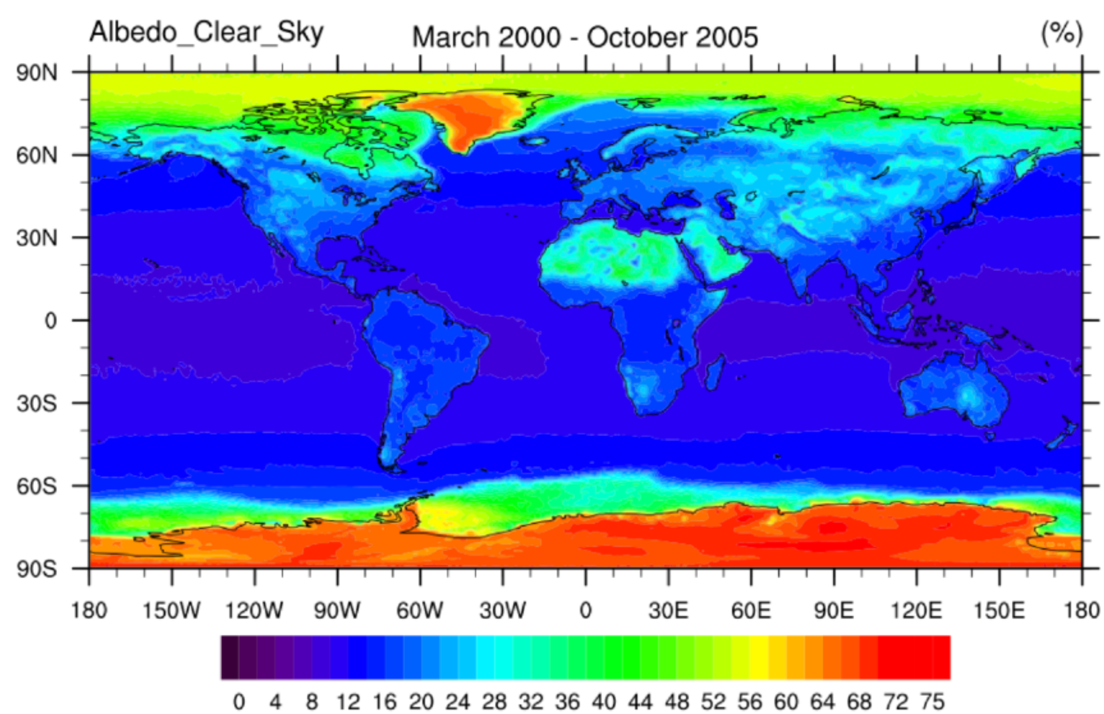
page 26 … vast sediment deposits in the Indus and Ganges valleys and other Himalayan rivers … Here is a representative paper on the relation between the Indian plate and Mesozoic warming: *http://lib.gig.ac.cn/local/nature/449,894.PDF*

Here is a paper by Maureen Raymo on the role of Himalayan weathering on long-term cooling since the Eocene optimum: *http://www.liv.ac.uk/~jan/teaching/References/Raymo%201994b.pdf*

page 27 … But what could they be? … The graph here is the original work of Lorraine Lisiecki and Maureen Raymo, published in 2005. It is a synthesis, like Zachos graph, of multiple independent sea-floor studies, providing a detailed proxy record for the whole Pliocene & Pleistocene epochs - the "age of ice". The study is here: *http://large.stanford.edu/publications/coal/references/docs/Lisiecki_Raymo_2005_Pal.pdf*

page 29 … an interval of 5-10,000 years before a new glaciation is triggered … The polar ice caps are an important controller of Earth's energy balance. They act like giant mirrors, reflecting most solar radiation right back to space - of course the reflected quantity makes no contribution to warming the planet at all. The total surface area of the ice at the poles varies between about 40 million square kilometers in March to 48 million in September - about 9% of the surface of the planet. At any one time, the seasonal sea-ice is around half of this, and the combined permanent Antarctic and Greenland ice sheets are nearly all the rest, with mountain ice caps and glaciers making a small contribution. The biggest seasonal change in albedo is the winter snow fall in the northern hemisphere. This causes the annual albedo maximum in September.

The average albedo of sea-ice is around 50-60%; of continental ice-sheet about 75%; and fresh-fallen snow at least 90%. Even though most of Earth's albedo is



due to atmospheric reflection, changes in the seasonal extent (and reflective properties) of the polar mirrors are significant contributions to the surface albedo, as the map shows. In this study, albedo has been averaged over a few years to indicate the contribution of Arctic and Antarctic sea-ice, the two continental ice-sheets, snowy tundra and mountains, the big deserts, and the ocean.

page 29 … this is called the Milankovitch theory … Milutin Milankovitch published the results of his laborious calculations in 1920. It took another 60 years before confidence in his conclusions became near-universal … as usual, the relation between orbital properties and the climate turned out to be more complex than the originator had thought. But now we have great confidence that Earth responds this way to regular orbital forcing, acting as trigger for potent system feed-backs.
You can look at this short review of the theory here:
http://wps.prenhall.com/wps/media/objects/2513/2574258/pdfs/E16.7.pdf
If you want something a bit more technical, look here:
http://onlinelibrary.wiley.com.ezproxy.library.uq.edu.au/store/10.1029/RG026i004p00624/asset/rog1295.pdf?v=1&t=hoohq3wr&s=ab36525d087ce96a2ae8ae7a1020919af03a65eb

page 30 … EPICA collaboration and completed in 2004 … You can read more about this remarkable project here: http://cdiac.ornl.gov/trends/co2/ice_core_co2.html

page 32 … Mid-Pliocene sea-level was 15-25 m higher than now … You can read a study on the mid-Pliocene warm interval here:
http://homepages.see.leeds.ac.uk/~earamh/Files/PAGES_Pliocene/Key%20references/Raymoetal.pdf

page 32 … the middle Miocene - 15 million years ago … The study that provided this result was published in 2009. It is, for the time being, our best answer to the all-important question, "what will happen to the climate if the atmosphere were to stabilize at 400-425 ppmv?" The answer is sobering enough - but of course it is not exactly pertinent since we are nowhere near the political resolve needed to stop additions to the atmospheric greenhouse. Even achieving a peak concentration of 600 ppmv would be very demanding now we have left it so late. You can examine the study here: *http://www.seas.harvard.edu/climate/seminars/pdfs/tripati.etal.sci.2009.pdf*

page 33 … more like the one inhabited by dinosaurs than the one humans have known … In my opinion, the best way to get an idea of the climate consequences of our present policies is to read Kevin Anderson and Alice Bows' 2008 paper, or the 2012 update. The authors are more transparent discussing the nexus between policy and future climate than the usual rhetoric. Their conclusions are arresting.

http://rsta.royalsocietypublishing.org/content/366/1882/3863.full

http://www.whatnext.org/resources/Publications/Volume-III/Single-articles/wnv3_andersson_144.pdf