Chapter 40. Target CO_2: Where Should Humanity Aim?

A whirlwind began in 2006 in the wake of the clumsy attempt by NASA Public Affairs to censor my public statements. They achieved the opposite effect, as the publicity led to numerous invitations from universities and environmental organizations to give talks on climate change.

There was another unintended effect. The censorship made me think more broadly about the context of climate change. I had to begin my talks with the caveat that any statements related to policy were my personal opinion. We government scientists were warned repeatedly to speak only about the narrow science topic, and not to venture into policy implications.

The climate topic has many facets, including energy systems, human health, economics and political science. Why were we scientists told not to connect the dots among all these facets? Were we to leave that to politicians whose pockets were being filled by money from special interests? This did not seem to be the idea of how a democracy was to work. I thought the idea of a democracy was for the public to be informed – honestly informed.

Stabilizing climate will be a complex problem, involving many disciplines. Scientists have experience with complex problems with many facets. The scientific method – including its continual skepticism and avoidance of ideology – is crucial for finding a successful pathway.

Still, I preferred doing science research and considered communication a chore. But I was tugged by a few people and was soon drawn into the broader climate problem.

Bill McKibben is a sensitive, considerate person. He was the first one to shudder upon realization that nature is no longer natural.[1] He was apologetic in 2007 when he asked me a second time: what is the appropriate target for atmospheric CO_2 amount? A specific target would help focus the work of activists, engage the public, and perhaps draw a line in the sand.

He was planning to form an organization 450.org. Several years earlier I thought that 450 ppm was a good target for maximum CO_2 amount. That was my assumption in 2000 when I defined the "alternative scenario" – alternative to IPCC scenarios that all reached higher CO_2 levels.

However, I had since realized that even 450 ppm was too much CO_2 on the long run. The CO_2 level in 2007, 385 ppm, already produced threatening signs such as loss of Arctic sea ice, damage to coral reefs, shifting climate zones, and increasing climate extremes. Moreover, we knew Earth was out of energy balance, so there was a lot more warming "in the pipeline" without further CO_2 increase above 385 ppm. So, the target almost surely should be less than 385 ppm.

Bill agreed to hold off until my talk at the AGU annual meeting in December 2007. I would focus my talk on various criteria that could help define a safe level of atmospheric CO_2.

Earth's paleoclimate history provides guidance with a precision and reliability that climate models cannot match. Ice cores were usually the paleoclimate data source of choice for those scientists concerned about human-made climate change. That's understandable because ice cores provide precise data on atmospheric composition as well as climate change.

However, ice cores cover only several hundred thousand years. That sounds like a long time, but Earth was mostly in ice ages during that time. The ice cores encompass several interglacial periods, but none of them were much warmer than our present global temperature.

Therefore, it is useful to also look at a longer period – all the way back to when there were no ice sheets on Earth. We can do that via ocean sediment cores. In the same way that snow piles up year after year on Antarctica, so sediments accumulate on the ocean floor.

The stuff accumulating includes the shells of tiny microscopic animals called foraminifera (forams, for short) preserved in the mud. The shells record information on ocean temperature and chemistry at the time the shells were growing.

It would be nice if I could say that I realized that I should ask the best relevant scientists in the world to collaborate on a paper that challenged conventional ideas about the dangerous level of CO_2. Actually, it was more a case of stumbling into it by accident.

James Zachos of the University of California at Santa Cruz compiled the most complete set of ocean core data. Zachos is soft-spoken, but when he gives a talk his peers give undivided attention; he is authoritative and insightful about the information on climate and ocean chemistry that can be extracted from the ocean cores. Zachos was first author of an iconic paper[2] about climate change in the Cenozoic era – the past 65 million years – the period that began just after the asteroid impact that led to extinction of the last non-avian dinosaurs.

The iconic graph in Zachos' iconic paper was for change of the oxygen isotope ratio[3] in foram shells in a single curve that covered the entire 65 million years of the Cenozoic era. Oxygen isotopes provide a proxy (indirect) measure of the ocean temperature at the time the foram shell formed, but the volume of ice locked in continental ice sheets also affects the isotope ratio. I wanted to use the isotope data – with an approximation to separate the temperature and ice volume effects – to obtain an ocean temperature graph for the entire Cenozoic era.

When I requested isotope data from Zachos, he kindly provided a more complete, unpublished version of his data. That's when I wondered: might Zachos agree to be a co-author on a "target CO_2" paper? His involvement would enhance the stature of the paper. But first I should complete my talk for the AGU meeting and write a draft of the paper to help persuade him.

"Climate tipping points" was the title of my talk[4] at the American Geophysical Union meeting on 13 December 2007. I defined a tipping point as the point at which no additional forcing is needed for rapid climate change to occur with large climate impacts. I defined the "point of no return" as the point at which irreversible climate impacts become unstoppable.

My objective was to find an upper limit for long-term CO_2 amount. Maintenance of shorelines, Arctic sea ice, and mountain glaciers as a fresh water source, and avoidance of excessive ocean acidification and shifting climate zones each suggested a target CO_2 not greater than 300-350 ppm. Restoration of Earth's energy balance required CO_2 reduction to about 350 ppm.

After my talk, Valerie Masson-Delmotte asked why I used the 420,000-year Vostok ice core data, rather than the newer Dome C core, with its 800,0000-year record. Valerie was well on the way to becoming the world's leading paleoclimate expert on ice core studies. Of course, I asked her for the Dome C data – and I acquired another potential high-profile co-author.

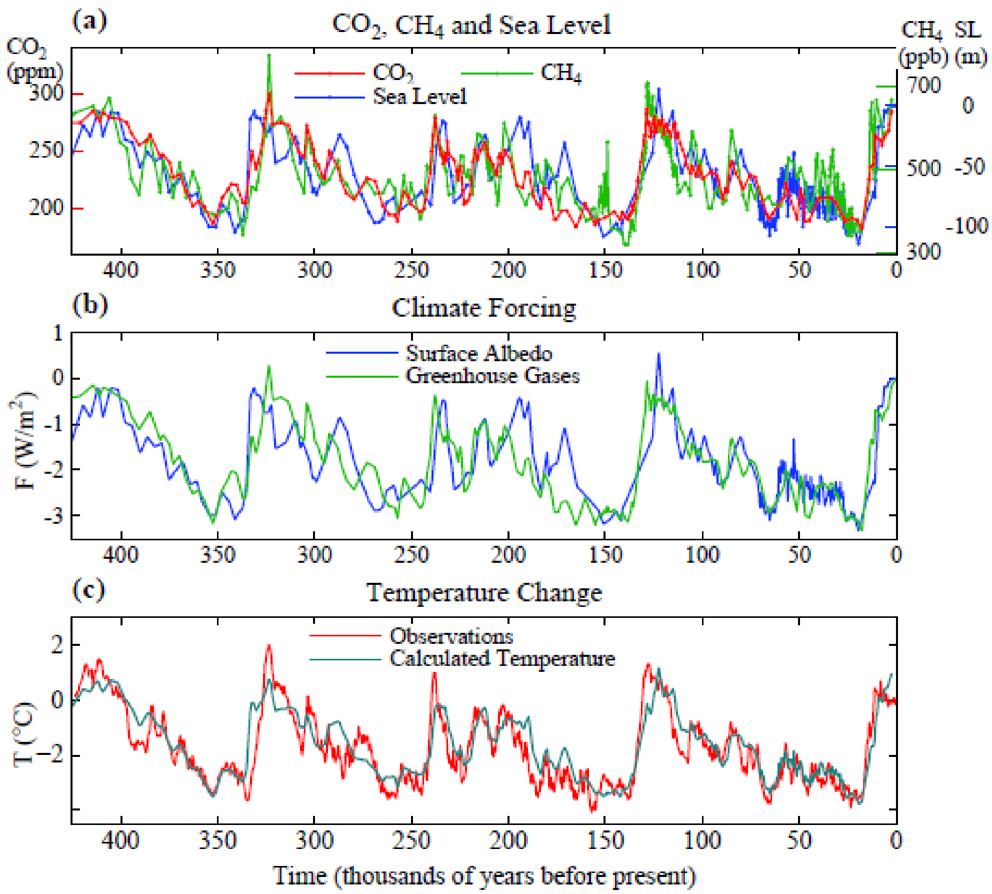

Fig. 40.1. Greenhouse gas and sea level changes yield climate forcings and thus global temperature change. Observed temperature is half of Antarctic temperature change.

After we had a complete draft paper, I received a message from a perturbed Robert Berner of Yale University – the father of long-term carbon cycle modeling – asking: why had I not asked him to join the effort? I immediately invited him. I had already asked other leading researchers in paleoclimate and the carbon cycle: Mark Pagani, Maureen Raymo and Dana Royer.

Their expertise was needed not only to assure that the science was right. I would submit the paper to a new journal, in hopes of achieving rapid publication. The high-profile co-authors helped assure that the paper received prompt attention.

Target CO_2 must be less than 350 ppm, we concluded – less than the existing CO_2 amount! Several criteria in my AGU talk implied that 300 ppm may turn out to be a better target, but "<350" was sufficient for policy purposes. There will be no need for greater precision for a long time, because it will take decades to stop CO_2 growth and get CO_2 back near 350 ppm. By then we will have a sharper understanding and empirical evidence that helps us refine the target. It is better not to reduce CO_2 more than necessary, because CO_2 is beneficial to plant growth.

We can't simply use paleo CO_2 levels to define the target. We have altered Earth's surface and our activities inject aerosols into the atmosphere; both of these increase Earth's albedo. Even if we stop burning fossil fuels, our activities will still inject dust and other aerosols into the air. It is unlikely that the optimum CO_2 amount will be as low as the preindustrial CO_2 level, but it will depend on how successful we are in reducing emissions of CH_4 and other gases.

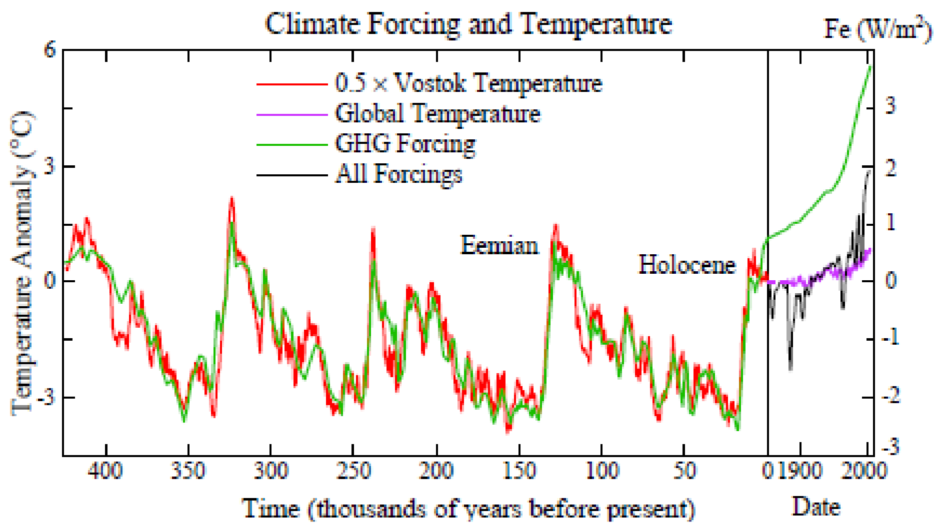

Fig. 40.2. Temperature (left scale) and climate forcing (right scale). The time scale is expanded beginning in 1850. Forcings since 1850 include greenhouse gases (GHGs), human-made aerosols, volcanic aerosols and solar irradiance changes.

Earth's energy imbalance will provide a quantitative measure of how well we are doing in stabilizing climate. We will need to achieve at least a slightly negative energy balance for the purpose of cooling the ocean and stabilizing the ice sheets.

Our Target CO_2 paper[5] **illustrated mechanisms** of glacial-interglacial climate change (Fig. 40.1). Greenhouse gas amounts were known from the composition of air bubbles in the ice cores;[6] this air was trapped as snow piled up year after year and compressed into ice. Isotopic composition of the ice reveals the Antarctic temperature when the snowflakes formed. Gas amount and temperature, from the same ice core, are on a consistent time scale.

Earth's surface albedo change is calculated from the changing size of continental ice sheets, which is inferred from change of sea level. Sea level change is inferred from ocean sediment cores.[7] Absolute dating of ocean cores can have errors of several thousand years, so the alignment of ice core and ocean core data is not perfect.

When the surface albedo and greenhouse gas forcings in Fig. 41b are added together and multiplied by the climate sensitivity 3°C for doubled CO_2 (i.e., ¾°C per W/m^2), the result agrees closely with Antarctic temperature divided by two (Fig. 40.1c). This assumed relation between Antarctic and global temperature change is only approximate; alternative assumptions serve mainly to alter the inferred global climate sensitivity. In a closer look at that issue in Chapter 25, we concluded that equilibrium climate sensitivity is in the range 2.67-4°C for doubled CO_2.

A sobering message about climate change is delivered more forcefully by Fig. 40.2[8] from the Target CO_2 paper. Estimated global temperature change (half of the Vostok Antarctic change) is graphed with the greenhouse gas climate forcing. This is the appropriate comparison going forward, when we should consider ice sheet change as a climate feedback, not as a forcing.

Congruity of greenhouse gas climate forcing and global temperature change is striking. Greenhouse gases exerted tight control on Earth's temperature in the natural world. No climate model is involved in this comparison. Greenhouse forcing is calculated from simple equations.[9] Greenhouse gas amounts and the temperature record are from the Vostok ice core. Comparison of measured and calculated temperatures are equally striking for the 800,000-year Antarctic Dome C ice core, as shown in the Supplementary Material of the Target CO_2 paper.

Humanity began to dominate emission of greenhouse gases with the industrial revolution, shown in expanded time scale on the right side of Fig. 40.2. By 2007 the greenhouse gas forcing was approaching 4 W/m^2, but it was partly offset by negative human-made aerosol forcing. The offset was nearly total until the past 50 years, when aerosol growth slowed and greenhouse gas growth accelerated. Net forcing in Fig. 40.2 includes the natural volcanic aerosol and solar irradiance forcings, which have a detectible effect on short-term climate but little effect on long-term climate.

Implications of Fig. 40.2 are staggering. Unless growth of GHGs is stopped, and reversed, we are headed toward planetary conditions very different than humanity has experienced. Observed global warming in the 20th century was less than 1°C, but much more is in the pipeline.

Moreover, the warming usually described as "in the pipeline," which can be estimated from Earth's energy imbalance, refers to fast feedbacks. Slow feedbacks will certainly add still more warming. What is uncertain is how fast the slow feedbacks will come into play.

My concern is that "slow" climate feedbacks will begin to come into play in a significant way in less than a century. Slow feedbacks include ice sheet disintegration, vegetation migration, and greenhouse gas release from soil, tundra and ocean sediments.

The urgency of the situation seemed clear. The world's nations should have been taking actions to alter their energy pathway. Fossil fuel emissions had to be phased down. We needed to move with all deliberate speed toward carbon-free energies.

That didn't happen. On the contrary, emissions accelerated. In the years leading up to the 1997 Kyoto Protocol, fossil fuel CO_2 emissions increased about 1.5 percent per year. In the years following Kyoto, global emissions increased 2.5 percent per year.

Scientists presented the 2007 IPCC reports blandly, it seemed to me, reporting the state of the climate and modeling alternative scenarios for the future. They took pride in offering no policy advice. Their hard work was appreciated – they received the Nobel Prize for their effort.

Was this the most effective approach? Maybe so. If we instead run around with our hair on fire, it makes a scene, but does it generate the needed action?

Still, it seemed to me that IPCC was not transmitting an appropriate sense of urgency for a climate system characterized by a delayed response and amplifying feedbacks.

Was "scientific reticence" affecting communication? Scientific reticence is real. I felt it in 1989 in Amherst, where, as described by Dick Kerr,[10] a secret ballot was expected to yield a result quite different from the public statements.

Scientific reticence leapt to mind in 2006 as I was being questioned, and boxed-in, by a lawyer for the plaintiffs in Automobile Manufacturers versus California.[11] I was testifying on behalf of California in their effort to require higher vehicle efficiencies than federal laws required.

The lawyer, with aplomb, requested that I identify glaciologists who agreed publicly with my assertion that sea level was likely to rise more than one meter this century if greenhouse gas emissions followed an IPCC business-as-usual scenario: "name one!"

I could not, instantly. I was thinking in terms of the IPCC report. If I had thought more quickly, I would have described the sense of urgency that I felt from field glaciologists such as Eric Rignot, Jay Zwally, Konrad Steffen and Roger Braithwaite. The IPCC process did not transmit well their concerns about the potential for ice sheet instability.

This experience persuaded me to write an article[12] on scientific reticence, including references to scholarly papers. I already mentioned the effect of fear of the penalty for "crying wolf," which exceeds concern about "fiddling while Rome burns." A human tendency to prefer immediate over delayed rewards is described as "delay discounting."

Scientific reticence is real, but it is not the main reason for the public's limited understanding of climate science. A bigger communication problem is caused by politicization of climate change.

Climate change did not have to be politically divisive, with conservative political parties in denial of the seriousness of the issue. Conservation had long been consistent with the philosophy of political parties on the right. In the United States Republican Party, Richard Nixon supported the Clean Air Act and Ronald Reagan supported laws to protect the ozone layer.

Politicization of climate change was sealed in concrete with award of the Nobel Prize to Al Gore for his role in bringing the climate change issue to public attention, most spectacularly with the film *An Inconvenient Truth*. However, Al Gore should not be blamed for the politicization. The fossil fuel industry was already focusing most of its support on the rightwing. To be sure, the fossil fuel industry also gives money to the leftwing political parties to ensure that heavy direct and indirect fossil fuel subsidies remain in place, but it gives more money to the rightwing.

Solution of the climate problem is almost impossible without addressing the role that money – bribery – has assumed in usurping power in democratic nations. I thought there were other nations where this was not true, but in visiting a dozen nations during the next several years I realized that money was distorting political decisions in all of the democracies – it was only more subtle in some cases. However, let's not get ahead of the story.

In 2008 I had a wonderful opportunity: to give the Bjerknes lecture at the annual AGU meeting. It gave me a chance to get into the task of trying to understand why our climate model responded so dramatically to freshwater injection onto the ocean by melting ice sheets. On a more personal level, my Bjerknes talk described a step into a world of expanded horizons.

Chapter 41. Bjerknes Lecture

A one-hour talk can cover a lot of stuff, especially if specific concise words are prepared and read to avoid any hemming and hawing. I needed to be prepared, because I had a science story, but I also wanted to get into implications. The title of my talk[13] was Climate Threat to the Planet: Implications for Energy Policy and Intergenerational Justice.

Let's start with the science. I had become suspicious that something was fundamentally wrong with global climate models – or else with the measurements of Earth's energy imbalance.

Let me explain. Climate sensitivity had become clear enough. Paleoclimate data showed that climate sensitivity was about 3°C for doubled CO_2, as Charney had estimated. Doubled CO_2 is a forcing of 4 watts per square meter (4 W/m^2). So, climate sensitivity is about 0.75°C per W/m^2.

If we know climate sensitivity, and if we know the climate forcing by greenhouse gases, all we must do is multiply them together and we get the global warming, right? That's almost right.

Let's try it. Keeling measured CO_2 changes. CH_4, N_2O and CFCs are also measured, and we know from ice cores how much of each gas there was before humans began mucking around. The greenhouse gas climate forcing could be calculated easily. Everybody agreed that it was about 3.5 W/m^2. 3.5 times 0.75 is about 2.6°C. Oops. Actual global warming in 2008 was 0.9°C since 1900.

Oh, we forgot the other big forcing: human-made aerosols. We don't measure those,[14] but we estimate that the aerosol forcing is about – 1.5 W/m^2. So, the net human-made forcing is about 2 W/m^2. Let's see, 2 × 0.75 is 1.5°C, still much larger than observed warming.

Ah, we forgot one other thing. Charney's sensitivity refers to the "equilibrium" response, that is after we have waited long enough for the planet to come to energy balance with space.

So, we need Earth's climate response function. After a forcing is applied to the planet, what fraction of the equilibrium response is achieved at any future time? Surely that is one of the most basic characteristics of the climate system, and thus of climate models, right?

We can find the response function by, say, doubling the amount of CO_2 in the air and waiting for the planet to warm up. This is often the first experiment a modeler does to calibrate a model.

Figure 41.1 is the response function of the model that we used for our puzzling freshwater experiment in October 2006. That's the model in which sea ice around Antarctica grew and the overturning circulation in the Southern Ocean shut down, even as CO_2 in the air increased.

What a slow response! Figure 41.1 shows that almost 50 percent of the final response is achieved within a decade, but only 60 percent after 100 years, and 90 percent after 1000 years.

Could the real-world climate response to a forcing be that slow? It's possible, but the ocean would need to mix heat into the deep ocean efficiently. That's not what Charney expected. He thought that the real world achieved almost 100 percent response within a few decades.

It seems to me that all models reporting results to IPCC should be required to report the climate response function of their model. This would help us understand the model results. Maybe some models cannot approach an equilibrium, but that, too, would be useful information.

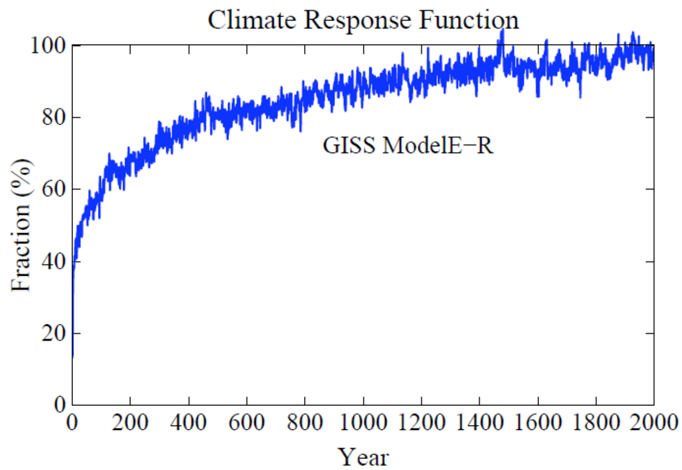

Figure 41.1. Climate model's response function: fraction of the final response versus time.

To encourage all modeling groups to report their model's response function, I reminded the audience of the response function's utility. As the simplest expression of Sir Isaac Newton's calculus,[15] it defines the expected global temperature response, for any climate forcing scenario.

I wondered if the climate models of the other major modeling groups were as slow as ours, so I wrote to lead modelers at NCAR (National Center for Atmospheric Research), GFDL (Geophysical Fluid Dynamics Laboratory) and the Hadley Centre in the UK.

These groups had not calculated a response function with a "step function" forcing, that is, with an instant doubling of atmospheric CO_2, but they each provided results of a long model run. Then I ran the GISS model for exactly the same forcing and compared the responses. GISS and GFDL responses are compared in Chart 27 of the Bjerknes lecture.

The other models were even slower than the GISS model. This increased my suspicion that all climate models, or at least most were mixing heat into the ocean faster than in the real world. How could most models have the same problem?

One possible explanation was in the "parameterizations" ocean models used for small scale turbulence not resolved by the model. This is the topic that I should have asked Carl Wunsch about. We had our own expert in turbulence theory at GISS, Vittorio Canuto. Canuto agreed that turbulence parameterizations in ocean models gave too much mixing in the upper ocean.

Another possibility: many ocean models had the same "grandparent": the GFDL MOM (modular ocean model). We suspected that there was an artificial "diffusion" of ocean properties in that model because of propagation of small errors in numerical finite differencing. Akio Arakawa and Gary Russell made special effort to minimize that problem, which might account for the fact that the response function for the GISS model was not quite as slow as the GFDL model.

My suspicion about ocean mixing in climate models was born in Earth's energy imbalance. Our 1997 paper *Forcings and chaos* (Chapter 34) inferred planetary energy imbalance of +0.67 W/m^2 in 1996 and our 2005 paper *Earth's energy imbalance* (Chapter 36) found an average imbalance of +0.85 W/m^2 during 1993-2003 and about 1 W/m^2 near the end of that period.

Observations of Earth's energy imbalance, based on measuring the change of the ocean's heat content, seemed to yield a smaller imbalance. However, there was large uncertainty because of limited sampling of the full ocean and inadequate calibration of the instruments.

So it seemed that ocean mixing was excessive in our model, and probably more excessive in the other models. This interpretation might explain why our climate model was more sensitive to freshwater injection than the other climate models.

Moreover, this interpretation implied that the real world is still more sensitive than our model to fresh water injection. In that case, shutdown of the overturning ocean circulations was a real possibility, and it could be much nearer than anyone was imagining.

Shutdown of the Southern Ocean overturning is an intriguing issue. If humans are going to cause a large, rapid sea level rise, it will be a result of ice sheet collapse in Antarctica. That's where a large volume of vulnerable ice sits on bedrock far below sea level, buttressed by ice shelves that reach 1-2 kilometers below sea level.

The foot of these ice shelves provides the strongest buttressing force. That's why shutdown of the Southern Ocean overturning circulation is so important. Warming of the ocean at the foot of the ice shelves would unleash ice above sea level that could raise sea level several meters.

We should look at Earth's history to see if we can find evidence of such events in the past. The best hope of uncovering evidence for a relevant event, rapid sea level rise caused by collapse of Antarctic ice, would be during a prior interglacial period as warm or warmer than the Holocene, when the only large ice sheet vulnerable to rapid collapse would be the Antarctic ice sheet.

In 2007 I discovered the papers of Paul Hearty on sea level, and began correspondence with him. Hearty used geologic evidence from many places around the world to chart sea level change during the Eemian period, which lasted from about 130,000 years ago to 116,000 years ago.

The Eemian was about 1°C warmer than the Holocene. Sea level reached heights as great as 6 to 9 meters (20-30 feet) higher than today. The most relevant feature in the Hearty sea level chart is a rapid sea level rise by at least 3 meters in about a century late in the Eemian.

Late Eemian collapse of Antarctic ice is consistent with Earth's orbital parameters. Earth's orbit was twice as eccentric as today (Fig. 25.4). Closest approach to the Sun was in (Southern Hemisphere) Late Spring to Summer, ideal conditions for Antarctic melt.

Simultaneously, high latitudes in the Northern Hemisphere were beginning to cool, as the orbital parameters favored initiation of Northern Hemisphere ice sheets as the first step into the next ice age. With the tropics still at interglacial warmth the latitudinal temperature gradients were large, thus capable of driving strong storms.

Hearty pointed to geological evidence of strong storms in Bermuda and the Bahamas during this period, including giant boulders located on the crest of a hill on Eleuthera. The boulders rest on Eemian soil but are composed of older rock, apparently ripped from the cliffs below and washed up the hill by powerful waves when sea level was higher.

Fig. 41.2. The 'bull' (left) and 'cow' boulders on coastal ridge of North Eleuthera Island, Bahamas. Anniek, present in both photos, is height 1.6 meters.

This was a spectacularly interesting scientific topic. I was eager to jump into it. Anniek and I spent three days, including 40th wedding anniversary, in Eleuthera, so as to examine the boulders and other storm evidence cited by Hearty.

However, progress required a better understanding of the ocean and ocean models. It would be best if we could fix the ocean mixing in the model – make it more realistic – which would likely affect the model's sensitivity to freshwater injection on the surface.

The freshwater problem had to wait. I needed a large block of time, at least six months, to focus on that problem and write a paper, even after we understood the ocean mixing issue. We would need to run a large set of climate simulations. Preferably these climate model experiments should be done with an improved version of the ocean model, and we would need to extract essential diagnostics from the model to compare with the real world.

However, finding that large block of time became almost impossible. This was the most hectic time in my life. I was becoming involved in the larger climate problem discussed in the latter part of my Bjerknes lecture: the implications for energy policy and intergenerational justice.

We had shown on the basis of several criteria that we needed to restore atmospheric CO_2 to a level probably somewhere in the range 300 to 350 ppm. For sure, if we wanted to preserve the planet on which civilization developed, CO_2 should be less than 350 ppm.

Nothing substantial was being done to prevent a march to greater and greater levels of CO_2. Governments pretended that they were taking action. In reality, governments and industry knew that CO_2 would continue to grow, even faster. They acted as if this were inevitable.

Was there no "free will" alternative to this march to climate disasters? The alternative that I suggested required phase-out of CO_2 emissions from coal, a rising carbon price to discourage unconventional fossil fuels and extraction of every drop of oil, sequestration of carbon via improved agricultural and forestry practices, and reduction of non-CO_2 greenhouse gases.

The United Kingdom, the United States and Germany, the three major nations most responsible on a per capita basis for human-made climate change, should have been and could have been leading the world toward a free-will alternative. They were not.

Fig. 37.3. Two-and-a-half-year-old Jake with his two-and-a-half-day-old sister, Lauren.

The most fundamental requirement is to stop subsidizing fossil fuels. The fastest and most economically sensible way to do this, I argued, was a gradually rising carbon tax collected directly from the fossil fuel companies at domestic mines and ports of entry. If 100 percent of the money is distributed uniformly to the public, the public would accept increased fuel costs.

We would have to figure out how to live without fossil fuels someday. Why not now?

It was a matter of intergenerational injustice, affecting the young and the unborn. We no longer had the "did not know" defense that our parents had. Our governments and industry knew where carbon emissions were headed as well as the expected and already occurring consequences. Industry and government actions raised ethical and legal liability questions.

I tried to appeal to the heart by showing a photograph of our newest grandchild, Jake, our son's first child. Jake had not done much of anything to cause global warming. He would likely still be alive near the end of the century, living in the greenhouse world that we choose to create.

Why did people not seem to understand this? Could we not find one country to serve as an example, to adopt the policies that are needed to move the world off fossil fuels and onto clean energies? Over several years I went to a dozen countries. In each country, a handful of people wanted to push governments to address climate change, but nothing of global import happened.

In my public talks, I used photos of my grandchildren to focus on intergenerational injustice. Jake was the perfect example. Jake has a severe life-threatening peanut allergy. He must always have with him an injection of medication in case of accidental exposure, yet he is optimistic. I would show the photo of him at age two and a half with his two-and-a-half-day-old baby sister, whom he believed he could protect. Why were we not protecting their future?

Isaac Held, a senior scientist at Geophysical Fluid Dynamics Laboratory, inspired my "Free Will" chart when he asked incredulously: "have we no free will?" Why should scientists not help governments understand free will alternatives? The carbon and energy problems would seem to be simpler than the climate problem. Right?

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[1] McKibben, B., The End of Nature, Random House, New York, ISBN 0-8129-7608-8, 1989.
[2] Zachos, J., M. Pagani, L. Sloan, E. Thomas and K. Billups, Trends, rhythms, and aberrations in global climate 65 Ma to present, *Science* 292, 686-693, 2001.

[3] Almost 99.8 percent of oxygen is O-16, which has 8 protons and 8 neutrons. About 0.2 percent is heavy O-18 with 10 neutrons. See discussion of Figure 18 in my first book, *Storms of My Grandchildren*.
[4] Hansen, J., Climate tipping points: the threat to the planet, annual AGU meeting, San Francisco, 13 Dec. 2007.
[5] Hansen, J., M. Sato, P. Kharecha, D. Beerling, R. Berner, V. Masson-Delmotte, M. Pagani, M. Raymo, D.L. Royer, and J.C. Zachos: Target atmospheric CO_2: Where should humanity aim? *Open Atmos. Sci. J.*, **2**, 217-231, 2008.
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[7] Siddall, M., E.J. Rohling, A. Almogi-Labin, Ch. Hemleben, D. Meischner, I. Schmelzer and D.A. Smeed, Sea-level fluctuations during the last glacial cycle, *Nature* 423, 853-858, 2003.
[8] See also an earlier version of this figure and discussion in Hansen, J., M. Sato, P. Kharecha, G. Russell, D.W. Lea, and M. Siddall: Climate change and trace gases. *Phil. Trans. Royal. Soc. A*, **365**, 1925-1954, 2007.
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[11] Central Valley Chrysler-Jeep v. Catherine Witherspoon, California Air Resources Board, United States District Court, Fresno, Case 1:04-CV-06663. The automakers were supported by a friend-at-court, the U.S. government.
[12] Hansen, J.E., Scientific reticence and sea level rise. *Environ. Res. Lett.*, **2**, 024002, 2007.
[13] Hansen, J., Climate Threat to the Planet: Implications for Energy Policy and Intergenerational Justice, Bjerknes Lecture, American Geophysical Union, San Francisco, CA, 17 December 2008. Note that my lecture was marred by an incorrect inference that Earth was near a runaway greenhouse effect. There is an uptick in climate sensitivity as Earth becomes warmer, as shown in Figure 7 of Hansen, J., M. Sato, G. Russell, and P. Kharecha: Climate sensitivity, sea level, and atmospheric carbon dioxide. *Phil. Trans. R. Soc. A*, **371**, 20120294, 2013, but a true runaway greenhouse requires more than a billion years – see Chapter 10.
[14] NASA chose not to measure the aerosol forcing, but there are indirect ways to infer that the aerosol forcing is probably about -1.5 W/m^2, as discussed in later chapters.
[15] Global temperature change T(t), in response to any climate forcing history F(t), is accurately calculated as simple integration of the response function over time: $T(t) = \int S\, R(t)\, [dF/dt]\, dt$, where dF/dt is the annual increment of the net forcing and the integration begins before human-made climate forcing became substantial. S is the equilibrium sensitivity (0.75°C per W/m^2) and R is the dimensionless response function. Note: if the ocean circulation breaks down, e.g., if the overturning circulations shut down, the response function may no longer be accurate and a full ocean-atmosphere model is required to calculate even global-average surface temperature.