Climate models

René D. Garreaud

Departement of Geophysics
Universidad de Chile
www.dgf.uchile.cl/rene
My first toy model
A system of coupled, non-linear algebraic equations

\[ X(t) = A \cdot X(t-1) \cdot Y(t) + B \cdot Z(t-1) + \varepsilon_x \]
\[ Y(t) = C \cdot X(t-1) \cdot Y(t-1) + B \cdot Z(t) + \varepsilon_y \]
\[ Z(t) = D \cdot Z(t-1) \cdot Y(t) + E \cdot X(t-1) + \varepsilon_z \]
\[ \varepsilon_x = \varepsilon_y = \varepsilon_z = 0 \]

\( X, Y, Z \): Time-dependent variables
Pressure, winds, temperature, moisture,….

\( A, B, C, D \): External parameter
Orbital parameters, \( \text{CO}_2 \) Concentration, SST (AGCM), Land cover

\( \varepsilon_x \ varepsilon_y \ varepsilon_z \) Randoms error
Set to zero \( \rightarrow \) Deterministic model
My first toy model

\[
X(t) = A \cdot X(t-1) \cdot Y(t) + B \cdot Z(t-1) + \varepsilon_x
\]

\[
Y(t) = C \cdot X(t-1) \cdot Y(t-1) + B \cdot Z(t) + \varepsilon_y
\]

\[
Z(t) = D \cdot Z(t-1) \cdot Y(t) + E \cdot X(t-1) + \varepsilon_z
\]

\[
\varepsilon_x = \varepsilon_y = \varepsilon_z = 0
\]

To run the model, we need:

• Initial conditions: \(X_0, Y_0, Z_0\)
• The values of the External Parameters \(\ldots\) they can vary on time
• A numerical algorithm to solve the equations
• A computer big enough
Weather forecast
Model predicts daily values

Climate Prediction
Model does NOT predict daily values but still gives reasonable climate state (mean, variance, spectra, etc…)

My First Toy Model

Temperature anomaly [°C]

Time [Days]
The Lorenz’s (butterfly) chaos effect

A slight difference in the initial conditions

Non-linear equations

Large differences later on
Nevertheless, simulations after two-weeks are still “correct” in a climatic perspective and highly dependent upon external parameters → models can be used to see how the climate changes as external parameters vary.

Two runs of the model, everything equal but parameter $A$

Note the “Climate Change” related to change in $A$
Examples of External Parameters that can be modified:

1. The relatively long memory of tropical SST can be used to obtain an idea of the SST field in the next few months (e.g., El Niño conditions). Using this predicted SST field to force an AGCM, allows us climate outlooks one season ahead.

2. Changes in solar forcing (due to changes in sun-earth geometry) are very well known for the past and future (For instance, NH seasonality was more intense in the Holocene than today). Modification of this parameter allow us paleo-climate reconstructions (still need to prescribe other parameters in a consistent way: Ice cover, SST, etc….hard!)

3. Changes in greenhouse gases concentration in the next decades gases give us some future climate scenarios.
Atmospheric circulation is governed by fluid dynamics equation + ideal gas thermodynamics

\[ \frac{d\vec{V}}{dt} + f\vec{k} \times \vec{V} = -\frac{1}{\rho} \nabla p - F_R + g \]

\[ \left( \frac{\partial}{\partial t} + \vec{V} \cdot \nabla \right) T - S_p \omega = Q_{RAD} + Q_{Conv} + Q_{Sfc} \]

\[ \nabla \cdot \vec{V} + \frac{\partial \omega}{\partial p} = 0 \]

\[ \frac{\partial (gz)}{\partial p} = -\frac{RT}{p} \]

\[ \frac{dq_v}{dt} = -C + E \]

\[ \frac{dq_r}{dt} = +C - E + S_r \]
¿¿¿Where is precipitation???

Water Vapor

Cloud droplets

Warm cloud

Rain droplets

Graupel/Hail

Ice crystal

Cold clouds

Snow

\[
\frac{dq_v}{dt} = -C + E_c + E_r
\]

\[
\frac{dq_c}{dt} = +C - E_c - A_c - K_c
\]

\[
\frac{dq_r}{dt} = A_c + K_c - E_r - F_r \quad \rightarrow PP_s \propto F_r
\]
Previous system is highly non-linear, with no simple analytic solution.

We solve the system using numerical methods applied upon a three-dimensional grid.
Global Models (GCM)

Δlat \sim Δ lon \sim 1° - 3°

Δz \sim 1 \text{ km}

Δt \sim \text{ minutes-hours}

Top of atmosphere: 15-50 km
# Global Models (GCM)

<table>
<thead>
<tr>
<th>Type</th>
<th>SST</th>
<th>Sea Ice</th>
<th>Land Ice</th>
<th>Biosphere</th>
<th>Land use</th>
<th>Complexity</th>
</tr>
</thead>
<tbody>
<tr>
<td>AGCM</td>
<td>P</td>
<td>P</td>
<td>P</td>
<td>P</td>
<td>P</td>
<td>1980-</td>
</tr>
<tr>
<td>CGCM</td>
<td>C</td>
<td>C</td>
<td>P/C</td>
<td>P/C</td>
<td>P</td>
<td>1990-</td>
</tr>
<tr>
<td>OGCM</td>
<td>C</td>
<td>C</td>
<td>P</td>
<td>P</td>
<td>P</td>
<td>2005-</td>
</tr>
<tr>
<td>ESM</td>
<td>C</td>
<td>C</td>
<td>C</td>
<td>C</td>
<td>C</td>
<td></td>
</tr>
</tbody>
</table>

A: Atmospheric Only; C: Coupled; O: Ocean; ESM: Earth-system models

External parameters: GHG, O3, aerosols concentration; solar forcing
Regional Models (LAM, MM)

$\Delta x \sim \Delta y \sim 1-50 \text{ km}$  $\Delta z \sim 50-200 \text{ m}$  $\Delta t \sim \text{ seconds}$

$L_x \sim L_y \sim 100-5000 \text{ km}$  $L_z \sim 15 \text{ km}$
Regional models give us a lot more detail (including topographic effects) but they need to be “fed” at their lateral boundaries by results from a GCM.

**Main problem:** Garbage in – Garbage out
Once selected the domain and grid, the numerical integration uses finite differences in time and space.

\[
\frac{\partial T}{\partial t} + u \frac{\partial T}{\partial x} = Q_{\text{diab}}
\]

**Numerical method**

(Stable & efficient)

\[
\frac{T_t^i - T_t^{i+1}}{\Delta t} + u_t^{i-1} \frac{T_t^i - T_t^{i-1}}{\Delta x} = Q_{\text{diab}}
\]

Sub-grid processes must be parameterized, that is specified in term of large-scale variables.
Thus, a real atmospheric model has

Dynamical Core

Cloud microphysics

Boundary layer turbulence

Convective clouds

Radiative Transfer

Surface processes

Param. otros procesos SG

For instance, MM5 (LAM) has 220 programs, 50 directories and 55,000 code lines F77...Ufff!