Atmospheric General Circulation Models: methodology, results, biases

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A brief introduction on General Circulation Models; horizontal representation; initial & boundary conditions

ensembles of AMIP-type experiments; coupled model experiments; CMIP inter-comparison;

Common biases in climate models

Boundary and initial condition problems: climate projections and predictions
Atmospheric General Circulation Models (AGCMs)

3-dim representation of the primitive equations system, that is a set of nonlinear differential equations to approximate dynamical and physical mechanisms operating in the atmosphere.

Models are defined through:

(i) the **Navier-Stokes equations**, which describe the motion of fluid substances and arise from Newton’s 2\textsuperscript{nd} law: six equations representing:
   - Conservation of momentum (equation of motion)
   - Conservation of mass (continuity equation)
   - Conservation of energy (thermodynamic equation)
   - Conservation of water (moisture equation)

(ii) horizontal and vertical representation of atmospheric variables;

(i) **numerical** techniques in order to solve the equations;

(i) physical parameterization (for all the processes smaller than the time-space scales chosen/used);

(i) boundary and initial conditions
Mathematical simulation of the atmosphere (dynamical and physical processes):

Dynamics: interactions between motions, thermodynamics and moisture processes

Physical processes: exchange of sensible and latent heat (surface fluxes) with the bottom of the atmosphere

Figure 3.8  Schematic of interactions between the dynamical aspects of climate models and various physical processes such as radiation, clouds, sensible and latent heat fluxes, and surface types. (After Dickinson 1986.)  From Washington & Parkinson, 2005

basic conservation equations energy, mass and water; external factors (radiation and interactive processes)
Modeling the climate system

Scientists apply that knowledge to a scaled-down, computer simulation of the planet: a global climate model.
Modelling the climate system

Discretization of time ($\Delta t$) and space ($\Delta x$, $\Delta y$, $\Delta z$)

The mathematical treatment of such a system of equations is terribly complex, so much that no solutions can be found, except for approximate solutions.

\[
\begin{align*}
\frac{\partial \psi}{\partial x} &= \frac{\psi_{i+1,j,k} - \psi_{i-1,j,k}}{2\Delta x} \\
\frac{\partial \psi}{\partial y} &= \frac{\psi_{i,j+1,k} - \psi_{i,j-1,k}}{2\Delta y} \\
\frac{\partial \psi}{\partial z} &= \frac{\psi_{i,j,k+1} - \psi_{i,j,k-1}}{2\Delta z}
\end{align*}
\]

In space:

\[
\psi^{\tau+1} = \psi^{\tau} + \Delta t \left[ \frac{\partial \psi}{\partial t} \right]_{\tau}
\]

In time:
Modelling the climate system

Equations are converted to computer code and climate variables are set

```
if (diagts .and. eots) then
  do 1500 m=1,nt
    do 1490 k=1,km
      fx = cst(j)*dyt(j)*dzt(k)/(c2dttsc*dtcel(k))
    do 1480 i=2,ntml
      boxfx = fx*xdt(i)*fn(i,k,jc)
      sddt = (ta(i,k,m)-t(i,k,jc,nn,m))*boxfx
      svar = (ta(i,k,m)**2-t(i,k,jc,nn,m)**2)*boxfx
      n = 0
    termbt(k,m,n) = termbt(k,1,m,n) + sddt
    tvar(k,m,n) = tvar(k,n,n) + svar
  n = nreg*(mskr(k)-1) + mskhr(i,j)
  if (n .gt. 0 .and. mskhr(i,j) .gt. 0) then
    termbt(k,1,m,n) = termbt(k,1,m,n) + sddt
    tvar(k,m,n) = tvar(k,m,n) + svar
```

A supercomputer solves all the equations, passing results to neighboring boxes and calculating the next set of initial conditions
Numerical methods:

**finite differences** – spatial and temporal derivatives are approximated by finite differences

**spectral methods** – truncated expansion of analytical spherical functions (spherical coordinate system)

**lagrangian and semi-lagrangian methods** – express the equation in Lagrangian form (trajectories, i.e. transport of water vapor and chemical constituents)

**spectral element methods** – computational domain organized into rectangular regions (elements) with variables (in each element) approximated by polynomial expansions – Garlekin’s method
the dimension of the basic grid determine the MINIMUM scale of phenomena that can be resolved (typical values for climate simulations – $\Delta x = \Delta y = 100$ km, $\Delta z = 50$ m, $\Delta t = 20$ min)

computational restrictions

sub-grid scale phenomena (cumulus convection, fronts, turbulence) **cannot be resolved explicitly** and they are expressed in terms of the resolved macro-scale parameters (PARAMETERIZATION)
Evolution of horizontal resolutions used for climate studies:

Climate modeling is a very computing-intensive field; model scientists always trying to get time on the newest, fastest supercomputers. As a general rule of thumb, **increasing the resolution** of a model **by a factor of two** means that about **ten times** as much computing power will be needed (the model will take ten times as long to run on the same computer).
Impact of the horizontal resolution (Indian summer monsoon rainfall)

From Cherchi and Navarra (2007)
Some physics in the real world is only known empirically OR the theory only really applies at scales much smaller than the model grid size. This physics needs to be ‘parameterised’ i.e. a formulation is used that captures the phenomenology of the process and its sensitivity to change but without going into all of the very small scale details. A simple example is the radiation code – instead of using a line-by-line code which would resolve the absorption at over 10,000 individual wavelengths, a GCM generally uses a broad-band approximation (with 30 to 50 bands).
Radiation scheme
Convection scheme
Atmosphere & climate system

Role of the atmosphere

FAQ 1.2, Figure 1. Schematic view of the components of the climate system, their processes and interactions.
Climate of a planet depends on:
- energy from the sun
- speed of planet’s rotation
- mass of the planet
- chemical composition of the atmosphere
- ocean-land distribution
- water properties
- coupled processes (feedbacks)

Role of the atmosphere:
- radiative processes (core of Earth’s energy budget)
- chemical processes (atmospheric composition)
- dynamical processes - global circulation (distribution of radiative and chemically active species; cloud formation; exchange of heat and moisture with bottom)
Chronology of climate model development

Adapted from IPCC 2007
Boundary and initial conditions

Boundary conditions:

Describe the influence of the “outside” upon the system (they may vary in time and they have to be specified as a function of time \( t \) to determine the future evolution of the system).

*For the atmosphere:*

**Upper boundary** (radiative transfer, incoming/outgoing SW and LW radiation); exchanges with space (except with sun) are neglected.

**Lower boundary** (ocean/sea ice – SST or coupled model; land/ice sheet – surface schemes or land surface models to consider exchange fluxes with the surface).

Initial conditions (full starting set of values in 3D space)

Possible initial conditions:
- stable solution (atmosphere at rest without horizontal gradient – physical processes are effective in restoring horizontal gradients – short memory of the atmosphere);
- observed atmospheric state (mandatory for climate and weather predictions – unbalanced with dynamical equations – spin up)
- balanced climatic state (when observed initial conditions are not required)
Lower boundary conditions (SST)

(a) **Fixed SST**
- From Navarra (1989)
- (i.e. annual mean, perpetual months)
- huge statistics – no seasonal cycle
- (climate variability is not correct)

(b) **Climatological SST**
- seasonal varying SST – repeated
- climatological seasonal cycle

(c) **Observed SST**

(d) **Coupled Model**

AMIP-type experiments (Gates, 1992) –
- same boundary conditions – different
  initial conditions (require ensembles)

CMIP protocol experiments: atmosphere
  and ocean have the same surface
  temperature, computed by the models
  depending on exchanged fluxes and
  interactions

From Navarra (1989)
the natural instability of the system is sufficient to generate different realizations of the climate variability -> set of ensembles with little perturbation of IC (e.g. different model start date)

Perturbations is needed to sample the internal variability of the model, which otherwise would be higher than the variability imposed by the BC

**chaos theory** – Lorenz attractor: a small change in the initial condition of the system, which causes a chain of events leading to large-scale phenomena (Lorenz, 1963; 1969)

*Fig. 6. Precipitation anomalies from each of the nine simulations, averaged over box 1—eastern equatorial Pacific region (upper), and over boxes 3 and 4 combined—east and west regions of the United States (lower).*

From Stern and Miyakoda (1995)
Atmospheric-forced & coupled model experiments

Mean JJA precip & 200 mb velocity potential - Obs

WI, B, WP benefit from coupling (Cherchi and Navarra, 2007)

The EI SST cold bias in the coupled simulation accounts for the rainfall systematic error in the area.
Cherchi et al. (2013)

South Asian monsoon precipitation (JJA mean, mm/d): CMIP5 models performance

For each model, the details in the spatial patterns and intensity of monsoon precipitation may differ from observations (top-left panel) – Metrics
Common biases in climate models

The representation of the mean state in the Pacific sector displays an anomalous symmetric structure about the equator, contrasting with the asymmetry characterizing the observed annual mean patterns of rainfall, sea surface temperature, and wind—possibly reflecting the interhemispheric differences for the oceans and continents distribution (i.e. Bellucci et al. 2010)

![Image of precipitation patterns](Image)
The largest positive SST biases occur along the eastern boundaries of the subtropical ocean basins, most notably off the coasts of southwest Africa, Peru–Ecuador–Chile, and Baja–Southern California. Very large biases (> 4°C) extend for thousands of kilometers along these coasts but typically extend only about 300 km offshore. The increase in resolution does not seem to solve the problem.
How do we use climate models?

**Climate simulations**: explore the mechanisms driving the climate variability and climate change. Process oriented investigations on a **wide range of spatial and temporal scales**.

**Climate projections**: assess the climate change signal according to prescribed scenarios of radiative forcing. Generally long simulations starting from spin-up initial conditions. Identification of long-term trends and changes in the statistics of parameters of interest.

**Seasonal predictions**: assess the climate variations mostly due to the internal variability of the climate system. **6-to-12 month simulations initialized with observed conditions** (specific start date). Prediction of possible anomalous conditions in the “current statistics” (current climate).

**Short-term projections**: assess the climate variations due to both the internal variability and changes in the external forcings. Ensembles of short-term (~10-to-30 years) projections, but **initialized with observed conditions** (specific start date). **Change in the statistics** of parameters of interest.
Climate projection: a boundary condition problem

Following the **chaos theory**, it is not useful to specify initial conditions in a long-lasting simulation, because the information imparted by the initial state is **lost** after very short time.

**Scenarios**: a selection of different climate **forcings** based on our prediction of socio-economic growth.

Change in any of the boundary conditions (projections are based on coupled runs, so...)
Climate projection: a boundary condition problem

September sea ice extent: Trends from CMIP5, CMIP3 and observations

* RCP 4.5 is a mild climate change scenario adopted in the $5^\circ$ Coupled Model Intercomparison Project (CMIP5, started in 2007), while SRES A1B is a mild scenario adopted by CMIP3, started in 2001. These results were used by IPCC for the publications of the Assessment Reports (AR4, 2007, AR5, 2014).
Observed & simulated continental & global scale changes in surface temperature

Observed change (black line); climate models simulations using natural (blue) and anthropogenic (red) forcings. Despite biases, models correctly reproduce climate change when anthropogenic forcing is taken into account.
Projection of South Asian summer monsoon precipitation change:

<table>
<thead>
<tr>
<th>Model</th>
<th>Observed Mean</th>
<th>Projected Mean</th>
</tr>
</thead>
<tbody>
<tr>
<td>AIR</td>
<td>840; 86.1</td>
<td>413; 44.3</td>
</tr>
<tr>
<td>CRU</td>
<td>765; 78.8</td>
<td>626; 82.8</td>
</tr>
<tr>
<td>IMD</td>
<td>919; 101.0</td>
<td>776; 104.7</td>
</tr>
<tr>
<td>ensemble mean</td>
<td>585; 88.0</td>
<td>600</td>
</tr>
</tbody>
</table>

Projected precipitation changes: role of CO2 and aerosols
(see Turner and Annamalai, 2012)
Projection of South Asian summer monsoon precipitation change

Projected precipitation changes: role of CO2 and aerosols (Turner and Annamalai, 2012)
Climate predictions: a boundary and initial condition problem

- Deterministic Forecast
- Reanalyses
- time
Climate predictions: a boundary and initial condition problem

Uncertainties on initial data could be large. To supply for this issue: ensemble technique with perturbed initial conditions.

Reanalyses

Uncertainty on Initial Conditions

Deterministic Forecast

Time
Climate predictions: a boundary and initial condition problem

Uncertainties on initial data could be large. To supply for this issue: ensemble technique with perturbed initial conditions.

Climatology: spectrum of all possible results

Probabilistic Forecast

Deterministic Forecast

Uncertainty on the forecasts

Uncertainty on Initial Conditions

Reanalyses

Readapted from Trzaska (http://portal.iri.columbia.edu)
The GCM simulates the physics of the atmosphere, land surface and ocean, representing a world close to reality. The addition of realistic initial conditions allows the model to evolve towards the most likely future climate state.
SUMMARY

General circulation models of the atmosphere are resolved by complicated equations that need to be discretized in order to find a solution.

Horizontal resolution plays an important role for a correct simulation of climate processes, a better representation of orography.

Two different approaches: AMIP-type (ocean is a boundary condition) and fully coupled type (ocean and atmosphere interact every time step).

Despite systematic biases, models are able to reproduce the past climate, when the anthropogenic forcing is introduced. It’s likely that future climate is also well projected.

The far target of climate projections makes the impact of initialization neglectable: instead, boundary conditions have a crucial role for the representation of future climate.

A realistic state initial state representation is needed for climate predictions.