Climate Models and Global Climate Change

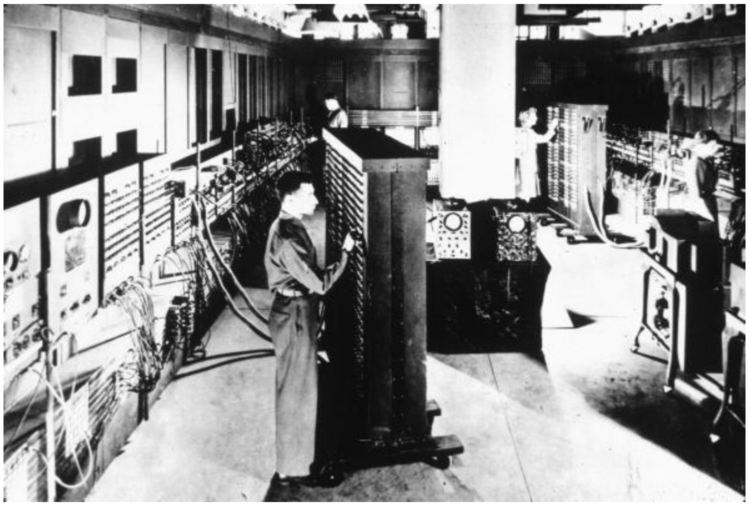
By Christopher Readinger

Global climate change leads to melting ice caps
http://www.spiritofmaat.com/announce/ann_dryice.htm

Although scientists now accept global warming as incontrovertible, humans continue to alter the composition of the atmosphere, primarily through the burning of fossil fuels. Climate models, which can provide an early warning of climate change, increasingly are called upon to help determine what environmental changes the climate may bring in the coming decades and centuries. While several types of numerical models help atmospheric scientists simulate earth systems, modern climate models, or General Circulation Models (GCMs), are a unique subset. They are designed to maximize capability in simulating general atmospheric circulation as well as interannual oscillations such as El Niño – Southern Oscillation (ENSO), and forecasting climatic trends decades or even centuries in advance.

Released December 2007

History of Climate Models



The ENIAC (Electronic Numerical Integrator and Computer)
2005 Getty Image, Inc.

Scientists employ computer models to assist in a wide variety of tasks, including forecasting day to day weather, analyzing local severe weather events, predicting future climates, and even modeling the atmospheres of different planets. Shortly after the invention of the computer however, scientists' goals were more humble, since they rarely had much more than a few bytes of memory to work with and had to spend a significant amount of time repairing hardware. In the mid-20th century, as the idea arose that computers could perform the myriad calculations to simulate atmospheric motion, scientists attempted to apply the pre-defined laws of physics and fluid dynamics to recreate large scale atmospheric circulation. After several attempts they soon learned that the atmosphere was much more complex than their simple models could handle. They were greatly limited by computer technology and more importantly lacking in important knowledge of how climatic processes interact and how they influence climate. On one of the early forecast models, run on ENIAC (electronic numerical integrator and computer), one of the first computers, the modelers found that a two dimensional simulation with grid points 700km apart with 3 hour time steps could forecast for a 24 hour period in about 24 hours, meaning that the model was just able to keep up with the weather as opposed to creating useful forecasts days in advance. Models were indeed simple compared to today; for example, after several failed attempts to create a basic representation of large scale atmospheric flow, scientists at Princeton University's Geophysical Fluid Dynamics Laboratory (GFDL) created a model that incorporated large eddies, making the simulation much more representative. This experiment was deemed a major success and the model is considered the first true GCM. It showed scientists just how significant transient disturbances and smaller scale processes are in influencing the transportation of energy and momentum throughout the atmosphere.

With this success research groups around the country began to develop their own models, including at UCLA's Lawrence Livermore National Laboratory (LLNL) and the National Center for Atmospheric Research (NCAR), further adding to the resources attempting to accurately forecast weather and model the climate system. With a greater number of scientists working on the problem, more was learned about the climate system and progress accelerated. In addition, the rapid increase in computer technology, from the few bytes of memory the first modelers had to work with, to kilobytes, megabytes, and gigabytes, enabled the creation of much more complex models.

Even with drastic advances in technology and scientific knowledge, climatologists still have to make many compromises in terms of realistically representing the Earth. For example, until recently most models focused only on atmospheric circulation (AGC models) whereas we now know that the oceans, cryosphere (glaciers, ice sheets, sea ice, snow cover), and land surface play extremely important roles in shaping our climate. Today, most models contain a separate or self-contained oceanic component that actively interacts with the model atmosphere. These are called Atmosphere-Ocean coupled models, or AOGCMs.

While early modelers made significant progress, the models still had problems reliably forecasting climatic trends or oscillations. Because the model resolution was extremely coarse many processes had to be parameterized. Model resolution is analogous to photographic resolution as a measure of how small you can look at details. In computer models resolution is important for small scale disturbances like thunderstorms and cyclones and also for accurate representation of the Earth. For example, in early GCMs the land surface resolution was so coarse that peninsulas and islands such as Florida and the UK did not exist and the Great Lakes were treated as land. While extremely fine resolution may be ideal, a balance must always be struck between model resolution and the computer power available. If a model takes months to run then it's not useful to modelers trying to do experiments. The computer power/resolution balance can be thought of as follows: for every doubling in spatial resolution (horizontal and vertical) there is an 8x increase in grid points to solve for, and very often to keep the model mathematically stable the time step must be halved as well, meaning you would need 16x more computer power just to double your model resolution.

The process whereby model resolution forces climatologists to simplify calculations is called parameterization. It is the recognition that, while we realize there is an important process here and we have an idea of its magnitude, we cannot possibly explicitly model it so we must attempt to treat it as realistically as possible. One important example of a parameterized process is convective clouds and thunderstorms. Thunderstorms, while extremely important in the atmosphere for transporting heat and water vapor, are also extremely small on the global-scale. A typical GCM grid box ranges from 100km – 300km and the typical thunderstorm is around 1km. Therefore convection must be treated in a much simpler way. While it seems unlikely and maybe unnecessary for convective clouds to ever be modeled in a GCM, parameterizations have also evolved over time and have become better at calculating the influence convection has in the atmosphere.

In the late 20th century, as models and computers became more complex and powerful, model design began to diverge into several subcategories focusing on different aspects of weather and climate, including Numerical Weather Prediction models (NWP), regional scale models, and mesoscale models. These models all differ from GCMs in that they focus on different aspects of the atmosphere. For instance, NWP models use a much smaller horizontal scale--the North American continent for example--and attempt to forecast small changes in weather over short periods of time (a few hours or days). These differ from GCMs in that they are highly sensitive to initial conditions, where meteorological data fed into the model have a dramatic influence on the output. These models deal with what is called the “initial value” problem in that, given meteorological data, the simulation will diverge from reality over time. Climate models are less dependent upon initial conditions and instead must deal with the “boundary value” problem. This occurs where, once the general circulation of the atmosphere has been established, it is difficult to create realistic climatic disturbances such as interannual oscillations (ENSO, PDO, NAO) or climatic trends caused by external forces.

Slowly but surely models have been developed, refined, and tested against real-world situations, to the point that in the 1990s many scientists say the modern GCM was established. While some model weaknesses persist in that they may have biases with parameters, such as too much rain in a region or too warm in another, atmospheric scientists have been able to include more and more climatic processes and better simulate the climate as we learn more about our environment and the importance of the terms in the equations.

Construction of a Modern Climate Model

Bluesky supercomputer, one of the world's fastest, at the National Center for Atmospheric Research
http://www.ucar.edu/research/prediction/climate.shtml

As climate models evolved through the 1990s, scientists began to shift focus from reproducing general circulation to experimenting with the feedbacks of climatic processes due to increasing greenhouse gases, changing ocean currents and the way the model responds to forced perturbations such as ENSO. As the next generation of models come out the improvements in the models make them more reliable for global predictions and more capable of regional analyses. Here is a simplified description of the anatomy of the latest version of the Community Climate System Model: CCSM3.

At their core, all GCMs employ a specific set of primitive dynamic equations, which allow the atmosphere to move in three dimensions, warm up and cool down, and transport moisture, etc. These equations are solved over and over again at specified locations in the model's three-dimensional space. There are two main methods for establishing the horizontal domain of a model. The simplest is to establish a grid along lines of latitude and longitude. For example, the CCSM3 can be run on a 2^o x 2.5^o grid. Another method is to treat atmospheric motion as waves using Fast Fourier Transforms (FFTs) to make the spectral conversion. The resolution then is represented as the number of waves that can be represented around the earth.

The CCSM3 uses wave numbers of T31, T42, and T85; where T represents the triangular truncation of the Fourier transform. This resolution can be approximated to longitude/latitude with a resolution of T31 and T85 is $3.75\,^{o}$ and 1.41^{o} respectively.

The vertical domain in the CCSM3 is represented by 26 levels, but is complicated by the fact that the atmosphere is compressible and gets exponentially less dense as you move up in altitude. Therefore, the model levels are irregularly spaced so as to have the most levels in the troposphere where most of the weather and interaction between climatic processes occurs. In addition, topography on the Earth's surface creates difficulties with using pressure as the vertical coordinate because in many locations the ground intersects pressure levels. The CCSM3, as most models, uses a variation of the terrain following coordinate called sigma (□.and is defined as:

$$\sigma = p/p_s$$

where p = pressure and p_s = pressure at the surface.

After the atmospheric core of the model has been constructed modelers must try to incorporate all of the other climatic processes and feedback mechanisms that influence climate so as to have an accurate, dynamic representation of the climate system. While the models of the past focused on the atmosphere and sometimes included the oceans, today's models contain separate modules for the land surface, oceans, and sea ice and sometimes include atmospheric chemistry and advanced treatment of aerosols.

The land surface component of the CCSM3 uses the same horizontal grid as the atmospheric component and has 10 subsurface layers to account for soil-atmosphere interactions. The land surface can also be classified as a variety of types including ice, water, urban, and vegetation. These distinctions are important for the radiation balance because the albedo of the land surface can change dramatically. For example, the albedo of urban black top is very close to 0, meaning it absorbs almost all radiation whereas the albedo of snow cover or white sand is closer to 1 meaning it reflects most radiation.

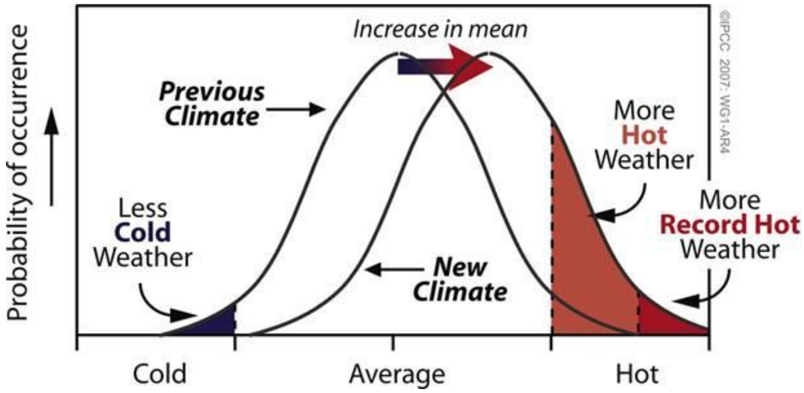
The ocean and sea ice modules of the CCSM3 use a slightly different horizontal grid from the atmosphere, although they have similar horizontal resolution. In addition, the ocean component uses either 25 or 40 vertical levels defined by depth, extending down to the ocean's deepest basins.

These components make up the newest version of the CCSM3 GCM and can be run in different configurations, primarily by varying the horizontal and vertical resolutions. It should be noted, however, that running the finest resolution configuration takes more than 1100 hours of computer time to simulate one year of the atmosphere. That is approximately 46 days and experiments looking at trends even 10 years into the future take significant time to complete. That is why, for the longer period experiments, scientists use the more coarse resolution.

GCMs have become integral for helping scientists study the Earth's large-scale circulations, forecasting interannual variability such as ENSO, and evaluating the possibility of climate change in the decades to come. GCMs differ from other models mostly in their spatial and temporal domains and the inclusion of many processes not needed for other models because of the longer time scales involved. Their spatial domain covers the whole globe as opposed to, for example, a numerical weather prediction (NWP) model which may cover only North America. On the temporal scale they attempt to simulate earth's atmosphere from periods of several months to several decades, whereas NWP models can forecast for periods as short as a few hours and up to several days relatively well.

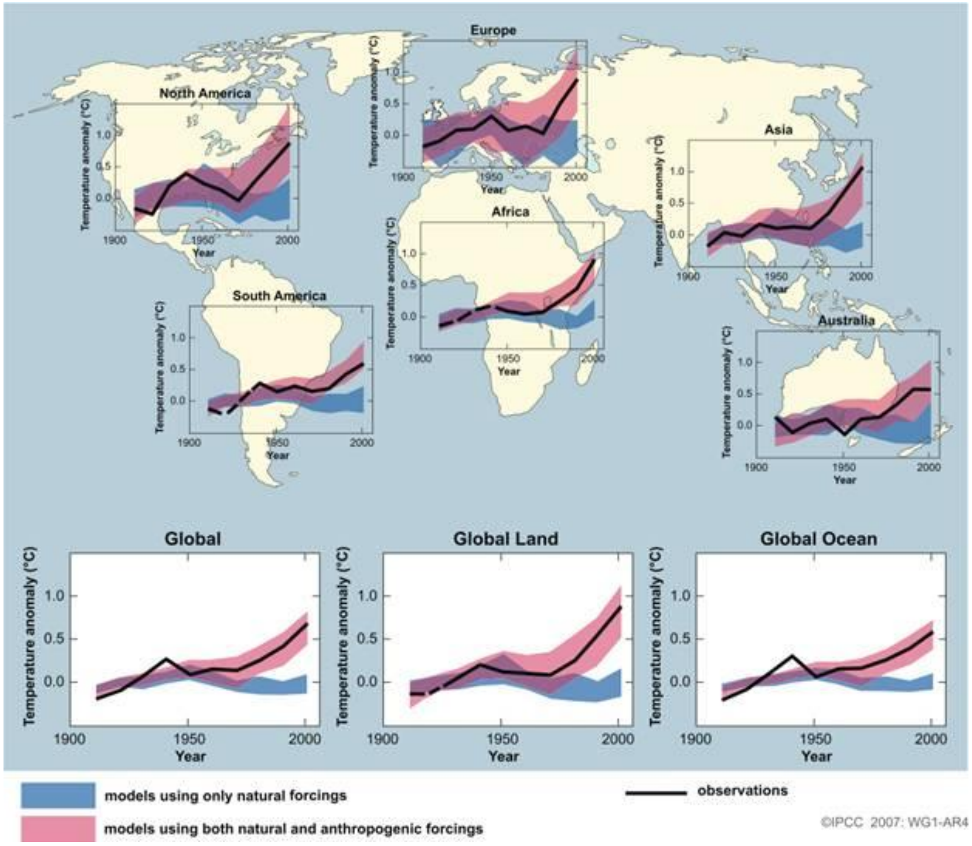
Climate Models in Action

As early as the 1960s the question of what rising levels of carbon dioxide might do to climate began to be raised. The best method to determine an answer was to be found in climate models with the aid of various types of proxy data, and data collected from meteorological networks around the world.



The effect on extreme temperatures when the mean temperature increases, for a normal temperature distribution.
Intergovernmental Panel on Climate Change, Fourth Assessment Report, 2007. Summary for Policy Makers
Available at http://www.ipcc.ch/

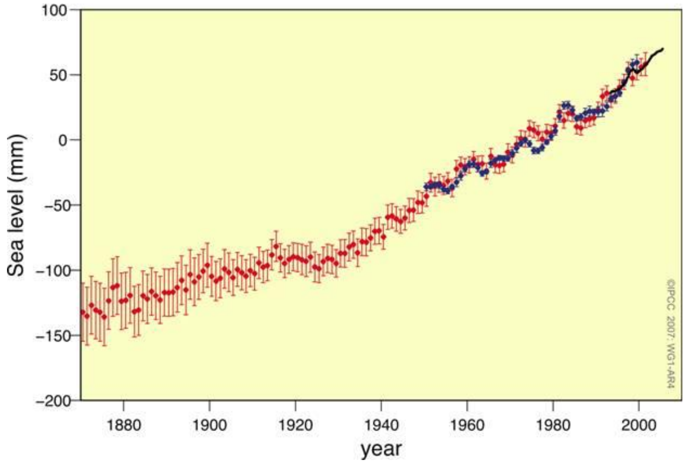
As the leading climate change research group in the world, the Nobel Prize winning In-ternational Panel on Climate Change (IPCC), established in 1988 by the World Meteorological Organization (WMO) and the United Nations Environment Programme (UNEP), places great emphasis on GCMs to forecast the possible changes caused by increased levels of carbon dioxide. The latest publication by the IPCC, the Fourth Assessment Report (AR4), outlines the improvements made to the more than 20 computer models since the Third Assessment Report (TAR) from 2001, and discusses in detail the results of the GCMs used in the experiments.



Comparison of observed continental- and global-scale changes in surface temperature with results simulated by climate models using natural and anthropogenic forcings. Decadal averages of observations are shown for the period 1906 to 2005 (black line) plotted against the centre of the decade and relative to the corresponding average for 1901–1950.
Intergovernmental Panel on Climate Change, Fourth Assessment Report, 2007, Summary for Policy Makers
Available at http://www.ipcc.ch/

Approximately 23 different models were used in AR4 and all were evaluated extensively before inclusion in the report. In the evaluations, models are run for historical periods to assess their ability to simulate known conditions as well as climatic variability and extremes. In addition they are often compared against periods from the distant past to assess how they handle climates that are very different from today. To participate, models run specific experiments designed to assess how much influence CO_2 has on global averaged temperatures, sea level, droughts, extreme temperatures, etc., for specific periods in the future. The results of all the models are then evaluated using several techniques, including looking at all of the results together and determining the “ensemble mean.” That is, since it is difficult to determine which model performs best, the average of all of the models is taken for the most robust result. To help determine the difference that increases in compounds like CO_2 and CH_4 can cause, experiments are conducted using varying levels of $CO_{2,}$ including pre-industrial levels. The lack of warming seen in these simulations compared to the meteorological observations and projections for the next few decades shows just how much we have influenced the climate system. To date, the results of these model experiments have been much what one would expect on a global scale with warmer averaged temperatures, rising sea levels, and thinning sea ice; however, it is the details and regional changes that interest governments and policy makers the most. Those changes are far more difficult to quantify, in part because of the model resolution and the difference in scale between modeling the global climate system and determining how much smaller feedbacks and trends influence a much smaller regional area.

I have attempted to describe the history and make-up of climate models in a very basic way; much more information can be found in scientific literature and from reliable sources on the internet. While early computer models produced suspect results and lacked many physical parameters known to play a role in Earth’s climate, today’s computer models have reached a point where the best models can begin to be treated with confidence if evaluated properly. Although there is still plenty of work that can be done in the atmospheric sciences and numerical modeling to improve today’s models significantly, it is time for policy makers and the public to begin listening to what the experts have to say.



Averages of the global mean sea level based on reconstructed sea level fields since 1870 (red), tide gauge measurements since 1950 (blue) and satellite altimetry since 1992 (black). Units are in mm relative to the average for 1961 to 1990.
Intergovernmental Panel on Climate Change, Fourth Assessment Report, 2007, Summary for Policy Makers
Available at http://www.ipcc.ch/

For those who may be interested in getting involved with climate models without going back to school, a program that may be of great interest is www.climate-prediction.net. This is a climate model ex-periment similar to the SETI program in that it uses thousands of idle online personal computers to run a climate model, as opposed to an on-site supercomputer.

References

Journals and Books

Delworth, T., 2006: PREFACE. *J. Climate*, **19**, 641.

Doney, S.C., K. Lindsay, I. Fung, and J. John, 2006: Natural Variability in a Stable, 1000-Yr Global Coupled Climate–Carbon Cycle Simulation. *J. Climate*, **19**, 3033–3054.

Gent, P.R., 2006: Preface to Special Issue on Community Climate System Model (CCSM). *J. Climate*, **19**, 2121.

Giorgetta, M.A., G.P. Brasseur, E. Roeckner, and J. Marotzke, 2006: Preface to Special Section on Climate Models at the Max Planck Institute for Meteorology. *J. Climate*, **19**, 3769–3770.

Johns, T.C., C.F. Durman, H.T. Banks, M.J. Roberts, A.J. McLaren, J.K. Ridley, C.A. Senior, K.D. Williams, A. Jones, G.J. Rickard, S. Cusack, W.J. Ingram, M. Crucifix, D.M.H. Sexton, M.M. Joshi, B.W. Dong, H. Spencer, R.S.R. Hill, J.M. Gregory, A.B. Keen, A.K. Pardaens, J.A. Lowe, A. Bodas-Salcedo, S. Stark, and Y. Searl, 2006: The New Hadley Centre Climate Model (HadGEM1): Evaluation of Coupled Simulations. *J. Climate*, **19**, 1327–1353.

Lin, J.L., G.N. Kiladis, B.E. Mapes, K.M. Weickmann, K.R. Sperber, W. Lin, M.C. Wheeler, S.D. Schubert, A. Del Genio, L.J. Donner, S. Emori, J.F. Gueremy, F. Hourdin, P.J. Rasch, E. Roeckner, and J.F. Scinocca, 2006: Tropical Intraseasonal Variability in 14 IPCC AR4 Climate Models. Part I: Convective Signals. *J. Climate*, **19**, 2665–2690.

Schmidt, G.A., R. Ruedy, J.E. Hansen, I. Aleinov, N. Bell, M. Bauer, S. Bauer, B. Cairns, V. Canuto, Y. Cheng, A. Del Genio, G. Faluvegi, A.D. Friend, T.M. Hall, Y. Hu, M. Kelley, N.Y. Kiang, D. Koch, A.A. Lacis, J. Lerner, K.K. Lo, R.L. Miller, L. Nazarenko, V. Oinas, J. Perlwitz, J. Perlwitz, D. Rind, A. Romanou, G.L. Russell, M. Sato, D.T. Shindell, P.H. Stone, S. Sun, N. Tausnev, D. Thresher, and M.S. Yao, 2006: Present-Day Atmospheric Simulations Using GISS ModelE: Comparison to In Situ, Satellite, and Reanalysis Data. *J. Climate*, **19**, 153–192.

Stott, P.A., G.S. Jones, J.A. Lowe, P. Thorne, C. Durman, T.C. Johns, and J.C. Thelen, 2006: Transient Climate Simulations with the HadGEM1 Climate Model: Causes of Past Warming and Future Climate Change. *J. Climate*, **19**, 2763–2782.

Vecchi, G.A., and B.J. Soden, 2007: Global Warming and the Weakening of the Tropical Circulation. *J. Climate*, **20**, 4316–4340.

Websites

Community Climate System Model - http://www.ccsm.ucar.edu/

Geophysical Fluid Dynamics Laboratory - http://www.gfdl.noaa.gov/

Climateprediction.net. Run a Climate model on your home computer - http://www.climateprediction.net/index.php

IPCC - http://www.ipcc.ch/

IPCC Fourth Assessment Report - http://ipcc-wg1.ucar.edu/wg1/wg1-report.html

CCSP Synthesis and Assessment Report 3.1 - http://www.climatescience.gov/Library/sap/sap3-1/public-review-draft/sap3-1prd-ch1.pdf

American Institute of Physics - http://www.aip.org/history/climate/GCM.htm