Chapter 38. Tipping Point

The tipping point concept was central in my Keeling talk in December 2005. By "tipping point" I referred to the fact that change initiated in a system dominated by amplifying feedbacks can reach a point such that continued change proceeds largely under its own momentum.

The tipping point that I focused on was the effect of a warming planet on ice sheets and sea level. From the abstract: "Sea level will increase slowly at first, as losses at the fringes of Greenland and Antarctica due to accelerating ice streams are nearly balanced by increased snowfall and ice sheet thickening in the ice sheet interiors. But as Greenland and West Antarctic ice is softened and lubricated by melt-water and as buttressing ice shelves disappear due to a warming ocean, the balance will tip toward ice loss, thus bringing multiple amplifying feedbacks into play and causing rapid ice sheet disintegration. The Earth's history suggests that with warming of 2-3°C the new equilibrium sea level will include not only most of the ice from Greenland and West Antarctica, but a portion of East Antarctica, raising sea level of the order of 25 meters (80 feet)."

Bill McKibben added the above quote and a few more sentences from my Keeling talk as a boxed insert titled "The 'Tipping Point?" to his article[1] in press at the *New York Revi*ew. In getting permission for this addition, Bill introduced me to Robert Silvers, editor of the *Review*.

It was a fortuitous introduction. Silvers invited me to review Tim Flannery's *The Weather Makers*. Flannery was concerned about the survival of species. Could human-made climate change drive a large portion of Earth's species to extinction?

Reviewing Flannery's book was a welcome opportunity. I had begun to wonder about the effect of global warming on wildlife. If there were a large deleterious effect on species, would that not be more important than sea level change? Is the tipping point concept relevant to survival of life? Given other stresses that humans are placing on wildlife, could global warming push the world's species beyond a tipping point to mass extinctions?

Flannery argued that 20 to 60 percent of the species on Earth could be driven to extinction by climate change, depending on the scenario for future fossil fuel use. How could global warming of several degrees have such a large impact? Life seems to be very adaptable and it has survived many large climate changes in the past.

While I was reading Flannery's book, I received an e-mail from a man in Arkansas who had watched an interview of me on the CBS news program *Sixty Minutes*.[2] The man wrote "I would like to tell you of an observation I have made. It is the armadillo. I had not seen one of these animals my entire life, until the last 10 years. I drive the same forty-mile trip on the same road every day and have slowly watched these critters advance further north every year and they are not stopping. Every year they move several miles."

At that time, I was working on a paper[3] on observed global temperature change, mainly with co-authors Makiko Sato and David Lea – Lea is an expert in paleoclimate and oceanography. We added to the paper several global maps of the rate that climate zones were shifting in the real world and in climate models for various scenarios of the future. We found that isotherms – lines of a given average temperature – were shifting poleward at rates of typically 50-100 kilometers (30-60 miles) per decade at middle and high latitudes during the past few decades.

Our climate model simulations showed that this rapid shifting of climate zones would continue throughout the 21st century under "business as usual" greenhouse gas scenarios. In contrast, the "alternative scenario" for greenhouse gas growth (Chapter 35) reduced the 21st century rate of migration of isotherms to about 10-15 kilometers (6-10 miles) per decade.

Animals are on the run. That was the first sentence of my article[4] – titled *The Threat to the Planet* – in the New York Review. Plants are migrating too. Earth's creatures, save one species, do not have thermostats in their living rooms that they can adjust for an optimum environment.

Armadillos are tough critters. They've been around at least 50 million years and they look like it. Some of them may meet their doom when they try to cross four-lane highways, but I'm not too worried for them. However, not all species are as mobile as the armadillo.

If the shift of climate zones is smaller than the range of a given species, its direct effect may be limited. However, alpine species, pushed to higher altitudes, and polar species can be pushed off the planet if the warming is too large.[5] Indeed, if isotherm migration continues to be rapid and inexorably poleward, it is likely to spell doom for many species. Because of interdependences among species, ecosystems may collapse.[6] That's a tipping point. Before giving credence to such speculation, let's check the paleoclimate record and real-world data of recent decades.

The fastest global warming that we know about was during the Paleocene Eocene Thermal Maximum (PETM), when global temperature increased about 6°C over a period of at least several thousand years.[7] That's a warming rate of about 0.1°C per century, twenty times smaller than our current warming rate of about 2°C per century. The millennial time scale of change in the PETM provided time for life to migrate and evolve. Horses, then about the size of small dogs, shrank to the size of house cats. Size may have evolved because smaller bodies have larger surface area to mass ratio, helping to keep the animal cool, or because of reduced food supply in a hotter, drier climate. The PETM did not witness excess extinctions on land, but there was major extinction of deep ocean foraminifera (tiny shelled animals).

Despite the slow pace of temperature change in the paleo record, a comprehensive correlation of biodiversity with sea surface temperature change over the past 520 million years indicates that climate change does account for a substantial portion of extinctions.[8] Paleoclimate data thus tend to support concern about the effect of global warming on extinctions.

Modern data add to our concern. Species are migrating in response to the rapid global warming of the past 50 years, which is almost 0.2°C (0.36°F) per decade. Camille Parmesan and Gary Yohe studied 1700 biological species[9] and found poleward migration of 6 km (4 miles) per decade and vertical migration in alpine regions of 6 meters (20 feet) per decade in the second half of the 20th century, migration rates much slower than the rate of isotherm movement.

The need to migrate is only one of the problems that humans are imposing on other species. Other stresses include our land use, nitrogen fertilization, introduction of exotic species, and overharvesting, as humans essentially take over the planet. IPCC estimates that the net effect could be commitment to loss of as much as a quarter to half of the species by the end of this century, if we continue with business-as-usual fossil fuel use. It's a hard problem, but this conclusion does not seem to be an exaggeration.

The migration and other problems for species would be much less if the regions presently set aside for nature were not so fragmented. Harvard biologist Edward O. Wilson proposes[10] that half of the land and half of the ocean be reserved for nature. He estimates that 84 percent of species could survive with that allotment.

Despite expected continued growth of human population in coming decades, an increased set-aside of land for nature is feasible and politically realistic. People are increasingly moving to urban areas. The exact fraction of Earth devoted to nature may be less crucial than other characteristics. In the Americas the priority and initial goal might be a contiguous "nature's corridor" stretching from the Arctic to the southern end of South America. The corridor might include some of the present National Parks in the United States.

Complete exclusion of humans from the land set aside for nature is probably not necessary or desirable. The land could be available to the public for appropriate recreational and educational purposes. Given the size of the imagined area, it should be possible to accommodate such uses without spoiling the objectives of nature preservation. In my view, Native Americans should be given preference for the limited residence and management responsibilities within the corridor, but this is a political issue that would need to be decided via a national conversation.[11]

How should we talk with children about climate change? Children are impressionable and can worry excessively. Most of us can probably remember exaggerated fears in our youth. Our concerns about climate change can frighten and harm children, who face many challenges today.

There are real climate threats, but they are not hopeless problems. We are putting many species under stress and sea level is rising about 3.5 centimeters (about 1.4 inches) per decade. These are warning signs, but not doomsday disasters. We can still save most of the species and keep shorelines close to where they are, if we have our wits about us.

When Anniek realized that one of our grandchildren was distressed by what he heard about climate change, she jumped in to reassure him that adults were working on the problem, there was no need to worry. My first idea – which was hardly original[12] and almost backfired – was to introduce our grandchildren to the miraculous monarch butterfly. Monarchs had been in decline for decades, mainly because of the decline in milkweed abundance. The female monarch lays her eggs on milkweed, which is the only food that the larvae (caterpillars) eat.

Sophie and Connor helped me transplant several milkweeds from the edge of Frogtown Road – where the milkweed would have been cut down by the county's mower – to the edge of our pasture, where our neighbors graze their horses. Our work paid off the first year: our bedraggled transplants, attracted at least one female Monarch, who produced a few larvae.

Unfortunately, the number of monarchs reaching the mountain in Mexico where they overwinter was a record low that winter. The next summer we saw no monarchs. I began to wonder if I might be causing our grandchildren to witness an extinction.

The third spring Connor grew some exotic tropical milkweed in flower pots. The ones that we planted by the horse fence were eaten by the horses, who never touched common milkweeds. Luckily, we also planted a few of the milkweeds in our flower garden.

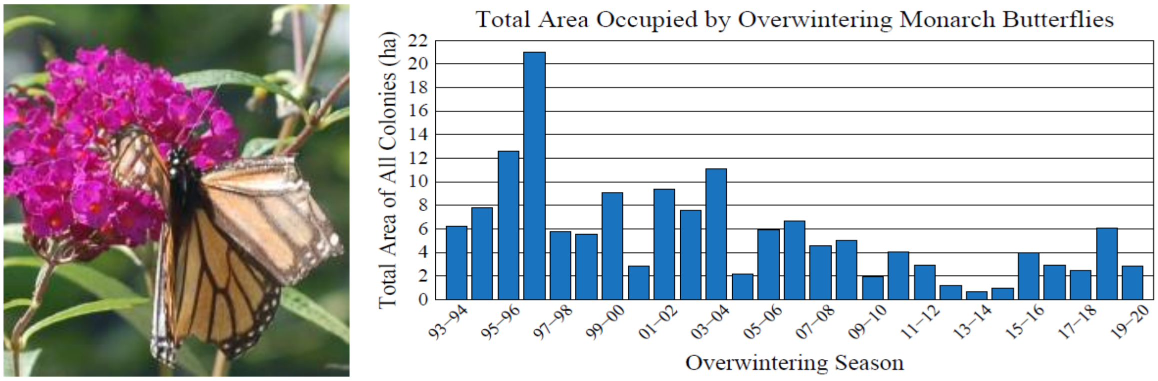

Fig. 38.1. Broken-wing female monarch. Graph: Monarchs overwintering in Mexico. They cluster together, which allows their number to be estimated from the area that they cover. Update of graph of Brower, L.P. et al. in *Insect Conservation and Diversity*.[13]

We saw two monarchs that summer. One, an easily-identified female with a broken wing (Fig. 38.1), had stayed around for more than a week when I left for a trip to Washington. The next day the remnants of a tropical storm dumped torrents of rain totaling almost eight inches. Trees were uprooted, because the ground was saturated prior to the storm.

The butterfly and larvae could not survive that deluge, I thought. But when I got home, the broken-wing butterfly was still flitting about the garden. Evidently, she had decided that our meager patch of milkweeds (chewed up by the larvae) and our butterfly bush would be the end of the line for her. The trip to Mexico would be a task for her children.

I could not find any chrysalis, but eventually two orange spots appeared in the nearby privet hedge – newly emergent butterflies, one male and one female, hanging upside down, seemingly exhausted by their breakneck trip from the land of the worm, waiting for their newfound wings to dry – I caught them both in one photo.[14] After a while the male began steadily crawling up the privet sprig. At the apex he sat for some time, beat his wings several times while holding onto the sprig, and then set sail to heights of 20-30 feet, flying once all around the yard before returning to land on the butterfly bush, where he presumably was gathering nourishment for a long trip. When I returned later in the day both butterflies were gone.

Perhaps they made it to Mexico and joined the crowd that you can see in this 3-minute video.[15] Be sure to stay for the spectacular finale. Monarch populations have rebounded a bit in recent years (Fig. 38.1) and efforts are being made to prevent logging of the forest area where they overwinter and to maintain milkweed abundance in North America.

But that's not enough. There's a more general requirement, which is important for many if not all species. To help clarify it, let's consider one more species.

Jeremiah, the frog, is a related story. Jeremiah's story is included in a letter to Sophie[16] that I wrote when I intended Sophie's Planet to be composed of a series of letters.

Early one summer, while pulling weeds around newly planted fruit trees, I heard what I first thought was a duck quack coming from the ditch on the corner of our property, where there was often standing water. Turned out it was a frog, croaking loudly. There was a smaller frog across the water, who sometimes answered with a weaker croak. They went silent when they saw me standing by the fence, but soon the big one resumed his croaking.

Fig. 38.2. Left: Jeremiah. Right: Saenz-Romero's grandson observing monarchs.

That summer we had drought for a few weeks. The puddle would have gone dry, so I hooked up a hose and refilled it. When Connor and Jake – our first two grandsons – and I went to check, Jeremiah would dive into the culvert beneath the road. Jeremiah is the name that we gave to the big frog. Jeremiah somehow became famous. We found a song about him,[17] – but he was misidentified as a bullfrog. Jeremiah is actually a green frog (Fig. 38.2).

Then one day the croaking stopped. The weeds along the road had been cut short by the county mower – even the cattails in the water were cut short. The next day there was still no croaking and no sign of Jeremiah. I told Anniek that we had an apparent case of frogicide.

A week later I heard a croak – pretty weak, but it was a thrill to hear it. I took the photo of Jeremiah hiding behind slashed vegetation, seemingly affected by a traumatic experience.

Jeremiah's ditch ends up in an arm of Lake Nockamixon, which may explain his origin. We thought we would catch Jeremiah and take him to a better place, but he escaped into the culvert, as if he didn't want to go. We decided to let him live out his life in the mud puddle -- if there was a big drought again, I would water the puddle. But we caught two of his offspring and took them to a good spot in an arm of Lake Nockamixon.

The green frog species may be in reasonable shape, but many amphibian species worldwide are in trouble for various reasons. My above letter to Sophie shows a golden frog of Central America, which apparently has gone extinct. One factor in its demise seems to have been a climate shift to more frequent and severe drought.

Shifting climate zones and increasing climate extremes are a problem for many species. As I continued to report in my communications about the Monarch status each winter, I often received responses from people about their own observations.

Cuauhtemoc Saenz-Romero, a Mexican scientist, sent a message about the effect of shifting climate zones on the oxamel fir tree habitat where the monarchs hibernate at altitudes 2.9-3.4 km in the Trans-Mexican Volcanic Belt. He included a photo of his two-year-old grandson looking up at millions of monarchs in the fir trees (Fig. 38.2) and photos of the trees, which are under stress from persistent drought. These are included in a later letter to Sophie.[18]

Continued shifting of climate zones expected as CO_2 increases implies that these fir trees won't survive in the butterfly reserve later this century.[19] Thus consideration is being given to planting the same fir trees at higher altitude for possible "assisted migration" of monarchs.

Such assisted migration has more chance of working than migration to Mars, but there is a better way. I don't mean to be flippant. In fact, we climate scientists should be apologetic. Why did it take so long to realize and communicate that the rapid human-caused poleward migration of isotherms needs to be halted and even reversed?

We should have done a better job of making clear earlier how deeply irrational our greenhouse gas emissions pathway has been over recent decades. We have been slow to recognize and articulate the low limits on greenhouse gas levels and global temperature change that are compatible with an acceptable future for humanity.

One consequence of this slowness – of the scientific community and policymakers – is that the topic of geoengineering necessarily enters the conversation. We ended our 2006 paper on global temperature change with the paragraph: "Inference of imminent dangerous climate change may stimulate discussion of 'engineering fixes' to reduce global warming. The notion of such a 'fix' is itself dangerous if it diminishes efforts to reduce CO_2 emissions, yet it also would be irresponsible not to consider all ways to minimize climate change. Considering the evidence that aerosol effects on clouds cause a large negative forcing, we suggest that seeding of clouds by ships plying selected ocean regions deserves investigation. However, given that a large portion of human-made CO_2 will remain in the air for many centuries, sensible policies must focus on devising energy strategies that greatly reduce CO_2 emissions."

The good news, I will argue, is that it is still possible to avoid consequences such as loss of coastal cities or loss of a large fraction of Earth's species. Moreover, the most effective and fastest way to return to an equable climate actually minimizes geoengineering.

The best chance for me to make that case is to continue the climate story as I learned it.

A climate tipping point was about to emerge in a climate simulation that we made in October 2006. At first, I thought that it might be a model problem. After all, we were using a model with very coarse resolution. It would be several years before we understood it well. Even when we persuaded ourselves that the model was right, how could we persuade the scientific community?

Chapter 39. The Freshwater Experiment

Is there a global warming time bomb? Maybe I was wrong. Maybe there isn't a global warming time bomb. I had to keep asking myself that question – that's the way science works. Also, what I was saying was not appreciated by NASA leaders or by many scientific colleagues.

I published the "time bomb" phrase first in the paper *Can We Defuse the Global Warming Time Bomb*[20], which I uploaded as a web publication on *NaturalScience* in August 2003. The time bomb phrase was intended to create a greater sense of urgency than emerged from IPCC.

I began working on the *Time Bomb* paper at least a year earlier in support of the idea that we needed an "alternative scenario" for greenhouse gases, alternative to the scenarios employed by IPCC. The IPCC scenarios employed at that time all led to warming of at least a few degrees Celsius, and thus all of their scenarios seemed to me to be exceedingly dangerous.

I put the *Time Bomb* paper on the web because I knew there was no chance of publishing it in the scientific literature. I was able to publish its predecessor paper, the *Alternative Scenario*, only because I sent it to the Proceedings of the National Academy of Sciences, where members of the Academy are able to publish with only cursory review. The *Alternative Scenario* paper was then criticized severely by the relevant research community, most of whom are involved in IPCC.

The *Time Bomb* paper was the main basis of my talks at the Council on Environmental Quality in 2003, at Goddard for the NASA Administrator in 2004, and at Iowa in October 2004. I gave my rationale in the *Time Bomb* paper, but it was an unrefereed paper in the gray literature.

Steve Schneider gave me a chance to explain the time bomb rationale, in a refereed editorial essay. I titled it *A Slippery Slope*.[21] The analogy was to a photograph, Figure 7 in the *Time Bomb* paper, which showed a professor and a few of his students standing near a stream of water on the Greenland ice sheet. The danger was stepping too near the stream's edge. If one slipped, there was little chance of clawing back to safety – it would be a hellish doom, down the moulin.

Figure 1 in my essay is shown here as Fig. 39.1. Greenhouse gases had already shot far above their range during hundreds of thousands of years. The gas amounts were probably approaching those in the Pliocene, a few million years ago, if they had not reached those levels already.

We knew relevant facts. Greenhouse gas changes accounted for half of the climate forcing that maintained glacial-to-interglacial climate changes. The other half was change of Earth's albedo (reflectivity) due to changing size of the ice sheets.

Greenhouse gas and albedo forcings were slow feedbacks in the climate changes that occurred on paleoclimate time scales, the drive for the climate change being changes of Earth's orbit. However, the climate system does not care whether the greenhouse gas changes are natural or human-made. The physics does not change. Added gases cause a planetary energy imbalance and Earth must warm up until energy balance is restored. Warming due to human-made gases is well underway but there is more on the way, as proved by Earth's energy imbalance.

Sea level was many meters higher when Earth was warmer. The principal question is how long it takes for ice sheets to melt and thus sea level to rise in response to a higher global temperature.

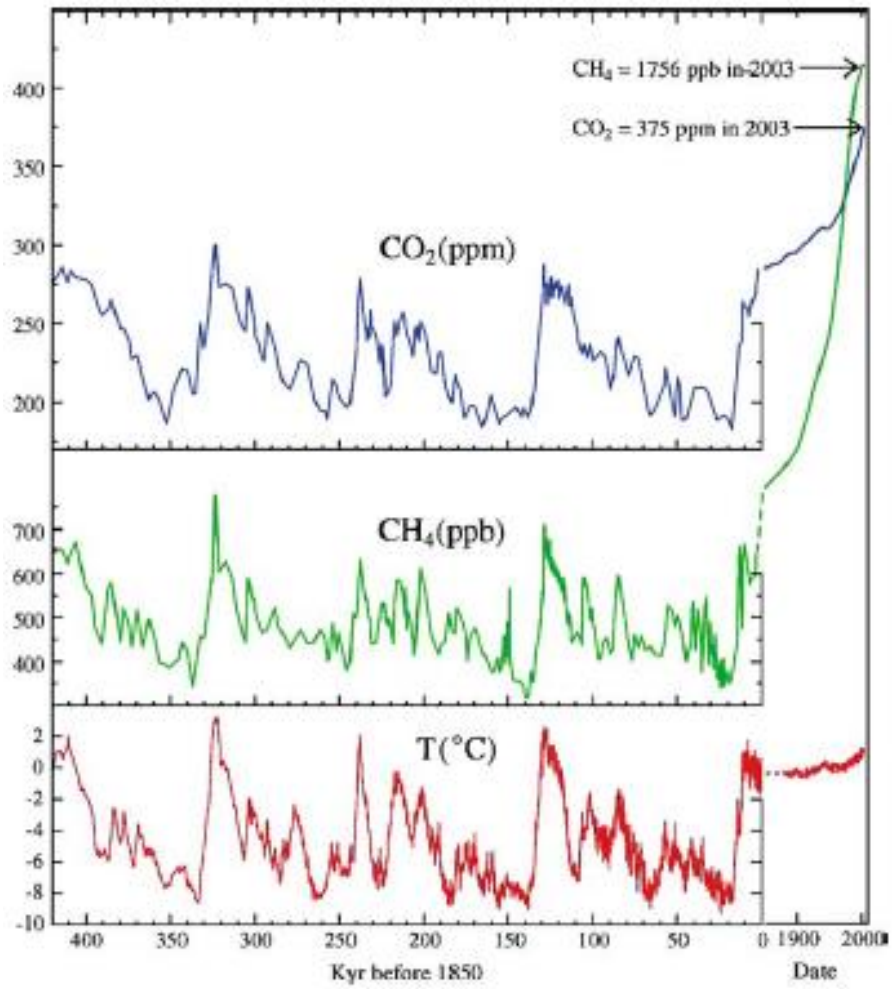

Fig. 39.1. Atmospheric CO_2, CH_4 and temperature based on ice core data of Petit et al. (1999). Modern observations, on the right, are plotted with an expanded time scale.

Ice sheet modeling: is something wrong with this picture? That was the title of a subsection in *A Slippery Slope*. The most recent IPCC report[22] at that time estimated a sea level rise of 40-45 cm in a century for the heavily studied IS92a scenario, which has 715 ppm CO_2 in 2100. The sea level rise was composed of 30 cm from thermal expansion of sea water, 10-15 cm from alpine glaciers, and no net change of the Greenland and Antarctic ice volumes.

CO_2 at 715 ppm was a time bomb, it seemed to me. IPCC treated ice sheets as being almost static. Could that be right? If it takes 1,000 years for large ice melt, perhaps it is o.k. to leave such a slow puttering time bomb for future generations – but are ice sheets really so lethargic?

I made an argument based on the rate that added CO_2 was causing energy to be pumped into the ocean. Our conclusion that Earth's energy imbalance was approaching 1 W/m^2 was published in *Science* in June 2005, but it was already known and the central point in my 2004 Iowa talk.

A global 1 W/m^2 energy source, if used entirely to melt ice, would raise sea level more than 10 meters (33 feet) in 100 years.[23] Initially, most of this extra energy is not melting ice – it is pumped into the ocean, where it raises the ocean temperature. However, as ice shelves that plug the ice streams are removed, ice will flow more readily into the ocean, especially from the West Antarctic ice sheet, which rests entirely on bedrock below sea level.

I suggested that there was an amplifying feedback, an iceberg cooling effect, which helps explain the sawtooth shape of paleoclimate warming and cooling cycles (Fig. 39.1). The warming phase and sea level rise are more rapid than the cooling phase as sea level falls. One reason for this is the fact that a lot of heat is soaked up by the phase change from ice to water.

This iceberg cooling effect increases the planetary energy imbalance. Cooling the ocean surface reduces outgoing energy, so the planetary energy imbalance grows. This provides a large additional source of energy for melting ice. Free energy! It's a big effect. Ocean circulation spreads the cooling over a wide area of ocean, even into regions without icebergs.

I wondered: did the climate models that IPCC relied on include the cooling effect of an increasing flux of icebergs from Greenland and Antarctica? I checked descriptions of several of the published climate models. None of them seemed to extract from the ocean the energy needed for the phase change from ice to water when icebergs melt.

Thanks to Gary Russell's ocean model, including his precise conservation of fundamental quantities such as heat, salt and momentum, we had a tool to investigate the iceberg effect. So, in October 2006 I defined experiments for Reto to carry out with our global climate model.

The experiments added a growing flux of icebergs from Greenland and Antarctica into the upper layers of the North Atlantic and Southern Oceans. We did not include icebergs per se – instead we added freshwater, but we also extracted from the ocean the amount of heat needed to melt the ice and raise its temperature from that of cold ice to the ambient ocean temperature.

The climate model results were stunning. The growing iceberg injection rate cooled the North Atlantic Ocean and shut down the Atlantic meridional overturning circulation (AMOC). The biggest surprise was an even larger effect in the Southern Ocean that surrounds Antarctica. The surface of the Southern Ocean cooled. As greenhouse gases and global temperature increased, the area of sea ice around Antarctica grew larger!

My first reaction was that we had made a discovery. I had a simple explanation for why we got an answer so different from that of other climate models. We had included the fact that melting ice extracts a lot of heat from the ocean.

The American Geophysical Union annual meeting would be in mid-December. I was scheduled to give a talk, so I could give our results there. First, though, I had to verify that iceberg cooling was why our result differed from other models. So, I asked Reto to rerun the experiments with increasing freshwater but without iceberg cooling. Result: the ocean surface cooling was not as great, but the overturning circulations still shut down and sea ice around Antarctica expanded.

Poof – the explanation was not going to be so simple. I could not present unusual results without a full understanding. Many of the model results in the IPCC report were from large groups that included oceanographic experts. We had a model with such coarse resolution (4×5 degrees for ocean and atmosphere) that most oceanographers would not respect it.

I still thought that our result could be right, but we had to prove it. That would be hard and would take years but the matter is important – let's examine why.

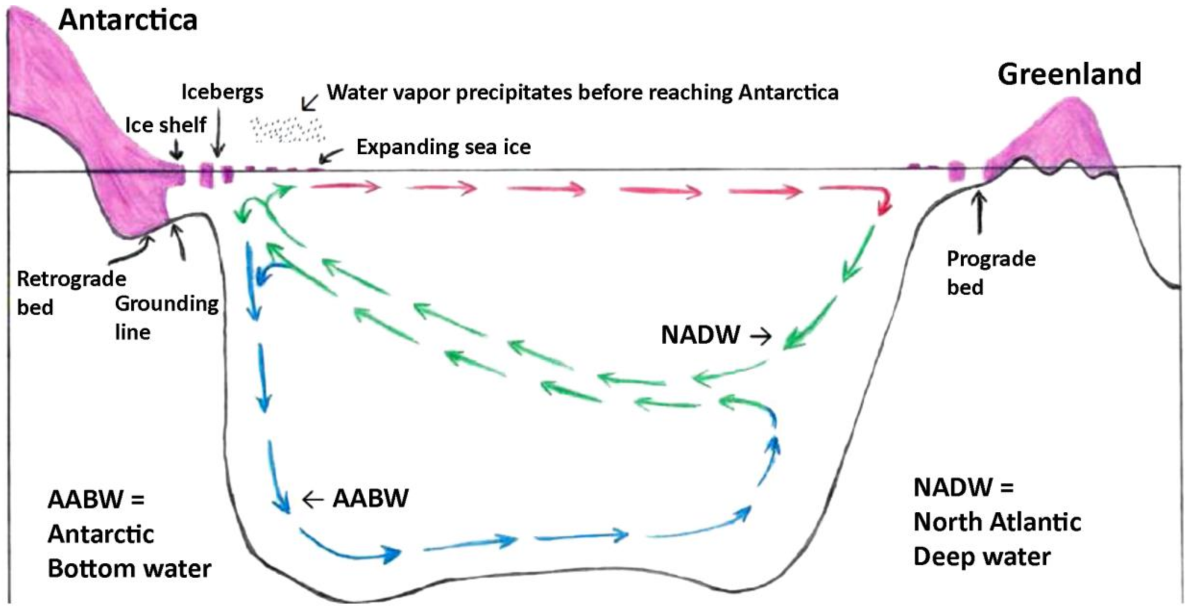

Fig. 39.2. Schematic diagram of the surface origin of two water masses that fill most of the world ocean: North Atlantic Deep Water (NADW) and Antarctic Bottom Water (AABW). The upper cell is the Atlantic Meridional Overturning Circulation (AMOC) and the deeper circulation is the Southern Meridional Overturning Circulation (SMOC).

A simplified diagram of the global ocean circulation (Fig. 39.2) helps explain ocean and climate changes during Earth's history and on-going human-caused changes.

The sinking red arrow in the north (right side of the diagram) is North Atlantic Deep Water (NADW) formation: salty water in the North Atlantic cools in the winter to a greater density, sinks to a depth of about 2 km, and moves south. Some of the NADW that reaches the Southern Ocean rises to the surface. There it is cooled further and becomes more saline as salt is expelled by sea ice as ocean water freezes during the Antarctic winter; this is the origin of the densest water in the ocean, Antarctic Bottom Water (AABW), which sinks to the ocean floor. AABW fills most of the world ocean below 2 km depth.

The Southern Ocean, under normal conditions, is an escape valve for ocean heat. In extreme cases the relatively warm NADW melts sea ice in the dead of winter, creating an area of open water, called a polynya. Air above the polynya, which is as cold as -20°C or -30°C when sea ice is present, rises to near the freezing point. Heat is pumped into the air and into space.

Shutdown of this escape valve has a profound implication. Our model found that the temperature of the ocean interior abutting the Antarctic continent began to rise, with maximum warming at depth 1-2 kilometers. This is the depth to which ice shelves extend, the tongues of ice that reach out from Antarctic ice sheets into the ocean. The ice shelves buttress the Antarctic ice sheet; thus as the shelves melt, icebergs are expelled into the ocean faster and faster.

The increasing iceberg flux cools the surface layer of the ocean around Antarctica. That's a diminishing feedback – it reduces global warming. However, it's an amplifying feedback for ice melt and sea level rise, because the cold, fresh surface water blocks the escape of ocean heat to space. That energy instead melts ice shelves, ice stream discharge increases, and sea level rises.

How much will sea level rise and how fast? What happens around Antarctica is more important than what happens in the North Atlantic. There is ten times more ice on Antarctica than on Greenland, and the most vulnerable ice sheet is West Antarctica.

If greenhouse gases continue to increase, growing ice melt will cause slowdown and eventual shutdown of AABW formation. Sea level rise will continue to accelerate at least until West Antarctic ice, which rests on bedrock far below sea level, is largely exhausted. Sea level rise, with East Antarctic and Greenland contributions, would be at least several meters.

That is a disaster scenario. Most coastal cities would be under water or at least dysfunctional.

However, I had no good basis to claim that our model was right and the others were wrong. There were shortcomings in our model in addition to its coarse resolution. We had to do a lot of work to gain confidence in the model and understand why our model gave a different result.

We would be jumping into a well-mined research field. Wally Broecker (Chapter 24) did a great job of alerting the scientific world and the public to the danger of possible shutdown of the North Atlantic overturning circulation (AMOC). The Atlantic Ocean circulation – including the Gulf Stream current in the upper ocean – carries warm water north, which is one reason that Europe is relatively warm despite its high latitude. The other reason is the atmospheric circulation, which on average brings air from lower latitudes to Europe.

Wally focused especially on the Younger Dryas event, which occurred 12,900 years ago. Over the preceding few thousand years, Earth's temperature rose slowly from the prior ice age almost to interglacial warmth. Then, in conjunction with an outburst of water from the giant Lake Agassiz that had formed abutting the south side of the retreating North American ice sheet, Greenland cooled 15°C within 10 years and much of Europe cooled by several degrees. Effects were smaller in the rest of the world – it was mainly a North Atlantic event.

Interpretation of the Younger Dryas event was that the freshwater from Lake Agassiz reduced the density of North Atlantic surface water so much that deep water formation shut down.

Wally's concern about a possible shut down of the North Atlantic overturning circulation stimulated climate research. He also reached the public. His 1987 article in *Natural History* magazine, *The Biggest Chill*, spawned a 1999 book, *The Coming Global Superstorm* by Art Bell and Whitley Strieber. This was followed by a 2004 science fiction disaster film, *The Day After Tomorrow*, which included a nonsensical, almost instantaneous, return to an ice age.[24]

The scientific community's concern, however, had diminished. The Intergovernmental Panel on Climate Change (IPCC) 2007 report concluded: "Based on current model simulations, the meridional overturning circulation (MOC) of the Atlantic Ocean will *very likely* slow down during the 21st century; nevertheless, temperatures over the Atlantic and Europe are projected to increase. The MOC is *very unlikely* to undergo a large abrupt transition during the 21st century."

The MOC is often – and more usefully – abbreviated AMOC, because they are referring to the overturning in the upper ocean associated with NADW formation. IPCC did not mention SMOC, the circulation associated with AABW formation.

Wally was not a climate modeler. He acceded to the conclusions of the modeling community, but retained a healthy skepticism about climate models. I shared Wally's skepticism.

Most climate models seemed to be lethargic. Human-made changes of atmospheric composition are large and much faster than in the paleoclimate record. Why did climate models not produce rapid changes, such as those known to have occurred in the real world?

Part of the problem is that climate models do not include realistic ice sheet models. Modeling ice sheets is hard. Continental scale ice sheets are affected by processes on a range of scales. Summer meltwater on an ice sheet can burrow a hole through the ice sheet, rush down the hole, and lubricate the base of the ice sheet as water flows downhill to the ocean. Ice sheet movement is fastest in narrow ice streams that discharge icebergs to the ocean. How easily ice can "flow" to the ocean depends on the topography beneath the ice sheet and even on the nature of the soil. The most important physics for the time scale of this and next century is likely at the interface of ice and ocean. It may require decades to build a realistic ice sheet model.

My talk[25] at the 2006 AGU meeting focused on ice melt and sea level rise. Precise satellite measurements of sea level were initiated in 1993 and measurements of the Greenland and Antarctic ice sheet masses in 2002. We also had ocean temperature data. Using all these, several co-authors and I concluded that about half of the observed sea level rise was from thermal expansion of a warming ocean. The other half was about equally from shrinkage of the ice sheets – Greenland and Antarctica – and melting of smaller glaciers.

Greenland and Antarctica thus were already contributing to sea level rise, and on the long term they surely would be the dominant cause of sea level rise. Paleoclimate data showed that global warming of even a few degrees would cause eventual sea level rise of many meters, which is inconsistent with retention of our shorelines and coastal cities. Paleoclimate data also show that once ice melt gets well underway, sea level can rise several meters in a century.

The situation was growing dangerous, but we scientists did not communicate that danger well. Earlier in 2006 I began to work with Matt Pawa, a bright young lawyer chosen by the Sierra Club to lead a fight for high automobile fuel efficiency standards in California: *Automakers v. California*.[26] As my expert report I used a presentation[27] that I gave in April 2006 at the National Academy of Sciences – this talk described the climate threat as well as I could.

But was it good enough? Opposing lawyers could point to IPCC reports that contradicted my report. IPCC did not see the likelihood of disastrous sea level consequences with 715 ppm CO_2. IPCC used "burning embers" to suggest that 2-3°C may be dangerous, a vague concept that would put only marshmallow pressure on governments.

IPCC represented the relevant scientific community. The commendable concept that policy be informed by science gave rise to a bureaucratic monstrosity, a scientific organization that pleased the governments by giving no policy advice while accepting a welcome raison d'être.

The problem was not the troops. Thousands of capable and exceptional scientists participated with expert contributions. Many chapters of the IPCC reports are invaluable references.

The problem with IPCC was not only that it abstained from offering advice based on the status of scientific understanding. IPCC became a pompous organization lording over those who would question its authority. An adequate understanding of the situation can be gleaned by reading the final paragraph of a rebuttal[28] to criticism of IPCC. That exchange concerned an arcane discussion of probabilities that is best ignored.[29] However, the final paragraph, dripping in condescension, reveals the sentiments of too many of the IPCC leaders, who feel that the world must wait for their authoritative decrees.

Richard Feynmann liked to remind us how real science works. We must continually question our conclusions, presenting all sides of an argument equally, and changing our conclusions when the evidence warrants it. I am no more critical of IPCC conclusions than of my own.

I disagree that conclusions about climate change must wait until IPCC goes through a ponderous process and that verdicts of IPCC are near gospel. IPCC conclusions, even after their extensive reviews, must be subjected to the same scientific process as all other analyses.

After my AGU talk I was surprised when Carl Wunsch approached me. Wunsch was perhaps the most authoritative oceanographer in the world, and he could be acerbic.[30] He was the force behind WOCE, the World Ocean Circulation Experiment, which aimed to obtain global observations required to understand the ocean, especially its dynamics.

Wunsch was precisely the person I should have talked with about the ocean. He asked the most penetrating questions about how the ocean works[31] and he had deep skepticism about models. Unfortunately, when he said that he "agreed with me," my latent diffidence resurfaced and I was too taken aback to think clearly. If I had engaged Wunsch to talk about our freshwater experiments, we might have made fast progress. Instead those climate simulations were placed on a backburner, where they remained much longer than I intended.

Fortunately, I was about to make a fundamental change in the way I worked. I was forced to learn how to ask help of scientists who were smarter and had deeper knowledge of a subject than I had. It was thanks to another push from Bill McKibben.

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[1] McKibben, B., The coming meltdown, *New York Review*, LIII, no. 1,12 January 2006. McKibben reviewed Mark Bowen's *Thin Ice: Unlocking the Secrets of Climate in the World's Highest Mountains*, Henry Holt, 463 pp., 2005. Bowen describes the science of climate change through the experience of Lonnie Thompson, the preeminent explorer of high-altitude glaciers as Thompson tries to decode climate secrets trapped in the ice

[2] Rewriting the Science, CBS Sixty Minutes, 17 March 2006. This interview occurred in early January, prior to Revkin's article in the Times that drew attention to censorship. The CBS interview was approved several months earlier, prior to the flair-up associated with my AGU presentation in December 2005. The approved interview concerned Arctic climate change, but the focus changed when Scott Pelley became aware of the censorship issue.

[3] Hansen, J., M. Sato, R. Ruedy, K. Lo, D.W. Lea, and M. Medina-Elizade. Global temperature change. *Proc. Natl. Acad. Sci.* **103**, 14288-14293, 2006.

[4] Hansen, J., 2006. The threat to the planet. *New York Rev. Books*, **53**, no. 12 (July 13, 2006), 12-16, 2006.

[5] Hansen, J., 2008: Tipping point: Perspective of a climatologist. In *State of the Wild 2008-2009: A Global Portrait of Wildlife, Wildlands, and Oceans*. E. Fearn, Ed. Wildlife Conservation Society/Island Press, pp. 6-15.

[6] Strona, G. and C.J.A. Bradshaw, Co-extinctions annihilate planetary life during extreme environmental change, Sci. Reports, 8:16724, 2018.

[7] McInerney, F.A. and S.L. Wing, The Paleocene-Eocene Thermal Maximum: A perturbation of carbon cycle, climate, and biosphere with implications for the future, Ann. Rev. Earth Plan. Sci. 39, 489-516, 2011.

[8] Mayhew, P.J., G.B. Jenkins and T.G. Benton, A long-term association between global temperature and biodiversity, origination and extinction in the fossil record, Proc. Roy. Soc. B 275, 47-53, 2008.

[9] Parmesan, C. and G. Yohe, A globally coherent fingerprint of climate change impacts across natural systems, Nature, 421, 37-42, 2003.

[10] Wilson, E.O., *Half-Earth: Our Planet's Fight for Life*, Liveright Publ. Corp., ISBN 978-1-63149-082-8, 2016.

[11] In contrast to tribal casinos, which have brought both economic benefits and problems for Native Americans, management of nature's corridor might be a less fraught opportunity. Indeed, some tribal leaders point out health and other merits of maintaining some traditional life style.
[12] Tallamy, D.W., Bringing Nature Home, Timber Press, London, ISBN-13:978-0-88192-992-8
[13] Brower, L.P., O.R. Taylor, E.H. Williams, D.A. Slayback, R.R. Zubieta and M.I. Ramirez, Decline of monarch butterflies overwintering in Mexico, Insect Cons. Diver. 5, 95-100, 2012.
[14] Hansen, J., It's a Hard-Knock Butterfly's Life, 28 September 2011.
[15] 3-minute video of Monarch butterflies, https://www.youtube.com/watch?v=lWOySU_hAz0
[16] Hansen, J., Butterfly report + Jeremiah, the frog, letter to Sophie, 1 November 2012.
[17] Jeremiah's song https://www.youtube.com/watch?v=QtYnCmw2CWE
[18] Hansen, J., Quest of a Broken-Wing Butterfly, letter to Sophie, 31 January 2014.
[19] Saenz-Romero, C., G.E. Rehfeldt, P. Duval and R.A. Lindig-Cisneros, *Abies Religiosa* habitat prediction in climatic change scenarios and implications for monarch butterfly conservation in Mexico, Forest Ecol. Manag. 275, 98-106, 2012.
[20] Hansen, J., Can we defuse the global warming time bomb? *naturalScience*, posted Aug. 1, 2003.
[21] Hansen, J.E., A slippery slope: How much global warming constitutes "dangerous anthropogenic interference"? An editorial essay. *Clim. Change* **68**, 269-279, 2005.
[22] IPCC, 2001, Houghton, J.T. et al., *Climate Change 2001: The Scientific Basis*, Cambridge Univ. Press, U.K.
[23] Correct calculation details are given in Table S1 of Hansen, J., L. Nazarenko, R. Ruedy, M. Sato, J. Willis, A. Del Genio, D. Koch, A. Lacis, K. Lo, S. Menon, T. Tovakov, Ju. Perlwitz, G. Russell, G.A. Schmidt and N. Tausnev. Earth's energy imbalance: Confirmation and implications. *Science* **308**, 1431-1435, 2005.
[24] Monbiot, G., A hard rain's a-gonna fall, *The Guardian*, 14 May 2004 https://www.theguardian.com/film/2004/may/14/climatechange
[25] Hansen, J., R. Bleck, E. Leuliette, K. Lo, R. Ruedy, M. Sato, S. Sun and J. Willis, Earth's Energy Imbalance and Ocean Heat Storage 14 December 2006.
[26] Central Valley Chrysler v. Catherine E. Witherspoon, Case No. 1:04-CV-06663 REC LJO, U.S. District Court, Eastern District of California – Fresno.
[27] Hansen, J., Global warming: have we passed a 'tipping point'?, National Academy of Science, 23 April.
[28] Allen, M., S. Raper and J. Mitchell, Uncertainty in the IPCC's 3rd assessment report, Science 293, 430-433, 2001.
[29] The derived probabilities for climate change depend upon numerous assumptions, some unstated and some unknowable. Arcane probabilities are a shield against criticism from the uninitiated and they often misinform about true uncertainties. Climate is more complex than chess, a lot more. Expert assessment will be our best tool for a long time to come. Expert assessments will converge as data and understanding grow.
[30] I had one prior encounter with Wunsch, in 1992 on a sun-drenched porch overlooking the harbor in Woods Hole, Massachusetts, when NASA conceived Mission to Planet Earth, still under scientific guidance of Richard Goody and others. I had the temerity to suggest that a satellite instrument intended to measure ocean height also be tasked to monitor vegetation height over land to help define the effect of deforestation and vegetation regrowth on Earth's carbon budget. Wunsch nearly bit my head off. He was right, and he was a tough character. He kept the satellite focused on ocean science, and the WOCE program was a huge success.
[31] Wunsch, C. and R. Ferrari, Vertical mixing, energy, and the general circulation of the oceans, Annu. Rev. Fluid Mech. 36, 281-314, 2004.