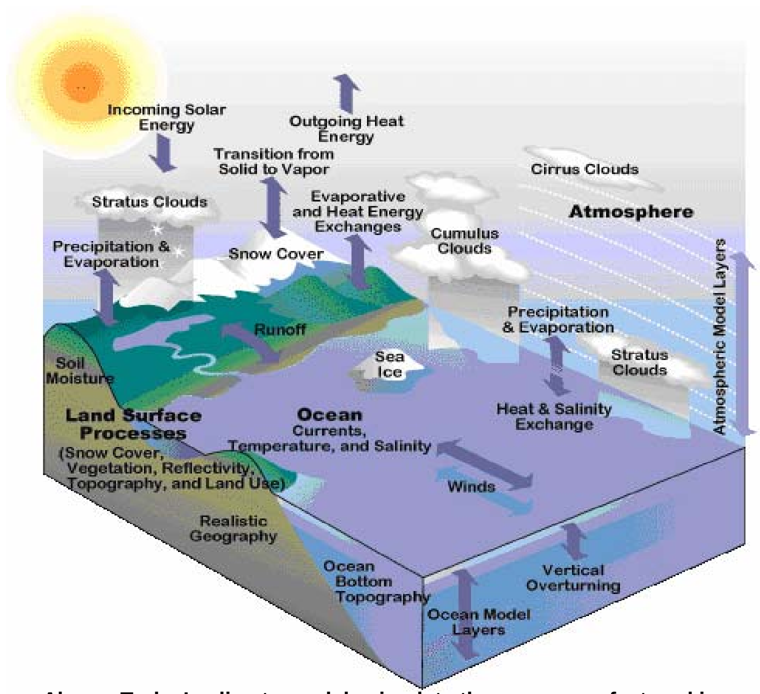
Earth Gauge
A National Environmental Education Foundation Program

Modeling the Earth's Climate

A Brief History

Climate and weather models are mathematical descriptions of the interactions between Earth system variables. In the late 19th century, the Norwegian meteorologist Vilhelm Bjerknes described the movement of heat, air and moisture through the atmosphere with a series of "primitive equations" based on laws such as the conservation of momentum, the conservation of mass and the first and second laws of thermodynamics. In the 1920s, the British mathematician Lewis Fry Richardson advanced this fledgling science of numerical weather prediction by dividing the Earth into territories of grid cells, with each grid cell having its own temperature, pressure, humidity, etc. Local winds, for example, could be forecast based on the current pressure differences amongst the surrounding cells. Today's weather and climate modeling is based on this approach of using the mathematical relationships that govern fluid dynamics and a simplified Earth divided into grid components to understand how the atmosphere functions and to forecast future conditions.



Above: Today's climate models simulate the processes featured in this diagram. *Image courtesy of UCAR.*

World War II and the Cold War were accompanied by increased public support for the geosciences. Better information about the upper atmosphere, largely provided by radiosondes and American bomber sorties, allowed for better mapping of the features (such as the jet stream, which was still theoretical until 1944) and properties (such as the rate that the temperature changes with altitude) of Earth's upper atmosphere. Yet, without a more efficient means of accounting for the overwhelming number of interactions and variables that determine daily weather, better observational data could do little to predict weather. Enter the digital computer age, which made it possible to create programs that would account for sufficient variables and interactions at rates that enabled effective forecasts. As computers grew in size, speed, and complexity, early modelers extended such simulations to longer time scales until they spanned decades, thus giving birth to the concept of climate models.

Decadal Highlights

- **The 1950s:** Early modeling efforts were sponsored by the Weather Bureau (now NOAA's National Weather Service) and several military branches. By the late 1950s, computers were able to simulate simple things like air flow, evaporation and the radiative effects of water vapor, carbon dioxide (CO_2) and ozone.
- **The 1960s:** By the mid-1960s, models could simulate a three-dimensional Earth lacking seasons and topography with features like the stratosphere, rising air in the tropics and subtropical deserts.
- **The 1970s:** By the end of the decade, models could represent the planet with land (including simple topography and coastlines), oceans, seasons and most of the basic features of our atmosphere.
- **The 1980s:** This period featured the development of "transient models," or simulations where properties of the atmosphere change over time as variables such as atmospheric composition or solar intensity change.
- **The 1990s onward:** Models continued to mature as the range of variables they covered expanded; they now account for things like ice cover, atmospheric chemistry, ocean circulation, soil layers and vegetation changes.

Types of Climate Models

Climate and weather models range from simple zero-dimensional equations describing radiative properties to the sophisticated three-dimensional General Circulation Models (GCMs). Three broad categories are described here:

- **Comprehensive Physical Climate Models:** These models predict different climate conditions based on variations in the components of the atmosphere, which affect how energy moves through the Earth system. The most sophisticated of these models are atmosphere-ocean general circulation models (AOGCMs), which account for, in as much detail as possible, the elements listed in the diagram on the previous page. Intermediate complexity models describe the processes in the AOGCMs, but in a more simplified manner. This simplification enables intermediate complexity models to give approximations of the climate centuries into the future, which AOGCMs cannot do effectively because of the computational costs involved.
- **Earth System Models (ESMs):** The climate system's adjustment to changes in Earth's energy balance includes shifts in where the Earth holds its carbon stocks (i.e. in the land, the ocean, or the atmosphere). ESMs account for this two-way dynamic between carbon distributions and climate shifts.
- **Integrated Assessment Models (IAMs):** IAMs incorporate potential future land cover, population and emission scenarios with simplified representations of the processes in AOGCMs and ESMs. IAMs attempt to couple human behavior with the climate system to produce projections for the future that can aid in planning for mitigation and adaptation.

Weather and Climate Models: What's the Difference?

Modern weather and climate models both predict future states of the atmosphere by using the primitive equations and interacting grid components described above. Weather and climate are fundamentally different things: weather describes the conditions of the atmosphere at a particular point in time, whereas climate is the composite of prevailing weather conditions averaged over a period of years (customarily 30 years). Weather and climate models have key differences:

- **Goals:** Weather models are designed to predict what the weather will be at a given location at some point over the next few days. They rely on constant inputs of detailed, real-time weather data from around the world (the model's "initial conditions") in order to accurately predict how these conditions will change over time. Climate models on the other hand are designed to reproduce observed Earth system properties (reflected in temperature/precipitation statistics and weather event frequency) and predict how the system will respond if certain key variables (atmospheric carbon concentrations, solar intensity, aerosol loads, etc.) are changed.
- **Resolution:** Weather models typically have much more detailed spatial resolution – they divide regions into smaller grid components than climate models do.
- **Time Steps:** Both weather and climate models have "time steps," which are the intervals between one set of calculations of grid component interactions and the next. The shorter the time step, the more detailed the representation of atmospheric processes. Time steps are a function of grid size: in higher resolution weather models, time steps are on the order of a few seconds; in climate models they are usually tens of minutes.
- **Variables:** Variables that are important for climate models (such as deep ocean conditions, which will eventually manifest into surface conditions) may not be important for short-term weather forecasts.

While the detail of the weather models makes them effective predictors of specific conditions a few days out, the underlying fluid dynamics equations contain inherent uncertainties (model uncertainties), which are compounded by the incomplete inputs of world weather conditions (initial uncertainties). The longer the weather simulations are, the more obvious these uncertainties become. After about a week, the calculations are less reliable. In climate models, many of the equations are simplified or approximated according to physical reasoning and observations. This allows climate models to run for longer periods of time while still producing meaningful results.

How Are Climate Models Evaluated?

Climate model projections can be evaluated using several lines of evidence: a) their ability to accurately simulate the present day climate; b) the agreement between different models (different models employ different assumptions); c) their ability to simulate conditions that occurred during the period of instrumental weather records; d) their ability to reproduce paleoclimatic conditions, which are estimated through proxy evidence such as ice cores and other sedimentary records.

Despite the sophistication of today's climate models, some issues, such as cloud and aerosol interactions, still need to be resolved. Overall, however, today's models accurately simulate well known atmospheric processes and the average conditions over the last 50 years. Models at NASA's Goddard Institute for Space Studies predicted that the 1991 eruption of Mt. Pinatubo in the Philippines would have a global 0.9 degree Fahrenheit cooling effect over a period of 18 months, which closely corresponded to observations. In July of 2009, a team using a supercomputer at the Oak Ridge National Laboratory in Oak Ridge, Tennessee was able to simulate the last 21,000 years of Earth's climate in enough detail to capture the abrupt climate changes that occurred at the end of the last ice age.

Resources

- For more information on the concept of grid resolution, visit **http://www.gfdl.noaa.gov/e-media-produced-by-gfdl-ccvp#cm101**.
- Run a climate model on your own computer! Visit **http://edgcm.columbia.edu/** for more details.
- For more information on climate modeling, visit **http://www.oar.noaa.gov/climate/t_modeling.html#figure4**.
- View Dr. Keith Dixon's (NOAA's Geophysical Fluid Dynamics Laboratory) presentation on the differences between weather and climate and ocean-atmosphere interactions at: **http://www.yaleclimatemediaforum.org/dl/ams/Dixon_wNotes_062109.pdf**

Some of the world's main climate modeling institutions include:

- The University Corporation for Atmospheric Research's National Center for Atmospheric Research in Boulder, Colorado – **http://www.ncar.ucar.edu/**
- NASA's Goddard Institute for Space Studies in New York, New York – **http://www.giss.nasa.gov/**
- The National Center for Computational Sciences at Oak Ridge National Laboratory in Oak Ridge, Tennessee – **http://www.nccs.gov/leadership-science/climate/**
- NOAA's Geophysical Fluid Dynamics Lab at Princeton, New Jersey – **http://www.gfdl.noaa.gov/**
- Commonwealth Science and Research Organization's (CSIRO) facility in Melbourne, Australia – **http://www.csiro.au/science/Climate-Change.html**
- The University of Tokyo's Center for Climate Systems Research in Tokyo, Japan – **http://www.ccsr.u-tokyo.ac.jp/ehtml/eccsr.shtml**
- Met Office's Hadley Center for Climate Prediction and Research in Exeter, U.K – **http://www.metoffice.gov.uk/climatechange/science/hadleycentre/**
- The Max Planck Institute for Meteorology's facility in Hamburg, Germany – **http://www.mpimet.mpg.de/en/wissenschaft/modelle.html**

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