Lab 3. Understanding of climate models

Climate models are computer programs simulating the key processes of the climate system. Comprehensive climate models are based on physical laws represented by mathematical equations, which are solved numerically on the computer. For practical purposes, simplifications are always made. If all our current understanding of the climate system were explicitly included, the model would be too complex to run on any existing computer. Also, the complexity of internal interactions makes it impossible to describe all of them on the basis of equations and empirical relationships.

Classification of climate models

Climate models may be classified in two ways:

1) By their **complexity** in terms of the number of dimensions they describe:
   - Zero-Dimensional Models treat the Earth as a whole with no change by latitude, longitude, or height. *Example*: Exercise 1 from Lab 2.
   - One-Dimensional Models allows for variation in one direction only. *Example*: Exercise 2 from Lab 2 (modeling of the temperature profile above the Earth's surface).
   - Two-Dimensional Models allow for variations in two directions. *Example*: Modeling of the Sea Surface Temperature (SST).
   - Three-Dimensional Models divide the Earth and the atmosphere into cubes, each cube has its own independent set of values for each of the climate parameters used in the model. *Example*: Ocean General Circulation Model (OGCM).

2) By their **scientific input** in terms of the basic physical principles they use:
   - Energy Balance Models work by calculating a balance between the radiation arriving at the planet and the energy leaving the planet. This balance results in a characteristic temperature of the planet.
   - Radiative Convective Models are generally used as one-dimensional models to model the temperature profile up through the atmosphere by considering radiative and convective energy transport up to the atmosphere.
   - General Circulation Climate Models are the most complex of climate models and are generally only formulated as three-dimensional models. They involve solving a series of atmospheric equations and have the potential to model the atmosphere very closely.

Energy Balance Models

These models are based on the global radiative balance. Viewing the Earth from outside, one observes an amount of radiation input which is balanced, in the long term, by the amount of radiation output. Since about 70% of the energy which drives the climate system is first absorbed at the surface, the surface albedo is a predominant factor controlling energy input into the climate system. The output energy is controlled by two factors: the temperature of the Earth and the transparency of the atmosphere to this outgoing thermal radiation.

- Zero-dimensional energy balance model

The earth is considered to have a uniform temperature over it's surface. This temperature is known as the global mean effective temperature T_e.

Example: A model accounting for the greenhouse affect. The outgoing longwave radiation is expressed as $R=B_1+B_2*T_e$, where B_1 and B_2 are radiation constants with default values of $204Wm^{-2}$ and $2.17Wm^{-2}C^{-1}$.

- One-dimensional energy balance model

The Earth is divided into several latitudinal zones. Each zone covers a certain number of degrees. The models are more complex than the zero-dimensional models because they include the effect of latitude on incoming solar energy.

Example: A simple latitudinally-resolved energy balance model. Each hemisphere is divided into 9 latitudinal zones. The model includes the effect of energy transport from one zone to another and checks for glaciation (the surface of a zone is automatically covered by ice if the conditions are appropriate).

Model input:

- solar fraction (a number between 0 and 1, which represents the proportion of the incoming energy which reaches the surface);
- radiation constants B_1 and B_2 ($R=B_1+B_2*T_e$);
- transport coefficient (a number describing transport of energy from one zone to another);
- critical temperature (a temperature below which the surface is completely covered by ice);
- surface albedo.

Model output:

- mean temperature of the surface;
- mean albedo of the surface;
- temperature and albedo for each zone.

Radiative Convective Models

These models are basically designed to determine average global temperatures. Although calculations of surface temperatures are the principle goal, the models also can be used to model the temperature profile up through the atmosphere. They operate by calculating the difference between up- and downward fluxes at different levels in the atmosphere according to the following general scheme:

1. Set up initial temperature profile;
2. Calculate the energy change in each layer of the atmosphere resulting from an imbalance between the net radiation at the top and bottom of the layer;
3. Convert this to the temperature change;
4. Compare to the initial temperature profile.

General Circulation Models

These models are designed to calculate the full three-dimensional character of the climate. There is a great variability of models: Ocean General Circulation Models (OGCMs), Atmospheric General Circulations Models (AGCMs), coupled atmosphere-ocean models, etc. The models are based upon physical laws describing the dynamics of atmosphere and ocean, expressed by mathematical equations and, sometimes, empirical relations. Current atmosphere models are solved spatially on a three-dimensional grid of point on the globe with a horizontal resolution typically of 250 km and some 10 to 30 levels in the vertical (1 km resolution). A typical ocean model has a horizontal resolution of 125 to 250 km and a resolution of 200 to 400 m in the vertical. Equations are typically solved for every half hour. Many physical processes, such as those related to clouds or ocean convection, take place on much smaller spatial scales than the model grid and therefore cannot be modeled and resolved explicitly. Their average effects are included as parameters of the model.

Importance of climate simulations

The main goal of climate models is to simulate and quantify natural climate variability and climate response to present and future human activities.

After a model has been created, the first step is to assess its quality by simulating the present climate for extended simulation periods, typically many decades, under present conditions without any change in external climate forcing. The simulated climate is compared with observations of the present climate. In this way the model is evaluated and its quality established.

Let consider an example when climate models can be useful. Measurements of the Earth's surface temperature have been regularly conducted since 1860. Figure 1a shows variations of the Earth's surface temperature over the last 140 years. Over the last 100 years the global average surface temperature has increased by 0.6 ± 0.2^{0}C.

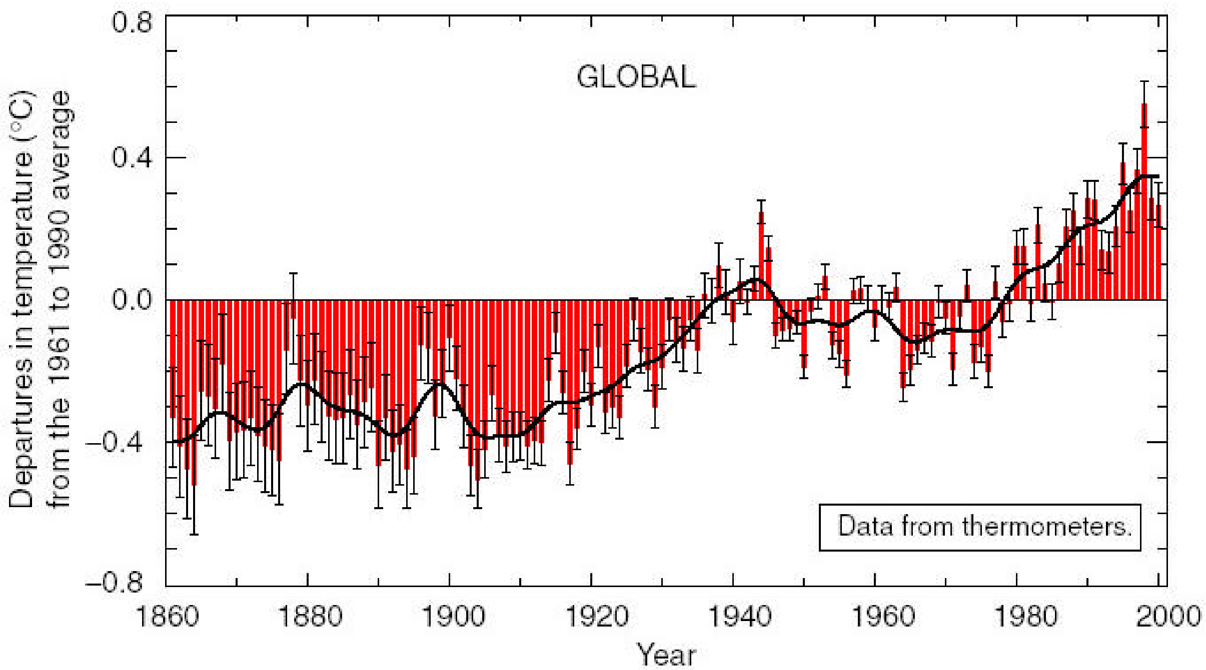

Figure 1a.

Figure 1b show variations of the average surface temperature of the Northern Hemisphere over the past 1000 years. The blue curve illustrates so-called indirect temperature measurements (tree rings, ice cores, corals and historical records).

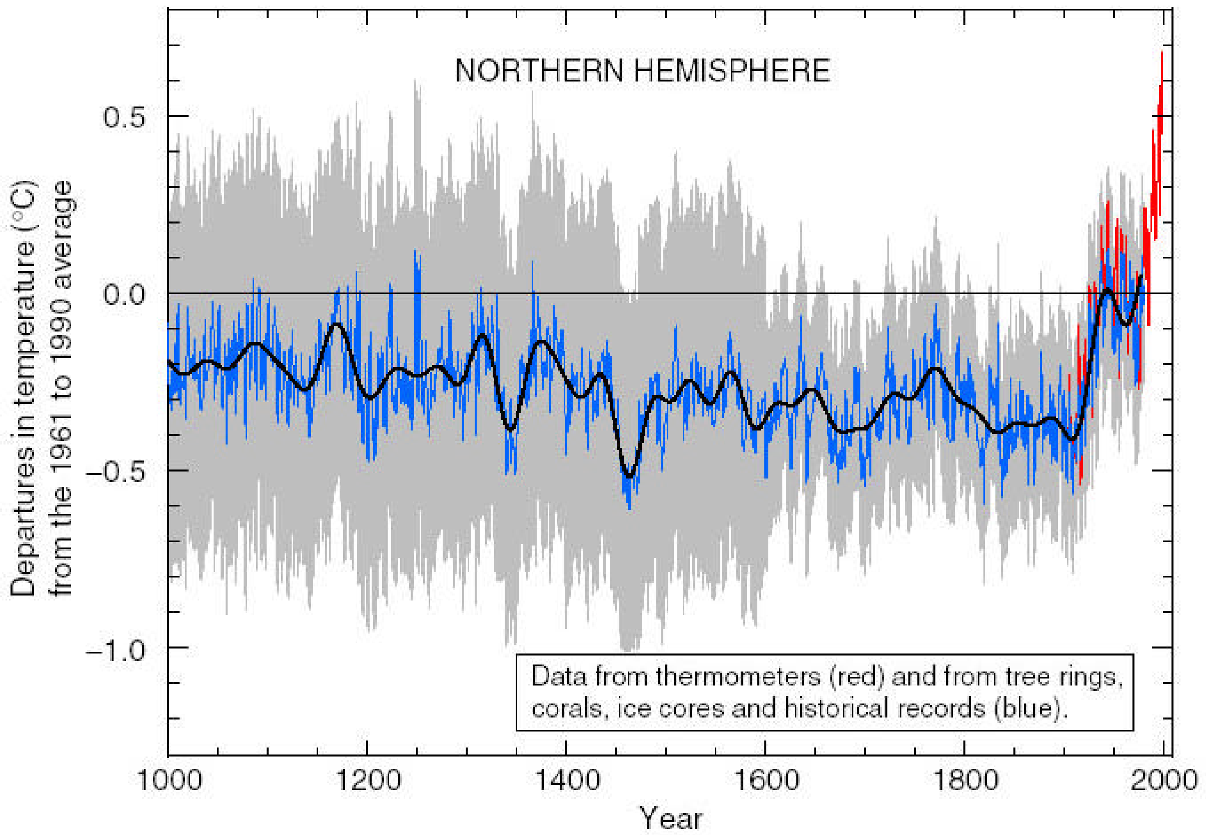

Figure 2b.

On the basis of these figures, a conclusion can be made that the 1990s have been the warmest decade and 1998 the warmest year of the millennium. The changes in the global climate have caused a reduction of the snow pack in the northern latitudes, a melting of mounting glaciers, a thawing of the Arctic permafrost, and a shrinking of the polar ice caps. The average sea level of the world's oceans has risen 10 to 20 cm in the last century.

Using climate models, scientists now estimate that the average global surface temperature will rise another 1.4^0C to 5.8^0C by the end of the 21^{th} century. The average sea level is expected to rise up to 90 cm more in the next 100 years.

Difficulties in climate simulations

- many processes and interactions in the climate system are non-linear

There is no simple proportional relation between cause and effect. A complex, non-linear system may display chaotic behavior. This means that the behavior of the system is critically dependent on very small changes of the initial conditions. This doesn't imply, however, that the behavior of non-linear chaotic systems is entirely unpredictable, contrary to what is meant by "chaotic" in colloquial language. The daily weather is a good example. The sensitivity of the climate system to small perturbations in initial conditions limits predictability of the detailed evolution of weather to about two weeks.

- *different response time of the various components of the climate system*

When variations in the external forcing occur, the response time of the troposphere is relatively short, from days to weeks; the stratosphere needs a few months to come into equilibrium; the oceans have a much longer response time, typically decades but up to centuries and millennia, due to their large heat capacity; the biosphere may respond fast, e.g., to droughts.

- *feedbacks*

The response of the climate to the internal variability of the climate system and to external forcing is further complicated by feedbacks. A process is called a **feedback** when the result of the process affects its origin thereby intensifying (positive feedback) or reducing (negative feedback) the original effect.

- *the present condition of the observational networks*

The present climatic conditions are the initial parameters for model simulations. Unfortunately, an available set of measurable weather variable covers a very short period of time and a limited number of areas. The density of observing stations always has been and still is inhomogeneous, with many stations in densely populated areas and virtually none in huge oceanic areas. Special earth-observation satellites provide a wide range of observations of various components of the climate system all over the globe. The problem is how to interpret data correctly. Corrections for the ellipsoidal form of the Earth's orbit, the presence of clouds in the sky, atmospheric transmission effects, instrumental biases and instabilities are required before using satellite data in climate models. Satellite data also require extensive ground measurements for their validation. The World Meteorological Organization and the International Oceanographic Commission have establish a Global Climate Observing System. GCOS includes atmospheric, oceanic and terrestrial networks.