

## **Climate Changes of the Past and Future**

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### **Planetary Climates**

The balance of radiant energy absorbed and emitted determines all planetary climates. Everything in the universe emits electromagnetic radiation. Emission depends very strongly on temperature (proportional to  $T^4$ ). When more energy is absorbed than emitted, planetary temperatures increase until increased emission restores the balance. When absorption decreases the planet cools and emission falls to restore the balance again. We'll consider this balance in detail, as it's the driver for everything that follows.

### **Climate Change in the Geologic Past**

In the deepest past (billions of years), this planet was so different from our familiar world of today that we'd hardly recognize it! Bare rock continents without plants or animals stood in an oxygen-free atmosphere bathed in UV under a weak sun. The development of photosynthesis about halfway through geologic time produced huge changes as oxygen consumed the methane that provided much of the greenhouse effect, leading to several episodes of catastrophic global ice all the way to the Equator!

Things settled down about half a billion years ago with a "geologic thermostat" keeping temperatures fairly constant. This geo-thermostat is mostly controlled by CO<sub>2</sub>, which is released from volcanoes by seafloor spreading and the subduction of tectonic plates. CO<sub>2</sub> is also consumed by chemical weathering of rocks, which is faster at higher temperature. CO<sub>2</sub> built up until climate warmed enough that the rate of CO<sub>2</sub> consumption by weathering matched the rate of production by volcanic outgassing.

The paleoclimate record gets better and more detailed as we approach the present. Over the past 543 million years the fossil record of plants and animals provides much more information. As tectonic plates moved around, sometimes volcanism and weathering got out of phase for tens of millions of years, leading to periods of cold climate with ice ages in Gondwanaland 400 million years ago and then very warm periods with alligators in the Arctic!

Since the dinosaurs died out 65 million years ago, climate has been cooling and CO<sub>2</sub> has been dropping as Antarctica drifted over the South Pole and opened up the

oceans at every longitude between 55 and 70 S. Continental ice first formed in East Antarctica 34 million years ago, reflecting lots of sun to space and causing more cooling. Huge mountain chains in Asia and the Americas were raised up and the weathering of all that fresh rock consumed a lot of CO<sub>2</sub>.

### **Ice Age Climates**

Ice sheets began to grow on the Northern continents about 3 million years ago, and Ice Ages have come and gone more than 20 times since then. Just 1 million years ago the Ice Ages settled into a very regular and pronounced 100,000-year cycle. These cycles are driven by very subtle changes in the Earth's orbit around the Sun, which are very well understood. But the actual timing of the growth and collapse of the great ice sheets is much more complicated and interesting. Growth of the ice is slow -- limited by the rate of snowfall far from the oceans, but ice sheet collapse is much faster -- limited only by the delivery of heat from the Sun and wind.

Modern humans appeared during the Last Ice Age, which reached its maximum extent "only" 18,000 years ago. Deglaciation took about 10,000 years, leading to a pretty stable climate since then as well as to the emergence of agriculture and civilization. Since the end of the Last Ice Age climate warmed a little, reaching a warmest period about 6,000 years ago, then cooled slowly until about 1850 AD in response to orbital changes.

### **The Discovery of Global Warming**

Since the Industrial Revolution, people have been extracting fossil carbon from the rocks and burning it to power the modern economy. Fossil fuel combustion adds CO<sub>2</sub> to the atmosphere much faster than geologic processes can remove it, and as a result the CO<sub>2</sub> has risen about 40% since preindustrial time.

In the 1820's, the French mathematician and physicist Joseph Fourier first showed mathematically that the Sun's radiation was insufficient to keep Earth's climate comfortably warm. He postulated that the atmosphere was transparent to incoming sunlight but partly opaque to outgoing radiation, and used the "greenhouse" analogy to describe this effect. In 1830's and 1840's, the Swiss geologist Louis Agassiz showed that the Earth had in fact been much colder in the past, with glaciers covering much of Europe and North America. He called this past period the Ice Age. In the 1860's John Tyndall discovered that CO<sub>2</sub> gas had precisely the radiative properties Fourier required (transparent to visible but opaque to infrared radiation). By 1896, Svante Arrhenius had measured the effect of CO<sub>2</sub> on the Earth's climate and calculated that extra CO<sub>2</sub> from burning coal might warm the climate by a few degrees Celsius. Most scientists expected CO<sub>2</sub> from burning coal to dissolve away into the oceans, but George Callendar conducted measurements around the world in the 1930's and showed that CO<sub>2</sub> was indeed rising slowly. He was pleased and speculated that the additional greenhouse effect might save the world from a future ice age! Finally in the 1950's Charles D. Keeling developed instruments for

precise measurement of CO<sub>2</sub> in air, and by the mid-1960s it was clear that CO<sub>2</sub> was rising fast. In 1965, 100 years after Tyndall's discovery of the radiative properties of CO<sub>2</sub>, a Science Advisory Committee warned President Lyndon Johnson that this rise would "cause marked changes in climate." Johnson passed this warning on in a special report to the US Congress in February 1965.

### **Climate Forcing, Response, and Sensitivity**

The most basic way to understand climate change is in terms of cause and effect. We define *climate forcing* as a net imbalance between the radiation absorbed and emitted by the Earth, in Watts per square meter ( $W m^{-2}$ ). We define the *response* to climate forcing as the change in global mean surface air temperature in degrees Celsius (C). The ratio of response in degrees of warming or cooling per  $W m^{-2}$  of change in radiation is called *climate sensitivity*.

Arrhenius showed in 1896 that if the Earth were a featureless ball in space, the climate sensitivity would be about 0.26 degree C per  $W m^{-2}$ . But with a climate sensitivity that small, we'd never have had Ice Ages or any of the other climate changes recorded in the rocks. Geology and more recent historical changes reveal that the actual sensitivity of the Earth's climate is about 0.8 C per  $W m^{-2}$ , about three times as great as the featureless ball in space. This extra sensitivity is caused by feedback processes that amplify the original change in the radiation. When it gets cold for example, snow and ice reflect sunlight to space and climate cools even more.

Doubling the amount of CO<sub>2</sub> in the atmosphere slows the outgoing radiation emitted by the Earth by  $3.7 W m^{-2}$ . Assuming the incoming sunlight doesn't change, this means the climate should warm by  $(3.7 W m^{-2}) \times (0.8 C \text{ per } W m^{-2}) = 3 \text{ Celsius}$ . This sensitivity to heat by CO<sub>2</sub> is consistent with the geologic record and does not require climate models to calculate, but it is in close agreement with modern calculations using climate models.

### **Earth System Models**

Modern climate models use a lot of arithmetic to represent the basic physics of the atmosphere, oceans, and the vegetated land surface. We use them to test our understanding of how the Earth works, and also to ask "what if" questions about the future. Since 1990, scientists have gone through a formal process to develop scenarios of future CO<sub>2</sub> emissions, climate forcing, and climate response using these models. The results of these calculations are reported to the governments of the world roughly twice a decade.

In the course, we will experiment with some extremely simple models of the Earth system that are easy to understand and to use for basic experiments. We will compare the results of our simple models to the geologic record and to historical climate, to get a feel for what they say and how reliable they are. You will be able to

use these models in your classroom, and you will have access to lots of observations of the climate system to use with your students.

## Climate Projections

There are three major sources of uncertainty about future climate. The biggest one is that we don't have any way to predict what future people will decide to do with energy, the economy, and fossil fuel combustion. The second is that the fraction of CO<sub>2</sub> that gets absorbed by the oceans and land may change in the future depending on changes in biology and land use in a changing climate. The third source of uncertainty involves the physics of the Earth system, but that's better known than the other two.

There are 7 billion people on Earth but only about 1 billion of us use a lot of energy. World population is only expected to grow about 30% by 2100, but energy demand is expected to grow by 300% as the number of energy users quadruples. If all those future people generate all that energy by burning coal, oil, and gas atmospheric CO<sub>2</sub> will triple by 2100. That would reduce Earth's emitted radiation by about  $6 \text{ W m}^{-2}$  until the climate warmed by about  $(6 \text{ W m}^{-2}) \times (0.8 \text{ C per W m}^{-2}) = 5 \text{ Celsius}$  as a global average. The oceans warm slowly because they have huge thermal mass, so land warms much more than the average over the world. Under this "business as usual" scenario, Central North America would likely warm around 15 Fahrenheit.

Water evaporates faster when it's warm, so evaporative demand would increase. Precipitation increases in a warmer world, but it doesn't fall evenly. In places where the extra precipitation doesn't keep up with the extra evaporation there will be more drought and wildfire. There would also be less snow here. Low-lying coastal regions would experience severe flooding because of rising sea level. The warming under a business as usual future would be about as strong as at the end of the last Ice Age, but instead of taking 10,000 years, it would take only 100 years.

Eventually, the world will make a transition to non-carbon energy. Unfortunately the extra CO<sub>2</sub> from the fossil fuel era is not chemically reactive so will remain in the atmosphere until it can dissolve into the deep oceans. This process is extremely slow because cold dense water at the ocean bottom doesn't mix well with less dense warmer surface water. A similar pulse of CO<sub>2</sub> released 55 million years ago took about 100,000 years to disappear.

## Simple, Serious, and Solvable

Future climate change is *simple*, by which I mean it's easy to understand. If people double or triple the amount of CO<sub>2</sub> in the atmosphere we expect the climate to warm for precisely the same reason that water warms up on a stove: heat in minus heat out is proportional to change in temperature. This is the same physics that makes day warmer than night, summer warmer than winter, and Phoenix warmer than Fargo. We've understood the basics for 150 years.

Future climate change is **serious**, by which I mean the consequences for the global economy and ecosystems are extreme and probably unacceptable. Without mitigation, the potential economic damages are easily in the tens of trillions of dollars. And the climate would take many thousands of years to return to what it's been since the last Ice Age.

Fortunately, this problem is also **solvable**. Careful studies have shown that even without waiting for new technologies we have a wide array of choices that will allow a huge expansion of the use of energy to lift billions of people out of poverty without adding excessive CO2 to the atmosphere. The costs of transitioning to a non-carbon economy are likely to be affordable and much cheaper than the damages of unmitigated global warming. Cost savings from energy efficiency will offset much of the cost of employing new technologies, and renewable energy costs are falling exponentially.