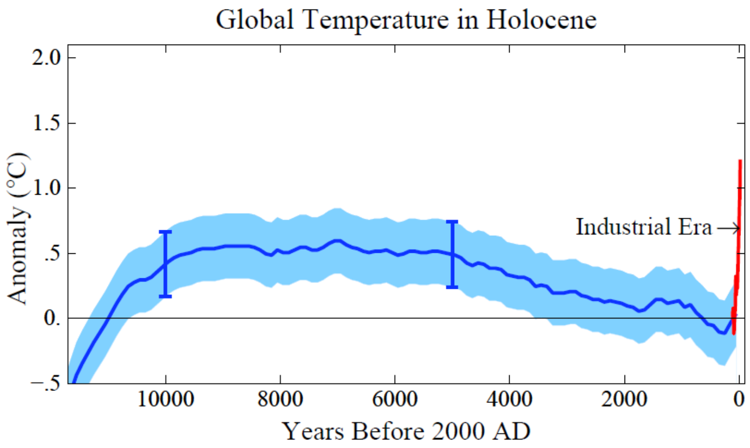

Fig. 25.1. Global temperature in the Holocene relative to 1880-1920 average.[1] Blue data are proxy temperature analysis of co-authors Shaun Marcott, Jeremy Shakun. Red line is from instrumental data for 1880-2020. Proxy data have 100-year smoothing. Light blue area is formal 95 percent confidence range.

Chapter 25. Paleoclimate and “Slow” Feedbacks

Earth’s climate undergoes large swings. We already mentioned the last ice age, when sea level was so low that people could walk from Asia to North America across a wide land bridge. These large climate swings raise the question: why should we be concerned about global warming of a few degrees? Life has survived – even thrived – in a world with changing climate.

That is a good question and there are other good reasons to briefly examine paleoclimate data at this point. Earth’s climate history contains a treasure of information that helps us understand how our climate system works, which is essential if we are to understand and reliably predict humanity’s impact on the natural world.

We will focus here on the climate change during the past several hundred thousand years, a time especially rich in data. The abundance of stable gases in Earth’s atmosphere over approximately the past 800,000 years has been measured using ice cores extracted from the Antarctic ice sheet. The ice sheet was formed by snow piling up year after year, trapping bubbles of ancient air as the snow compressed into ice. The temperature of the air above the ice sheets when the snowflakes formed is recorded in the relative abundance of oxygen and hydrogen isotopes in the ice. Climate records at other places on the planet are obtained from various proxy measures of climate change, such as tree rings and sediment cores from lakes and the ocean.

Let’s start with the Holocene, the warm interglacial period that began about 10,000 years ago. Global temperature was stable in the first half of the Holocene (Fig. 25.1), but cooled slowly by about half a degree Celsius (about 1 degree Fahrenheit) over the last 5,000 years. A temperature minimum occurred during the period 1300-1850 AD, which is termed “The Little Ice Age,” even though it was not a true ice age.[2] It was cold enough for winter fairs to be held on the River Thames in the United Kingdom. It was still cold enough in the late 1770s for soldiers in the Revolutionary War to drag cannons across the ice from Manhattan to Staten Island.

Absent humans, Earth was headed for the next ice age, as we will be able to explain later in this chapter. However, humans began to take control of atmospheric composition with the industrial

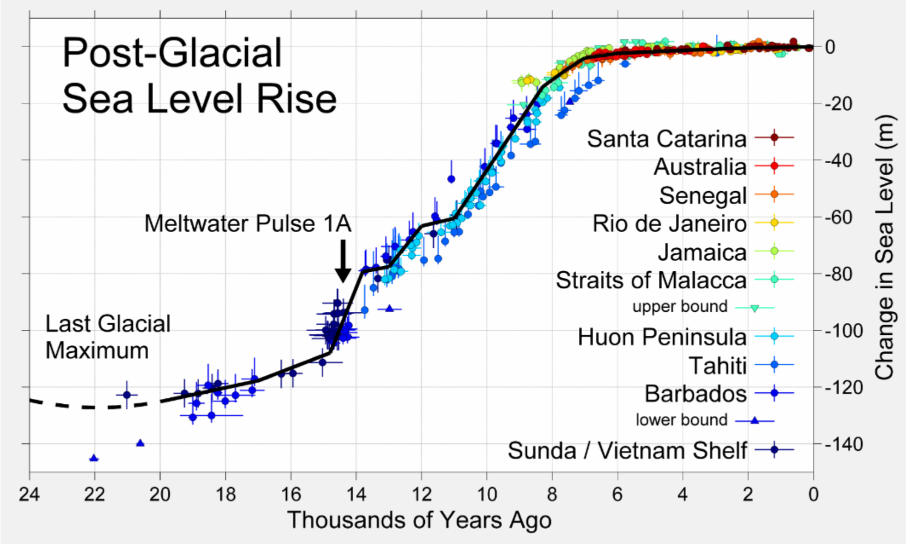

Fig. 25.2. Sea level since the last glacial period relative to present. Credit: Robert Rohde[3]

revolution. We are now entering a new geologic era, which Paul Crutzen has named the Anthropocene.[4] A unique characteristic of this era is the unprecedented rate of change of atmospheric composition. CO_2 is now increasing at least 10 times faster than at any known time in the paleoclimate record.[5] Global temperature is increasing rapidly, and Earth is warmer than at any prior time in the Holocene (Figure 25.1).

Sea level rise is one of the most difficult issues for scientists and humanity alike. Sea level is very sensitive to global temperature change, based on paleoclimate records, but how fast can sea level change? If it takes 1000 years for a large sea level rise to occur, we will be much less concerned than we would be with a large change this century.

A 120 meter (400 feet) sea level rise occurred between the last ice age and today, but it took place over 10,000 years (Fig. 25.2). Does that imply that melting an ice sheet the size of the one that covered most of Canada and parts of the U.S. requires 10,000 years? The ice sheet was about 3 kilometers (2 miles) thick at the center, so it would take time to melt, but 10,000 years? However, that long time scale may simply reflect the time scale of the forcing that caused the climate change. The main forcing had a full cycle time scale of about 20,000 years, as we will discuss, and therefore a half-cycle time scale from ice age to interglacial of about 10,000 years.

Nevertheless, when Earth's temperature approached the Holocene maximum 10,000 years ago (Fig. 25.1), sea level was still 60 meters below today's level (Fig. 25.2). It took a few more millennia for this continental ice sheet to fully melt. Does that slow response to global warmth imply that we need not be concerned about the potential sea level rise this century? No. First, a sea level rise of "only" a few meters could create havoc for coastal cities. Second, the strong human-caused drive for sea level change is being added much more rapidly than the weak natural forcing that produced an average sea level rise of about a meter per century and an occasional rise of several meters per century, as at Meltwater Pulse 1A (Fig. 25.2).

Are today's ice sheets on Antarctica and Greenland less vulnerable than the Laurentide ice sheet, the large North American ice sheet 20,000 years ago, which extended down to middle latitudes? Probably not. Indeed, the contrary seems more likely: large portions of the Antarctic and

Greenland ice sheets rest on bedrock below sea level, making them vulnerable to erosion by a warming ocean. This process, as we discuss later, is a crucial research topic.

Delayed responses are the bane of policymakers – witness the Coronavirus and resulting Covid-19 pandemic. The lags – between infection and symptoms, between first symptoms and illness, and between illness and ultimate consequences – make the problem difficult to control.

The climate system has lags in spades. Lag due to the ocean's thermal inertia is complicated, with a fast partial response in a decade or two and then a slow response over centuries that Isaac Held dubbed the "recalcitrant" response.[6] In addition, the paleoclimate data reveal "slow" feedbacks, such as melting of ice sheets and release of greenhouse gases by warming ocean, wetlands, tundra and continental shelves.

Earth's climate history reveals that the slow feedbacks amplify climate sensitivity. We refer to climate sensitivity including slow feedbacks as the Earth system sensitivity, to distinguish it from Charney's "fast feedback" climate sensitivity. Amplifying feedbacks, which dominate Earth's climate system, are a practical problem; the delayed climate response allows large consequences to build up before the public has seen enough climate change to spur remedial actions.

Although delayed response makes the climate problem difficult, slow feedbacks are our friend in one way: they provide us time to make changes before the potential consequences occur. The feedbacks in general are not "runaway" – they do not proceed from their own momentum alone – except in a few special cases that we will discuss later. In most cases, if we remove or reverse the drive, growth of the feedback can be stopped or reversed.

Let's not underestimate that task. Global temperature is now close to the level in the Eemian – the prior interglacial period when sea level reached a maximum 6-9 meters (20-30 feet) higher than today. Atmospheric CO_2 has passed 410 ppm and its annual growth rate – now averaging more than 2.5 ppm per year – increased in the past decade, despite widespread concern about climate change. CO_2 is now near the level in the Mid-Pliocene, about 3 million years ago, when sea level reached heights of 15-30 meters (50-100 feet) higher than today.[7]

What caused these large sea level changes? What caused the continual repetition of glacial-interglacial cycles, as ice sheets formed in Canada and northern Eurasia, grew as they pushed south, and then, relatively rapidly, retreated and disappeared?

Milutin Milankovitch, a Serbian geophysicist and astronomer, proposed in the 1920s that the glacial-to-interglacial climate oscillations are caused by perturbations of Earth's orbit. He was building on a 19th century hypotheses of James Croll and Joseph Adhémar. The essence of this orbital theory was confirmed in 1976 when Jim Hays of Columbia's Lamont-Doherty Geological Observatory and two colleagues[8] showed that climate-driven periodicities in ocean sediment cores matched the periodicities of Earth orbital perturbations.

The perturbations of Earth's orbit are caused by gravitational pull of other planets, mainly Jupiter and Saturn, and by tidal forces caused by the Sun and Moon. The orbital perturbations give rise to two effects, which are easy to understand.

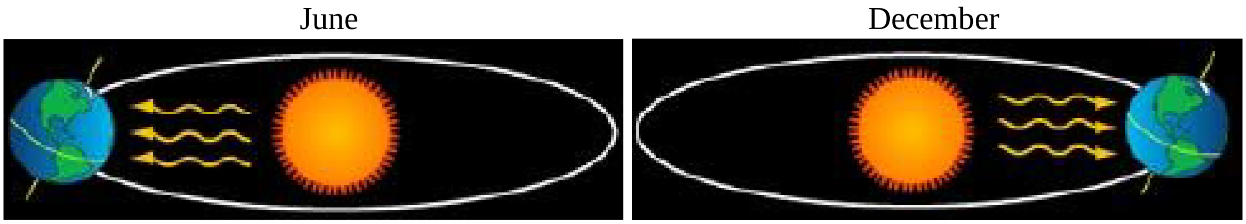

Fig. 25.3. Tilt of Earth's spin axis causes the seasons

Effect #1, the Tilt Effect, arises from the changing tilt of Earth's axis of rotation ("spin axis") relative to the plane of Earth's orbit. Tilt of the spin axis causes the seasons (Fig. 25.3) as Earth travels around the Sun each year. In June the tilt exposes the Northern Hemisphere to maximum sunlight; six months later the Southern Hemisphere receives maximum sunlight. Midway between, at Spring and Autumn Equinoxes, the hemispheres receive equal amounts of sunlight.

The spin axis tilt has a simple time variation. It changes over its full cycle, from minimum tilt (22.2° from straight up) to maximum (24.5°) and back to minimum in about 40,000 years (2nd panel in Fig. 25.4). When the spin-axis tilt is larger, more sunlight strikes polar regions during the summer melt season, which thus tends to melt high-latitude ice sheets.

Today the tilt (also called obliquity) is 23.4°, but decreasing – the spin axis is "straightening up." This favors growth of ice sheets, because insolation at high latitudes is decreasing. If Effect #1 were the only effect, Earth would be headed toward an ice age. Now let's check Effect #2.

Effect #2, the Eccentricity Effect, is a bit more complex in its origin, because it is determined by two orbital parameters, but in the end it is also simple. Effect #2 exists because Earth's orbit is not a circle; it is slightly elliptical. Today for example, the eccentricity is about 0.02, so when Earth is at perihelion – closest to the Sun – it is about three million miles (about five million kilometers) closer to the Sun and receiving 6.8 percent more solar radiation (insolation) than it does when it is at its greatest distance from the Sun.

Today perihelion is on 3 January, but perihelion marches slowly through the calendar. It will take more than 50 years for perihelion to advance to 4 January, and more than 20,000 years for perihelion to advance through the full calendar. The slow advance of the day of year (DoY) of perihelion is related to the third orbital parameter, which is described in astronomy as precession of the equinoxes. Earth's spin axis precesses, like a spinning top does as it slows down; it takes about 26,000 years for a complete revolution of the spin axis. The impact of precession on the DoY of perihelion is complex, but we need not be concerned about the geometry. What climate "cares" about is when Earth is closest to the Sun, and the continuous advance of that date through the year is reasonably simple, as shown in the 3rd panel of Fig. 25.4.

Ice sheet melt is promoted when the day of the year (DoY) of perihelion, when insolation is maximum, is during the season when it is warm enough for surface melt to occur. The resulting "albedo flip," the darkening of ice and snow that occurs when ice becomes wet, is a great amplifier of melt, as it causes a much larger fraction of incident sunlight to be absorbed (albedo, literally "whiteness," is reflectivity). Maximum melt occurs if perihelion occurs as soon as it is warm enough for melting, which is late spring (May in the Northern Hemisphere).[9]

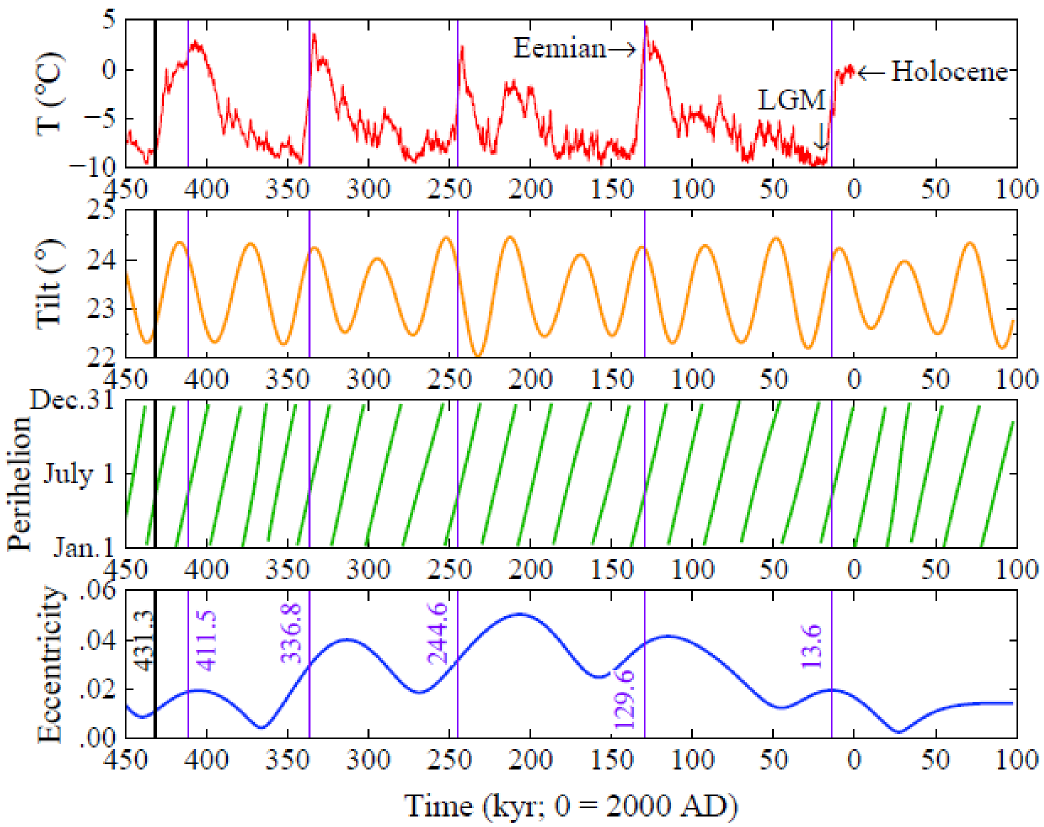

Fig. 25.4. Antarctic temperature and Earth orbital parameters (1 kyr = 1000 years). Vertical purple lines show fives cases when perihelion (Earth's closest approach to Sun) is at DoY = 135 (May 15) and the spin axis tilt is also large. LGM = last glacial maximum. Credit: orbital data from Gary Russell; temperature data from Jouzel et al. (2007).

The Eccentricity Effect increases as the orbit eccentricity increases. The Eccentricity Effect disappears as orbital eccentricity approaches zero, when Earth's orbit becomes a perfect circle.

The Antarctic ice cores reveal several ice age "Terminations," when the temperature jumped quite rapidly from ice age cold to interglacial warmth (Fig. 25.4). Northern Hemisphere ice (except Greenland) melted during these Terminations and sea level rose more than 100 meters. Terminations tend to occur when the maximum Eccentricity Effect (when perihelion occurred on DoY = 135 = 15 May) coincides with large tilt of Earth's spin axis, as was the case in the most recent four Terminations (Fig. 25.4). The interglacial occurring about 420,000 years ago is an interesting special case that we discuss below.

Eccentricity has the slowest and most complex variation of the three orbital parameters. A cyclic 100,000 year variation is superposed on a slower, 400,000 year variation discernable in the fourth panel of Fig. 25.4, as well as still slower change that we need not be concerned with. The total range of eccentricity is from near zero – a circular orbit – to about 0.068, with the maximum value in the past 400,000 years being about 0.05

Our second "orbital" figure (Fig. 25.5) examines the past 140,000 years in greater detail. The increased temporal resolution allows us to check more carefully all of the instances of maximum Eccentricity Effect, which recur at intervals of about 22,000 years.[10] We can also compare the Eemian and Holocene interglacial periods in greater detail. Sources of the data in Fig. 25.5 are given in Fig. 27 of a paper[11] that we will henceforth abbreviate as *Ice Melt (2016)*.

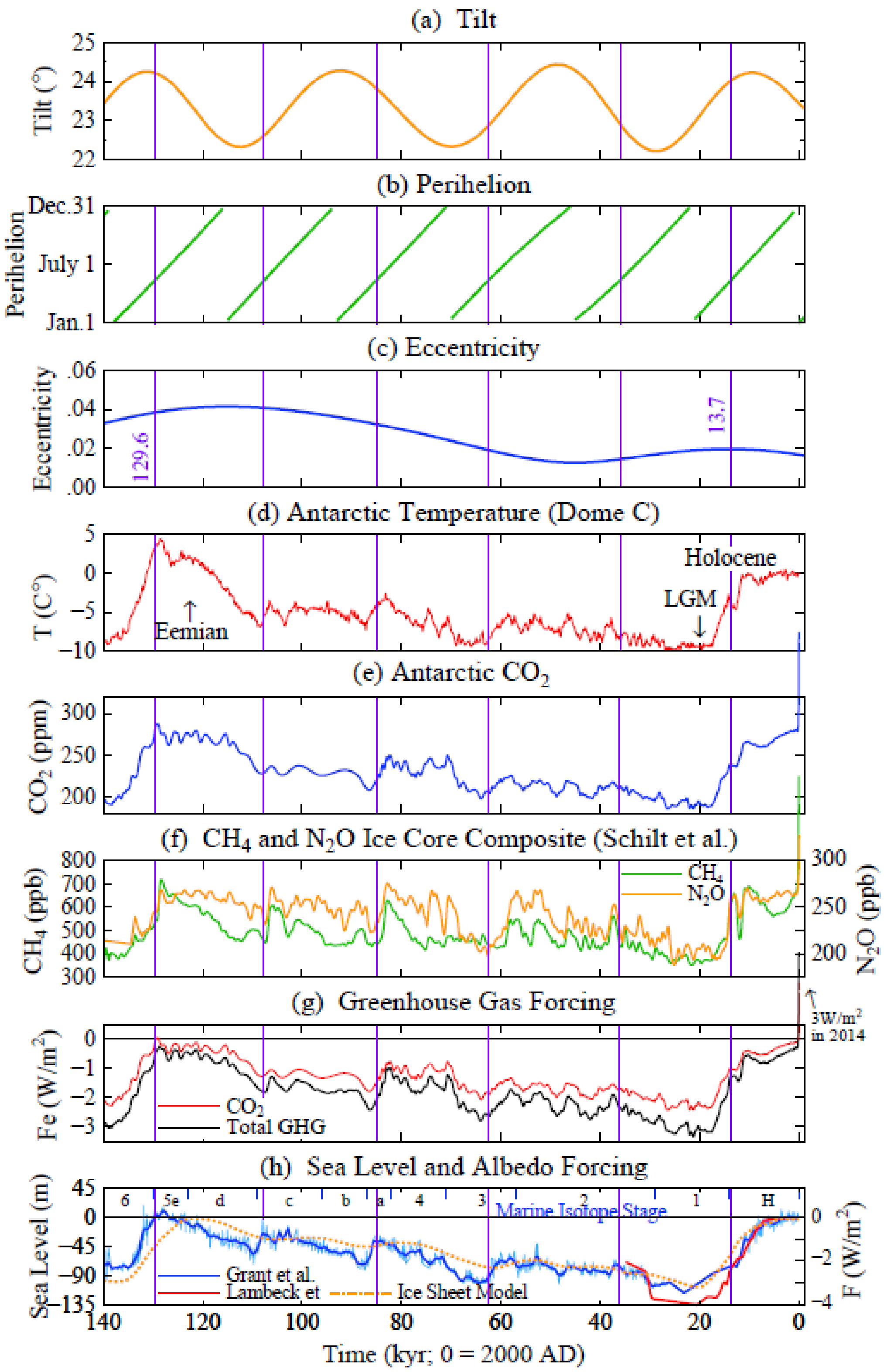

Fig. 25.5. Vertical bars are the dates when Eath's closest approach to the Sun is on 15 May. All panels use a consistent time scale[12] based on Antarctic ice cores, except panel (h) where the ocean core time scale leads to some displacements in time, especially of early dates. Greenhouse gases and surface albedo (ice sheet size) each cause maximum forcings about 3 W/m^2 over the course of a glacial-interglacial cycle. For data sources see Fig. 27 in our *Ice Melt (2016)* paper. Two extreme estimates of sea level, and thus albedo forcing, are shown for the past 40 kyr. Note failure of ice sheet model to capture rapid sea level change. ppm = parts per million, ppb = parts per billion.

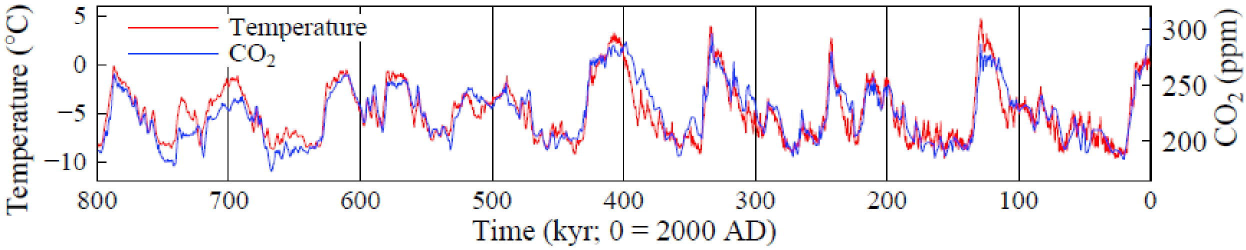

Fig. 25.6. CO_2 amount[13] and Antarctic temperature[14] relative to last 10 kyr.

Maximum Eccentricity Effect, when Earth is closest to the Sun on DoY 135 (May 15), occurs six times in the period of Fig. 25.5, as shown by vertical purple lines. Two of these six cases, at 129.6 and 13.7 kyr (thousands of years before 2000 AD), led to the Terminations that inaugurated the Eemian and Holocene interglacial periods.

Warming in the Eemian was greater than in the Holocene, as expected. The Tilt Effect was almost as large in the Holocene as in the Eemian, but the Eccentricity Effect is proportional to the eccentricity of Earth's orbit, which was 0.04 in the Eemian and 0.02 in the Holocene.

One of the four Eccentricity Effect maxima (vertical purple lines in Fig. 25.5) that failed to yield interglacial warmth – the one at about 86 kyr – had a stronger Eccentricity Effect (larger eccentricity) and a Tilt Effect almost as large as at the Termination that initiated the Holocene (panel a in Fig. 25.5). The 86 kyr orbital parameters did produce a sea level rise of about 50 meters and they also produced interglacial levels of CH_4 and N_2O, but they did not produce the atmospheric CO_2 and Antarctic temperature levels of interglacial periods.

The superficial reason that the orbital parameters at 86 kyr did not produce full interglacial warmth is that atmospheric CO_2 rose to only about 240 ppm. CO_2 is a powerful control knob for global temperature, as shown spectacularly by Antarctic ice core data [Fig. 25.6, from *Ice Melt (2016)* paper]. CO_2 is well-mixed in the global atmosphere, so measurement at a single place is relevant to the entire globe. Temperature change recorded in the ice core is valid only for Antarctica, but climate models and studies of empirical data indicate that global average temperature change on these time scales mimics Antarctic temperature change with a magnitude one-third to one-half as large as the Antarctic temperature change.

The astute scientist, stunned by the tight relation between CO_2 and temperature in Fig. 25.6, surely will ask what it implies about climate sensitivity. With the assumptions that (1) global temperature change is between 1/3 and ½ of Antarctic temperature change, (2) that surface albedo and greenhouse gases contribute equally to glacial-interglacial slow feedbacks, and (3) CO_2 is 80% of the greenhouse gas forcing, the correlation in Fig. 25.6 implies a doubled CO_2 sensitivity of 2.65-4°C – see footnote 3 of *Ice Melt (2016)*. This range is almost precisely the same as inferred in the most comprehensive modern analysis from many data sources.[15]

Figure 25.5 (g) and (h) show the climate forcings produced by changing greenhouse gases and the changing size of continental ice sheets.[16] The sum of these two forcings, multiplied by climate sensitivity ¾°C per W/m^2 (3°C for $2\times CO_2$) reproduces well the global temperature change during the entire period of ice core data, as we illustrate in a later chapter. The climate forcing produced by the 86 kyr Eccentricity Effect, despite the interglacial levels of N_2O and CH_4 that it produced, is too weak to yield interglacial global temperature, because of the low CO_2 amount. The question then becomes, why did CO_2 rise to higher levels at the Terminations that initiated the Holocene and Eemian interglacial periods?

The answer is uncertain, but likely involves carbon storage and release by the ocean. Biological and physical processes continuously transfer carbon from the atmosphere and ocean surface layers to the deep ocean. Carbon is returned to ocean surface layers and the atmosphere by ocean circulation, especially by the Southern Meridional Overturning Circulation (SMOC). SMOC – which is especially active during Terminations[17] – is the principal way that nature "ventilates" the deep ocean, bringing to the surface carbon that accumulates in the deep ocean during glacial periods, when the ocean tends to be stably stratified and thus not well-mixed. The vigor of SMOC and the length of the glacial period over which carbon accumulates in the deep ocean are potential factors in determining the post-glacial rebound of atmospheric CO_2.

These details may have seemed academic in the 1980s, when the main issue was climate sensitivity. Decades later, as the human-made climate threat became emeging reality, it would become clear that an understanding of "nuances" – such as the different climate responses in the Eemian and the Holocene – may be crucial, as humanity seeks to navigate its way back to an atmospheric composition that supports global habitability. Assistance in that quest is the aim of this book, so we will reach that topic in due course.

Greenhouse gas and surface albedo changes are described as "forcings" in Fig. 25.5. That is appropriate for calculating their contributions to global temperature change. However, to a large degree, greenhouse gas and surface albedo changes are slow, amplifying, climate feedbacks.

When Earth warms, for example, ice and snow melt and the ocean, soil and biosphere release more CO_2, CH_4 and N_2O to the atmosphere. Surface albedo darkening and greenhouse gas increase are amplifying feedbacks. When Earth cools, ice sheets grow, the ocean absorbs CO_2, and the soil and biosphere release less CH_4 and N_2O. Again, these are amplifying feedbacks.

A complication is caused by the fact that surface albedo and greenhouse gases can function as both forcings and feedbacks. In the case of glacial-interglacial oscillations it is difficult to precisely disentangle the albedo forcing and albedo feedback. Let's try to clarify the forcing and feedback roles with a specific discussion.

Forcings that drive huge glacial-interglacial climate swings are remarkably small. If atmospheric and surface properties of Earth are fixed, the changing orbital parameters yield almost no change in the amount of energy absorbed by Earth. Orbital changes in the past million years cause a global average variation in absorbed energy of only ±0.2 W/m^2.[18]

Atmospheric composition and surface albedo are not fixed, however. The ±0.2 W/m^2 global energy imbalance is not what drives glacial-interglacial climate oscillations. The drive is instead provided by the changing seasonal and geographical distribution of sunlight. At a given place, orbital changes alter seasonal radiation by as much as several tens of watts per square meter.[19]

In this example, the regional albedo increase is described properly as a climate forcing – a forcing that causes cooling. This cooling induces amplifying fast and slow feedbacks, including further increase of snow and ice cover. Long-lived greenhouse gases – CO_2, CH_4 and N_2O – spread the amplifying feedbacks globally by declining in abundance as Earth cools.

When orbital parameters drive the opposite phase – with increased incident sunlight over the ice sheet during the melting season – the ice sheet shrinks, causing warming. Fast and slow feedbacks amplify the warming. Increasing greenhouse gases spread the warming globally, reducing global snow and ice cover.

Back to the Little Ice Age (1300-1850). Was Earth, if humans played no role, headed toward the next real Ice Age? Yes it was. Both the Tilt and Eccentricity Effects are pushing Earth hard in that direction, and they will be doing so for several more millennia.

The tilt of Earth's spin axis is still "straightening up." Minimum tilt is not reached until 10 kyr in the future (Figs. 25.4 and 25.5). Thus the Tilt Effect favors ice sheet growth in the Northern Hemisphere for the next several millennia.

The Eccentricity Effect today – with Earth closest to the Sun in January – favors mild winters in the Northern Hemisphere, which promotes increased high latitude snowfall. The Eccentricity Effect also reduces summer insolation at high northern latitudes, which allows more snow to remain unmelted in the summer, so glaciers and Arctic ice caps grow. Perihelion will not reach DoY 135 (May 15), favoring Northern Hemisphere ice melt, until 7570 years in the future.

How much ice would have formed, if humans had not become climate-makers? Major ice ages, all the way to Last Glacial Maximum conditions, do not happen all at once. There is usually a stairstep procedure, as illustrated by the sea level curve in Fig. 25.5 (h) and the temperature curve in 25.5. Earth would have taken a big step down into the next major ice age during the next several millennia, if humans had not grabbed the control knob.

Loutre and Berger[20] suggested that the natural Holocene interglacial might have been extended for another 20 kyr, similar to the long interglacial 400 kyr ago. That interglacial is called Marine Isotope Stage 11 (MIS-11) based on the ocean core chronology in which it was first identified. However, as is clear from Fig. 25.4 and as recognized by Rohling,[21] Holocene orbital parameters are analogous to those of the second half of MIS-11, not the first half. When MIS-11 reached orbital parameters like those in the Holocene now, it was headed into an ice age.

The first half of MIS-11 is also easy to understand from Fig. 25.4. When optimum Late Spring insolation (Perihelion on 15 May) occurred 431.3 kyr ago, deglaciation was slow to get started (and thus Antarctic temperature was slow to rise), because Tilt was near a minimum. However, even though Late Spring Perihelion optimizes ice melt, as long as Perihelion is in Northern Hemisphere Summer ice melt is enhanced. For Perihelion to move from 15 May to the end of Summer required almost 8 kyr, during which time the Tilt was increasing rapidly, ice melt increased, and Antarctic temperature rose toward interglacial level. As Perihelion moved into a season not optimum for melt, Tilt increased to a large peak value, allowing Earth to remain in interglacial conditions. When 15 May Perihelion was next reached, 411.5 kyr ago, deglaciation proceeded rapidly and sea level achieved a maximum.

Back to the future. Humans now turn the climate control knob, for better or worse. Human impact may have begun several millennia ago.[22] In any case, humans are now in control of global climte forcing (Fig. 25.5). There will never be another Ice Age on Earth, unless humans go extinct. A single CFC factory can produce enough greenhouse gas to prevent an Ice Age.

Instead of an Ice Age, we face the need to turn back the control knob that humanity inadvertently twisted rapidly toward Hothouse Earth. We have time to turn the knob before extreme consequences occur, but we need to proceed with deliberate, informed actions during the next several decades. Further paleoclimate studies will help refine targets for atmospheric composition and clarify the urgency of corrective actions.

In summary, Earth's paleoclimate history provides a great amount of information about the climate system. From my perspective, it was clear that major progress had been made in the five years following the 1979 Charney report. Two important conclusions had emerged.

First, there was improved knowledge of the "Charney" climate sensitivity – the "fast-feedback" climate sensitivty – in which the effects of slow feedbacks such as ice sheet melting are neglected. Second, there was realization of the long delayed response of the climate system, and thus the large amount of climate change still "in the pipeline."

The Charney report estimated climate sensitivity for 2×CO_2 as 3 ± 1.5°C. This had large uncertainty, and not even the usual 95 percent confidence range. Charney explained that he meant that there was a 50 percent chance that the equilibrium global warming for doubled CO_2 was between 1.5°C and 4.5°C, with a 25 percent chance that the sensitivity was less than 1.5°C.

Five years later, with the help of paleoclimate data it was clear that climate sensitivity was high. There were uncertainties in paleoclimate data, such as the ice sheet size and tropical ocean temperatures, but the effect of uncertainties could be minimized via the constraint that Earth had to be in energy balance during both the last ice age and during the Holocene. We showed in our 1984 paper[23] for the Ewing Symposium volume that the paleo data constrained climate sensitivity to the range 2.5-5°C for doubled CO_2 with a high degree of confidence.

Our climate feedback analysis also showed why a best estimate for climate sensitivity near 3°C was consistent with an uncertainty range 2.5-5°C. Two or more amplifying feedbacks combine so as to make the upper limit very sensitive to small errors in the individual feedbacks.[24]

The second conclusion, about the delayed response of climate, had policy implications. The warming "in the pipeline," without any additional change of atmospheric composition, made a "wait and see" climate policy dangerous for young people and future generations.

The delayed response is caused, in part, by the thermal inertia of the ocean and by the fact that feedbacks come into play not in response to the the climate forcing, but rather in response to the temperature change driven by the climate forcing. This delays the full climate response to several decades and even centuries, even for fast feedbacks alone.

In addition, paleoclimate data revealed that most slow feedbacks, such as ice sheet and tundra melt, are amplifying feedbacks. Thus slow feedbacks exacerbate the delayed response issue.

So in the mid-1980s we knew enough about climate change that scientists needed to inform the public and policymakers. There were serious policy implications. It was well understood that CO_2 produced by burning fossil fuels was the principal human-made climate forcing.

Politicians had done a good job of taking care of the ozone problem. We could expect them to also do a good job in addressing fossil fuel emissions, right? That's what they are paid to do, to look after the well-being of the public, right?

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[3] https://commons.wikimedia.org/wiki/File:Post-Glacial_Sea_Level.png

[4] Crutzen, P. J. and Stoermer, F. F.: The "Anthropocene", *IGBP Newsletter*, **41**, 12–14, 2000.

[5] There are spikes in the paleo record in which the amount of CO_2 in the air "suddenly" increased, for example, the Paleocene-Eocene Thermal Maximum (PETM), which occurred more than 50 million years ago, as discussed in my first book, *Storms of My Grandchildren*, 320 pp., Bloomsbury, New York, 2009. During the PETM atmospheric CO_2 at least doubled, probably due to the melting of methane hydrates on continental shelves or permafrost on Antarctica, or both, but the PETM CO_2 increase occurred over a few millennia, while the equivalent human-made increase of greenhouse gases is occurring over 1-2 centuries, at least 10 times faster than the natural change.

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[10] Perihelion DoY = 15 May occurred 129.6, 107.6, 85.0, 62.5, 36.0 and 13.7 kyr before year 2000 AD, and the next one will be 7.6 kyr in the future. The corresponding intervals are 22.3, 26.5, 22.5, 22.6, 22.0, and 21.3 kyr.

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[16] A record of sea level change for this era is used to infer the changing size of large ice sheets, which in turn allows calculation of the albedo forcing. Details are given in the Supplementary Material of our *Target CO_2 (2008)* paper.

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[18] See Fig. S3 in Supplementary Material of Hansen, J., M. Sato, P. Kharecha, D. Beerling, R. Berner, V. Masson-Delmotte, M. Pagani, M. Raymo, D.L. Royer, and J.C. Zachos, 2008: Target atmospheric CO_2: Where should humanity aim? *Open Atmos. Sci. J.*, **2**, 217-231

[19] See Figure 5.19 of http://www.climate.be/textbook/chapter5_node12.xml

[20] Loutre and Berger (Marine Isotope Stage 11 as an analogue for the present interglacial. Global Plan. Change, 36, 209-217, 2003) suggest that the Holocene could be prolonged, like the interglacial 400 kyr ago. However, when orbital parameters of that interglacial mimicked those today, Earth was headed into the next glacial time (Fig. 25.4).

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