The integrated Earth System Model (iESM)

WILLIAM COLLINS

WITH JAE EDMONDS, PETER THORNTON, ALLISON THOMSON, AND THE IESM TEAM

Lawrence Berkeley National Laboratory
Oak Ridge National Laboratory
Pacific Northwest National Laboratory – Joint Global Change Research Institute
University of Maryland
Science gaps in current paradigm

- In the present world, emissions mitigation analysis is undertaken under the assumption that **the climate is not changing**.

- Climate impacts analysis is undertaken with the assumption that **no resources are being diverted to address climate change**.

- Changes in response of the coupled climate-energy-land model are significantly different than in the un-coupled models.

- Tighter integration of IAMs and ESMs could provide **fully consistent analysis** of potential future climate change, emissions mitigation options, and impacts and adaptation options will be possible.
Motivation for integrating IAMs and ESMs

- **Opportunities:** Build unified framework for water/energy/climate
- **Possible solution:** Unite IA and climate in single framework
- **Potential upsides:** Quick “look-see”, inclusion of feedbacks, and stronger IA foundations
- **Prototype:** Initial release of an iESM built on CESM
Three major objectives of iESM project

- Create a first generation integrated Earth System Model (iESM) with both the human components of an IAM and a physical ESM.

- Develop linkages within the iESM and apply the model to improve our knowledge of coupled physical, ecological, and human system.

- Add hydrology and water demand, allocation, and availability to IA.
Foundations for iESM are:
- Global Change Assessment Model (GCAM): RCP 4.5
- Global Land Model (GLM): Land-use in AR5
- Community Earth System Model (CESM): IPCC simulations
Multi-phase coupling of IAMs and ESMs / EMICs

CMIP5
Feedback coupling of IAMs and ESMs / EMICs?

CMIP5

IAM → RCP Handshake → ESMs / EMICs

C stocks, productivity

Climate

Up/down scaling (space and time)

Atm CO₂

CMIP6 ?
iESM links 4 models: GCAM, GLM, CLM, & CESM

1. GCAM (Human Dimensions Elements only; 15 ghgs, aerosols, SLS; 14 geopolitical regions; 151 Ecoregions)

2. GLM (\(\frac{1}{2} \times \frac{1}{2}\) degree grid land-use-land-cover.)

Fossil Fuel & Industrial Emissions (Gridded)

ESM1 (3. CLM & 4. CESM)
Transition to fully coupled implementation

“Sneaker Net” Version

Issues:

• Diversity of languages

• Large amount of effort to conduct this relay race

• Human effort scales directly with coupling frequency.

Automated and Integrated Version

Advantages:

• Unified Implementations

• Long-time integrations handled by CESM system.

• Researcher’s time freed for devising new experiments.
GCAM RCP 4.5 Characteristics

- **Regional Details:**
  - **Regional Scope:** Global
  - **Number of Sub-Regions:** 14

- **Time Step:** 15 years

- **Time Frame:** 1990 to 2095

- **Model Type:** Dynamic Recursive

- **Equilibrium Type:** Market Equilibrium

- **Underlying Computing Framework:** Object Oriented (C++)
New treatment of Agriculture and Land Use

The GCAM 3.0 Agriculture and Land Use Regions

151 Different AgLU Supply Regions
A variable time-step version of GCAM

- From 15 year interval to 5 year interval

CCSM/CLM  

GCAM

Nuclear Energy: Total and Additional Generation

- 15 yrs - Nuclear Total
- 15 yrs - Nuclear New
- 5 yrs - Nuclear Total
- 5 yrs - Nuclear New

EJ

2005 2020 2035 2050 2065 2080 2095
Downscaling via the Global Land Model

**LAND-USE HISTORY**
- Agriculture
- Wood harvest
- Transitions
- Gridded
  - 1500-2005

**IAMs/RCPs FUTURE**
- Population
- Socioeconomic
- Energy
- Land-use
  - Gridded/Regional
  - 2005-2100

**LAND-USE HARMONIZATION**
- Consistency
- Integration
- Gridding
  - 1500-2100

**ESMs**
- Climate
- C Stocks/Fluxes
- Biophysical effects
Coupling of IAMs to ESMs and EMICs: *Example: land-use / land-cover change*
Current iESM Coupling Implementation

- **CCSM**
  - **ATM** (Atmosphere)
  - **LND** (Land)
  - **OCN** (Ocean)
  - **ICE** (Sea Ice)

- **Component Models**
  - **CAM**
  - **CLM**
  - **IAC** (giac, diac, siac)
  - **POP**
  - **CICE**

- **Driver Models**
  - **GCAM** (or other IAM)
  - **GLM** (Downscaling)

**Status:**
- iESM code is written.
- iESM code is running at multiple DOE computing centers.
- Validation against conventional uncoupled RCP integrations is underway.
The iESM Coupling Diagram

<table>
<thead>
<tr>
<th>Coupler</th>
<th>Input</th>
<th>Output</th>
<th>Status</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>IAM</td>
<td>Downscaling</td>
<td>Running</td>
</tr>
<tr>
<td>2</td>
<td>Downscaling</td>
<td>Land Model</td>
<td>Running</td>
</tr>
<tr>
<td>3</td>
<td>Land Model</td>
<td>IAM</td>
<td>Running</td>
</tr>
<tr>
<td>4</td>
<td>IAM</td>
<td>Land Model</td>
<td>Coded</td>
</tr>
<tr>
<td>5</td>
<td>Downscaling</td>
<td>IAM</td>
<td>Coded</td>
</tr>
<tr>
<td>6</td>
<td>Land Model</td>
<td>Downscaling</td>
<td>Coded</td>
</tr>
</tbody>
</table>
The iESM Information Exchange

- **IAM** (currently GCAM)
  - Crop
  - Pasture
  - Other
  - Wood harvest
  - Forest

- **GLM** (Downscaling)
  - Crop
  - Pasture
  - Natural Vegetation
  - Wood harvest
  - Primary Land
  - Secondary Land
  - Wood harvest

- **CLM** (Land Model)
  - PFT
  - Wood harvest
  - Grazing

- **GCAM2GLM**
  - NPP & HR by CLM PFT
  - NPP & HR by GCAM Crop

- **GLM2IAC**
  - NPP & HR by CLM PFT
**Status:**
- We emulate sneaker-net using 15-year timesteps.
Proof of principle tests of iESM

RCP scenarios have significant LULCC.

We can now reproduce this LULCC in iESM.

LULCC: Land Use and Land Cover change.
Emulation of pasture distributions using iESM

**Status:**
- We can reproduce the distributions of pasture to 1 part in 100,000.
Experiment 0 work flow

GLM

Transition matrix

CLM translator

dynpft file

Historical LULCC information

GCAM scenario LULCC information

RCP 4.5 Land Use

CLM / CCSM

Climate change

Carbon stocks

Carbon fluxes and [CO₂]
Experiment 1:
Simplest possible feedback from CESM to GCAM

- Send maps of carbon density, by plant type, from CLM to GCAM.
- GCAM updates its carbon densities based on changes from CLM.
- GCAM recreates RCP, with new LULCC path, based on carbon densities.
Opportunities afforded by integration

- **Immediate** tests of climate impacts for future scenarios.

- Tool to enable “no regrets” scenario/path development.

- Advances in internally consistent treatment of water, energy, and climate in mitigation pathways.

- Quantification of impacts of feedbacks and interactions that are yet to be treated under current protocols and yet could be significant on mitigation timescales.
Challenge: Rationalize exchange of IAM trajectories of forcing agents w/ ESMs & EMICs
CMIP5: The RCP Handshake Process

<table>
<thead>
<tr>
<th>Variable</th>
<th>Units</th>
<th>Spatial scale</th>
<th>Regional and sectoral emissions</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Greenhouse gases</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CO₂ (fossil fuel, industrial, land use change)</td>
<td>ppm and Pg/yr</td>
<td>Global average</td>
<td>Sum</td>
</tr>
<tr>
<td>CH₄</td>
<td>ppb and Tg/yr</td>
<td>Global average</td>
<td>Grid¹</td>
</tr>
<tr>
<td>N₂O</td>
<td>ppb and Tg/yr</td>
<td>Global average</td>
<td>Sum</td>
</tr>
<tr>
<td>HFCs²</td>
<td>ppb and Tg/yr</td>
<td>Global average</td>
<td>Sum</td>
</tr>
<tr>
<td>PFCs²</td>
<td>ppb and Tg/yr</td>
<td>Global average</td>
<td>Sum</td>
</tr>
<tr>
<td>CFCs²</td>
<td>ppb and Tg/yr</td>
<td>Global average</td>
<td>Sum</td>
</tr>
<tr>
<td>SF₆</td>
<td>ppb and Tg/yr</td>
<td>Global average</td>
<td>Sum</td>
</tr>
<tr>
<td><strong>Aerosols²</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sulfur (SO₂)</td>
<td>Tg/yr</td>
<td>Generated by CM community³</td>
<td>Grid</td>
</tr>
<tr>
<td>Black Carbon (BC)</td>
<td>Tg/yr</td>
<td>Generated by CM community³</td>
<td>Grid</td>
</tr>
<tr>
<td>Organic Carbon (OC)</td>
<td>Tg/yr</td>
<td>Generated by CM community³</td>
<td>Grid</td>
</tr>
<tr>
<td><strong>Chemically active gases</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CO</td>
<td>Tg/yr</td>
<td>Generated by CM community³</td>
<td>Grid</td>
</tr>
<tr>
<td>NO₅</td>
<td>Tg/yr</td>
<td>Generated by CM community³</td>
<td>Grid</td>
</tr>
<tr>
<td>VOCs²</td>
<td>Tg/yr</td>
<td>Generated by CM community³</td>
<td>Grid</td>
</tr>
<tr>
<td>NH₃</td>
<td>Tg/yr</td>
<td>Generated by CM community³</td>
<td>Grid</td>
</tr>
</tbody>
</table>

Van Vuuren et al, 2008
Relation of iESM to CESM’s new Societal Dimensions Working Group (SDWG)

SDWG Areas of Interest:

- Land use
- Agriculture (AgMIP)
- Urban areas and energy use
- Water in IAMs
- Forestry management
- Assessing renewable energy potentials
- Air quality, climate, and impacts

CESM is primarily sponsored by the National Science Foundation and the Department of Energy

http://www.cesm.ucar.edu/management
Next steps for the integrated Earth System Model

- **Proof-of-concept experiments of extensibility to other IAMs that conform to the RCP “handshake” protocol.**

- Friendly-use release to CESM Societal Dimensions Working Group and global climate community.

- Extensions underway to handle forcings besides LULCC: full RCP complement of LLGHGs, aerosols, etc.

Moss et al, 2010
Plans for public release of iESM

Next milestone: “Friendly” release to SDWG:
- Code (for inspection)
- User documentation and technical manuals
- Peer-reviewed papers describing iESM
- Input and output from the iESM

Proposed timeline of public release:
- December 2012: “Friendly release to SDWG”
- February 2013: Review by the SDWG
- Summer 2013: Review by CESM Scientific Steering Committee
- December 2013: Public release of iESM as part of CESM

iESM framework will admit other IAMs (tests underway)

How to join SDWG:
http://www.cesm.ucar.edu/working_groups/Societal/
Discussion

- Capability to run all RCPs with output from IAMs participating in RCP process substituted for GCAM?
  - Testing underway using IMAGE.

- Capacity to use other RCP models interactively in iESM?

- Extensibility of iESM framework to link other IAMs and ESMs?

- Potential for iESM to advance community interactions?