Review of Climate Models

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Outline

- Climate System
- Modelling Concepts
- Model Evaluation
- Climate change simulations
- Regional Climate Models
- Hydrological models
- Global Framework for Climate Services
The Climate System

Atmosphere

- Evaporation
- Precipitation

Biosphere

- Run-off
- Soil Moisture

Oceans

- Sea Ice
Key questions about the climate system and its relation to human kind

What changes have occurred?
Observations:
- temperatures
- precipitation

How well are the past and present climates understood?

What changes could lie ahead?
Simulations:
- natural variation
- forcing agents
The Greenhouse effect

1 Solar radiation passes through the clear atmosphere.
   Incoming solar radiation: 343 Watt per m²

2 Net incoming solar radiation:
   240 Watt per m²

3 Some solar radiation is reflected by the atmosphere
   and earth’s surface
   Outgoing solar radiation:
   103 Watt per m²

5 Some of the infrared radiation is absorbed and re-emitted by the
   greenhouse gas molecules. The direct effect is the warming of the
   earth’s surface and the troposphere.
   Surface gains more heat and infrared radiation is emitted again

4 Solar energy is absorbed by the earth’s surface and warms it...
   168 Watt per m²

6 Some of the infrared radiation passes through the atmosphere
   and is lost in space
   Net outgoing infrared radiation:
   240 Watt per m²

Sources: Okanagan university college in Canada, Department of geography, University of Oxford, school of geography; United States Environmental Protection Agency (EPA), Washington; Climate change 1995, The science of climate change, contribution of working group 1 to the second assessment report of the intergovernmental panel on climate change, UNEP and WMO, Cambridge university press, 1996.
The World in Global Climate Models

Source: IPCC AR4 (WG1)
Atmosphere/Ocean General Circulation Models

• Mathematical models that describe the behaviour of atmospheric and oceanic processes on different space and time-scales. These models are based on physical laws governing the atmospheric/ocean dynamics and the complex interactions involved.

• Powerful and physically based tools for understanding and predicting the weather and climate on different space and time scales. These models simulate the complex nature of the 4-dimensional evolution (3-D space and time) of winds, pressure, temperature, humidity, rainfall, clouds, soil-moisture, snow, ocean temperature, ocean currents, sea-level height, salinity etc.

• Physical processes of convection, radiative transfer, planetary boundary layer and surface hydrological processes, horizontal and vertical mixing etc are described in the GCM by parameterization schemes.
Oceans -- Soil -- Cyosphere -- Biosphere

Numerical Models - Atmosphere: Physical context

Wind

Temperature

Water Vapor

Radiation

Evaporation

Sensible Heat

Latent Heat

Solar Radiation

Earth Radiation

Pression

Transport

Cooling

Heating

Emission

Absorption

Reflection

Transport

Oceans -- Soil -- Cyosphere -- Biosphere
Numerical Models - Ocean Physical context

Atmosphere

Salinity

Temperature

Density

Currents

EVAPORATION

RAIN

Latent Heat Flux

Sensible Heat

Atmospheric radiation

Solar Radiation

Wind Stress

Transport

Transport

Sensory Heat

Density
Operational organisation

A typical run:

Initial condition $\to$ model $\to$ Boundary condition $\to$ forecast

time $t$ $\to$ time $t+1$
Modelling Global Climate

Vertical exchange between layers of momentum, heat and moisture

Horizontal exchange between columns of momentum, heat and moisture

Vertical exchange between layers of momentum, heat and salts by diffusion, convection and upwelling

Orography, vegetation and surface characteristics included at surface on each grid box
Modelling climate

- Representation at finite resolution and timestep
  - grid point and spectral methods
- Solve (integrate) governing differential equations
- Prognostic variables
  - take information from timestep to timestep
- Other quantities diagnosed – diagnostic variables
- Sub-model coupling or prescribed boundary conditions
## Coupled atmosphere / ocean climate model

### Atmosphere:
- Density
- Motion
- Water

### Ocean:
- Density (inc. Salinity)
- Motion

<table>
<thead>
<tr>
<th></th>
<th>Sea Ice</th>
<th>Land</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ocean: Density (inc. Salinity) Motion</td>
<td></td>
<td></td>
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</tbody>
</table>
An Emerging Seamless Climate Prediction Framework

- **Forecasting Lead Time**
  - Minutes
  - Hours
  - Days
  - 1 Week
  - 2 Weeks
  - Months
  - Seasons
  - Years
  - Decades
  - Centuries

- **Forecast Uncertainty**
  - Scenarios
  - Outlook
  - Predictions
  - Assessments
  - Threats
  - Warnings & Alert Coordination

- **Weather**
- **Climate Variability**
- **Climate Change**
- **Anthropogenic Forcing**

- **Applications**
  - Protection of Life & Property
  - Water Management
  - Space Applications
  - Transportation
  - Fire Weather
  - Hydropower
  - Agriculture
  - Water Resource Planning
  - Recreation
  - Ecosystem
  - Energy
  - Health
  - Commerce
  - State/Local Planning
  - Environment

Adapted from: NOAA
Table 10.4. Summary of climate change model experiments produced with AOGCMs. Numbers in each scenario column indicate how many ensemble members were produced for each model. Coloured fields indicate that some but not necessarily all variables of the specific data type (separated by climate system component and time interval) were available for download at the PCMDI to be used in this report; ISCCP is the International Satellite Cloud Climatology Project. Additional data has been submitted for some models and may subsequently become available. Where different colour shadings are given in the legend, the colour indicates whether data from a single or from multiple ensemble members is available. Details on the scenarios, variables and models can be found at the PCMDI webpage (http://www-pcmdi.llnl.gov/ipcc/about_ipcc.php). Model IDs are the same as in Table 8.1, which provides details of the models.

* Some of the ensemble members using the CCSM3 were run on the Earth Simulator in Japan in collaboration with the Central Research Institute of Electric Power Industry (CRIEPI).
Model Evaluation

- A specific prediction based on a model can often be demonstrated to be right or wrong, but the model itself should always be viewed critically.
- Confidence in a model can be gained through simulations of the historical record, or of palaeoclimate.
- Testing models’ ability to simulate ‘present climate’ (including variability and extremes) is an important part of model evaluation.
Annual Precipitation (cm) 1980-1999
Predicting climate change

EMISSIONS

CONCENTRATIONS
CO₂, methane, etc.

HEATING EFFECT
‘Climate Forcing’.

CLIMATE CHANGE
Temp, rain, sea-level, etc.

IMPACTS
Flooding, food supply, etc.

Scenarios from population, energy, economics models
Carbon cycle and chemistry models
Gas properties
Coupled climate models
Impacts models

Source: MetOffice, UK
Attribution

- Observed changes are
  ☑ consistent with expected responses to natural+human forcings
  ☒ inconsistent with alternative explanations (e.g., natural only)
Figure 10.5. Time series of globally averaged (left) surface warming (surface air temperature change, °C) and (right) precipitation change (%) from the various global coupled models for the scenarios A2 (top), A1B (middle) and B1 (bottom). Numbers in parentheses following the scenario name represent the number of simulations shown. Values are annual means, relative to the 1980 to 1999 average from the corresponding 20th-century simulations, with any linear trends in the corresponding control run simulations removed. A three-point smoothing was applied. Multi-model (ensemble) mean series are marked with black dots. See Table 8.1 for model details.
Figure 11.2. Temperature and precipitation changes over Africa from the MMD-A1B simulations. Top row: Annual mean, DJF and JJA temperature change between 1980 to 1999 and 2080 to 2099, averaged over 21 models. Middle row: same as top, but for fractional change in precipitation. Bottom row: number of models out of 21 that project increases in precipitation.
GCMs to Regional Adaptive Responses: Modelling Path
Limited Area models

For specific domain of interest one can use « Limited Area Model » allowing a finest description of the atmosphere evolution and consequently a forecast at smaller scales (compared to the global one)
Limited Area models

*Limited Area Model*: The LAM must be coupled to a global model which regularly gives boundary conditions to the LAM during the whole integration (e.g. each 6 hours).
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Regional Climate Models (RCMs)

- High resolution, limited area models, driven at boundaries by global model data
- Same physical processes (atmosphere and land) represented in model
- Comprehensive output data set
Why use a Regional Climate Model?

- RCMs (~50 km resolution) add regional detail to global model simulations - both of current climate and future climate change
  - Better representation of islands, coastal areas and complex topography
  - Finer scale appropriate to realistic simulation of mesoscale weather systems
  - More realistic simulation of extreme events (e.g., improved simulation of severe tropical cyclones)
Why Regional Models? …

- GCM's performance in reproducing regional climate detail is rather poor
  - Due to low horizontal resolution, small-scale affects (such as topography) important to local climate could not be poorly represented in the GCM
  - Model deficiencies in the representation of physical and dynamical processes.

- Higher horizontal resolution model may be needed for reproducing regional climate details

- Two main reasons that prevent GCMs from being run at mesoscale resolutions
  - Computing resources.
  - Model physical parameterisation
(a) The real world

(b) The world as represented by models
Regionalization Approaches (Empirical)

- **Empirical approaches**
  - Used to relate large scale predictors to characteristics of small scale climate variables.

- **Semi-empirical approaches**
  - GCMs are used to describe atmospheric response to large scale forcings of relevance to climate change and empirical techniques account for the effect of mesoscale forcings.

- Both these methods suffer from lack of physics and dynamics associated with mesoscale forcings, but they are practical to use because of their computational efficiency.
Regionalization Approaches (Dynamical)

• Dynamical Modeling Approaches
  – Use a Regional Climate Model in which mesoscale forcings are described by increasing the model resolution only over specific areas of interest.
  – This can be accomplished either by employing
    • Variable resolution grids
    • Nested modeling technique
  – Advantage
    • Physically based & hence they can capture the non linearities relating mesoscale processes to the large scale flow
Climate Model Projections

- Starting point for most climate scenarios
- Large-scale response to anthropogenic forcing
- Coupled Atmosphere-Ocean Global Climate Models (AOGCMs)
- High resolution/variable resolution AGCMs
- (High resolution) Regional Climate Models (RCMs)
- Statistical downscaling
- AOGCMs are coarse and may have large biases
- High resolution AGCMs are expensive
- RCMs inherit errors from driving model
- Statistical methods are based on current climate and trained on short-term variability
## Uncertainties in Climate Scenarios

<table>
<thead>
<tr>
<th>Source of Uncertainty</th>
<th>Represented in Climate Scenarios?</th>
<th>Ways to address it</th>
</tr>
</thead>
<tbody>
<tr>
<td>Alternative emission scenarios</td>
<td>Yes</td>
<td>Scale GCM patterns by the ratio of the radiative forcing</td>
</tr>
<tr>
<td>Emissions to concentrations</td>
<td>No</td>
<td>Use GCMs that include interactive chemistry and carbon cycle</td>
</tr>
<tr>
<td>Modelling the climate response</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Different responses by different GCMs</td>
<td>Yes</td>
<td>Use a range of GCMs</td>
</tr>
<tr>
<td>for the same forcing.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Signal (response)/ noise (internal climate variability)</td>
<td>Not normally</td>
<td>Use ensemble simulations</td>
</tr>
<tr>
<td>Providing regional climate scenarios</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Baseline and future climates</td>
<td>Yes</td>
<td>Use observed or model baseline and different methods for changes</td>
</tr>
<tr>
<td>Adding high resolution detail</td>
<td>Yes</td>
<td>Use of a range of dynamical and statistical techniques</td>
</tr>
</tbody>
</table>
Climate Scenarios: Suitability Criteria for Impact Assessment

• Consistency
• Physical plausibility and Realism
• Appropriateness
• Representativeness
• Accessibility
**CLIMATE SCENARIO CONSTRUCTION FOR IMPACT ASSESSMENT**

- **Natural Forcing** (orbital; solar; volcanic)
- **Anthropogenic Forcing** (GHG emissions, land use)

**Data Sources**
- Historical Observations
- GCMs

**Methods**
- Statistical Methods
- Dynamical methods
- Direct GCM or interpolated scenarios

**Scenarios**
- Baseline Climate
- GCM present climate
- GCM future climate
- analogue scenarios
- Incremental Scenarios For sensitivity studies
- Simple Models

**Validation**
- GCM validation
- Pattern Scaling

**Regionalization**
- Global mean annual temperature change

**Impacts**
CCM3-IBIS Structure

Schematic of the Coupled Community Climate Model (CCM3) - Integrated Biosphere Simulator (IBIS).
Terrestrial Hydrology Model with Biogeochemistry (THMB)

Source: EPA & Purdue University
THMB Features

- **Input:**
  - Surface and sub-surface runoff (from observations or model)
  - Surface morphology
- **Simulates (at 10km resolution):**
  - Transport of rivers across land surface to oceans and inland drainage basins.
  - Storage of water in lakes, wetlands, and reservoirs.
  - Transport of solutes in streams (nitrogen)
  - Seasonal inundation of floodplain
Linked to IBIS through shared water budget

IBIS (terrestrial)

Atmosphere
(prescribed atmospheric datasets)

Land Cover
(natural vegetation, human land use)

Surface Morphology
(river flow, potential surface water bodies)

Nitrogen Inputs
(eg. agriculture activity, soil mineralization)

THMB (aquatic)

- Runoff, groundwater
- Evaporation, precipitation
- Nitrate inputs
- Instream removal

Linear Reservoir model

- River discharge
- Surface water (area and volume)
- Nitrate flux
- Nitrate mass

Nitrate leaching

canopy physics
energy balance water balance aerodynamics

soil physics
energy balance water balance

plant physiology
photosynthesis & leaf respiration stomatal conductance

vegetation dynamics
allocation turnover growth of leaves, stems & roots mortality & disturbance

below-ground C and N cycling
decomposition, soil respiration mineralization, denitrification, nitrification
Soil and Water Assessment Tool (SWAT)

- SWAT provides opportunity for scenario generation
- GIS framework: acts as a pre-processor for the distributed modelling and is also a powerful tool for visualization of the outputs/results in terms of V & A
SWAT Model Components

Features

- Physically based
- Distributed model
- Continuous time model (long term yield model)
- Uses readily available data
- Suitable for long term impact studies
World Climate Conference-3

Geneva, Switzerland
31 August–4 September 2009

Better climate information for a better future
Global Framework for Climate Services

Sectoral Users

User Interface Programme

Climate Services Information System

Research & Modeling and Prediction

Observations and Monitoring
Elements of Climate Services Information System

- Global Users
- Regional Users
  - Regional Climate Outlook Forums
- National Sectoral Users
  - National COF
- Regional Climate Centres
- National climate services
- Global climate centres
Concluding Remarks

- Global climate models have been making remarkable progress, but challenges remain; uncertainties inevitable.
- Observed data crucial for evaluating model skills.
- Regional approach in climate model applications provides useful synergy and also facilitates consistency and consensus in understanding future scenarios (e.g., through RCOFs).
- User-targeted climate products essential to ensure their relevance to decision making; scale-relevance and downscaling crucial.
- Global Framework for Climate Services aims to bridge the gap between users and providers of climate information.