5. General Circulation Models

I. 3-D Climate Models (General Circulation Models)

To include the full three-dimensional aspect of climate, including the calculation of the dynamical transports, requires solving numerically the energy, momentum, mass and water vapour conservation equations, as well as including physical processes such as cloud generation, turbulent heat transports between the ground and air, transports of heat and moisture within the ground, etc.

General Circulation Models (GCMs) were originally adapted from weather forecasting models. However, in weather forecasting models many physical processes that are not important on short time scales are not included: radiation, ground physics, boundary layer physics, clouds, snow/ice, ....
II. Uses of GCMs

1. To understand the current atmospheric circulation (i.e. atmospheric dynamics and physics)
2. To provide short term weather forecasts.
3. To estimate the impact of initial ground or ocean conditions on monthly and seasonal weather.
4. To simulate past climates, so as to improve our understanding of the earth’s climate system.
5. To estimate future climate changes resulting from natural or anthropogenic processes.
Three-Dimensional Global Climate Change Model

- Biogeochemistry of Greenhouse Gases
- Ocean Circulation
- Man-Made Pollution
- Hydrology & Vegetation
- Large-Scale Atmospheric Circulation
- Atmosphere & Oceanic Convection
- Earth-Sun Heat Balance
- Ocean-Atmosphere Interaction
III. Mathematical Formulation

GCMs need to solve a set of fundamental equations in order to obtain values for the wind, temperature, moisture and pressure at each location in the earth’s atmosphere.

1. Conservation of momentum (F=ma)

West wind: \[ \frac{\partial u}{\partial t} = - (u \frac{\partial u}{\partial x} + v \frac{\partial u}{\partial y} + w \frac{\partial u}{\partial z}) - \frac{1}{\rho} \frac{\partial P}{\partial x} - fv - Friction \]

South wind: \[ \frac{\partial v}{\partial t} = - (u \frac{\partial v}{\partial x} + v \frac{\partial v}{\partial y} + w \frac{\partial v}{\partial z}) - \frac{1}{\rho} \frac{\partial P}{\partial y} + fu - Friction \]

Vertical wind: \[ \frac{\partial w}{\partial t} = - (u \frac{\partial w}{\partial x} + v \frac{\partial w}{\partial y} + w \frac{\partial w}{\partial z}) - \frac{1}{\rho} \frac{\partial P}{\partial z} - g - Rot - Fric \]

Advection of momentum
Pressure gradient
Rotation effect
Hydrostatic approx.
2. Conservation of mass:

Density ($\rho$):
\[
\frac{\partial \rho}{\partial t} = -\left(\frac{\partial \rho u}{\partial x} + \frac{\partial \rho v}{\partial y} + \frac{\partial \rho w}{\partial z}\right)
\]

Mass flux divergence

3. Conservation of energy:

Temperature ($T$):
\[
\frac{\partial T}{\partial t} = -c \left(\frac{u \partial T}{\partial x} + \frac{v \partial T}{\partial y} + \frac{w \partial T}{\partial z}\right) + \text{Net Rad. (SW+LW)} +
\]
\[
+ \text{Sensible heat from surface} + \text{Latent heat } (-L\frac{\partial q}{\partial T})
\]
4. Conservation of moisture:

Specific Humidity (q):

\[ \frac{\partial q}{\partial t} = - \left( u \frac{\partial q}{\partial x} + v \frac{\partial q}{\partial y} + w \frac{\partial q}{\partial z} \right) + \text{Evap.} - \text{Precip.} \]

5. Equation of state:

Pressure (P):

\[ P = \rho RT \]

R = dry air gas constant

This gives us 7 equations with 7 unknowns: u, v, w, \( \rho \), T, q, P
This set of nonlinear partial differential equations cannot be solved analytically, and therefore has to be solved numerically, with finite time steps and grid boxes.

On the right hand side of the above fundamental equations appear source terms which are determined by various physical processes in the atmosphere (friction, radiation, heat fluxes, evaporation, precipitation).

Figure 1. Schematic illustration of the processes and typical vertical gridding in the current generation of global climate models. Fully coupled versions of the atmosphere-ocean-land components are just beginning to become available.
For global climate models (GCMs) the temporal resolution is ~1 hour for source terms (“physics”), and ~15 minutes for the non-source terms (“dynamics”), with a spatial resolution of ~100-500km horizontally, and 1km vertically.

[Weather forecast models run for shorter simulations (days) and therefore can have finer resolution]
\[ \sigma = \frac{p}{\rho_s} \quad z = \text{Height (meters)} \]

\[
\begin{align*}
\sigma &= 0 \\
\sigma &= 0.016 \quad z \approx 27,900 \\
\sigma &= 0.070 \quad z \approx 18,330 \\
\sigma &= 0.165 \quad z \approx 12,890 \\
\sigma &= 0.315 \quad z \approx 8,680 \\
\sigma &= 0.500 \quad z \approx 5,430 \\
\sigma &= 0.685 \quad z \approx 3,060 \\
\sigma &= 0.835 \quad z \approx 1,490 \\
\sigma &= 0.940 \quad z \approx 520 \\
\sigma &= 0.990 \quad z \approx 80 
\end{align*}
\]

Fig. 10.3 Example of the vertical grid spacing in sigma coordinates, and the corresponding average altitudes of the levels in a nine-level atmospheric general circulation model employed by Manabe et al. (1970).
Values at $t_1$ are specified from observations and the model physics. the values at $t_2$ are updated via the fundamental equations based on the values at $t_1$.

\[
\frac{\partial A}{\partial t} = (\text{quantities derived at } t_n)
\]

\[
A(t_n) = A(t_{n-1}) + \text{(quantities derived at } t_n)\]

This provides the basis for making predictions for a day, month or year…. BUT errors propagate!

**Horizontal and Vertical Differencing:**

For the horizontal gradients we use approximate derivatives:

\[
\frac{\partial u}{\partial x} \approx \frac{\Delta u}{\Delta x} \approx \frac{(u_2-u_1)}{\Delta x}
\]

For vertical gradients:

\[
\frac{\partial u}{\partial z} \approx \frac{\Delta u}{\Delta z} \approx \frac{(u_b-u_a)}{\Delta z}
\]
FIG. 5. Horizontal grid schemes A, B and C. Dots are primary gridpoints where pressures and temperatures are computed. Arrows are secondary gridpoints where horizontal winds are computed.

Arakawa B-scheme
The prescribed parameters and boundary conditions in GCMs are:

- Radius, surface gravity, and rotation speed of the Earth
- Solar constant and orbital parameters of the Earth
- Total mass of the atmosphere, and its composition
- Thermodynamic and radiation constants of atmospheric gases and clouds
- Surface albedo and soil type
- Surface elevation
Figure 5.3. The distribution of land and ocean as resolved by the 4° latitude × 5° longitude grid of the OSU atmospheric GCM. For clarity, the continental grid points are not shown. The contours show the surface elevation of the continents (10^2 m). (After Schlesinger and Gates, 1981.)
Low resolution

High resolution
III. Physics of Source Terms

Determining how to model the physical source terms is of major importance in order to correctly model the atmosphere. All physical processes need to be approximated in global models. Parameterizations (simplified formulations relating sub-grid scale phenomena to the large scale parameters) need to successfully simulate the physical processes, without using prohibitive amounts of computer time. The differences that exist between different GCM climate predictions are mainly due to the different formulations used in the source terms.

Friction in the momentum equation: This is very complicated due to the difference in scales. Parameterizations need to relate turbulence on small scales to large scale GCM parameters.

Radiation in the energy equation: This is fairly well done, however clouds cause uncertainties.

Fluxes of heat and moisture from the ground and ocean in the energy and moisture equations: Over land this is difficult due to vegetation.

Condensation of water (rain and clouds) in the moisture and energy equ.: Very complicated due to the scaling problem, together with our uncertainties in the physical processes that produce precipitation.
Modeling the Climate System

Includes the Atmosphere, Land, Oceans, Ice, and Biosphere

Atmospheric GCM

Atmosphere (Temperature, Winds, and Precipitation)

Cirrus Clouds

Stratus Clouds

Evaporation

Heat & Salinity Exchange

Winds and Waves

Ocean

Ocean GCM

Ocean Model Layers

Ocean Bottom Topography

Vertical Overturning

Marine Biology

Realistic Geography

Ocean (Currents, Temperature, and Salinity)

Lakes and Rivers

Land Surface (Topography and Reflectivity)

Vegetation and Ecology

Soil Moisture

Runoff

Human Influences and Land Use

Evaporative and Heat Energy Exchanges

Aerosols

Snow Cover

Transition from Solid to Vapor

Outgoing Heat Energy

Incoming Solar Energy

Stratus Clouds

Precipitation Evaporation

Clouds

Atmospheric Model Layers
IV. Model Processes

1. Numerical solution of the fundamental equations of conservation of momentum, heat, mass and moisture.

2. Radiative processes: Calculation of shortwave and longwave radiative transfer within a multi-layered atmosphere.

Fig. 18. Clear sky solar heating rate profiles due to water vapor absorption in model midlatitude summer and subarctic winter atmospheres. The profiles were calculated for $\theta_0 = 60^\circ$ and $a_x = 0.07$ for a variety of different absorption parameterizations which use either different absorption data and/or different extraterrestrial solar fluxes (refer Table 4 and discussion in text) (from Wang, 1976).
Figs. 5a and b. The difference between the exact cooling rate (based on a line by line computation) and the cooling rate using a $k$ distribution method (labeled as present method) and the cooling rate using a 20 interval band model approach (Rodgers-Walshaw method). The cooling rate differences apply only for the spectral regions 0–580 cm$^{-1}$ and 1220–2020 cm$^{-1}$ for a tropical (a) and subarctic winter (b) atmosphere (modified from Chou and Arking, 1980).
Net solar flux at surface

June 1981
3. Below ground processes: Transport of heat and moisture within the ground.

4. Subsurface ocean processes: transport of heat and momentum within the ocean.

5. Ground surface layer processes: surface runoff of rainfall, surface albedo of soil, vegetation, snow/ice, ocean.
6. Atmospheric surface layer processes: Calculation of atmospheric surface layer values of temperature, humidity, wind and wind stress, in conjunction with calculations of fluxes of heat and moisture between the ground or ocean surface and the surface layer of the atmosphere.

7. Boundary layer processes: mixing of heat, moisture and momentum fluxes from the atmosphere surface layer into the well-mixed region above the surface, approximately 1km, by turbulence.
8. Convection: mixing of heat, moisture and momentum within the atmosphere by organized sub-grid scale convective processes.


10. Precipitation and associated processes: Generation of rain or snow by supersaturated processes, either large-scale or convective, along with re-evaporation in possible unsaturated levels below.

11. Interaction with top (boundary conditions): Minimization of spurious influence of the model top on atmospheric processes (e.g. wave propagation).
Clouds
12. Associated models:

*Middle Atmosphere Model*: raising the model top to great altitudes (e.g. 85km).

*Ocean Models*: calculation of ocean general circulation to interact with the atmospheric model (ocean mixed layer or full ocean model).

*Chemical Tracer Models*: calculate distributions of atmospheric trace gases using winds generated by the GCM and photochemical models.

*Simpler (2-D) models*: make use of GCM results to develop parameterizations for use in simpler and faster models.
V. Major difficulties for simulating climate

1. Have to parameterize unknown or uncertain processes – friction and some fluxes involve turbulence; cloud physics is uncertain; in-ground processes are uncertain.

2. Have to parameterize small-scale processes using a grid of finite size (100s of km); convective processes can occur on a 10 km scale.

3. The finite difference approximations to the differential equations become worse as larger spatial and temporal scales are used.

4. For short term predictions, initial conditions (observations) are important.
Figure 2. Annual mean zonal mean surface temperatures for the current climate from the GISS GCM (G’s), the GFDL GCM (P’s), the NCAR GCM (N’s), and observations (O’s).
Fig. 10.9 Maps of (a) computed and (b) observed February monthly mean air temperatures (K). [Top computed distribution from Manabe and Stouffer (1980); bottom observed distribution from Crutcher and Meserve (1970) and Taljaard et al. (1969) as printed in Manabe and Stouffer (1980), © American Geophysical Union.]
Fig. 10.10  Maps of (a) computed and (b) observed temperature difference (K) between August and February. The contour interval is 2 K when the absolute value of the temperature difference is less than 10 K and is 10 K when it is more than 10 K. [Top computed distribution from Manabe and Stouffer (1980); bottom observed distribution from Crutcher and Meserve (1970) and Taljaard et al. (1969) as printed in Manabe and Stouffer (1980), © American Geophysical Union.]
Fig. 10.13  (a) Simulated and (b) observed annual mean sea surface temperature (SST) in °C. [From Manabe et al. (1990); bottom panel data from Levitus (1982). Reprinted with permission from the American Meteorological Society.]
Fig. 10.11 Map of mean precipitation rate (a) computed and (b) observed for December–February (DJF). Heavy stippling indicates areas where the precipitation is $>0.5$ cm day$^{-1}$, and light stippling indicates where it is $<0.1$ cm day$^{-1}$. Both maps are smoothed. [Observations from Jaeger (1976) as printed in Delworth and Manabe (1988). Reprinted with permission from the American Meteorological Society.]
Fig. 10.12  Same as Fig. 10.11 except for June through July (JJA). [Observations from Jaeger (1976) as printed in Delworth and Manabe (1988). Reprinted with permission from the American Meteorological Society.]
Fig. 10.8  Zonal cross sections of zonal-mean wind simulated in a GCM (top) and observed (bottom) during the solstitial seasons of December–February (left) and June–August (right). [From McFarlane et al. (1992). Reprinted with permission from the American Meteorological Society.]
Figure 1. Annual mean zonal mean total northward atmospheric energy transport for the current climate from the GISS GCM (G’s), the GFDL GCM (P’s), the NCAR GCM (N’s), and observations (O’s).
Fig. 10.16  Zonally integrated mass transport of the atmosphere and ocean for an equilibrium climate with an active thermohaline circulation. Units are megatons s\(^{-1}\) (10\(^9\) kg s\(^{-1}\)). [From Manabe et al. (1990). Reprinted with permission from the American Meteorological Society.]
Northward transport of Sensible Heat

Northward transport of Energy

Northward transport of Momentum
Tropospheric Precipitable Water
Fixed SSTs
A Global Climate Forcings

- All Greenhouse Gases
- Black Carbon (BC)
- Solar Irradiance
- Snow Albedo (BC effect)
- Stratospheric Aerosols
- Reflective Tropospheric Aerosols
- Aerosol Indirect Effect
- Land Use

Forcing (W/m²)

Temperature Change

- Run 1
- Run 2
- Run 3
- Run 4
- Run 5
- 5 Run Mean
- Observations

ΔT (°C)

1880 1900 1920 1940 1960 1980 2000
Surface Air Temperature Anomalies

ΔT Anomalies Relative to 1971-2000 Mean

Global Average ΔT

1971 (Model Year)

GFDL CM 2.1 Climate Model
Schmidt et al., 2006: Present-day atmospheric simulations using GISS ModelE: Comparison to in situ, satellite and reanalysis data, J. Climate, 19, 153-192.