Some remarks on climate modeling

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Selected overheads by Doug Nychka
Outline

• Hierarchy of atmospheric modeling strategies
  – 1D Radiative Convective models
  – 3D General Circulation models (GCMs)

• Conceptual Framework for General Circulation Models

• Scale interaction problem
  – concept of resolvable and unresolvable scales of motion

• Model Validation and Model Solutions
The Earth’s climate system
Principles of Atmospheric Modeling

• Scientific basis for atmospheric simulation
  – rooted in laws of classical mechanics/thermodynamics
    – developed during 18th and 19th centuries (see Thompson, 1978)
  – early mathematical model described by Arrhenius (1896)
    – surface energy balance model

• Two modeling approaches developed over last century
  – based on energy balance requirements
  – dynamical models (e.g., explicit transports)
Conceptual Framework for Modeling

• Can’t resolve all scales, so have to represent them

• Energy Balance / Reduced Models
  – Mean State of the System
  – Energy Budget, conservation, Radiative transfer

• Dynamical Models
  – Finite element representation of system
  – Fluid Dynamics on a rotating sphere
  – Basic equations of motion
  – Physical Parameterizations for moving energy
Atmospheric modeling hierarchy

Understanding has been aided by a hierarchy of approaches

Consider the flux form of thermodynamic energy equation

\[ c_p \frac{\partial T}{\partial t} = -c_p \nabla \cdot (VT) - c_p \frac{\partial (\omega T)}{\partial p} + c_p \frac{\kappa \omega T}{p} + Q_{\text{rad}} + Q_{\text{conv}} \quad (1) \]

where \( T \) - temperature; \( V \) - horizontal wind vector; \( p \) - pressure; \( \omega \) - vertical pressure velocity; \( Q_{\text{rad}} \) and \( Q_{\text{conv}} \) - net radiative and convective heating

- Simple Zero-Dimensional (Energy Balance) Climate Model

  - Averaging (1) over horizontal and vertical space dimensions yields

  \[ c_p \frac{\partial < \hat{T} >}{\partial t} = < S > - < F > \]

  where \( S \) is net absorbed solar radiation and \( F \) is longwave radiation emitted to space

For a long-term stable climate, \( < S > - < F > = 0 \)
Atmospheric modeling hierarchy

- Simple One-Dimensional (Radiative-Convective) Climate Model
  - Averaging (1) over horizontal space dimensions yields
    
    \[ c_p \frac{\partial < T >}{\partial t} = < Q_{\text{rad}} > + < Q_{\text{conv}} > \]

    where a globally averaged vertical profile of \( T \) can be determined from expressions for \( < Q_{\text{rad}} > \) and \( < Q_{\text{conv}} > \)

- Higher-order models determined by form of averaging operators
1D Radiative Convective Model

Manabe & Wetherald 1967

Radiative Equilibrium
Clear sky

Radiative-Convective Equilibrium
1D models: Doubling CO2

Manabe & Wetherald 1967

TABLE 5. Change of equilibrium temperature of the earth’s surface corresponding to various changes of CO₂ content of the atmosphere.

<table>
<thead>
<tr>
<th>Change of CO₂ content (ppm)</th>
<th>Fixed absolute humidity</th>
<th>Fixed relative humidity</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Average cloudiness</td>
<td>Clear</td>
</tr>
<tr>
<td>300 → 150</td>
<td>−1.25</td>
<td>−1.30</td>
</tr>
<tr>
<td>300 → 600</td>
<td>+1.33</td>
<td>+1.36</td>
</tr>
<tr>
<td></td>
<td>Average cloudiness</td>
<td>Clear</td>
</tr>
<tr>
<td></td>
<td>−2.28</td>
<td>−2.80</td>
</tr>
<tr>
<td></td>
<td>+2.36</td>
<td>2.92</td>
</tr>
</tbody>
</table>

Fig. 16. Vertical distributions of temperature in radiative convective equilibrium for various values of CO₂ content.
Top of Atmosphere Net Radiation Budget and Implied Meridional Energy Transport

TOTAL ANNUAL MEAN NET RADIATION AT TOA FOR ISCCP-FC & ERBE (ADJUSTED)

TOTAL NORTHWARD ENERGY TRANSPORT FROM ISCCP-FC, ERBE AND PEIXOTO & OORT

Zhang and Rossow (1997)

J. J. Hack/A. Gettelman: June 2005
Atmospheric General Circulation Models and Climate Simulation

- Three-dimensional, uses topography of land and bathymetry oceans
- Still reduced models of the climate system, apply “averaging operator” to governing equations
- Atmospheric General Circulation Models (AGCMs)
  - simulate detailed “weather” fluctuations in the fluid system
  - day-to-day solution details are non-deterministic (Lorenz, 1962)
  - apply “averaging operator” to detailed solution sequence
  - utility lies in prediction of statistical properties of the fluid system
    - chronological sequence of intermediate states unimportant
Modeling the Atmospheric General Circulation

Some physical components:
- fluid dynamics for the atmosphere
- physics/dynamics of phase change
- radiative transfer (aerosols, chemical constituents, etc.)
- atmospheric chemistry (trace gas sources/sinks, acid rain, etc.)
- interactions between the atmosphere and ocean (e.g., El Nino, etc.)
- impacts of anthropogenic and other biological activity on atmospheric composition.
Meteorological Primitive Equations

Momentum equation (in Lagrangian frame)

\[ \frac{dv}{dt} + 2\Omega \times v = \frac{1}{\rho} \nabla p - gk + D \]

- \( v \) 3-d velocity vector
- \( p \) pressure and \( \rho \) density (also part of thermodynamic equation)
- \( gk \) gravity
- \( \Omega \) coriolis force.
- \( D \) friction/viscosity

\( \nabla \) is gradient vector
Thermodynamic Equation

\[ \rho c_v \frac{dT}{dt} + p \nabla \cdot v = -\nabla \cdot F + \nabla \cdot (k \nabla T) + \rho \dot{q} \]

- \( T \) temperature
- \( c_v \) specific heat constant volume
- \( F \) heat absorbed from radiative effects
- \( k \) Thermal conductivity
- \( \dot{q} \) internal heating rate

Need an additional equation for water vapor to handle \( F \) and \( \dot{q} \).

How many independent variables?

- \( v \) is unconstrained.
- \( T, p, \rho \) are constrained by the gas law (equation of state)
- Rest of quantities can be related to these.
Global Climate Model Physics

Terms D, F, q represent physical processes

- **Equations of motion, D**
  - turbulent transport, generation, and dissipation of momentum

- **Thermodynamic energy equation, F, q**
  - convective-scale transport of heat
  - convective-scale sources/sinks of heat (phase change)
  - radiative sources/sinks of heat

- **Water vapor equation**
  - convective-scale transport of water
  - convective-scale water sources/sinks (phase change)
Scales of Atmospheric Motions

Anthes et al. (1975)
Parametrizations

Representations of physical processes that occur on scales below the numerical truncation limit. To close the governing equations, it is necessary to incorporate these effects

Some important physical processes:

• Moist Processes
  – Moist convection, shallow convection, large scale condensation

• Radiation and Clouds
  – Cloud parameterization, radiation

• Surface Fluxes
  – Fluxes from land, ocean and sea ice (from data or models)

• Turbulent mixing
  – Planetary boundary layer parameterization, vertical diffusion, gravity wave drag
Coupled Models = Increased Technical Complexity

Note: Ocean GCM’s are as complex as Atmosphere GCM’s!
How can we evaluate simulation quality?

• Continue to compare long term mean climatology
  – average mass, energy, and momentum balances
  – tells you where the physical approximations take you
    – but you don’t necessarily know how you get there!

• Must also consider dominant modes of variability
  – provides the opportunity to evaluate climate sensitivity
    – response of the climate system to a specific forcing factor
  – evaluate modeled response on a hierarchy of time scales
  – exploit natural forcing factors to test model response
    – diurnal and seasonal cycles
    – El Niño Southern Oscillation (ENSO)
    – intraseasonal variability; e.g., MJO
    – solar variability
    – volcanic aerosol loading
Comparison of Mean Simulation Properties
NCAR Community Earth System Model 1.0

Simulation of current climate -- differences as great as +- 4C.
Simulated transport of heat from equator

Annual Implied Northward Heat Transports
Atmosphere = (TOA Required - Ocean) Heat Transports

Heat Transport (PW)
Latitude

b40.1850.track1.2deg.wcm.007

NCEP Derived
**Observations: 20th Century Warming Model Solutions with Human Forcing**

Simulations for 4th Assessment Report
IPCC:

**Observations**
Model average
Individual runs
(58/14)
Summary

- Global Climate Modeling
  - complex and evolving scientific problem
  - parameterization of physical processes pacing progress
  - observational limitations pacing process understanding

- Parameterization of physical processes
  - opportunities to explore alternative formulations
    - exploit higher-order statistical relationships?
  - exploration of scale interactions using modeling and observation
    - high-resolution process modeling to supplement observations
      - e.g., identify optimal truncation strategies for capturing major scale interactions
    - better characterize statistical relationships between resolved and unresolved scales