The Art and Science of Climate Modeling

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(with sincere thanks to Bill Collins, LBNL)
Outline

- Global Climate Change: A Grand Challenge
- The Complexity of the Climate System
- Physically-Based Climate Modeling
- Quantifying Uncertainty
- The Future of Climate Modeling
Greenhouse Gas Concentrations

Concentrations of Greenhouse Gases from 0 to 2005

- Carbon Dioxide (CO₂)
- Methane (CH₄)
- Nitrous Oxide (N₂O)

Year

0 500 1000 1500 2000

CO₂ (ppm), N₂O (ppb)

250 300 350 400

CH₄ (ppb)

600 800 1000 1200 1400 1600 1800 2000

IPCC 2007
Future greenhouse gas emissions, concentrations and radiative forcing.
Forcing: Changes in Exchange of Energy

Radiative Forcing Components

<table>
<thead>
<tr>
<th>RF Terms</th>
<th>RF values (W m⁻²)</th>
<th>Spatial scale</th>
<th>LOSU</th>
</tr>
</thead>
<tbody>
<tr>
<td>Long-lived greenhouse gases</td>
<td>CO₂</td>
<td>1.66 [1.49 to 1.83]</td>
<td>Global</td>
</tr>
<tr>
<td></td>
<td>N₂O</td>
<td>0.48 [0.43 to 0.53]</td>
<td>Global</td>
</tr>
<tr>
<td></td>
<td>CH₄</td>
<td>0.16 [0.14 to 0.18]</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Halocarbons</td>
<td>0.34 [0.31 to 0.37]</td>
<td></td>
</tr>
<tr>
<td>Ozone</td>
<td>Stratospheric</td>
<td>-0.05 [-0.15 to 0.05]</td>
<td>Continental to global</td>
</tr>
<tr>
<td></td>
<td>Tropospheric</td>
<td>0.35 [0.25 to 0.65]</td>
<td></td>
</tr>
<tr>
<td>Anthropogenic</td>
<td>Stratospheric water vapour from CH₄</td>
<td>0.07 [0.02 to 0.12]</td>
<td>Global</td>
</tr>
<tr>
<td>Surface albedo</td>
<td>Land use</td>
<td>-0.2 [-0.4 to 0.0]</td>
<td>Local to continental</td>
</tr>
<tr>
<td></td>
<td>Black carbon on snow</td>
<td>0.1 [0.0 to 0.2]</td>
<td></td>
</tr>
<tr>
<td>Total Aerosol</td>
<td>Direct effect</td>
<td>-0.5 [-0.9 to -0.1]</td>
<td>Continental to global</td>
</tr>
<tr>
<td></td>
<td>Cloud albedo effect</td>
<td>-0.7 [-1.8 to -0.3]</td>
<td></td>
</tr>
<tr>
<td>Linear contrails</td>
<td></td>
<td>0.01 [0.003 to 0.03]</td>
<td>Continental</td>
</tr>
<tr>
<td>Natural</td>
<td>Solar irradiance</td>
<td>0.12 [0.06 to 0.30]</td>
<td>Global</td>
</tr>
</tbody>
</table>

Total net anthropogenic                |                   | 1.6 [0.6 to 2.4] |        |        |
Projections of Global Change

![Graph showing projections of global warming](image-url)

- A2
- A1B
- B1
- Constant composition commitment
- 20th century

Global surface warming (°C)

Year

GCEP

IPCC, 2007
Impacts on Water Resources: Snow Water

Ghan & Shippert, 2007
Changes in Sea Ice Coverage

GCEP

Meehl et al, 2005

September Arctic sea ice extent (credit: NSIDC)
Projections for Global Sea Level Rise

![Graph showing projected sea level rise from 2100 to 2300. The graph plots thermal expansion (m) on the y-axis against year on the x-axis. Different lines represent varying scenarios or data sets, with projections increasing over time.]

IPCC, 2007
Melting of Greenland

Year 0
Volume 100%

Year 270
Volume 80%

Year 710
Volume 60%

Year 1130
Volume 40%

Year 1760
Volume 20%

Bedrock altitude (m)

Ice thickness (m)

Ridley et al., 2005
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Exchange of Energy in the Climate System

Kiehl & Trenberth, 1997
Components of the Climate System

Changes in the Atmosphere: Composition, Circulation
- $N_2$, $O_2$, $Ar$, $H_2O$, $CO_2$, $CH_4$, $N_2O$, $O_3$, etc.
- Aerosols
- Volcanic Activity
- Atmosphere-Biosphere Interaction
- Land-Atmosphere Interaction

Changes in the Hydrological Cycle
- Clouds

Changes in the Cryosphere:
- Snow, Frozen Ground, Sea Ice, Ice Sheets, Glaciers

Changes in/on the Land Surface:
- Orography, Land Use, Vegetation, Ecosystems

Changes in the Ocean:
- Circulation, Sea Level, Biogeochemistry

Ice-Ocean Coupling

Heat Exchange

Wind Stress

Precipitation, Evaporation

Atmosphere

Terrestrial Radiation

Human Influences

Glacier

Landsurface

Soil-Biosphere Interaction

Biosphere

Ice Sheet

Pacific Northwest
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IPCC, 2007
Aerosol Processes

- condensation
- evaporation
- surface chemistry
- coagulation
- water uptake
- oxidation
- precursor emissions
- activation
- diffusion
- subcloud scavenging
- scavenging
- new particle formation
- aqueous chemistry
- evaporation
- dry deposition
- primary emissions
Aerosol Radiative Forcing Mechanisms
Earth System Interactions

Atmosphere

H₂O, CO₂, CH₄, O₃, clouds, aerosol (S, N, BC, OC, Fe, NaCl)

Sea Ice
H₂O

Ocean
H₂O, CO₂, OC, S, N, NaCl, Fe

Land
H₂O, OC, N

Heat, H₂O, BC

Heat, H₂O, CO₂, S, VOC, OC, N, Fe, NaCl

Heat, H₂O, CO₂, CH₄, VOC, BC, OC, N, Fe

Heat, H₂O, BC

H₂O, OC, N

H₂O
Characteristic time scales in the Earth system

**Atmospheric composition**
- Mixing of GHGs in global atmosphere (2 to 4 years)
- Time for 50% of a CO₂ pulse to disappear (50 to 200 years) - WGI:3,4
- Time for 50% of a CH₄ pulse to disappear (8 to 12 years) - WGI:4

**Climate system**
- Air temperature to respond to CO₂ rise (120 to 150 years) - WGI:9
- Transport of heat and CO₂ to the deep ocean (100 to 200 years) - WGI:9,11
- (Up to 10 000 years) Sea level to respond to temperature change - WGI:9,11
- (Up to 10 000 years) Ice caps to respond to temperature change - WGI:11

**Ecological system**
- Acclimation of plants to high CO₂ (1 to 100 years) - WGI:3
- Life of plants (1 to 1000 years) - WGI:3, WGI:5
- Decay of plant material (0.5 to 500 years) - WGI:3

**Socio-economic system**
- Change in energy end-use technologies (1 to 10) - WGI:3,5,9
- Change energy-supply technologies (10 to 50) - WGI:3,5,9
- Infrastructure (30 to 100) - WGI:3,5,9
- Social norms and governance (30 to 100) - WGI:3,5,9

**Years**
- 0
- 200
- 400
- 600
- 800
- 1000
- 1200

SYR - FIGURE 5-1
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Brief History of Climate Modeling

- **1922: Lewis Fry Richardson**
  - Basic equations and methodology of numerical weather prediction

- **1950: Charney, Fjørtoft and von Neumann (1950)**
  - First numerical weather forecast (barotropic vorticity equation model)

- **1956: Norman Phillips**
  - 1st general circulation experiment (two-layer, quasi-geostrophic hemispheric model)

- **1963: Smagorinsky, Manabe and collaborators at GFDL, USA**
  - Nine level primitive equation model

- **1960s and 1970s: Other groups and their offshoots began work**
  - University of California Los Angeles (UCLA), National Center for Atmospheric Research (NCAR, Boulder, Colorado) and UK Meteorological Office

- **1990s: Atmospheric Model Intercomparison Project (AMIP)**
  - Results from about 30 atmospheric models from around the world

- **2001: IPCC Third Assessment Report**
  - Climate projections to 2100 from 9 coupled ocean-atmosphere-cryosphere models.

- **2007: IPCC Fourth Assessment Report**
  - Climate projections to 2100+ from 23 coupled ocean-atmosphere-cryosphere models.
Richardson’s Vision of a Climate Model

“Myriad computers are at work upon the weather of the part of the map where each sits, but each computer attends only to one equation or part of an equation. The work of each region is coordinated by an official of higher rank. Numerous little 'night signs' display the instantaneous values so that neighboring computers can read them. Each number is thus displayed in three adjacent zones so as to maintain communication to North and South of the map…”

Lewis Fry Richardson
Weather Prediction by Numerical Process (1922)
Basic Conservation Equations for the Atmosphere

- **Momentum:**
  \[
  \frac{d\mathbf{V}}{dt} = -\alpha \nabla p - 2\Omega \times \mathbf{V} - g \mathbf{k} + F + D_m
  \]
  - where \(\alpha = 1/\rho\) (\(\rho\) is density), \(p\) is pressure, \(\Omega\) is rotation rate of the Earth, \(g\) is acceleration due to gravity (including effects of rotation), \(\mathbf{k}\) is a unit vector in the vertical, \(F\) is friction and \(D_m\) is vertical diffusion of momentum

- **Heat:**
  \[
  \frac{dT}{dt} = Q/c_p + (RT/p)\omega + D_H
  \]
  - where \(c_p\) is the specific heat at constant pressure, \(R\) is the gas constant, \(\omega\) is the vertical velocity, \(D_H\) is the vertical diffusion of heat and \(Q\) is the internal heating from radiation and condensation/evaporation; \(Q = Q_{rad} + Q_{con}\)

- **Mass (water vapor or other tracers):**
  \[
  \frac{dq}{dt} = E - C + D_q
  \]
  - where \(E\) is the evaporation, \(C\) is the condensation and \(D_q\) is the vertical diffusion of moisture
Vertical Discretization of Equations

Vertical Grid for Atmosphere
Horizontal Discretization of Equations

T31  
T42  
T85  
T170
Physical Parameterizations

- Processes that are not explicitly resolved by the basic conservation equations on the grid of the model need to be represented by *parameterizations*.

- There are three types of parameterizations:
  1. Subgrid transport of momentum, heat, moisture and other constituents by convective clouds, turbulence, gravity waves, and precipitation
  2. Processes that contribute to internal (diabatic) heating
     - Radiative transfer
     - Condensation and evaporation
  3. Processes that involve variables additional to the basic atmospheric variables (e.g. land surface processes, carbon cycle, chemistry, aerosols, etc)
Art and Science

- Ideally all physical processes are represented with a strong physical basis, such as conservation of mass and energy.
- Much of the physics and chemistry of the climate is understood at the microscale, but the coarse resolution of global models introduces errors that must be addressed.
- Treatments of subgrid variability of processes can be introduced, but it is an art.
- Some of the physics and chemistry is not understood, so that some microscale empiricism is also necessary.
- In the end uncertain parameters are adjusted to improve the climate simulation.
- This tuning process requires great physical intuition.
- Automation of the tuning process is attractive but challenging.
From Laboratory Studies to Global Modeling

Integrated Assessment Models

Global Climate Models

Global Atmosphere Models

Regional Atmosphere Models

Cloud Property and Process Models

Aerosol Property and Process Models

Lab Experiments

Field Studies

Ocean, Land, Sea ice Models

Field Studies

anthropogenic emissions

biogenic emissions

modules

modules

modules

modules

data

data

data
The current version includes:

- **Biogeophysics**
- **Hydrology**
- **River routing**

The next version will include:

- **Natural and human-mediated changes in land cover**
- **Natural and human-mediated changes in ecosystem functions**
- **Coupling to biogeogeochemistry**

**Processes Included in the CCSM Land Model**

- **Biogeophysics**
- **Hydrology**

Diagram showing processes such as Carbon Dioxide Storage, Radiative Fluxes, Photosynthesis, and Water Cycle components.
Subgrid Structure of the Land Model

Gridcell

Landunits
- Glacier
- Wetland
- Vegetated
- Lake
- Urban

Columns

PFTs

Soil Type 1
Configuration of NCAR CCSM3
(Community Climate System Model)

Atmosphere
(CAM 3.0)
T85 (1.4°)

Land
(CLM2.2)
T85 (1.4°)

Coupler
(CPL 6)

Ocean
(POP 1.4.3)
(×1°)

Sea Ice
(CSIM 4)
(×1°)
The Development of Climate models, Past, Present and Future

- Mid-1970s: Atmosphere, Land surface, Ocean & sea-ice model
- Mid-1980s: Atmosphere, Land surface, Ocean & sea-ice model
- Early 1990s: Atmosphere, Land surface, Ocean & sea-ice, Sulphur cycle model
- Late 1990s: Atmosphere, Land surface, Ocean & sea-ice, Sulphate aerosol, Non-sulphate aerosol, Carbon cycle model
- Present day: Atmosphere, Land surface, Ocean & sea-ice, Sulphate aerosol, Non-sulphate aerosol, Carbon cycle model, Dynamic vegetation, Atmospheric chemistry
- Early 2000s?: Atmosphere, Land surface, Ocean & sea-ice, Sulphate aerosol, Non-sulphate aerosol, Carbon cycle model, Dynamic vegetation, Atmospheric chemistry
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Why are there multiple Climate Models?

▶ Ongoing research on processes:
  - The carbon cycle
  - Interactions of aerosols and clouds
  - Interactions of climate and vegetation

▶ No “1st principles” theories (yet) for:
  - Physics of cloud formation
  - Physics of atmospheric convection

▶ Inadequate data to constrain models
“Products” of Global Climate Models

► **Description of the physical climate:**
  - Temperature
  - Water in solid, liquid, and vapor form
  - Pressure
  - Winds and currents

► **Description of the chemical climate:**
  - ozone
  - aerosols and precursor gases
  - carbon dioxide and other GHGs

► **Space and time resolution (CCSM3):**
  - 1.3 degree atmosphere/land, 1 degree ocean/ice
  - Time scales: hours to centuries
Simulation of Sea-Surface Temperature

CCSM3
Sea surface temperature
mean = 19.83

ANN
Min = -3.34 Max = 29.54

HadISST
Sea surface temperature
mean = 17.08

Min = 0.00 Max = 29.56

CCSM3 - HadISST
mean = 0.03
rmse = 1.53

Min = -9.26 Max = 13.47
Simulation of Annual Mean Precipitation

observed

multimodel mean simulated
Koppen Classification of Climate
Aerosol Optical Depth

MAM3

MODIS

MAM7

MISR

GCEP
Global Metrics of Performance

ANN: SPACE-TIME

Reference Grids Used

- / + Bias
\(\nabla\)  >20%
\(\nabla\)  10-20%
\(\nabla\)  5-10%
\(\nabla\)  1-5%
○  <1%

RMSE Bias
1.000  1.000
1.133  1.523
1.157  1.609

Correlation

Standardized Deviations (Normalized)

0.0 - Sea Level Pressure (ERA40)
1 - SW Cloud Forcing (CERES2)
2 - LW Cloud Forcing (CERES2)
3 - Land Rainfall (30N-30S, GPCP)
4 - Ocean Rainfall (30N-30S, GPCP)
5 - Land 2-m Temperature (Willmott)
6 - Pacific Surface Stress (5N-5S,ERS)
7 - Zonal Wind (300mb, ERA40)
8 - Relative Humidity (ERA40)
9 - Temperature (ERA40)
The 20th Century Test: Global Mean Surface Air Temperature
Climate Feedback Mechanisms

Bony et al., 2006
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In the past, we have generally used offline models to predict concentrations and read these into CCSM.

This approach is simple to implement, but

– It cuts the feedback loops.
– It eliminates the chemical reservoirs.

The next CCSM will include these interactions.
CCSM4: a 1st generation Earth System Model

Coupler

Land

Atmosphere

Ocean

Sea Ice

C/N Cycle Dyn. Veg. Land Use Ice Sheets

Gas chem.

Prognostic Aerosols

Upper Atm.

Ecosystem & BGC

Climate Forcings (W/m²): 1850-2000

Fig. 1. Estimated climate forcings; error bars are partly subjective 1σ uncertainties.
Flux of CO$_2$ into the world oceans

(Ocean ecosystem model)
Downscaling Climate Change

- **Current global models cannot provide climate at the resolution needed for impact assessment.**

- Three downscaling methods are available:
  - Statistical
  - Dynamical
  - Subgrid physics

Qian et al., 2009
Global Cloud Resolving Models
Earth – Human Interactions

Humans
energy use, water use, agriculture, livestock, forestry

Atmosphere
CO₂, CH₄, S, CO, VOC, OC, BC, NOₓ, Fe
heat, H₂O

Surface
H₂O, N
H₂O
heat, H₂O, CO₂, CH₄, VOC, BC, OC, N, Fe, NaCl
Balancing Demands on Resources

**New Science**

- ESM+multiscale GCRM
- Code Rewrite

**Better Science**

- Earth System Model
- Climate Model

**Resolution**

- 1Km
- AMR
- Regular

**Ensemble size**

- 1000
- 10

**Timescale**

- (Years*timestep)
- 2005
- Terascale
- 5
- 50
- 500
- Petascale
- 1.4°
- 160km
- 0.2°
- 22km
- 14°
- Earth System Model

**Data Assimilation**

- ES+multiscale GCRM

**Cost Multiplier**

- 10
- 10
- 10
- 10
- 10
- 10
- 10

**Exascale**

- 2015
- 2010

**Lawrence Buja (NCAR)**
Conclusions

Modern climate models can be applied to:
- Studying the integrated climate system
- Modeling climates of the past
- Projecting future climate change and its impact

Challenges ahead for modelers:
- Process-oriented modeling of the climate
- Coupled chemistry/climate modeling

Challenges ahead for the community:
- Better linkages between modelers, health specialists, & policy makers
- Better modeling of chemical and biological climate change