GEOG 401
Climate Change
Earth System Models
Milestones in Climate Science

- Fourier describes atmosphere's contribution to planetary temperature
- Tyndall describes CO₂'s blocking of infrared
- Arrhenius calculates warming from doubling of CO₂
- Callendar proposes that warming is occurring
- Water vapor feedback described
- Hulburt calculates 4°C warming from doubling of CO₂ with H₂O feedback, and refutes Angstrom
- CO₂ sources identified. Models describe Earth systems, feedbacks, carbon cycle and climate
- Satellite observation of enhanced greenhouse effect
- Manabe and Wetherald build first model of Earth's entire climate
- Keeling Direct CO₂ measurement
- Warnings by scientific community to policy makers begin.
- Hansen predicts further warming; testifies before congress
- Instrumental temperature record begins
- Greenhouse effect on Venus measured
- *Rate of lunar heat loss measured

Source: All events are from Spencer Weart's The Discovery of Global Warming unless noted otherwise: www.aip.org/history/climate/timeline.htm.
* Pierrehumbert, Principles of Planetary Climate
** Nature, 15 March 2001
Historical Climate Changes

Global Land and Ocean Temperature Anomalies, January-December

1880-2015 Trend
+0.07°C/Decade

Temperature Anomalies

Anomaly (°C)

Anomaly (°F)
Why use a climate model?

• No observations from the future
• No other planet earth to experiment with
• Models help predict future changes
• Models help understand the processes related to change
• Models can be tested by simulating past climate and comparing results with observations
What is a Model (in Science)?

- A simplified representation of a real or hypothetical system
- Visual models: e.g., pictures, diagrams, flow charts, maps
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- Mathematical models:
  - Simple: A graph or equation derived from observations, using statistics
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  Physical models: e.g., scale model of a watershed

  Mathematical models:
   – Simple: A graph or equation derived from observations, using statistics
   – Complex: Computer program incorporating theoretically-based knowledge and/or statistically-based representations; linking together interacting parts of a complex system

![Scatterplot of Weight vs Height](chart.png)
How do climate models differ from each other?

• Different models have a wide range of complexity in terms of:
  – Spatial resolution—horizontal and vertical
  – Time step
  – Domain (global, regional, point)
  – Processes represented interactively vs. prescribed
Model Complexity

- Simplest global climate model (zero-dimensional model):
  \[(1 - a) S \pi r^2 = 4 \pi r^2 \epsilon \sigma T^4\]  
  Radiative equilibrium model

- Increasing complexity (one-dimensional model):
  Radiative-convective model  
  (Manabe and Wetherald, 1967)
Model Complexity

• Higher dimension models
  (intermediate complexity models):
Model Complexity

• General Circulation Models (GCMs)
Climate Model 3-D Spatial Structure

3-D exchanges of heat, moisture, and other atmospheric properties for each grid cell
In the Atmospheric Column
Wind vectors, humidity, clouds, temperature, and height

Vertical exchange between levels

Horizontal exchange between columns

Timestep 30 minutes, grid spacing 3° x 3°

At the surface
Ground temperature, water, and energy fluxes
FAQ 1.2, Figure 1. Schematic view of the components of the climate system, their processes and interactions.
Atmospheric composition and climate model (based on MAGICC 6.0) in IMAGE 3.0

- **Input**
  - NEP (Net Ecosystem Production)
  - CO₂ emission from energy and industry
  - Land-use CO₂ emissions
  - Non-CO₂ GHG emissions (CH₄, N₂O, Halocarbons)
  - CO₂ NAMVC emissions
  - Radiative forcing (RF) factors
- **Output**
  - Ocean carbon uptake
  - CO₂ concentration
  - Non-CO₂ GHG concentrations
- **Flowchart**
  - Ocean carbon model
  - Atmospheric concentration of CO₂
  - Atmospheric concentrations of CH₄, N₂O, O₃ and Halocarbons
  - Concentrations translated into Radiative Forcing
  - Aerosol module, scaling of radiative forcing
  - RF of aerosols
  - RF of CO₂, CH₄, N₂O, O₃ and Halocarbons
  - Upwelling and Diffusion Climate model
  - Geographic pattern scaling
  - Global mean temperature
  - Temperature, precipitation
  - No. of wet days (historical data)
  - Cloudiness (historical data)

Source: PBL, 2014
Figure 1.2. The complexity of climate models has increased over the last few decades. The additional physics incorporated in the models are shown pictorially by the different features of the modelled world.
Need for Super Computers

- Atmospheric and ocean fluid motion can be described by a set of differential equations.
- Equations do not have an analytical solution.
- Can be solved by numerical methods:
  - Derivatives are approximated by differences in values of key variables in adjacent grid boxes.
  - Atmosphere is divided into a 3-D grid system.
  - Calculations must be repeated many times until solution converges.
  - Simple calculations, but MANY of them.
Spatial Resolution

Schematic for Global Atmospheric Model

Horizontal Grid (Latitude-Longitude)

Vertical Grid (Height or Pressure)

http://celebrating200years.noaa.gov/breakthroughs/climate_model/welcome.html
Spatial Resolution

AR5: "70km maximum horizontal resolution; up to 90 layers in the atmosphere and over 60 in the ocean."
Processes

Growth of Climate Modeling

- Atmospheric/Land Surface/Vegetation
- Ocean
- Coupled Climate Model
- Sea Ice
- Sulfate Aerosol
- Interactive Vegetation
- Biogeochemical Cycles
- Carbon Cycle
- Ice Sheet
- Marine Ecosystems
- Upper Atmosphere
- Atmospheric Chemistry
- Dust/Sea Spray/Carbon Aerosols

- 60s
- 70s
- 80s
- 90s
- 00s
- 10s
Earth System Modeling
“geospatially-explicit, process-based, & coupled”

THE DATA MODULES

THE OUTPUT VARIABLES

Political Boundaries
Climate
Infrastructure
Landcover & Biodiversity
Soils
Topography

COMPUTATION ENGINE
THE MODELS AND CALCULATIONS

GHG Emissions
Hydroelectric
Agriculture Productivity
Floods & Droughts
Soil Moisture
What is an Earth System Model?

Climate Model

Atmospheric GCM

Ocean GCM

Land physics and hydrology

Atmospheric circulation and radiation

Chemistry - CO$_2$, NO$_x$, SO$_4$, aerosols, etc

Sea Ice

Ocean ecology & Biogeochemistry

Ocean circulation

Plant ecology & land use

Land physics & hydrology
Parameterization

- **Parameterization**: a simplified representation of a process that is too complex or operating at too small a scale to be represented physically.

- Examples of parameterized processes in climate models:
  - Clouds
  - Precipitation
  - Aerosols
  - Radiation
  - Boundary layer processes
Models and Observations

1. **Importance of observations to models**
   - “Without data, the models are just abstractions.”
   - Model initialization
   - Model optimization (calibration)
   - Model evaluation (validation)
   - Data assimilation

2. **Importance of models to interpreting data**
   - Models allow use of observations in development and refinement of theory

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Conservation of momentum
\[
\frac{\partial \vec{V}}{\partial t} = -(\vec{V} \cdot \nabla) \vec{V} - \frac{1}{\rho} \nabla p - \vec{g} - 2\vec{\Omega} \times \vec{V} + \nabla \cdot (k_m \nabla \vec{V}) - \vec{F}_d
\]

Conservation of energy
\[
\rho c_V \frac{\partial T}{\partial t} = -\rho c_V \vec{V} \cdot \nabla T - \nabla \cdot \vec{R} + \nabla \cdot (k_T \nabla T) + C + S
\]

Conservation of mass
\[
\frac{\partial \rho}{\partial t} = -(\vec{V} \cdot \nabla) \rho - \rho (\nabla \cdot \vec{V})
\]

Conservation of \( H_2O \) (vapor, liquid, solid)
\[
\frac{\partial q}{\partial t} = -(\vec{V} \cdot \nabla) q + \nabla \cdot (k_q \nabla q) + S_q + E
\]

Equation of state
\[
p = \rho R_q T
\]
Optimization

• Many components of large complex models use parameters whose values must be specified by the modeler

• To better constrain parameter values, models can be tested against observations

• The model is “optimized” by adjusting parameter values to obtain model output that best fits observations
Uses of Observed Data in Modeling Context

- Forcing variables
- Characterization (parameter values)
- Optimization variables
  - Calibration
  - Validation
Model Evaluation

FAQ 8.1, Figure 1. Global mean near-surface temperatures over the 20th century from observations (black) and as obtained from 58 simulations produced by 14 different climate models driven by both natural and human-caused factors that influence climate (yellow). The mean of all these runs is also shown (thick red line). Temperature anomalies are shown relative to the 1901 to 1950 mean. Vertical grey lines indicate the timing of major volcanic eruptions. (Figure adapted from Chapter 9, Figure 9.5. Refer to corresponding caption for further details.)
Model Evaluation
Model Evaluation

Figure 8.5. Annual mean precipitation (cm), observed (a) and simulated (b), based on the multi-model mean. The Climate Prediction Center Merged Analysis of Precipitation (CMAP; Xie and Arkin, 1997) observation-based climatology for 1980 to 1999 is shown, and the model results are for the same period in the 20th-century simulations in the MMD at NCAR. In (a), observations were not available for the grey regions. Results for individual models can be seen in Supplementary Material, Figure S3.9.
Figure 1.1. Yearly global average surface temperature (Brohan et al., 2006), relative to the mean 1961 to 1990 values, and as projected in the FAR (IPCC, 1990), SAR (IPCC, 1996) and TAR (IPCC, 2001a). The “best estimate” model projections from the FAR and SAR are in solid lines with their range of estimated projections shown by the shaded areas. The TAR did not have “best estimate” model projections but rather a range of projections. Annual mean observations (Section 3.2) are depicted by black circles and the thick black line shows decadal variations obtained by smoothing the time series using a 13-point filter.
Model Evaluation

Figure 8.11. Normalised RMS error in simulation of climatological patterns of monthly precipitation, mean sea level pressure and surface air temperature. Recent AOGCMs (circa 2005) are compared to their predecessors (circa 2000 and earlier). Models are categorised based on whether or not any flux adjustments were applied. The models are gauged against the following observation-based datasets: Climate Prediction Center Merged Analysis of Precipitation (CMAP; Xie and Arkin, 1997) for precipitation (1980–1999), European Centre for Medium Range Weather Forecasts 40-year reanalysis (ERA40; Uppala et al., 2005) for sea level pressure (1980–1999) and Climatic Research Unit (CRU; Jones et al., 1999) for surface temperature (1961–1990). Before computing the errors, both the observed and simulated fields were mapped to a uniform 4° x 5° latitude-longitude grid. For the earlier generation of models, results are based on the archived output from control runs (specifically, the first 30 years, in the case of temperature, and the first 20 years for the other fields), and for the recent generation models, results are based on the 20th-century simulations with climatological periods selected to correspond with observations. (In both groups of models, results are insensitive to the period selected.)
Model Evaluation

(a) Temperature anomaly (K)

- CMIP3
- CMIP5
- observations

Year

1860 1880 1900 1920 1940 1960 1980 2000
Data Assimilation

The Satellite Data Assimilation System
- Data acquisition
- Built on the EALCO model and the wealth products at CCRS
- Multi-source data integration & assimilation
- High-level products generation
- Ecosystem future scenarios & assessment
Data Assimilation

Sequential, intermittent assimilation

Sequential, continuous assimilation

Non-sequential, intermittent assimilation

Non-sequential, continuous assimilation
Reanalysis Datasets

• Gridded historical climate datasets
• Continuously updated
• Produced by assimilating observations into a numerical weather prediction model
• Examples: NCEP/NCAR, MERRA, ECMWF, JRA-25
Uncertainty

• **Parametric uncertainty** – many processes are “parameterized” based on empirical measurements; “correct” parameter values are often not well known

• **Structural uncertainty** – inadequate (incomplete or incorrect) mathematical representation of processes

• **Residual uncertainty** – arises from uncertainty in external forcing

• **Intrinsic uncertainty** – essential randomness of the system – our inability to fully describe the processes producing variability
Why do we have so many different climate models and climate model runs?

• Different models and multiple model runs allow assessment of uncertainty due to:
  – Model structural differences
  – Selection of parameter values
  – Emissions scenario choice
  – Different initial conditions: internal variability
Ensembles

- Ensembles are sets of model runs
- **Initial condition ensembles** allow quantification of the effects of slight differences in the specification of initial conditions; this is often used as a measure of internal climate variability
- **Perturbed physics ensembles** are produced by systematically changing parameter values across a known range of uncertainty
- **Multi-model ensembles** are runs of the same scenario by different models
Emissions and Concentration Scenarios

• Changes in atmospheric GHG concentrations are driving climate change
• Emissions are driving the GHG concentration changes
• Future emissions depend on a host of socio-economic and technological factors
• Future human behavior is not predictable in a deterministic sense
• Scenarios are developed from “what if?” type questions
• Scenarios are used to explore possible futures
Concentration Approach

- TAR and AR4 model experiments were done using a set of GHG concentration scenarios from the *Special Report on Emission Scenarios* (SRES, IPCC, 2000)
- Approx. 40 SRES scenarios can be divided into four main groups: A1, A2, B1, B2
- A subset of the SRES scenarios was used by each modeling group to simulate future climate
Emissions Approach

- With the advent of Earth System Models, GHG concentrations are interactively calculated in the model.
- With ESMs it is now possible to use emissions scenarios instead of concentration scenarios.
- New approach used for AR5: Representative Concentration Pathways (RCPs).
Representative Concentration Pathways (RCPs)

- Named for the forcing in 2100
- RCP2.6: 2100 forcing = 2.6 W m\(^{-2}\)
- RCP4.5
- RCP6.0
- RCP8.5
Projections of Global Temperature Change

Figure 12.5 | Time series of global annual mean surface air temperature anomalies (relative to 1986–2005) from CMIP5 concentration-driven experiments. Projections are shown for each RCP for the multi-model mean (solid lines) and the 5 to 95% range (±1.64 standard deviation) across the distribution of individual models (shading). Discontinuities at 2100 are due to different numbers of models performing the extension runs beyond the 21st century and have no physical meaning. Only one ensemble member is used from each model and numbers in the figure indicate the number of different models contributing to the different time periods. No ranges are given for the RCP6.0 projections beyond 2100 as only two models are available.
Uncertainty

Box 11.1, Figure 1 | The evolution of observation-based global mean temperature $T$ (the black line) as the difference from the 1986–2005 average together with an ensemble of externally forced simulations to 2005 and projections based on the RCP4.5 scenario thereafter (the yellow lines). The model-based estimate of the externally forced component $T_f$ (the red line) is the average over the ensemble of simulations. To the extent that the red line correctly estimates the forced component, the difference between the black and red lines is the internally generated component $T_i$ for global mean temperature. An ensemble of forecasts of global annual mean temperature, initialized in 1998, is plotted as thin purple lines and their average, the ensemble mean forecast, as the thick green line. The grey areas along the axis indicate the presence of external forcing associated with volcanoes.
Uncertainty