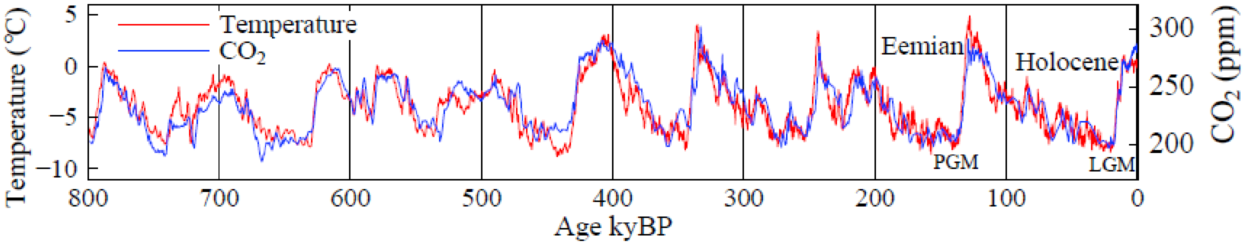

Fig. 25.1. Atmospheric CO_2[1] and Dome C Antarctic temperature[2] relative to last 10 kyr. LGM and PGM are the last and the prior glacial maxima; Eemian is the prior interglacial.

Chapter 25. Paleoclimate and "Slow" Feedbacks

Earth's climate undergoes huge, natural, swings. Civilization developed in the Holocene, an interglacial period of benign climate, now 11,700 years long (Fig. 25.1). Yet "only" 20,000 years ago, during the Last Glacial Maximum (LGM), so much water was locked in ice sheets that sea level was 400 feet (120 m) lower than today – people could walk from Asia to North America across a wide land bridge (Chapter 1). Hays *et al.*[3] showed that the climate oscillations correlate with small perturbations of Earth's orbit, caused by gravitational tugging on Earth by the heavy planets, Jupiter and Saturn, and by tidal forces exerted on Earth by the Sun and Moon. Orbital perturbations have little effect on the amount of sunlight striking Earth, but they alter the seasonal and geographical distribution of sunlight, thus spurring two "slow"[4] climate feedbacks: change in the area of reflective ice and snow, and change in the amount of greenhouse gases (GHGs) in the air. These feedbacks result in the large global climate oscillations in Fig. 25.1.

Climate swings between glacial and interglacial conditions contain a treasure of information that helps illuminate how the climate system works. The changing amounts of atmospheric CO_2, CH_4 and N_2O are known precisely for the past 800,000 years, based on the composition of air bubbles that were trapped in the Antarctic ice sheet, as the ice sheet built up from snowfall and compressed into ice. Knowledge of changes of these stable gases in Antarctica tells us their global history to high accuracy because Earth's atmosphere mixes globally within a few years.

Global temperature is harder to measure because temperature varies geographically. Also, most temperature estimates are based on proxies, i.e., quantities that yield an indirect measure of temperature. For example, Antarctic temperature in Fig. 25.1 is based on hydrogen and oxygen isotopes in an ice core. A more direct measure of past Antarctic temperature was obtained recently by measuring ice temperature through the depth of the borehole of the 800,000-year ice core.[5] Today's ice temperature retains a measure of ice temperature when the ice formed millennia ago due to the low conductivity of heat in ice. The borehole temperatures suggest that the proxy temperature measurements in Fig. 25.1 overestimate Antarctic temperature change by a factor of two or more. This still-debated scale change for Antarctic temperature, *per se*, has limited effect on estimated global temperature change because the Antarctic continent covers only 2.8% of the globe. Instead, because ocean covers 70% of Earth's area, global temperature change depends mainly on uncertainty about sea surface temperature change (Chapter 23).

The Holy Grail of climate research – Charney's equilibrium climate sensitivity (ECS) – has remained elusive. For several decades the average ECS from climate models was near 3°C for 2×CO_2, as the models included only modest cloud feedback that amplified the fixed-cloud ECS of ~2.4°C for 2×CO_2 (Chapter 23). In recent years several GCMs incorporating more realistic

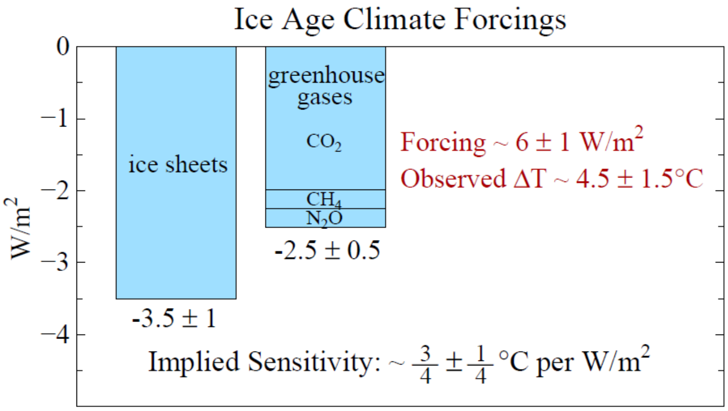

Fig. 25.2. LGM cooling of 4.5°C implies a sensitivity ~3°C for 2×CO_2 (4 W/m^2) forcing.

cloud microphysical processes find ECS ~4-6°C for 2×CO_2, as we will discuss in a later chapter. However, models alone are unlikely to yield a precise ECS because of the complexity of clouds and inherent uncertainty about whether all feedback processes are included in GCMs.

ECS can be defined precisely, if global temperature change between glacial and interglacial times is known. Glacial climates such as the LGM (20 ky ago, ky = kiloyears) and interglacial climates such as the mid-Holocene (prior to substantial human-made effect) were in equilibrium; Earth was in energy balance and global temperature was stable (Fig. 25.1). Forcings maintaining glacial-interglacial temperature change were surface albedo (reflectivity) change due to ice sheet area change and GHG changes. The forcings and their efficacies[6] are defined by straightforward calculations; the forcing change between the LGM and Holocene totals ~6 W/m^2. Thus, ECS would be ~3°C for 2×CO_2, *if* the LGM cooling were 4.5°C (Fig. 25.2).

The great potential to achieve Charney's holy grail via comparison of glacial and interglacial equilibrium states lay dormant for 40 years. A recent analysis[7] concludes that the LGM was actually 6-7°C colder than the Holocene, as we will discuss in a later chapter. Thus, ECS is likely in the range 4-5°C. High sensitivity has profound implications that we must explore, but the discussion in the remainder of this chapter is independent of whether ECS is ~3°C or higher.

Glacial-interglacial ice sheet and GHG changes are slow, amplifying, feedbacks. Warming climate melts ice and snow, exposing a darker surface that absorbs more sunlight, increasing the warming. Warmer climate also drives greater amounts of long-lived GHGs – CO_2, CH_4 and N_2O – into the air. These albedo and GHG amplifying feedbacks are understood, at least qualitatively. Charney's decision to ignore the ice sheet and GHG feedbacks was a stroke of genius, as it left a tractable problem that could be addressed with existing global climate models (GCMs), which became the focus of climate research and the principal tool of the Intergovernmental Panel on Climate Change (IPCC) in its role as the scientific advisory body for the United Nations. The broad scientific research community soon recognized the importance of the slow feedbacks that Charney had set aside, and thus introduced the concept of Earth System Sensitivity[8] (ESS) to include the feedbacks that Charney had ignored in defining ECS.

Still, the IPCC kept its focus on GCMs, ECS, the projected level of human-made global warming in 2100, and consequences of the warming in 2100. Less attention was paid to the implications of the 2100 warming for people and nature living beyond 2100, including effects locked in for today's young people, their children, and their grandchildren.

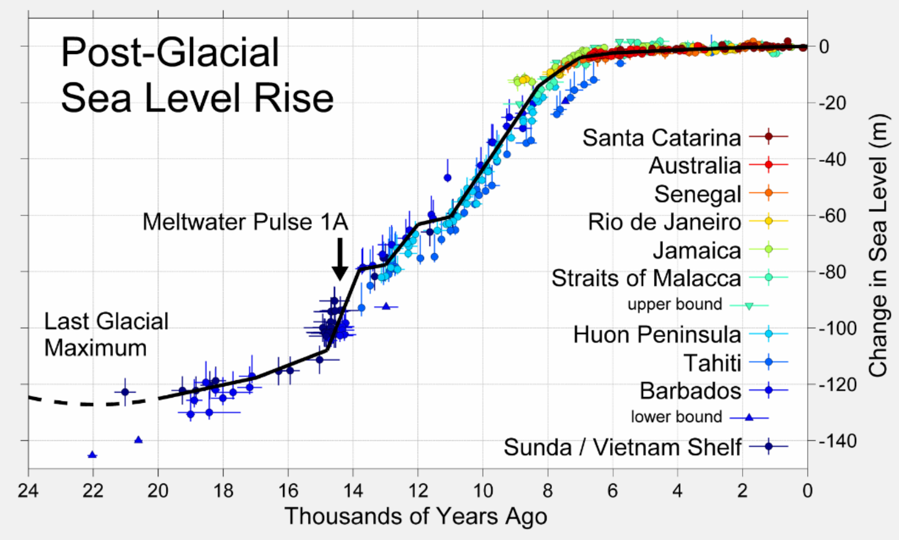

Fig. 25.3. Sea level since the last glacial period relative to present. Credit: Robert Rohde[9]

Sea level rise is the most crucial delayed response of climate that we must convey to the public and policymakers for the sake of future generations. Yet IPCC early on created the impression that large sea level rise is not a major issue for today's young people. Potential sea level rise in 2100 was estimated as a few tens of centimeters, enough to be a nuisance for some coastal communities, but not a global threat. Paleoclimate data tell a very different story.

Sea level rose 120 m (400 feet) as Earth warmed after the last ice age (Fig. 25.3), but the sea level rise occurred over 10,000 years. Does that mean 10,000 years are needed to melt a large ice sheet? Surely not. Instead, that melt period reflects the long timescale for change of the weak paleoclimate forcing that caused the climate change and ice melt. Even this slow, weak, forcing caused an average rate of sea level rise of 1.2 m (4 feet) per century, and during Meltwater Pulse 1A (Fig. 25.3), sea level rose about 20 meters in 500 years, thus 4 meters (13 feet) per century.

Are today's ice sheets less vulnerable than the Laurentide ice sheet, the large North American ice sheet 20,000 years ago, which extended down to middle latitudes? No, at least not the parts of the Antarctic and Greenland ice sheets that rest on bedrock below sea level. Direct contact with the ocean makes the ice sheets vulnerable to erosion by a warming ocean. Humanmade climate forcing is growing more than 10 times faster than any known forcing in Earth's history. Therefore, understanding the sea level rise threat will require all of our tools: information from Earth's paleoclimate history, observations of ongoing climate processes, and modeling.

The remainder of this chapter discusses causes of the remarkable glacial-to-interglacial climate oscillations that characterize Earth's recent history. This topic may be challenging for the non-scientist, but it is needed to glean insight about ice sheet stability and prospects for rapid sea level rise. If you choose to peruse this section, you can earn your PHD[10] award.

Milutin Milankovitch, a Serbian geophysicist and astronomer, building on a 19th-century hypothesis of James Croll and Joseph Adhémar, proposed in the 1920s that glacial-to-interglacial climate oscillations are caused by perturbations of Earth's orbit. Hays *et al*.[3] confirmed the essence of the orbital theory by showing that climate-driven periodicities in ocean sediment cores match the periodicities of Earth's orbital changes.

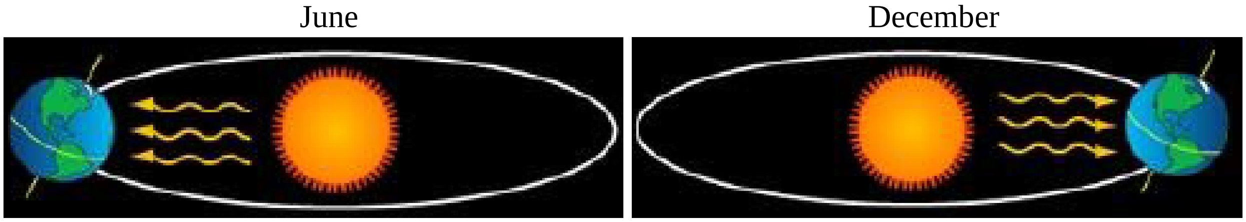

Fig. 25.4. Tilt of Earth's spin axis causes the seasons

Paleo analyses involve three orbital parameters: 1) **Tilt** (also called obliquity) of Earth's spin axis relative to Earth's orbital plane, 2) **Eccentricity** of Earth's orbit, which is slightly elliptical, 3) **Precession** of the spin axis, which wobbles like a top. Let's avoid complex geometry via a slight reframing of the problem in terms of the quantities that affect climate – the geographical and seasonal distribution of sunlight on Earth. Orbital perturbations give rise to two effects.

Effect #1, Tilt effect: tilt of the spin axis causes the seasons (Fig. 25.4) 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 tilt (24.5°) and back to minimum in about 40,000 years (2nd panel in Fig. 25.5). When the spin-axis tilt is larger, high latitudes in both hemispheres receive increased insolation, thus tending to melt high-latitude ice sheets. Today the tilt is 23.4°, but decreasing – the spin axis is "straightening up." This favors growth of ice sheets, because insolation at high latitudes is decreasing.

Effect #2, Perihelion effect depends on two orbital parameters, eccentricity and precession. Effect #2 exists only because Earth's orbit is not a circle. Eccentricity of Earth's orbit today is about 0.02, so when Earth is at perihelion – closest to the Sun – it is about three million miles (five million kilometers) closer to the Sun and receiving 6.8 percent more solar radiation (insolation) than it does at its greatest distance from the Sun.[11]

Perihelion today is on 3 January, but perihelion marches slowly through the calendar. It takes more than 50 years for perihelion to advance one day (to 4 January), and more than 20,000 years for perihelion to advance through the full calendar. This slow advance of the day of year (DoY) of perihelion is related to precession of the spin axis, which takes about 26,000 years for a complete revolution. However, in addition, the elliptical orbit itself precesses. Combination of these two precessions is complex, but we need not be concerned about the geometry. What climate cares about is the day-of-year when Earth is closest to the Sun. The continuous advance of that date through the year is relatively simple, as shown in the 3rd panel of Fig. 25.5.

Hold on! Don't give up. Just one more technical thing: "albedo flip," a snow/ice process that affects ice sheet stability and global climate.[12] If a snow/ice surface begins to melt, it becomes darker – its albedo (reflectivity) decreases from 80 percent to 40 percent or less. The earlier the albedo flip, the longer the melt season. Perihelion in early spring causes the longest melt season and greatest melt. For the Northern Hemisphere ice sheets of interest, greatest melt occurs with perihelion near May 15, which is DoY = 135. Now we can discuss terminations.

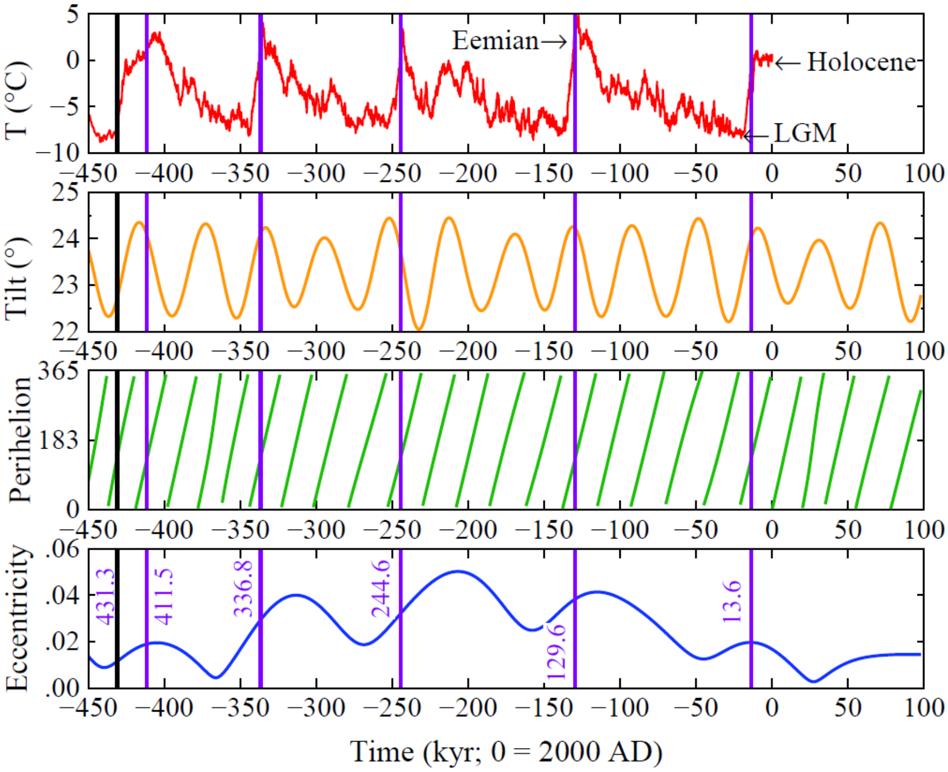

Fig. 25.5. Antarctic temperature and Earth orbital parameters (1 kyr = 1000 years). Vertical purple lines show five cases when perihelion (Earth's closest approach to Sun) is at DoY = 135 (May 15) when also the spin axis tilt is large. LGM = last glacial maximum. Credit: orbital data from Gary Russell; temperature data from Landais *et al*. (2021).[2]

Terminations. Wally Broecker, again, was the straw that stirred the drink – at least one of the straws. When a leading scientist writes a paper[13] with a one-word title, *Terminations*, it helps draw attention to a topic – specifically to the several cases, at intervals of about 100,000 years, in which climate went rapidly from extreme glacial conditions to a warm interglacial period (top panel of Fig. 25.5). Northern Hemisphere ice sheets (except Greenland) melted during the terminations and sea level rose 100 meters (330 feet) or more.

Terminations occur when the Tilt and Perihelion effects are in sync, so that both effects promote ice melt in the Northern Hemisphere. Each of the two effects has a cycle in which its forcing of ice sheet melt or ice sheet growth changes slowly over millennia. For example, the tilt increases from its average value (when its effect on ice sheet size is neutral) to maximum tilt in about 10,000 years, decreases over 10,000 years back to neutral effect, and goes through 20,000 years with a smaller tilt that favors ice growth in both polar regions. The fastest orbital forcing (the Perihelion effect) grows from neutral to maximum melt in 5,000 years and decays to neutral in another 5,000 years. The magnitude of the Perihelion effect is modulated by (proportional to) the eccentricity of the orbit, as the effect disappears with a circular orbit.

Termination I, which ushered in the Holocene, provides an example. Peak surface melt rate on Northern Hemisphere ice sheets is at 13.6 kyBP, but positive orbital forcing and ice sheet decay began 5 ky earlier. Orbital forcing operates by altering surface albedo and GHGs, mainly CO_2. By 14.6 kyBP, CO_2 had increased from 188 ppm at glacial maximum to 228 ppm, causing a 1.1 W/m^2 GHG forcing (Fig. 25.6). Ice sheet albedo decrease (see sea level rise, Fig. 25.3) likely

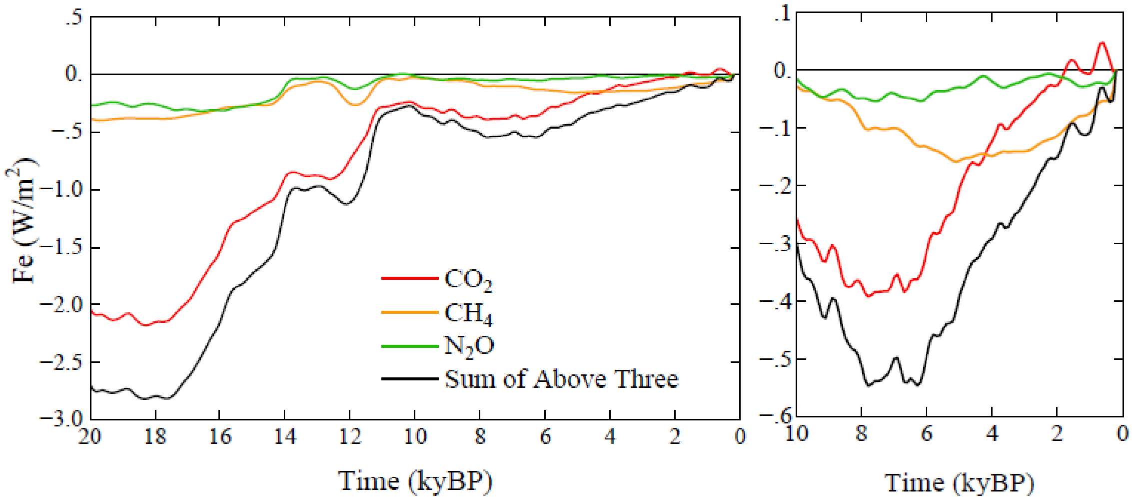

Fig. 25.6. GHG climate forcing in past 20 ky with vertical scale expanded for the past 10 ky on the right. GHG amounts[14] and formulae for their effective forcings[7] are published.

doubled the orbitally-driven forcing to about 2 W/m^2. This 2 W/m^2 forcing was enough to drive ice sheet collapse at 14.6 kyBP, producing Meltwater Pulse 1A,[15] with about 20 meters (65 feet) of sea level rise in 500 years. The main ice sources were the North American and Scandinavian ice sheets,[16,17] presumably the marine-abutting portions susceptible to rapid collapse.

The Holocene is not quite as warm as the three prior interglacials (top panel, Fig. 25.5), due to the present small eccentricity of Earth's orbit (bottom panel, Fig. 25.5), as the Perihelion effect is proportional to eccentricity. Holocene temperature remained stable after the Perihelion effect began to decline at 13.6 kyBP because the Tilt effect (second panel, Fig. 25.5) was still increasing. After the Tilt effect peaked at 10 kyBP, the Northern Hemisphere should have begun to cool, causing the slow feedbacks – GHGs and surface albedo – to begin to push the climate toward the next ice age. Indeed, the Northern Hemisphere did begin to cool and global GHGs began to decrease, but six or seven thousand years ago the GHGs reversed course and began to increase slowly. Holocene climate remained stable. This GHG reversal (Fig. 25.6) was probably a human-made effect,[18,7] as we will discuss in a later chapter.

Other terminations and interglacial periods can be understood with similar considerations, even the unusual, long, Holstein interglacial about 400 kyBP.[19] The Holstein stretched over two Perihelion cycles connected by a strong Tilt cycle, with the help of the 10,000-year half-width of the warming portion of the Tilt cycle. Oh, my!! Why are we getting into the weeds, especially when the weeds are still being debated today? Because it provides an example of the way that science works. To use a more noble vegetation for the metaphor: scientists must work to understand trees, as they strive to see the forest for the trees.

Struggle to understand climate detail makes it difficult to communicate with the public. Albert Einstein was disgusted with media reports that "give the lay public misleading ideas about the character of research. The reader gets the impression that every five minutes there is a revolution in science, somewhat like the *coup d'etat* in some of the smaller unstable republics."[20] Einstein knew that new details on a tree seldom revolutionize our understanding of the forest, yet reports confuse the public and facilitate people who wish to profit from public confusion. We scientists, as well as the media, need to do a better job of describing the forest – but it is a hard job.

The forest had emerged from the trees by the 1980s, with the help of paleoclimate data. First, paleo data confirmed Charney's conclusion that climate was sensitive; indeed, paleo data favored high climate sensitivity, 2.5-5°C for doubled CO_2 (Chapter 17). Second, orbital changes were only the pacemaker of the ice ages: the chief mechanisms of climate change were CO_2 change and surface albedo change. Third, humans were now the driver of climate change; we had taken control of atmospheric CO_2 amount, overwhelming its natural variations.. Fourth, the delayed response of climate had emerged as a major complication, as, in words of E.E. David at the Ewing Symposium (Chapter 23) "…where there is such a long delay, the system breaks down, unless there is anticipation built into the loop."

So, by 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 understood that CO_2 from fossil fuels was the main human-made climate forcing, and it was reaching levels that would, eventually, have enormous consequences. 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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[1] Luthi D, Le Floch M, Bereiter B *et al*. High-resolution carbon dioxide concentration record 650,000-800,000 years before present. *Nature* **453**, 379-82, 2008

[2] Landais A, Stenni B, Masson-Delmotte *et al*. Interglacial Antarctic-Southern Ocean climate decoupling due to moisture source area shifts. *Nature Geosci* **14**, 918-23, 2021

[3] Hays JD, Imbrie J, Shackleton NJ. Variation in the Earth's orbit: pacemaker of the ice ages. *Science* **194**, 1121-32, 1976

[4] Footnote: At the Charney and Ewing meetings it was assumed that ice sheet and GHG feedbacks were slow enough to ignore on time scales of a century or less. Our occasional quotes on "slow" are a reminder that such an assumption is dubious, especially for strong human-made forcings.

[5] Buizert C, Fudge TJ, Roberts WHG *et al*. Antarctic surface temperature and elevation during the Last Glacial Maximum. *Science* **372**,1097-101, 2021

[6] Hansen J, Sato M, Ruedy R *et al*. Efficacy of climate forcings. *J Geophys Res* **110**, D18104, 2005

[7] Hansen J, Sato M, Simons L *et al*. Global warming in the pipeline. *Oxford Open Clim Chan* **3(1)**, doi.org/10.1093/oxfclm/kgad008, 2023

[8] Lunt DJ, Haywood AM, Schmidt GA *et al*. Earth system sensitivity inferred from Pliocene modelling and data. *Nature Geosci* **3**, 60-4, 2009

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

[10] Footnote: Piled higher and deeper, which is about all that professional scientists can claim.

[11] Eccentricity 0.02 is so small that the orbit looks almost like a perfect circle. However, at closest distance to the Sun, i.e., at perihelion, Earth is more than 2% closer to the Sun than it is at its greatest distance. The amount of solar energy on a unit area on Earth is proportional to the square of the distance from the Sun. Earth's orbit will become closer and closer to a perfect circle in the next 25,000 years (Fig. 25.5).

[12] Hansen J, Sato M, Kharecha P et al.: Climate change and trace gases. *Phil Trans Royal Soc A* **365**, 1925-54, 2007

[13] Broecker WS. Terminations, in *Milankovitch and Climate*, Part 2, Eds A Berger *et al*, pp 687-98, D. Reidel, Norwell, MA, 1984

[14] Schilt A, Baumgartner M, Schwander J *et al.* Atmospheric nitrous oxide during the last 140,000 years. *Earth Planet Sci Lett* **300**, 33-43, 2010

[15] Fairbanks RG. A 17,000-year glacio-eustatic sea level record: influence of glacial melting rates on the Younger Dryas event and deep-ocean circulation. *Nature* **342**, 637–42, 1989

[16] Brendryen J, Haflidason H, Yokoyama Y *et al*. Eurasian ice sheet collapse was a major source of Meltwater Pulse 1A 14,600 years ago. *Nature Geosci* https://doi.org/10.1038/s41561-020-0567-4, 2020

[17] Lin Y, Hibbert FD, Whitehouse PL *et al*. A reconciled solution of Meltwater Pulse 1A sources using sea-level fingerprinting. *Nature Comm* https://doi.org/10.1038/s41467-021-21990-y, 2021

[18] Ruddiman WF, Fuller DQ, Kutzbach JE *et al.* Late Holocene climate: natural or anthropogenic? *Rev Geophys* **54**, 93-118, 2026

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[19] The Holstein interglacial was initiated by Termination V (terminations are given Roman numerals increasing backward in time). The perihelion drive, centered at 431.3 kyBP, would not have raised Holstein temperature even to the Holocene level, except for the overlapping drive of the tilt effect: as the weak perihelion drive declined, the growing tilt effect maintained the weak warming. As the next perihelion peak (at 411.5 kyBP) approached, the tilt and perihelion effects were in sinc and powered the strong Holstein interglacial, which was thus unusually extended.

[20] Bernstein, J. *The New Yorker*, 5 November 1990, p. 154.