Ocean and Sea Ice Modeling in the High Desert

In the high and dry desert of northern New Mexico—7,500 feet above sea level and nearly 800 miles from the nearest coast—scientists are modeling the ocean and sea ice. It's all part of a greater effort to understand global climate change, which has emerged as a major driver of energy policy. If it weren't for the spectre of climate change, the U.S. could burn coal with abandon to produce electricity for decades to come. But even before fossil fuels were widely accepted as one cause of climate change, another form of energy conversion threatened to spark a climate catastrophe. Over 20 years ago, scientists began worrying that the awesome energy of $E=mc^2$, unleashed through nuclear war, could initiate nuclear winter.

In the summer of 1983, Nobel Laureate Hans Bethe, famous for his work on the Manhatttan project and for his theory of energy production in stars, was making his annual trip to Los Alamos National Laboratory. At that time, the media had been headlining the possibility of a nuclear winter resulting from the Cold War turning hot. The subject was introduced to the scientific community by the seminal TTAPS (Turco, Toon, Ackerman, Pollack, and Sagan) paper, published in *Science* in 1983. Carl Sagan carried the issue to the public media to push for reductions in the superpowers' nuclear arsenals. The subject was quickly engulfed in more political rhetoric than scientific investigation, and Hans Bethe was concerned that the subject was not receiving the critical analysis it deserved. He encouraged the management at Los Alamos to undertake an initiative to model nuclear winter scenarios. Bethe's influence was instrumental in establishing the modeling effort that would put Los Alamos "on the map" for climate modeling.

Los Alamos needed a climate expert to lead the nuclear winter modeling effort. The job naturally fell to Robert C. Malone, a physicist who had earned his Ph.D. in 1973 from Cornell with a thesis on the cooling rate of neutron stars. One of his thesis advisors had been, by coincidence, Hans Bethe. Bob Malone had been strongly influenced by the first Earth Day held in 1970 and brought his research interests from neutron stars down to earth. His interest was in climate modeling, but with no opportunities in that field during the mid-70's, he accepted a job at Los Alamos in the laser-fusion program. The possibility of producing limitless, cheap energy from seawater through fusion was the next best thing.

In 1978, the Director of Los Alamos's Theoretical Division, Peter Carruthers, was convinced that global warming was a significant energy-related issue and created a position at Los Alamos in global climate modeling. Malone seized the opportunity to return to his primary interest and got the climate modeling job. There was just one problem. As Malone recalled, "there was no expertise in climate modeling at Los Alamos (myself included)!" His first priority was to quickly learn the state of the art in climate modeling and get himself involved in something relevant. To that end, he spent the summer at the National Center for Atmospheric Research (NCAR) and established good working relationships with some of the top climate modelers in the country. The experience proved so valuable that Bob spent two months at NCAR each summer from 1979 to 1983. By then, the potential for program growth was looking bleak. Los Alamos's internal Institutional Supporting Research and Development Fund would not support the program to grow beyond one person, and external funding granted by the Department of Energy was pulled in the face of budget cuts. That's when Hans Bethe and nuclear winter arrived at Los Alamos.

Before 1983, getting funds for climate modeling at Los Alamos was a hard sell, but after the nuclear winter scare, the relevance of climate modeling to the Laboratory's primary mission was hard to deny. Institutional funding was increased and the Defense Nuclear Agency, responsible for coordinating all federal nuclear winter research efforts, also added funding after visiting Los Alamos to review the program. This enabled Bob Malone to focus solely on nuclear winter scenarios for the next 4 years and to bring in a radiative transfer expert, Larry Auer.

The pressure to succeed skyrocketed in January 1984 when Los Alamos Director Don Kerr wrote a 3-page letter to Frank Press, President of the National Academy of Sciences, in which he outlined the five major objectives of Los Alamos's climate modeling research plan:

- Construct models for nuclear war scenarios that will provide the three-dimensional source function for smoke and dust;
- Enhance the radiation model to treat absorption and scattering by aerosols;
- Construct physics modules to handle the transport and dispersion of aerosols by model-generated wind-fields and subgrid-scale turbulence;
- Incorporate a modern parameterization of vertical turbulent transport;
- Develop parameterizations for both wet and dry scavenging (particulate removal) of smoke and dust.

The letter stated that these tasks would be carried out over the next few years, but that pace was far too leisurely because NCAR and Lawrence Livermore National Laboratory (LLNL) already had a big head start. Furthermore, the National Academy of Sciences was planning a major symposium on Nuclear Winter in March 1985, and NCAR and LLNL were already on the agenda. Los Alamos was not. Malone felt that to succeed, Los Alamos had to participate in that symposium, or the Laboratory might as well drop the project because it would be too far behind to contribute anything original. The small Los Alamos team made steady progress but the workload was enormous. They had some but not all of the pieces needed to meet their research

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Manhattan Project pioneer and Nobel Laureate Hans Bethe was concerned that nuclear winter was not receiving the critical analysis it deserved. He encouraged the management at Los Alamos to undertake an initiative to model nuclear winter scenarios. That initiative started Los Alamos researchers down a road that eventually led to one of the most successful and widely used ocean and sea ice models in the world. Hans Bethe recently passed away on March 6th of this year at the age of 98.

In a large-scale exchange of nuclear weapons, smoke from resulting fires could shroud the Northern Hemisphere. (Globe graphic concept by Jon Lomberg, www.jonlomberg.com)

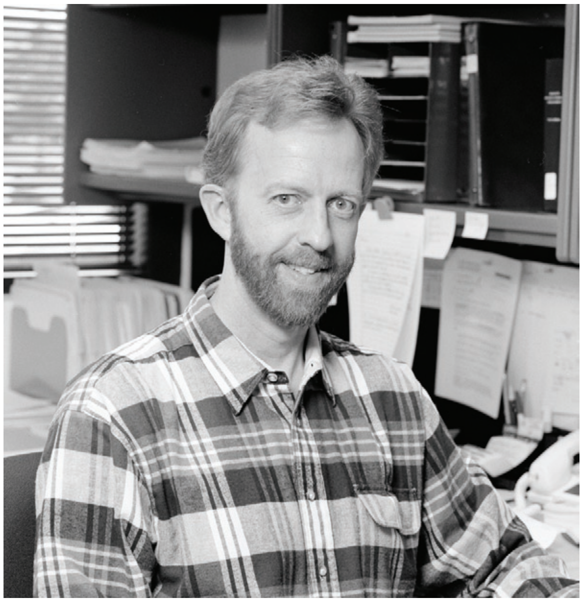
What is Nuclear Winter?

"Nuclear winter" was the name given to the potential climatic effects of a large-scale exchange of nuclear weapons. Those effects could include

- Dust, radioactivity, and various gases thrown into the atmosphere and transferred to distant parts of the globe;
- Plumes of smoke sent into the atmosphere from burning cities, forests, and grasslands;
- Daylight reduced to near darkness for days and to twilight for weeks;
- Temperature drops that don't return to normal for more than a year;
- Climate irregularities for years.

Along with the other catastrophic effects of the explosions, these nuclear winter conditions could lead to harvest failures and reduced wild plant growth causing famine for humans, livestock, and wild animals.

Source: Greene, Percival, and Ridge. Nuclear Winter: The Evidence and the Risks. *Polity Press: Cambridge, 1985.*



Robert C. Malone was the driving force behind climate modeling at Los Alamos from before the nuclear winter program to the development of the highly successful ocean and sea-ice models, POP and CICE. He earned a Ph.D. in theoretical physics from Cornell University in 1973 and initially came to Los Alamos to model laser-driven and magnetically confined plasmas for fusion research. He is now retired from Los Alamos National Laboratory.

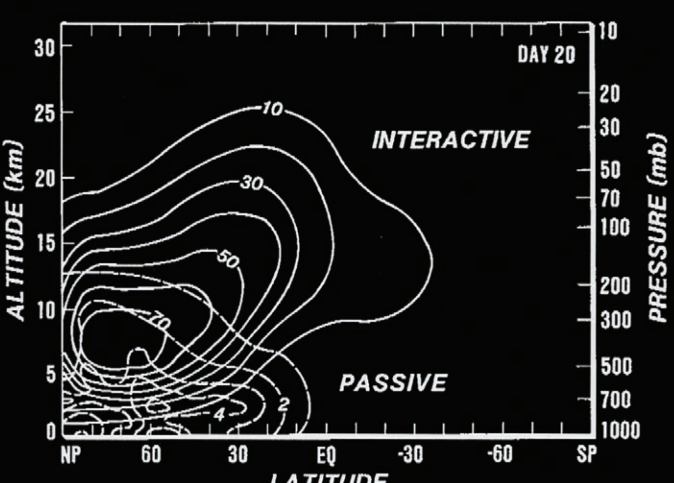
objectives, but the pieces had to be integrated into the full model, debugged, tested, and validated against whatever observational measurements could be found. After that, they would have to carry out simulations for a range of targeting scenarios at different seasons of the year, compare the "active smoke" cases with the normal climate, and interpret the results. More brainpower was critical, but funding for another full-time Ph.D. scientist didn't arrive until mid-1984, and qualified candidates were scarce. Enter Gary Glatzmaier.

Glatzmaier was a post-doc at Los Alamos who had just applied for a job at NCAR to work on their Community Climate Model (CCM). He initially approached Malone for advice on how to get a job at NCAR. But when Bob learned that Gary, while a graduate student, had written a three-dimensional, time-dependent, spherical solar dynamo model using spectral-transform methods–exactly the same methods used in CCM—he was sure he had the right person for Los Alamos's team. Gary was comfortable working with big codes and had a broad background in physics and hydrodynamics.

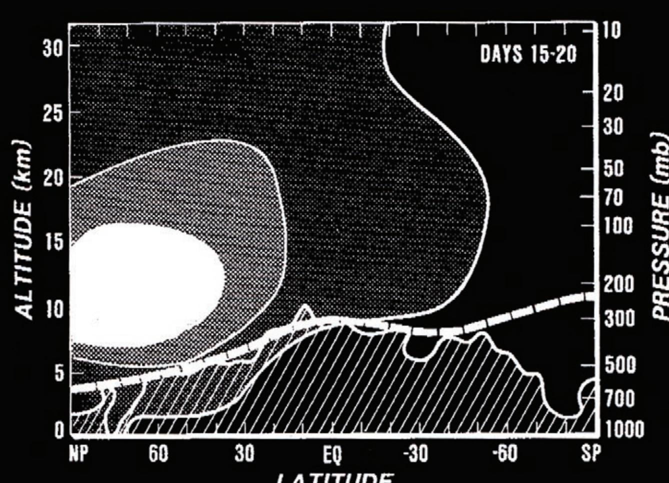
By October, the team had incorporated the horizontal smoke advection scheme and completed the first three objectives. Preliminary results, showing smoke transported in three dimensions and interacting with solar radiation, were so interesting that Brian Toon, Rich Turco, and Tom Ackerman (3 of the 5 authors of the TTAPS paper) came to Los Alamos. They were impressed and pleased because the Los Alamos model showed that under some circumstances solar heating of the smoke caused the tropopause to lower from its normal height (~10 km) to 5 km or lower. Solar heating in the smoke cloud also caused the smoke to rise above the lowered tropopause, thereby isolating it from scavenging by precipitation, which is confined below the lowered tropopause. This effect greatly increases the lifetime of the smoke. However, the predicted surface-temperature reductions were only about half as large as calculated by TTAPS in their one-dimensional model, but still very significant for large nuclear exchange scenarios. Turco and Toon told Carl Sagan about the model and results, and Sagan encouraged the National Academy of Sciences to invite Los Alamos to the March symposium.

On February 1, Bob Malone received an invitation and an apology from the National Academy of Sciences as well as a letter from Carl Sagan expressing his pleasure that Los Alamos would attend and present its results. The caller from the National Academy said they had not expected Los Alamos to have results so quickly. Of course, neither did anyone at Los Alamos, but after Glatzmaier joined the team, the rate of progress skyrocketed. Within just 7 months, the various bits and pieces were integrated into a model that met all the research objectives listed above except number 4. Their rapid success

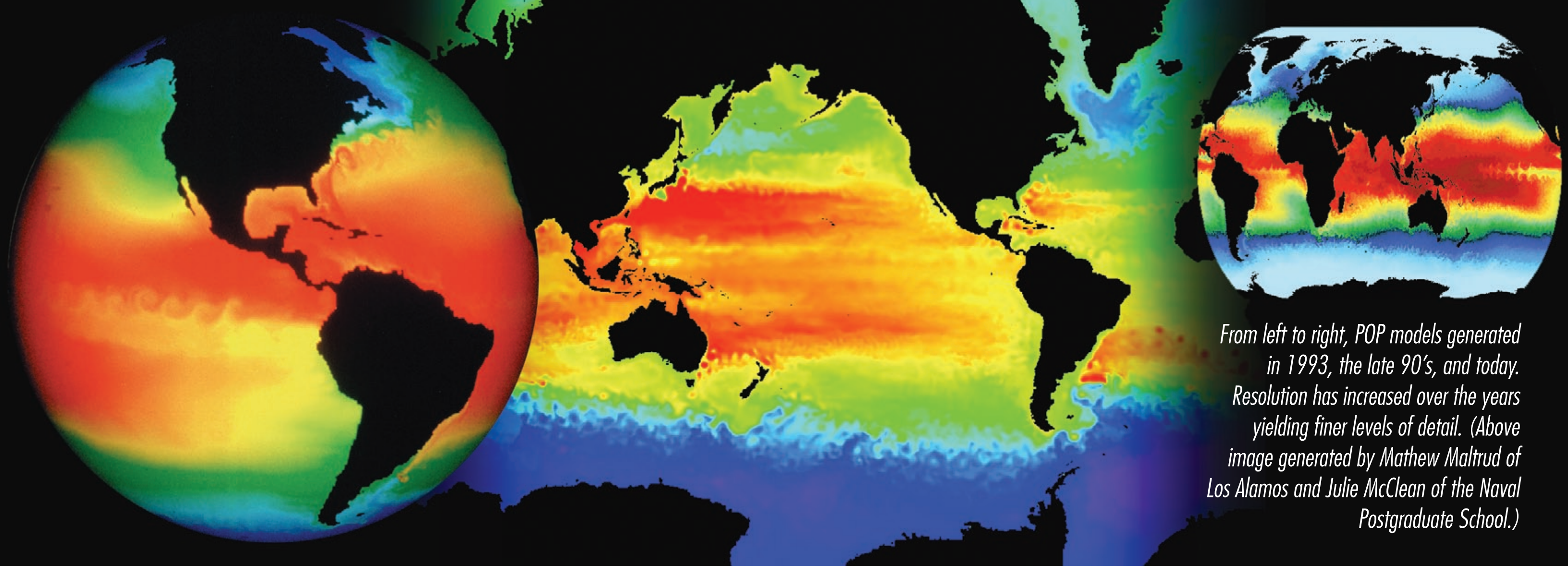
(Below and facing page) Models then and now—the graphs below represent results of nuclear winter modeling presented at the 1985 National Academy of Sciences conference. Images on the facing page show the evolution of ocean models at Los Alamos over the last 12 years.



The contour lines indicate how much smoke is left in the atmosphere 20 days after an exchange of nuclear weapons and how it is distributed over lattitude and altitude.



The relative positions of the modified tropopause (dashed line), precipitation (slanted lines), and smoke distribution (dotted areas) 20 days after an exchange of nuclear weapons.



From left to right, POP models generated in 1993, the late 90's, and today. Resolution has increased over the years yielding finer levels of detail. (Above image generated by Mathew Maltrud of Los Alamos and Julie McClean of the Naval Postgraduate School.)

earned the nuclear winter modeling team a Los Alamos Distinguished Performance Award in 1985.
After the symposium, Steve Schneider of NCAR, during an interview with the *Washington Post*, graciously acknowledged that Los Alamos had the most complete model. Warren Washington, also of NCAR, included Los Alamos's work in his book *An Introduction to Three-Dimensional Climate Modeling*.

But despite Los Alamos's success and Department of Energy enthusiasm over the climate-modeling project, no funding increase came and in 1987, the Defense Nuclear Agency eliminated Los Alamos's funding. They felt that the global modeling aspect of nuclear winter was under control and money had to be directed to other nuclear winter projects. Despite this abrupt end to the project, nuclear winter had established Los Alamos's credibility in climate modeling. Malone and Glatzmaier were invited to give many talks on their work, even in Australia and New Zealand during trips paid for by those governments.

Still, without substantial funding from DOE, Los Alamos had no chance of competing with such giants as NCAR, the Max Planck Institute in Germany, the Hadley Centre in England, and the Geophysical Fluid Dynamics Laboratory at Princeton. These institutions each had a large technical staff, an official mandate, and a relatively stable budget to perform global atmospheric modeling. Atmospheric modeling was all but dead at Los Alamos, so the team moved on to other activities.

The outlook changed again, however, when the Department of Energy formed a committee, which included Bob Malone, to plan a new initiative to bring massively parallel computing to climate modeling. In 1991, the new program was dubbed CHAMMP (Computer Hardware, Advanced Mathematics, and Model Physics) and David Bader from Pacific Northwest National Laboratory was appointed to run it. Bader asked Malone to serve as Director of Model Development.

While CHAMMP was still in its formative stage, Malone made a crucial decision: if Los Alamos participated in CHAMMP, it would be in ocean modeling. While there was no future for Los Alamos in global atmospheric modeling, the picture was quite different in ocean modeling. At the time, there were only a few ocean models, and most of them were spin-offs from a 1969 model developed at the Geophysical Fluid Dynamics Laboratory (GFDL). Massively parallel computers, like the kind Los Alamos had to support its nuclear testing mission, were particularly well-suited to global ocean models because mesoscale eddies in the ocean are about ten times smaller (20-200 km) than eddies in the atmosphere. This means that ten times as many grid-points are required in both horizontal dimensions and, because the time step must be reduced by a factor of ten also, a factor of a thousand more computations is required.

Bob Malone hired Rick Smith and John Dukowicz whose expertise in nuclear physics and applied mathematics allowed them to completely reformulate the GFDL ocean model and incorporate new algorithms that would parallelize efficiently. Smith named the new code the "Parallel Ocean Program" or "POP." In 1992, Malone, Smith, and Dukowicz received a Los Alamos Distinguished Performance Award for POP, and in 1994 they won the Computerworld-Smithsonian Award in the Science category.

Over the past decade, Los Alamos's Climate, Ocean, and Sea-Ice Modeling (COSIM) Project grew to include a dozen full-time scientists and two post-docs of various backgrounds working on POP and CICE (the sea-ice model). Today it has a few less staff members than at its peak, but is still very active. Los Alamos is recognized as one of two major ocean modeling centers and is the leader in eddy-resolving ocean simulation. In sea-ice modeling, Los Alamos is perhaps the best in the world. NCAR's Community Climate System Modeling (CCSM) project has adopted POP and CICE for the ocean and sea-ice components. CCSM is available worldwide over the web and serves the university community in the U.S. making it the most widely used climate model in the world. As a result, Los Alamos's ocean and sea ice models will play an important role in our understanding of global climate change.

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— Robert Malone and Anthony Mancino