Modeling Uncertainty Project: Full Permutation Experiment with GCAM

Haewon McJeon and the GCAM Team

Snowmass CCIIA
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Agenda

- GCAM: The Global Change Assessment Model
- Model Results
  - Population
  - GDP
  - Energy
  - Carbon Dioxide Emissions
  - Carbon Dioxide Concentration
  - Total Forcing
  - Temperature
- Remarks
GCAM: The Global Change Assessment Model
Integrated Assessment Models (IAMs)

IAMs integrate human and Earth system science.

- IAMs provide insights that would be otherwise unavailable from disciplinary research.
- IAMs capture interactions between complex and highly nonlinear systems.
- IAMs provide Earth system science researchers with information about human systems such as GHG emissions, land use and land cover.

IAMs provide important, science-based decision support tools.

- IAMs support national, international, regional, and private-sector decisions.
GCAM: The Global Change Assessment Model

14 Region Energy/Economy Model Regions
151 Agriculture and Land Use Model Regions

- GCAM is a **global integrated assessment model**
- GCAM links **Economic, Energy, Land-use, and Climate** systems
- Emissions of **16 greenhouse gases and short-lived species**: CO$_2$, CH$_4$, N$_2$O, halocarbons, carbonaceous aerosols, reactive gases, sulfur dioxide.
- Runs through **2095** in 5-year time-steps.
- GCAM is implemented using **object-oriented programming**, providing a robust and flexible platform for future work.
- Documentation available at: [wiki.umd.edu/gcam](http://wiki.umd.edu/gcam)

- Started in 1978 – a DOE-SC investment to address the need for an explicit research tool to assess the link between human energy systems and carbon emissions (part of the Carbon Cycle Program back then).
- 1984 first integration of GCAM (then called Edmonds-Reilly) with the DOE carbon cycle model.
- Formerly known as MiniCAM
Overview of Human Systems in GCAM

Energy System
- Resource Bases
- Energy Conversion Technologies
- Energy Demand Technologies

Energy Supply
- Coal, Gas, Oil
- Renewables
- Electricity
- Hydrogen

Energy Markets
- Fossil fuel prices
- Electricity prices
- Hydrogen prices

Fossil and Industrial Emissions

Other Markets
- Emissions Permits
- Portfolio Standards

Agricultural Markets
- Crops prices
- Livestock prices
- Forest Product prices
- Bioenergy prices

Agricultural Demand
- Crops
- Livestock
- Forest Products

Agricultural Technologies

Agricultural Supply
- Crops
- Livestock
- Forest Products
- Bioenergy

Land Characteristics

Land Use and Land Use Change Emissions

Ocean Carbon Cycle

Atmospheric Composition, Radiative Forcing, & Climate

Terrestrial Carbon Cycle

Regional GDP
- Labor Productivity
- Labor Force

Economy

Ocean Carbon Cycle

Atmospheric Composition, Radiative Forcing, & Climate

Terrestrial Carbon Cycle

Climate System
Uncertainty Research with GCAM
Uncertainty Analysis of the IEA/ORAU CO$_2$ Emissions Model (Reilly et al. 1987)

Table 2. Assumed Correlations

<table>
<thead>
<tr>
<th>Variables: Energy/CNP feedback elasticity OECD, non-OECD, Middle East</th>
<th>Parameter</th>
<th>Correlation</th>
<th>Explanation</th>
<th>Justification</th>
</tr>
</thead>
<tbody>
<tr>
<td>regional E/CNP feedback elasticity</td>
<td>5.4</td>
<td>0.8</td>
<td>Regional</td>
<td>Similar transmission mechanisms, but magnitude of response is uncertain.</td>
</tr>
<tr>
<td>Income Elasticity: OECD, USSR, and LDCs</td>
<td>7.8</td>
<td>0.9</td>
<td>Regional income elasticities</td>
<td>Similar transmission mechanism. Middle East may be less similar due to dominance of oil production in the economy.</td>
</tr>
<tr>
<td>Labor Productivity: EDC's, DC's</td>
<td>31.32</td>
<td>0.9</td>
<td>Regional productivity</td>
<td>Engine of growth hypothesis; growth linked via capital, knowledge flows.</td>
</tr>
<tr>
<td>Exogenous energy efficiency, labor productivity in developed region</td>
<td>12.33</td>
<td>0.9</td>
<td>Labor and energy productivity</td>
<td>Increase in basic knowledge is the driving force and affects all factors equally.</td>
</tr>
<tr>
<td>Labor productivity in developed regions, with technological change in coal supply; technological change in shale oil supply, and technological change in nuclear power</td>
<td>31.69</td>
<td>0.6</td>
<td>Labor productivity and technological change in energy production</td>
<td>Increase in basic knowledge is the driving force and affects labor productivity and energy production technologies similarly.</td>
</tr>
<tr>
<td>Labor productivity with environmental cost of shale oil production and environmental cost of nuclear power</td>
<td>31.73</td>
<td>0.9</td>
<td>Labor productivity and environmental costs</td>
<td>Higher income capita, implies higher demands for clean environment.</td>
</tr>
</tbody>
</table>

Figure 1. Plot of carbon emission percentiles based on 400 runs.
Uncertainty in integrated assessment models: modeling with MiniCAM 1.0 (Scott et al. 1999)

Global Mean Surface Temperature

Research on Technology Uncertainty

2005-2095 Cumulative Primary Energy Consumption (Thousand EJ of Fossil Energy Equivalent)

2005-2095 NPV of Stabilization Cost (2005 Constant Trillions of Dollars)
Global Biomass Primary Energy Consumption By Concentration Target
No CCS

- 60-70th Percentile
- 55-60th Percentile
- 50th-55th Percentile
- 45th-50th Percentile
- 40-45th Percentile
- 30-40th Percentile
- 95th % Unconstrained
- 50th % Unconstrained
- 5th % Unconstrained
Global Biomass Primary Energy Consumption By Concentration Target
No CCS

EJ

2005 2010 2015 2020 2025 2030 2035 2040 2045 2050 2055 2060 2065 2070 2075 2080 2085 2090 2095

60-70th Percentile
55-60th Percentile
50th-55th Percentile
45th-50th Percentile
40-45th Percentile
30-40th Percentile

95th %
50th %
5th %

60-70th Percentile
55-60th Percentile
50th-55th Percentile
45th-50th Percentile
40-45th Percentile
30-40th Percentile

95th % Unconstrained
50th % Unconstrained
5th % Unconstrained

60-70th Percentile
55-60th Percentile
50th-55th Percentile
45th-50th Percentile
40-45th Percentile
30-40th Percentile

95th % 450
50th % 450
5th % 450

300
250
200
150
100
50
0
Research on Regional Building Energy Use Uncertainty
Model Results
World population (million)

- How wide is the uncertainty range of the future population?

- Benefits and costs of heavy focus on the tails.
  - Broader coverage. Avoid unexpected surprise.
  - Loss of statistical power.

- Considering small number of samples, better to narrow the focus range?
Gross world product

- Population variance and productivity variance are identical by design.
- Covariance between age structure and productivity will be a complicated issue.
Total final energy consumption (EJ)

Population variance - Large constant
Productivity variance - Small diminishing
Total final energy consumption

- Population variance has larger impact than productivity variance by model construction.
  - Subsistence level energy consumption.
  - Energy consumption satiation.

- Primary energy (fossil equivalent) may be a better measure for overall scale of energy system.
Total CO2 emissions (GtCO2)
Total CO2 emissions (GtCO2)
Carbon Price has disproportionate impact by design.

Recommend adding more carbon price paths for mapping out the mitigation space.
- At least two price paths to get curvature.
- More for assessing threshold effects.

The dual problems of climate change mitigation:
- How much can be mitigated at a given price? – current approach
- How much does it cost to mitigate a given quantity? – RCP approach
2050 Atmospheric concentrations CO2 (ppm)

- **Productivity variance**: Small
- **Population Variance**: Large
- **Carbon Price Impact**: Medium

<table>
<thead>
<tr>
<th>TFP1</th>
<th>TFP2</th>
<th>TFP3</th>
<th>TFP4</th>
<th>TFP5</th>
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- **POP1**
- **POP2**
- **POP3**
- **POP4**
- **POP5**
2050 Total Radiative Forcing (Wm\(^{-2}\))

- Productivity variance - Small
- Population Variance - Large
- Carbon Price Impact - Medium

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- carbon tax
2010 Total Radiative Forcing (Wm\(^{-2}\))

- **TFP1**
- **TFP2**
- **TFP3**
- **TFP4**
- **TFP5**

**POP1**
**POP2**
**POP3**
**POP4**
**POP5**

- no policy
- carbon tax
2030 Total Radiative Forcing (Wm\(^{-2}\))

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- **TFP1**, **TFP2**, **TFP3**, **TFP4**, **TFP5**
- **POP1**, **POP2**, **POP3**, **POP4**, **POP5**

- **0**, **2**, **4**, **6**, **8**, **10**, **12**
2040 Total Radiative Forcing (Wm$^{-2}$)

- **TFP1**
- **TFP2**
- **TFP3**
- **TFP4**
- **TFP5**

- **no policy**
- **carbon tax**

- **POP1**
- **POP2**
- **POP3**
- **POP4**
- **POP5**
2080 Total Radiative Forcing (Wm$^{-2}$)

The diagram shows the total radiative forcing in 2080 for different TFP scenarios under no policy and carbon tax conditions. Each scenario is represented by different markers:

- **TFP1** (diamonds)
- **TFP2** (squares)
- **TFP3** (triangles)
- **TFP4** (crosses)
- **TFP5** (pluses)

The forcing values are indicated on the y-axis, ranging from 0 to 12 Wm$^{-2}$, with markers placed at intervals of 2 Wm$^{-2}$.

- **No policy**
- **Carbon tax**

The diagram compares the radiative forcing for each TFP scenario under both policy conditions.
- Uncertainty exacerbates over time.
- Stock accumulation effect.
**2050 Temperature TSC = 3.0 (deg C)**

- **Productivity variance - Small**
- **Population Variance - Large**
- **Carbon Price Impact - Medium**

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* TSC: Temperature Sensitivity Coefficient
2100 Temperature TSC = 3.0 (deg C)
2100 Temperature TSC = 6.0 (deg C)

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- POP1
- POP2
- POP3
- POP4
- POP5
2100 Temperature TSC = 4.5 (deg C)
2100 Temperature TSC = 3.0 (deg C)
2100 Temperature TSC = 1.5 (deg C)
2100 Temperature TSC = 0.5 (deg C)
Temperature (deg C)

To be focusing on extreme TSC, or not to be…
Mitigation costs (trillions, 2005$)

- Productivity variance - Small
- Population Variance - Large

- TFP1
- TFP2
- TFP3
- TFP4
- TFP5

- POP1
- POP2
- POP3
- POP4
- POP5

Increasing Difference w.r.t. Time
Remarks

- Second trial of MUP model sensitivity analysis.
- Population has larger variance than productivity.
  - Subsistence level energy consumption.
  - Energy consumption satiation.
- Carbon Price is treated differently, but shows large impact.
- Uncertainty tend to exacerbate over time. Multi-level stock accumulation effect.
- Limits to scenario growth:
  - More focus on extremes for scholarly interest,
  - Or more focus on the “probable” region?
  - Other efficient sampling method?
- Other uncertain variables:
  - Natural Gas and other fossil fuel resources.
  - Technology: TEaM project
  - Behavior: ADVANCE
The End