Chapter 24. Deep Water and Two Angels

It was a stressful time. When research funds dry up, government labs survive via their civil service positions, with salaries supported by "hard" government funds. The Goddard Institute for Space Studies, however, had few civil service positions. Most of our researchers, students, and computer programmers were employed either on our cooperative agreements with Columbia University or our support services contractor staff. Their salaries were paid with "soft" research funds, which we had to obtain by writing research proposals.

High potential candidates Inez Fung and Tony Del Genio would have been hired quickly into civil service jobs in any other government laboratory, thus freeing up the soft money that was being used to pay their salaries. Inez was not yet a U.S. citizen, so Tony was our best bet to be approved for civil service hire, but Meredith, the Director of Earth Sciences at Goddard Space Flight Center, to whom I reported, rebuffed my request. Meredith made no bones about it: we could expect generous support only if we moved to Greenbelt.

John Hoffman of EPA provided funding to us in 1982 in return for our help in preparing an EPA report, *Can We Delay A Greenhouse Warming* published in 1983. That report was not welcomed by the Reagan Administration. We lost most of our EPA funding.

Our costs had to be cut. I called a staff meeting to discuss the GISS tax, the money collected from every researcher who had a grant – a funded project. NASA institutional funds paid some of our administrative costs, but our researchers were required to pay part of our unique costs, such as the need for our own library and computer operations.

The tax rate was rising. One item that stood out like a sore thumb was the Broecker tax, which had risen to more than $80K, the funding required in those days to cover the full costs of three of Broecker's graduate students. Broecker's students were not involved with research at GISS. If we kept our money, rather than give it to Broecker, it could alternatively cover the costs of one of our scientists and a graduate student working at GISS.

There was no real debate. A grumble: "Can't Wally write his own proposal?" Proposal writing is difficult and results are uncertain; why should our limited proposal success be used to support an outside scientist? It was not that simple, though. We wanted to have good relations with Columbia, with Lamont, and with Broecker in particular.

There was another complication. The same cooperative agreement funding Broecker's students was used to pay the salaries of some Columbia research scientists, including Inez Fung, who were working mainly at GISS. We did not want their status to be affected. However, we concluded that the Lamont Director would want to retain these research scientists for multiple reasons, including a pecuniary one: Columbia and Lamont collected overhead on their salaries.

A crisis and stalemate followed when I informed Wally that, beginning the next year, we would no longer be providing funds to him. Broecker promptly wrote a 4-page memo addressed to Barry Raleigh, the Director of Lamont, with a cover note to me: "Jim, Unless you object, I will send this to Barry. Wally"

The bottom line of Wally's memo to Raleigh was "I have decided not to accept the offer to direct the Climate Center. Please put a hold on the publicity people until a new candidate has been selected." This was with reference to the newly planned Center for Climate Research. Columbia and Lamont public relations people were planning a press conference to be held in Low Library on the main campus, to announce the new Center. The Center would be housed at Lamont, but was described as "In Cooperation with Goddard Institute for Space Studies (NASA)."

Wally's memo explained his decision: "It would tie my tongue. At least part of Jim Hansen's unhappiness in connection with our funding arrangement has to do with my criticism of some of his people." His memo went on to criticize Michael Rampino, Inez Fung and Vivian Gornitz, scientists who spent most of their time at GISS, while employed by Columbia on the cooperative agreement between GISS and Lamont. His rationale for rejecting the directorship was that he wanted to be free to criticize unfettered by the "politics" that a Director must consider.

Wally's invented reason for my funding decision was nonsense and his criticisms of these people, who were all capable scientists, were not valid. Inez Fung, for example, was a broad thinker, articulate, with Charney-trained credentials, a future star and member of the National Academy of Sciences. Mike Rampino had accepted an offer from New York University and was leaving Lamont – and Wally knew that. The memo made sense only as a threat to me. Wally was putting the Director of Lamont in an awkward spot – Broecker was the only conceivable choice to head the Climate Center.

Why mention such stuff? It's a picture of reality. Science is not a walk in a rose garden. Science is not simply the pleasure of finding things out. Reality includes struggle and competition that can lead to tension that hampers research. Better diplomacy and communications skills would have helped to minimize problems, but those skills were not in my toolkit.

I never showed Wally's memo to anyone. I still have it, in Wally's longhand, with his various scratch-offs and insertions. I never answered it. I was not about to compromise on the funding issue. Fortunately, Columbia had found an exceptional Director for Lamont in Barry Raleigh, who soothed the waters by encouraging GISS and Lamont seminar exchanges. Nevertheless, we were in standoff, with the Center for Climate Research put on hold.

Heaven seemed to be looking out after us at GISS, though, and sent two angels. Angel #1 had already arrived, but I did not recognize her as an angel. Later I concluded that she might have been like the angel in *It's a Wonderful Life* -- she had not yet won her wings.

Ruth Levenson called soon after she arrived at Columbia in the fall of 1982 as an Associate Provost for Special Projects. I should have guessed right off the bat that she was an angel. She seemed to have no clear purpose. She had been trained in music and nursing and had been around the block, working in Israel and Europe, speaking several languages fluently.

She was looking for something good to do. Was there something that NASA could do with the University, preferably with multiple departments? Yes, I had a suggestion – research in global change and global habitability. I gave her a copy of the report from the Woods Hole workshop.

Ruth had energy, love of people, and a special talent in organizing seminars. Immediately the idea of a Global Habitability Seminar came up. We went together to see Dean Pickering of the School of International Affairs. The International Affairs building had a large seminar room overlooking the campus – the perfect place for the seminar.

Ruth went straight to the top. She got meetings with Hans Mark, NASA Deputy Administrator, and Noel Hinners, Goddard Director. They liked the seminar idea. It might help NASA define a Global Habitability program and gain support for it. Hans Mark agreed to provide financial support from NASA for a monthly Global Habitability seminar beginning in the fall of 1983.

Ruth and I met for lunch at the Symposium Restaurant to plan the first few seminars. Hans Mark agreed to give the first seminar in September 1983. We would invite Wally Broecker to give the October seminar, on climate change. The November seminar would be on deforestation.

The second angel arrived in early 1984. Again there was no way to recognize that he was an angel. He was optimistic and good-natured; he joked that at the end of the day it was "time to belly up to the bar." He looked like he was very good at that. Maybe he was not a real angel.

Frank Martin was the Director of the newly formed Space and Earth Sciences Directorate at Goddard. NASA science had been reorganized. Somebody at the top – I assumed that it was Hans Mark – decided that Earth Sciences would gain by integration with Space Sciences.

What a great idea. I would report to angel Martin, with easy access to his deputy, Jim Trainor. There was a sudden change in the climate at GISS, a burst of fresh air, a salubrious breeze that swept over us. Martin evaluated our work favorably.

Martin's biggest impact was on our "hard money" (civil service) staff. Our most recent hire of a scientist on civil service was David Rind in 1979. Martin allowed us to hire civil servants the same as if we were a Goddard division located in Greenbelt. GISS was no longer under siege from the south. I suggested to Anniek that it was a good time to make a large pot of hutspot.[1]

Frank Martin and his deputy, Jim Trainor, were throwbacks to the old can-do NASA. No half-day staff meetings at Goddard. A crisp one-hour staff meeting, a one-on-one meeting with Frank or Jim, and then I was on my way back to New York. They understood science and supported it.

Following Martin's first Space and Earth Sciences staff meeting in Greenbelt, I met with Jim Trainor and discussed the need for research funding at GISS. Trainor had an instant suggestion. The Goddard Director, Noel Hinners, had been given a new pot of money, a "Director's Discretionary Fund (DDF)," seed money to support promising ideas in science and technology.

DDF funding would be a one-time shot, so it could not fund a continuing research program, but it gave me an idea. Several months earlier, when we were initiating the Global Habitability seminars, Wally Broecker had suggested, instead, a series of mini-workshops, 2-3 days each on specific science problems. Ruth Levenson would have nothing of it. Ruth was a tough cookie and would not be bullied; she carried out the Seminars as we had decided.

However, Wally's suggestion of mini-workshops was also a great idea. DDF funding could cover the cost of a single workshop. A productive workshop might help advance the idea of a continuing series of workshops, which could help define a global change research program.

Wally was so widely respected internationally that an invitation from him would attract the top dozen or so scientists needed for interdisciplinary brainstorming on a hot topic. Workshop organization is a big task, but with $50K from the DDF fund we could hire a post-doc part-time to help with organization and still have enough money to pay participant travel costs.

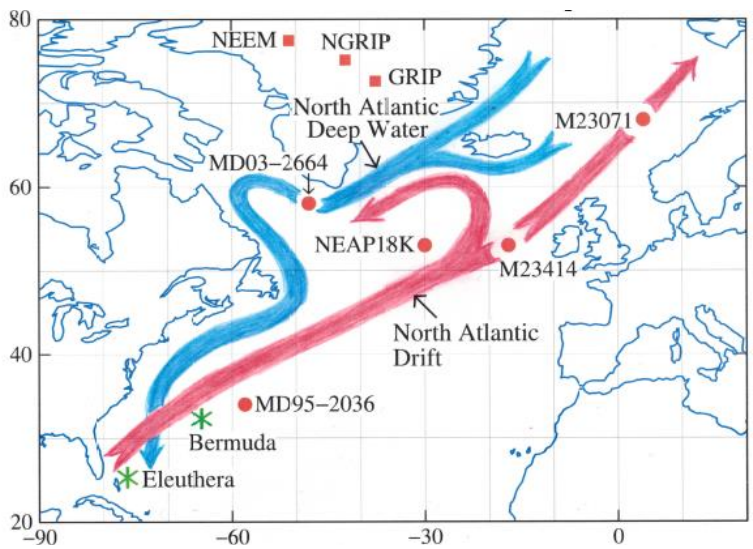

Fig. 24.1. Simplified sketch of the upper ocean North Atlantic Current and North Atlantic Deep Water return flow. Some of the ice core and ocean core drill sites are indicated.

North Atlantic Deep Water Formation was Wally's choice for the workshop topic. It was a hot topic because of unusual recent data from Greenland ice cores. Ice cores, extracted from the Greenland and Antarctic ice sheets, were still relatively new in 1984, but it was realized that they contained a lot of potential information about paleoclimate, Earth's ancient climate.

The center of the ice sheets is too cold for melting, so snow keeps piling up. As the snow piles up, it compresses into ice, trapping bubbles of ancient air. By extracting a core of the Antarctic ice, we can sample bubbles of ancient air going back at least 800,000 years.

These bubbles provide an invaluable, precise record of the changing atmospheric composition of stable gases, including carbon dioxide (CO_2) and methane (CH_4) for a period of almost a million years. The amount of the third most important stable greenhouse gas, nitrous oxide (N_2O), is also recorded, but the amount of N_2O is altered by chemical reactions with dust in those periods when the polar air was especially dusty.[2]

Greenland is warmer than Antarctica. Greenland largely melted during the Eemian period, 120,000 years ago, so its best data is post-Eemian, but that still allows a good record for more than 100,000 years. The emerging Greenland ice core data were puzzling, to say the least.

Willi Dansgaard (Denmark) and Hans Oeschger (Switzerland) presented data from the joint American-Danish-Swiss Greenland ice sheet program at the 1982 Ewing Symposium.[3] The oxygen and hydrogen isotopes in the ice preserved a record of atmospheric temperature at the time of snowflake formation and the air bubbles recorded atmospheric CO_2, CH_4 and N_2O.

Greenland climate fluctuated rapidly many times, based on the ice core records. Temperature changes of several degrees Celsius occurred in periods as short as a few decades or less. Atmospheric CO_2 also seemed to experience rapid changes during the warmer times, but it was suspected that the CO_2 changes were an artifact of surface melt in those warm periods.

Antarctic ice cores eventually proved that rapid atmospheric CO_2 changes did not actually occur. CO_2 is well-mixed globally, so changes would need to occur also in Antarctica, if they were real. However, the rapid Greenland temperature changes were real and they begged an explanation.

Wally Broecker was perceptive to focus attention on the North Atlantic Ocean. The North Atlantic is a gateway to the deeper ocean. The North Atlantic is the saltiest of the major ocean basins. Therefore in the winter, as the surface ocean cools and approaches the freezing point, the North Atlantic water becomes very dense and sinks toward the ocean bottom.

After sinking, this dense North Atlantic Deep Water moves south, as indicated by blue arrows in the simplified sketch (Fig. 24.1), filling the lower half of the North Atlantic Ocean. This southward transport is balanced by northward transport of warm water, including the Gulf Stream, in the upper half of the ocean (red arrows). Heat carried by this ocean flow, and heat carried by prevailing atmospheric winds from the southwest, keeps Europe warmer than would otherwise be expected, given its high latitude.

Wally suspected that changes in North Atlantic Deep Water formation were key to understanding climate changes on Greenland and possibly in the rest of the world. We devised a focused question for the workshop: “What controls the rate of deep water formation in the North Atlantic Ocean and what repercussions would there be from changes in this rate?”

Using Wally’s name, it was easy to get the best relevant people in the world to attend the workshop. The workshop did not answer the workshop’s fundamental questions, nor was that expected. We could address pieces of the puzzle, for example, one reason that the North Atlantic is so salty is that Mediterranean water, extremely salty due to the dry subtropical climate there, flows out the Strait of Gibraltar at depth, into the North Atlantic region.

Instead we produced recommendations for measurements and modeling needed to investigate the important issues. We published these and the author presentations in a workshop report.[4]

Arnold Gordon of Columbia Lamont-Doherty gave a talk, and a corresponding paper in the Conference Publication, entitled “North Atlantic Deep Water and the World Ocean” describing how North Atlantic Deep Water fit into the global ocean circulation system. He followed that with a comprehensive paper[5] on the topic.

Wally published *The Biggest Chill* in *Natural History*,[6] introducing the terminology “the great ocean conveyor belt” for this ocean circulation, with a beautiful illustration by Joe Le Monnier. Reaction to Wally’s paper was as close as a scientist could come in those days to “going viral,” with both the scientific community and with the lay community.

Arnold will be forever peeved, because he was first to describe the globally connected ocean circulation, but Wally’s showmanship was important and useful. Wally had an unmatched ability to ask penetrating questions and spur the community to try to answer them.

Wally’s seminal contributions in geochemistry, oceanography, and paleoclimate earned him the respect of his peers as the leading scientist in the world in the field of global climate. There was a hint that he achieved a nirvana that escaped even Galileo in his acknowledgments in the paper *The Great Ocean Conveyor*:[7] “I thank Exxon Corporation and Livermore National Laboratory for their generous support of my research. Instead of requiring me to write long proposals and reports, they encouraged me instead to put this effort into articles such as this.”

The new Climate Center at Lamont was announced on 7 June 1984 at a press briefing, two days after the Deep Water workshop. Wally had agreed to be Director. David Rind, Bill Rossow and I attended the briefing to describe interactions of GISS with the Climate Center.

At the Goddard Institute, the salubrious Space and Earth Science breeze lasted only three years, but that was long enough for us to obtain the long-delayed civil service positions for Tony Del Genio and Inez Fung. We also got positions for planetary scientists Michael Allison and Barbara Carlson, atmospheric chemist Michael Prather and paleoclimatologist Dorothy Peteet.

All of these new staff members at GISS were capable of writing winning funding proposals. Frank Marten had strengthened us and got us into a condition such that we could survive hard times. That strength would be needed as we were about to enter a long, arid period, characterized by debilitating fights over the nature of the NASA Earth Observing System.

Yet I believe that we owed most to Angel #1, Ruth Levenson, who was our champion with NASA as well as with the Columbia hierarchy. I needed her help to open the opportunities in global change research. I regret that I never properly thanked her and gave her a big hug before she died of cancer in 1997 at age 68. Forgive me if I misrepresent any aspects of her religion, but from my perspective it seemed to me that she won her wings

The Deep Water problem would fester for decades. Wally seemed to be suggesting that events in the North Atlantic Ocean could drive climate change all around the world. This interpretation implied that a small tail was capable of wagging a big dog. This possibility made Wally worried that humans may be on the verge of unleashing an enormous global climate change that might even threaten civilization.

Wally was not a climate modeler, but he spurred research worldwide. Over the next decade or so, the community of global climate modelers shoved Wally back into his place, concluding that North Atlantic deep water formation was an interesting, important phenomenon, but it was not as sensitive as Wally feared – we were nowhere near unleashing a shutdown of the North Atlantic circulation, with all of the consequences that it may imply.

It would be still many more years before it would become apparent that the modelers were wrong. Wally was, to a large degree, right. The story, and what went wrong with the models, is important and in the end this story can be readily understood.

In 1984, however, we did not have the tools to investigate the North Atlantic deep water problem, and to Wally's consternation and continuing displeasure, I did not devote my research in that direction. Our climate model at GISS did not yet include a dynamical ocean. Our computer was too old and slow for climate simulations that included a dynamical ocean with a resolution that could produce a realistic ocean circulation.

Instead, in 1984 we initiated climate simulations to study effects of increasing greenhouse gases, using observed changing amounts of those gases. We employed only a simple ocean model that included the ocean's heat capacity, but excluded the possibility of changes in ocean dynamics. Even with this simplified model, it took three years to complete the simulations on our computer.

Our approach to climate studies includes information gleaned from three sources: (1) climate models, (2) modern observations of ongoing changes, and (3) paleoclimate. We were fortunate at GISS to be located close to Lamont, which is a world leader in paleoclimate studies.

Jim Hays of Lamont had given a talk at GISS in 1976, reporting on what would be one of the most famous papers in climate science: *Variations in the Earth's Orbit: Pacemaker of the Ice Ages*.[8] This was my first taste of paleoclimate studies. Hays' co-authors were John Imbrie of Brown University and Nicholas Shackleton of Cambridge University.

They presented the first persuasive case that huge climate oscillations during Earth's history were a result of small variations of Earth's orbit and the tilt of Earth's rotational axis. This work implied that climate was remarkably sensitive to even small forcings.

During the last ice age, 20,000 years ago, the ice sheet covering Canada and parts of the U.S. was so large, locking up so much water, that sea level was 120 meters (400 feet) lower than today. That was when early Americans were camping out in Beringia. As discussed earlier, when the ice sheet began to melt, these first Americans moved south, populating North America, Central America, and South America.

Climate oscillations in Earth's history are especially useful for evaluating climate sensitivity and providing information about "slow" climate feedbacks. Chapter 25 dives into paleoclimate science, where I have moderately reframed the usual way of looking at Earth orbital effects on climate. I hope this approach is accessible, providing even the non-scientist a good notion of what our research is about. However, a reader uninterested in even this complexity can jump to the summary at the end of the chapter, where I describe my perception of the status of the science in the mid-1980s. In Chapter 26 I resume, in the mid-1980s, a chronological account of the climate story as seen through my eyes.

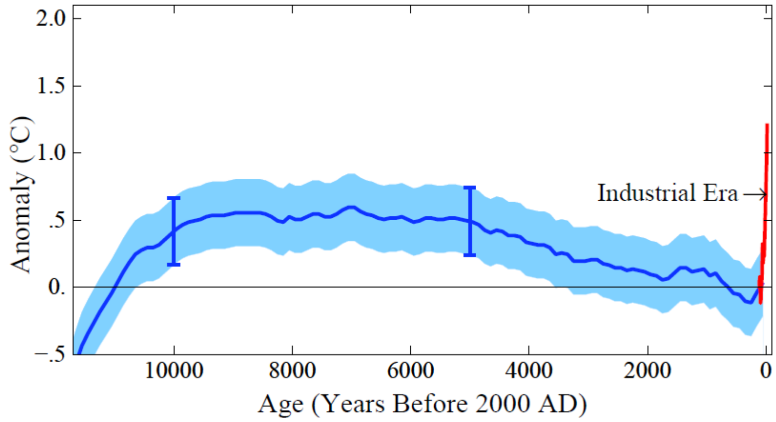

Fig. 25.1. Global temperature in the Holocene, relative to 1880-1920 average; blue data are from proxy temperature analyses of Shaun Marcott, Jeremy Shakun and colleagues; red data are instrumental measurements for 1880-2020. Proxy data have 100-year smoothing. Light blue area is formal 95 percent confidence range, but there is the possibility of systematic error; discussion and references in.[9]

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 with rich data sources. 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 1250-1850 AD, which is termed "The Little Ice Age," even though it was not a true ice age. 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.

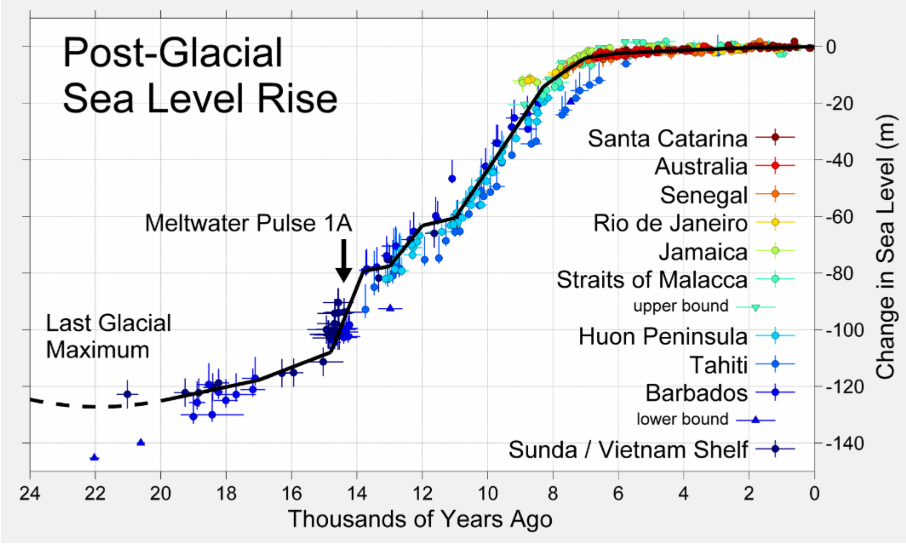

Fig. 25.2. Sea level since the last glacial period relative to present. Credit: Robert Rohde[10]

Absent humans, Earth was headed for the next ice age. However, humans began to take control of atmospheric composition with the industrial revolution. We are now entering a new geologic era, which Paul Crutzen has named the Anthropocene.[11] 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.[12] Global temperature is increasing rapidly, and Earth is now 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 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? Unfortunately, that long time scale may simply reflect the time scale of the drive (forcing) that caused the climate change. The principal forcing had a full cycle time scale of about 20,000 years, as we will discuss, thus a 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 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. Delay in the surface temperature response to a climate forcing caused by the ocean's thermal inertia, which we will illustrate in a later chapter, is itself complicated, characterized by a fast partial response in a decade or two and then slow response over centuries, which Isaac Held dubbed the "recalcitrant" response.[13] 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 these slow feedbacks amplify climate sensitivity and thus climate change. We refer to climate sensitivity including slow feedbacks as the Earth system sensitivity, to distinguish it from the idealized "fast feedback" climate sensitivity that Charney defined. Fast and slow amplifying feedbacks, which dominate Earth's climate system, cause a practical problem, because the delayed climate response allows large potential 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.[14]

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 Adher. The essence of the orbital theory was confirmed in 1976 when Jim Hays of Columbia's Lamont-Doherty Geological Observatory and two colleagues[15] 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. There are three relevant orbital parameters, but they give rise to only two important effects, which are easy to understand.

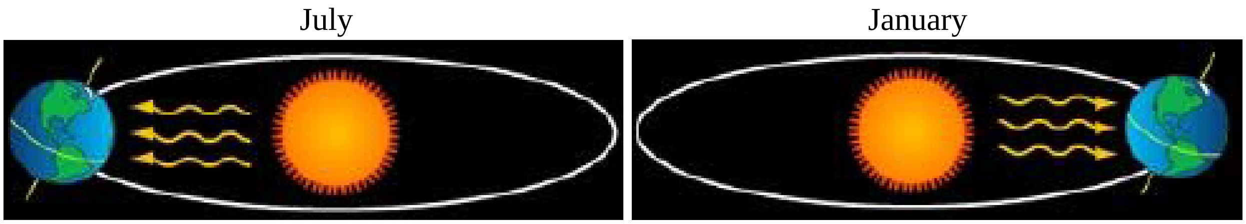

Fig. 25.3. Tilt of Earth's spin axis causes the seasons

Earth's axis of rotation, its "spin axis," today is tilted by about 23.4 degrees to the plane of Earth's orbit. This tilt gives rise to the seasons (Fig. 25.3) as Earth travels around the Sun each year. In June the tilt exposes the Northern Hemisphere to maximum sunlight, while six months later the Southern Hemisphere receives maximum sunlight. Halfway in between, at the Spring and Autumn Equinoxes, the hemispheres receive an equal amount of sunlight. The tilt of the spin axis has a simple time variation. It changes over its full cycle, from minimum (22.2°) tilt to maximum (24.5°) and back to minimum in about 40,000 years.

Earth's orbit about the Sun is not a perfect circle, it is slightly elliptical, with an eccentricity today of about 0.02. 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 than it does when it is at its greatest distance from the Sun. 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 third 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.

The first two parameters, the tilt (also called obliquity) of the spin axis and the eccentricity of the orbit are easy to comprehend. The third parameter is usually described as precession of the equinoxes. Precession is demonstrated by the spinning of a top as it slows down. However, it is not necessary to think about the geometry. The only effect of precession that we must consider is its effect on the calendar date at which Earth is closest to the Sun. Today Earth is closest to the Sun on January 3, but time of closest approach is slowly increasing. In just over 50 years, because of precession, it will have increased one day to January 4. In about 20,000 years, closest approach will have moved through the calendar and be back at January 3.

The three orbital parameters have two significant effects on climate. Effect #1 is simple, caused by change of the tilt of Earth's spin-axis relative to the orbital plane. When the spin-axis tilt is larger, more sunlight strikes polar regions during the melt season, which tends to diminish high-latitude ice sheets. Let's call effect #1 the "Tilt Effect." As the spin axis "straightens up," the Tilt Effect favors growth of high latitude ice sheets.

Effect #2 concerns the day of year (DoY) of closest approach of Earth to the Sun. Ice sheet melt is promoted if the DoY of closest approach 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 it 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 the day of closest approach occurs as soon as it is warm enough for melting, which is late spring (May in the Northern Hemisphere).[16] Let's call effect #2 the "Precession Effect."

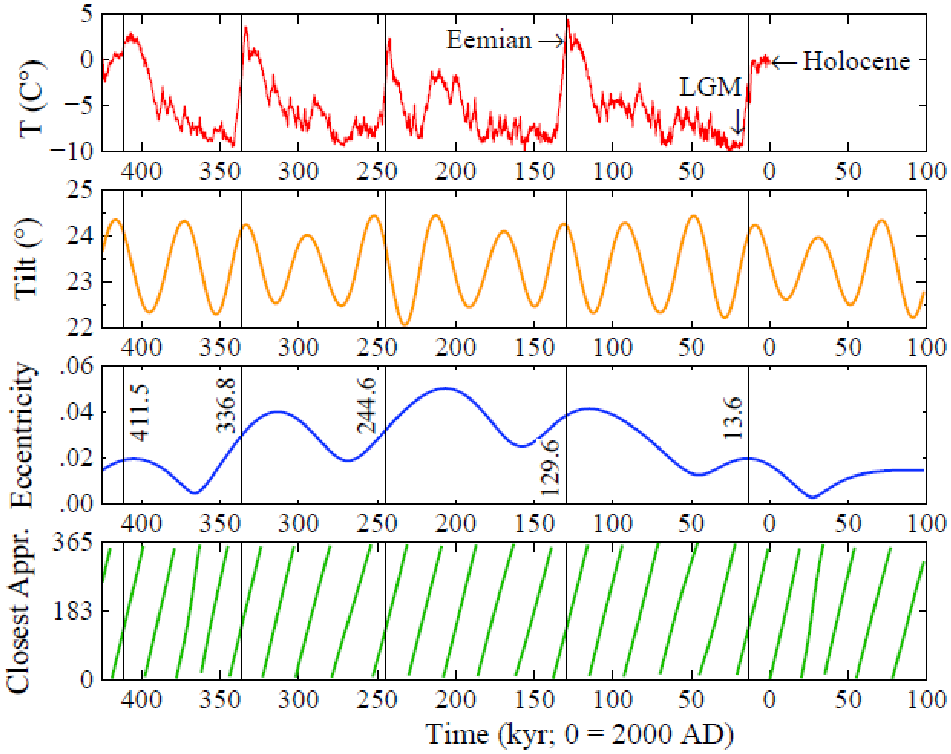

Fig. 25.4. Antarctic temperature for past 425,000 years (1 kyr = 1000 years) and Earth orbital parameters. Vertical black lines are drawn when Earth's closest approach to the Sun is at DoY = 135 (May 15), in five cases when Earth's spin axis tilt was also large. Credit: Gary Russell provided orbital data; temperature data from Jouzel et al. (2007).

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

The climate record provided by Antarctic ice cores is characterized by several sharp ice age "Terminations," when the temperature jumps from ice age cold to interglacial warmth within several millennia (Fig. 25.4). Northern Hemisphere ice (except Greenland) melted during these Terminations and sea level rose more than 100 meters. As shown by vertical black lines in Fig. 25.4, these terminations all occurred when the maximum Precession Effect (DoY of Earth's closest approach to the Sun in mid-May) coincided with large tilt of Earth's spin axis.

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 Precession Effect, which recur at intervals of about 20,000 years. 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[17] that we will henceforth abbreviate as *Ice Melt (2016)*.

Maximum Precession 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 black 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. However, the Precession Effect is proportional to the eccentricity of Earth's orbit, which was 0.04 in the Eemian and 0.02 in the Holocene.

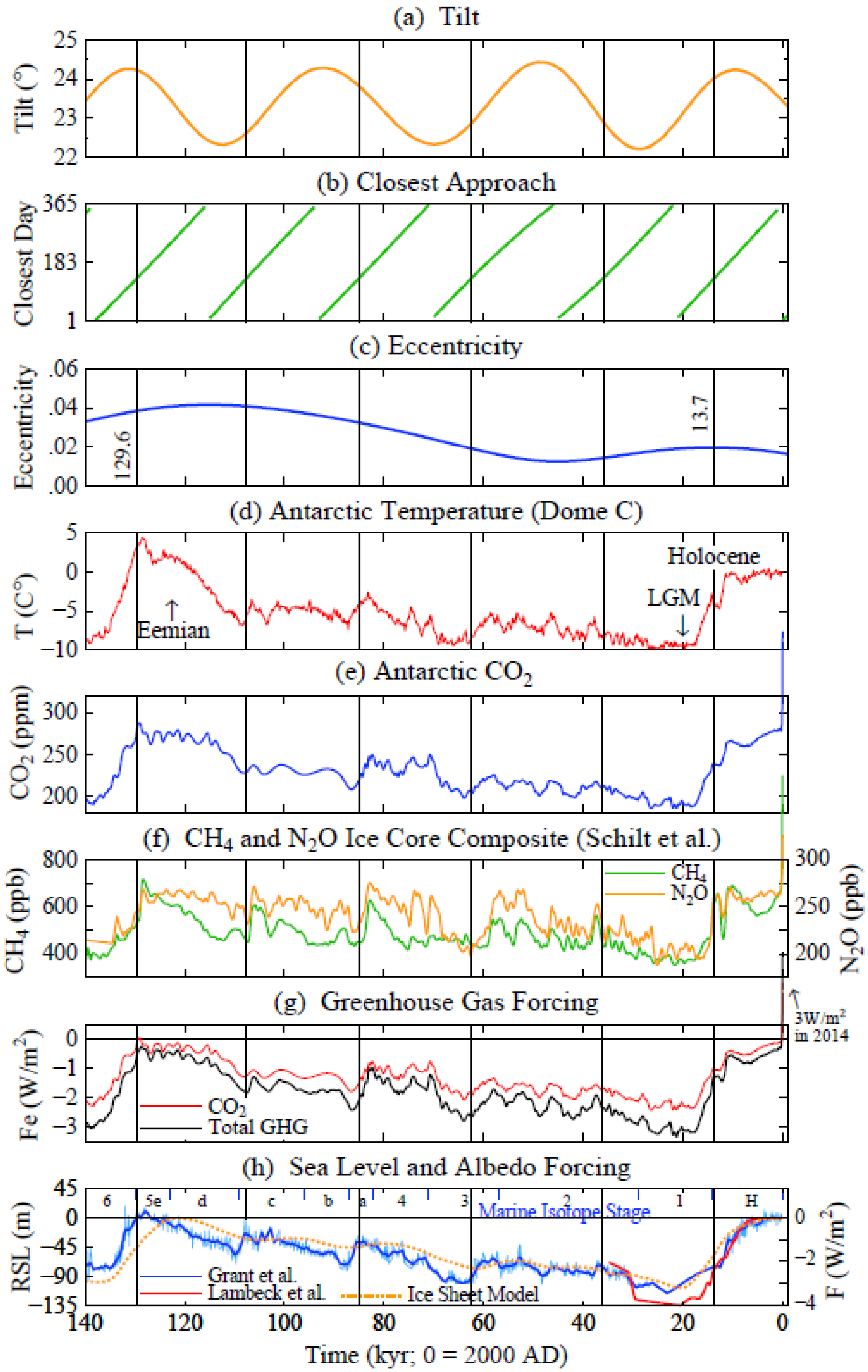

Fig. 25.5. Vertical bars are the dates when Eath's closest approach to the Sun is on 15 May. All panels use a consistent time scale[18] based on Antarctic ice cores, except panel (h) where the ocean core time scale leads to some displacements in time, especially of early dates. Greenhouse gases and surface 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.

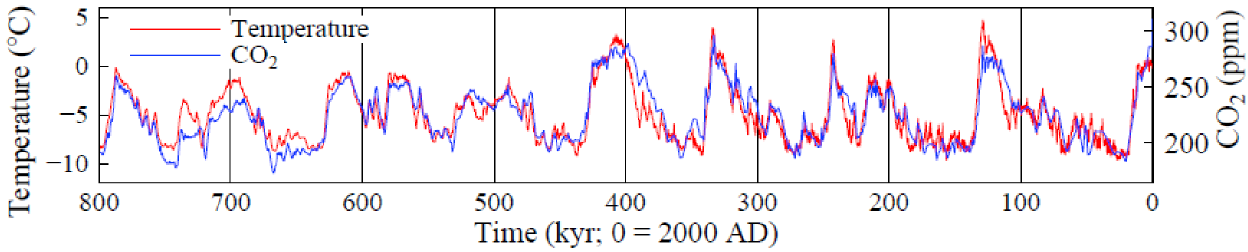

Fig. 25.6. CO_2 amount[19] and Antarctic (Dome C) temperature[20] relative to last 10 kyr.

One of the four cases with maximum Precession Effect (vertical bars) that failed to yield interglacial warmth – the one at about 86 kyr – had a stronger Precession Effect (larger eccentricity) and a Tilt Effect almost as large as at the Termination initiating 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 only to 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 empirical data studies 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.[21]

Panels g and h of Fig. 25.5 show the climate forcings produced by changing greenhouse gases and the changing size of continental ice sheets.[22] 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 Precession 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 – 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.

In the 1980s these details may have seemed academic. Big issues then were climate sensitivity and, I suggested, the delayed climate response and warming "in the pipeline.' A few decades later, however, when the importance of understanding the Eemian period and its relevaance to the future became clear, these issues would return with an urgency attached.

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.[23]

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.[24]

Today the Precession effect – with Earth closest to the Sun in January – favors mild winters in the Northern Hemisphere, which promotes increased high latitude snowfall. This Precession Effect also reduces summer insolation, which allows more snow to remain unmelted in the summer at high northern latitudes, so glaciers and Arctic ice caps grow. That was the situation at the time of the Little Ice Age, as Earth was moving toward the next glacial cycle – but humanity and the Industrial Revolution intervened before large ice sheets began to spread over the land.

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.

In summary, Earth's paleoclimate history provides a great amount of information about the climate system. From my perspective, it seemed that a lot of progress had been made in the five years after 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 large delayed response of the climate system, and thus the large amount of climate response still "in the pipeline." This arises in part from the thermal inertia of the ocean, but amplifying slow feedbacks add to the delay and eventual response.

The Charney report estimated climate sensitivity for doubled atmospheric CO_2 as 3 ± 1.5°C. This was a large uncertainty, and the range was not the standard 95 percent confidence. Charney explained that he meant that there was 50 percent chance that the equilibrium global warming for doubled CO_2 was within the range 1.5°C to 4.5°C.

Paleoclimate data showed that climate sensitivity was high, in the upper part of Charney's range. There was uncertainty in paleoclimate data such as the size of the ice sheets and tropical ocean temperature, but Earth had to be in energy balance during the last ice age and in the Holocene. We showed in our 1984 paper[25] for the Ewing Symposium volume that the paleo data constrained climate sensitivity to the range 2.5-5°C for doubled CO_2 with 95 percent 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.[26]

The second conclusion, about 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.

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 a forcing by decades to centuries, even for fast feedbacks.

Moreover, paleoclimate data revealed that slow feedbacks, such as ice sheet and tundra melt, are predominantly amplifying feedbacks. Slow feedbacks thus magnify the delayed response issue.

So we knew a lot about climate change already in the mid-1980s, enough that scientists needed to inform the public and policymakers. There were obvious policy implications. The largest human-made climate forcing was CO_2 produced by burning fossil fuels. 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] Mashed and boiled potato, carrot and onion stew associated with liberation of Leiden in 1574. Dutch rebels had regained the central city, but were starving, under siege by the Spanish army until the rebels breached the dykes, flooding the city surroundings. Legend is that the Dutch shared a pot of warm hutspot left by the fleeing Spaniards.
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[10] https://commons.wikimedia.org/wiki/File:Post-Glacial_Sea_Level.png
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[12] 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 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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[21] The curious scientist is probably asking whether the tight relation between CO_2 and temperature in Fig. 25.5 does not imply a precise climate sensitivity. Assuming that global mean temperature change is 1/3 to ½ of that in Antarctica implies a doubled CO_2 sensitivity of 2.65-4°C – see footnote 3 of *Ice Melt (2016)* paper. The calculation assumes that CO_2 is 80% of the greenhouse gas forcing and that surface albedo and greenhouse gases contribute equally to glacial-interglacial slow feedbacks.
[22] 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.
[23] 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
[24] See Figure 5.19 of http://www.climate.be/textbook/chapter5_node12.xml
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[26] For the same reason, 3°C for $2\times CO_2$ continues to be the best estimate within the range 2.65-4°C for $2\times CO_2$ that we now obtain from the tight CO_2 temperature relation in Fig. 25.6.