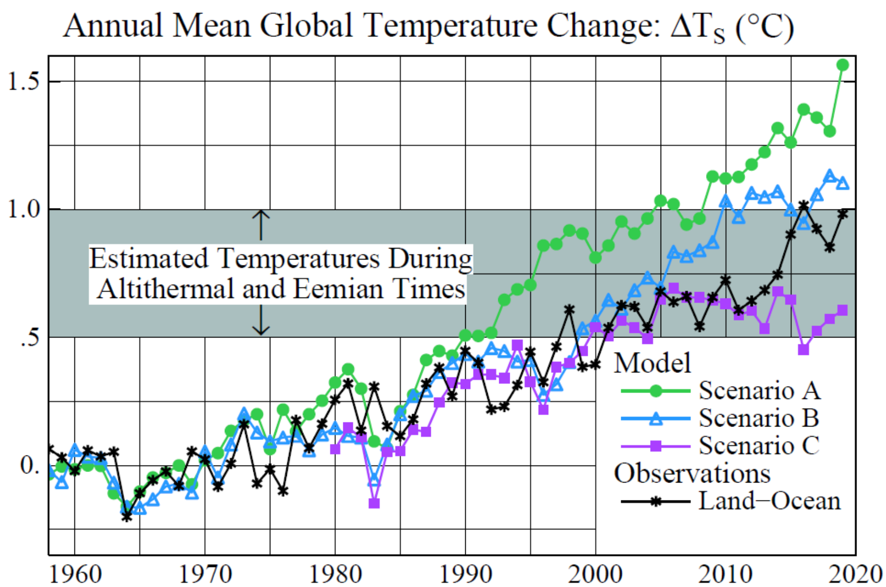

Fig. 30.1. Simulated global surface temperature for three scenarios and observations.

Chapter 30. How Well Did Our 1988 Model Do?

Global climate models are an essential tool in Earth scientists' tool box. Models are an imperfect simulation of the real world – it is difficult to accurately include all significant real world processes – yet models are an invaluable tool, if their limitations are recognized.

Jule Charney provided an iconic example of thoughtful use of models in leading the 1979 climate study at Woods Hole (Chapter 17). Charney favored the complex global climate models (GCMs) that incorporate the general circulation of the atmosphere, because he could use these to investigate the role of various climate processes including feedback effects.

Charney was delighted that the two GCMs available in 1979 that incorporated the upper ocean and had been used for doubled CO_2 experiments, Suki Manabe's model and our (GISS) model, gave widely different results for 2×CO_2: 2°C for Manabe and 4°C[1] for GISS. This provided incentive for examining and comparing all of the processes in the models.

I like to imagine what Jule Charney would ask if he came back to visit us today. Probably he would want to know about real global temperature change and how well our model simulated it.

Here is my dream. I start by showing Fig. 30.1 to Charney. Jule fixes his attention first on the observations. The real world has warmed about 1°C relative to the base period 1951-1980, so Earth's temperature now exceeds that of the Altithermal – a name used in Charney's time for the early Holocene. Jule's imagined words are in quotation marks.

"One degree warming is not surprising, if you did nothing to slow down growth of CO_2. I'm a bit surprised, though that you say it is a warm as in the Eemian – the prior interglacial – we thought of the Eemian as substantially warmer conditions."

The Eemian was different for sure. Sea level reached 6-9 meters (20-30 feet) higher than today, but recent studies show that global temperature was not much warmer than today – maybe a few tenths of a degree, there is uncertainty, but we will soon be there, if we are not already.

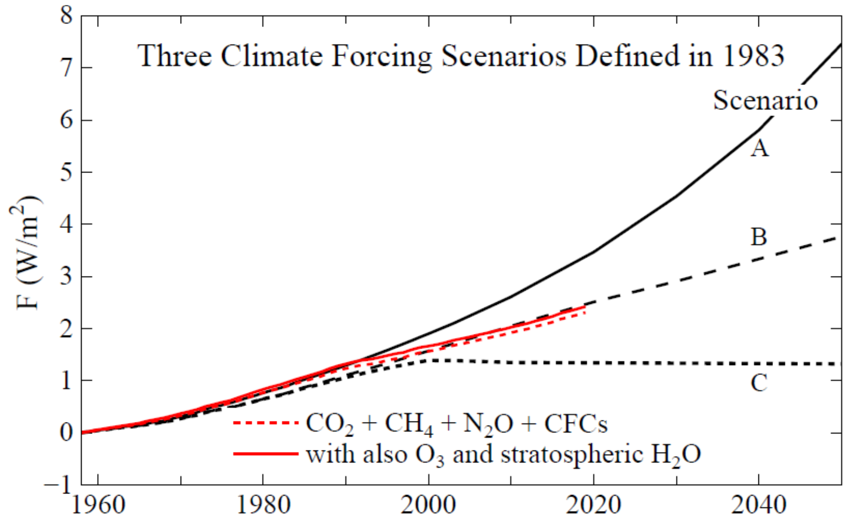

Fig. 30.2. Greenhouse gas climate forcing for three scenarios and for the real world (red).

Charney is silent for a moment, then: "Well, ice sheets take time to melt. You may still avoid that if you understand the situation well. What have you learned?"

I had to admit that it took a few years, but we documented the model's physics well, including about 100 short model runs to test the effect of many parameters. The paper was published in *Monthly Weather Review*[2] in 1983. Our 2×CO_2 simulation was presented in 1982 at the Ewing Symposium (Chapter 23) and documented in a paper[3] in the Ewing volume in early 1984.

Charney is not surprised about how long it took to make simulations in which the greenhouse gases increase year-by-year as in the real world. After all, his first numerical weather forecast (in 1950 on ENIAC) took a whole day to make a 24 hour forecast for the U.S. We initiated runs in 1983. All runs were done by 1987 and we published the paper[4] describing them in 1988.

"I'm surprised that you're still using Jastrow's computer. But what are the three scenarios, A, B and C? What were the forcings in the model that drove the global warming?"

Scenario A has continued exponential growth of greenhouse gases. The world followed that path for decades, but growth slowed when concerns about ozone depletion led to a phaseout of CFCs.

Scenario C brackets the scenario range on the low side. It has the optimistic assumption that greenhouse gas amounts would be stabilized after year 2000. Obviously, that did not happen.

Scenario B – which we described as the most realistic – has continued growth of the greenhouse climate forcing at a rate of about 0.04 W/m^2 per year. The red line is the climate forcing calculated for the actual ("real world") greenhouse gas changes.

"Hmm. Your scenario B climate forcing (Fig. 30.2) was dead on the mark!"

That was partly luck, I explained. Real world (observed) growth of the long-lived greenhouse gases – CO_2, CH_4, N_2O and the CFCs – was slightly smaller than in scenario B. The greenhouse climate forcing in our climate model included only the direct climate forcing by these specific gases, as shown by the black lines – the dashed line is scenario B.

The radiative forcing due to the real world (observed) changes of these gases is shown by the dashed red line – it's slightly smaller than scenario B. However, we now know that increasing CH_4 causes an increase of tropospheric ozone (O_3) and an increase of stratospheric water vapor (H_2O). When we include the climate forcing by O_3 and stratospheric H_2O, the total forcing[5] is even closer to the forcing that we used in the model run with scenario B.

"So you have a model run with almost precisely the true greenhouse gas forcing. It looks like the model warms more than the real world (Fig. 30.1). Let's figure out how much and why."

Yes, if we fit a straight line to observed global temperature for the period 1985-2019 the observed warming is 0.71°C. Similarly, the modeled warming with scenario B is 0.94°C.

"That ratio, 0.71 over 0.94, is about ¾. Your model sensitivity is 4°C for doubled CO_2. That would suggest that the real world climate sensitivity is about 3°C for doubled CO_2, just as our Academy study estimated 40 years ago."

It's not quite that simple. If greenhouse gases were the only important climate forcing, your interpretation would be almost right. The observed warming would actually imply a somewhat smaller climate sensitivity, closer to 2.5°C for doubled CO_2, because over a period of just a few decades the warming does not increase in proportion to equilibrium climate sensitivity. Shortly after you left the planet we realized that the higher sensitivities require much longer to reach their equilibrium response – but let's not worry about that detail, I will give you a paper.[6]

There is a bigger problem. Greenhouse gases are not the only important climate forcing. Human-made atmospheric aerosols also cause a substantial forcing, It's a negative forcing, a cooling forcing, because aerosols' main effect is to reflect sunlight and thus reduce heating of Earth. The net global climate forcing is less than that of greenhouse gases alone.

We didn't include aerosols in our climate model, because we had no data for the aerosol forcing. We thought that the net aerosol effect might be small. Aerosols seemed to be decreasing in the developed world, because of public concern about air pollution. Reduced air pollution in the developed world might offset rising aerosol amounts in much of the world.

Now the evidence indicates that global aerosols increased over the past century, including the period since 1958. It's likely that warming since 1958 has been reduced by increasing aerosols. And there is new evidence that our model sensitivity of 4°C for $2\times CO_2$ is about right.

Unfortunately, because of the aerosol uncertainty, we cannot use the observed warming in the past century to infer climate sensitivity – or to fully assess the model. We need aerosol data.

"**Aerosol data? You have had 40 years to get aerosol data!** We started the Global Atmospheric Research Program during the Kennedy Administration. I was certain that you would have added the extra measurements by now."

Charney sat down, exasperated. I tried to apologize for our slowness, but it didn't help. Then I started wondering – was I dreaming? How could Charney "get a pass" to come back to Earth?

"There's a lot of concern up there about what's going on down here. Now I'm beginning to see their way of thinking. They think that you are not taking care of what you were given, and they are puzzled that people are not using the brains they were given."

I felt bad to see Charney dejected – it was not his nature. Then I had an idea. I would tell him about the remarkable developments in paleoclimate data. He was aware of the CLIMAP effort to deduce sea surface temperature during the last ice age. Even if some of us had not done our jobs well, there were others who did great. Knowledge of climate sensitivity had improved.

Real world data provide the most reliable and most accurate assessment of climate sensitivity. In contrast, with climate models you never know whether you have included all of the important climate feedback effects or how accurately you have calculated them.

Some scientists, paleoclimatologists, have done a spectacular job. They have been able to reconstruct how the atmospheric composition changed and how climate changed over hundreds of thousands of years. The most precise data are from ice cores. They have drilled all the way to the base of the Antarctic ice sheet. They sample air that was trapped as the layers of snow were compressed into solid ice. Climate data for millions of years are extracted from ocean sediment cores, although, unfortunately, ocean cores do not yield accurate atmospheric composition.

I explained how data on climate conditions during the last major ice age, the Last Glacial Maximum (LGM) 20,000 years ago, provided an empirical measure of climate sensitivity. There was more CO_2, CH_4 and N_2O in the preindustrial Holocene atmosphere than during the LGM. The increase of those gases provided a forcing of about 3 W/m^2. The surface of Earth is also darker in the Holocene with no large ice sheets on North America and Eurasia. The additional sunlight absorbed is another climate forcing of about 3 W/m^2. This total forcing of 6 W/m^2 was long thought to have caused a global temperature change of 4.5°C ± 1.5°C. So climate sensitivity seemed to be ¾°C ±¼°C per W/m^2, which is 3°C ± 1°C for doubled CO_2.

"Wonderful – it agrees with what we got in 1979! And the uncertainty is reduced a bit. So, it seems that 3°C is the best estimate for doubled CO_2 climate sensitivity? That sensitivity would fit the warming observed in the last half-century, too, with maybe a small aerosol cooling effect."

That's what I thought for a long time, but there was one nagging fly-in-the-ointment. When we did climate model simulations with fixed Last Glacial Maximum boundary conditions, we found that Earth was out of energy balance – the energy being radiated to space was larger than the energy in absorbed sunlight. Earth was trying to cool off. The model was not in equilibrium, but we know the real world had to be close to equilibrium. The implication was that something was wrong with our assumed boundary conditions for the ice age.

The most likely problem was ice age sea surface temperatures (SSTs) that the paleoclimate research community had constructed. The actual SSTs must have been colder than what we put in the model – and there were good independent reasons to be suspicious about the ice age SSTs. This was all discussed in relation to the Ewing Symposium at Lamont, which was held in 1982.

The upshot was that, in our Ewing Symposium paper, we concluded that climate sensitivity was high, somewhere in the range 2.5-5°C for doubled CO_2. Unfortunately, the range was still large because of uncertainty about just how cold the ice age was.

"**Is it really so hard to reconstruct global temperature**?" John Imbrie and the CLIMAP project estimated SSTs during the Last Glacial Maximum (LGM) long ago.

There were issues about the CLIMAP data. It's a big job to assess and integrate the many types of data, but a lot of good work has been done recently. A comprehensive study[7] has just been published by Jessica Tierney and colleagues. They also review earlier work. They conclude that the LGM was about 6°C colder than the Holocene, with uncertainty range 5.7°C to 6.5°C. So we now have a tightly constrained LGM cooling. The total forcing of 6 W/m^2 by greenhouse gas plus surface albedo changes produced global warming of 6°C, so the implied climate sensitivity[8] is 1°C per W/m^2 or 4°C for doubled CO_2.

The paleoclimate research community has made good progress in empirical assessments of climate sensitivity (Chapter 25).[9] This includes reconstruction of climate conditions when Earth was much warmer, even ice-free. It seems that the main reason for higher global temperature was a larger amount of atmospheric CO_2, but proxy measures of CO_2 for those ancient times are much less accurate than the ice core CO_2 data for more recent times.

Gary Russell has a simplified version of his global climate model with sensitivity 1°C per W/m^2 or about 4°C for doubled CO_2. We used that model for simulations to infer the CO_2 amount that is required to produce the warmer climates of the past 65 million years, and we also defined the amount of CO_2 that would be required if climate sensitivity were smaller.[10]

Since we published our paper there have been studies with improved assessment of early CO_2 levels, for example, a paper[11] that I just read by Tammo Reichgelt and colleagues on CO_2 levels during the Miocene.[12] To make a long story short, when we compare such studies with our calculations for the past 65 million years we conclude that best agreement with the inferred CO_2 levels implies a fast-feedback climate sensitivity not less than about 4°C for doubled CO_2.

The implication for study of the period 1958-2019 is that the sensitivity of our model, 4°C for doubled CO_2, was close to optimum. Although 4°C sensitivity is near the upper end of the range in recent assessments of fast-feedback climate sensitivity (Chapter 25), there is another consideration. When we use fixed ice age surface properties and greenhouse gas amounts in empirical assessment of climate sensitivity we are lumping all processes that change surface albedo into the slow feedback category. In reality some Earth system processes that amplify the climate response, such as poleward migration of vegetation and increased wetting (darkening) of ice sheet surfaces can begin to come into play during the 1958-2019 period. Stated differently, the appropriate sensitivity for the past century and current century is a bit higher than the fast-feedback sensitivity inferred by comparing paleoclimate equilibrium states.

"**So, the problem becomes more interesting.** The greenhouse gas climate forcing you used was almost exactly right. The climate sensitivity of your model was also about right. However, the real world did not warm as much as the model calculated. Therefore you conclude that there is another forcing, a negative forcing, which reduces the net forcing and thus reduces global warming. Or your model did not treat the ocean correctly."

I would not say it that way. Aerosols aren't as obscure as "dark matter" in the universe. There is now a lot of independent evidence that human-made aerosols produce a negative forcing, and that negative forcing grew over the period from 1958 to the present.

"I am not criticizing the climate modeling experiments, which made good sense. I'm just surprised that you don't know the aerosol forcing even now. Why didn't you just measure it?"

It's not so easy, you know, aerosols are not uniformly mixed in the atmosphere like the long-lived greenhouse gases – measurements are needed over the entire planet. Also, it's not just the effect on sunlight of the aerosols themselves. Aerosols are condensation nuclei for cloud drops, so human-made aerosols alter cloud properties. We must measure that, too.

"I thought aerosols were your special expertise. Bob Jastrow claimed that you measured the aerosol properties on Venus much more accurately than they are known on Earth even today, and that you discovered a rainbow in the clouds of Venus. Why didn't you measure aerosols and clouds on Earth? What have you been doing the last 40 years!?"

Now it's my turn to slump in my chair. It's a long story. I was going to include it in this book that I'm writing. I wrote a few chapters about Venus aerosols and aerosols on Earth, but the book got too long and the aerosol story is depressing so I did not finish it; I removed those chapters. I may put them in another book and call it *The End of the Rainbow*.

Aerosols are important for interpreting the past and for the future. We have overshot safe levels of greenhouse gases, but the slow response of parts of the climate system allows the possibility of avoiding unacceptable consequences such as loss of coastal cities and mass migrations.

We must restore a slightly cooler climate, probably more like that in the early 20th century, if we are to avoid those consequences. Aerosols necessarily will play a role as we manage the restoration of a healthy planet, so we need to understand aerosols well and their effects on clouds. I will write about this in the final chapter of my present book.

"I don't have time to wait for your book! I must go back tomorrow. I have a dinner date tomorrow."

A date? You have dates where you are?

"Sure. I went to the good place. Can't you just write down a summary of what went wrong with the aerosol measurements? Why measure greenhouse gases more and more accurately and ignore a comparable forcing by aerosols? It does not seem to make sense."

I suppose that I can write a page or so about that – if I leave out all emotions – just the facts.

"Well, it had better be good – otherwise I won't get a pass to come back down again. It's not easy, you know!"

I was starting to think it was all a dream. Yes, surely it was a dream. Yet Charney did not let go. "Everybody is saying that global warming is an 'existential threat' and yet for 40 years you did not measure the second largest climate forcing?   This aerosol story seems really weird! How did you handle aerosol forcing in your climate models? You had to do something."

So the discussion with Charney continued a while.

---

[1] Warming in our 2×CO_2 experiment had reached only 3.5°C at the time of the Charney study, but the equilibrium response was 4°C warming as reported in our paper in the 1984 Ewing volume.
[2] Hansen, J., G. Russell, D. Rind, P. Stone, A. Lacis, S. Lebedeff, R. Ruedy, and L. Travis: Efficient three-dimensional global models for climate studies: Models I and II. *Mon. Weather Rev.*, **111**, 609-662, 1983.
[3] Hansen, J., A. Lacis, D. Rind, G. Russell, P. Stone, I. Fung, R. Ruedy and J. Lerner, Climate sensitivity: analysis of feedback mechanisms, in American Geophysical Union *Geophysical Monograph* **29,** 130-163, 1984.

[4] Hansen, J., I. Fung, A. Lacis, D. Rind, S. Lebedeff, R. Ruedy, G. Russell, and P. Stone: Global climate changes as forecast by Goddard Institute for Space Studies three-dimensional model. *J. Geophys. Res.*, **93**, 9341-9364, 1988.
[5] The climate forcings are computed with equations in Table 1 of Hansen, J., M. Sato, R. Ruedy, A. Lacis and V. Oinas, Global warming in the twenty-first century: an alternative scenario, Proc. Natl. Acad. Sci 97, 9875-9880, 2000. The CH_4 amount is increased by the factor 1.4 to account for tropospheric O_3 and stratospheric H_2O changes.
[6] Hansen, J., G. Russell, A. Lacis, I. Fung, D. Rind and P. Stone, Climate response times: dependence on climate sensitivity and ocean mixing, *Science*, **229**, 857-859, 1985.
[7] Tierney, J.E., J. Zhu, J. King, S.B. Malevich, G.J. Hakim and C.J. Poulsen: Glacial cooling and climate sensitivity revisited, Nature, 584, 569-573, 2020.
[8] Tierney et al. (2020) report a broader sensitivity range, 2.4-4.5°C for $2\times CO_2$, but they note that the sensitivity is about 4°C if estimated efficacies of the forcings are accounted for. Efficacies (Hansen, et al., Efficacy of climate forcings, J. Geophys. Res., 110, D18104, 2005) are automatically included, correctly, in GCM simulations that employ comprehensive atmospheric radiation calculations, as in our GCM-derived 6 W/m^2 LGM forcing.
[9] Beware that some studies treat natural aerosol changes as a climate forcing. Aerosol and cloud changes that occur with climate change are probably better treated as fast feedbacks, not as climate forcings, when we empirically assess climate sensitivity. Human-made aerosols and their effects on clouds, on the other hand, are a climate forcing – an imposed perturbation of the climate system.
[10] Hansen, J., M. Sato, G. Russell, and P. Kharecha: Climate sensitivity, sea level, and atmospheric carbon dioxide. *Phil. Trans. R. Soc. A*, **371**, 20120294, doi:10.1098/rsta.2012.0294, 2013.
[11] Reichgelt, T., W.J. D'Andrea, A.Valdivia-McCarthy, B.R.S. Fox, J.M. Bannister, J.G. Conran, W.G. Lee and D.E. Lee, Elevated CO_2, increased leaf-level productivity, and water-efficiency during the early Miocene, Clim. Past, 16, 1509-1521, 2020.
[12] The Miocene Epoch extended from about 23 million years ago to 5.3 million years ago.