Advances in modeling energy, water, and land processes and their interactions

John Reilly

MIT Joint Program On the Science and Policy of Global Change

The Joint Program is Funded by the U.S. Department of Energy (DOE), Office of Science under award DE-FG02-94ER61937 (An Integrated Framework for Climate Change Assessment) and a consortia of industrial and government sponsors.

Dec. 7, 2017

http://globalchange.mit.edu/
MIT Joint Program on the Science and Policy of Global Change
Vision and Overview

We explore the interplay between our global environment, economy, and other human activities, to discover the key processes & interactions and provide a better science basis for decision-making in the public & private sectors.

Our Goals:

- Perform & objectively assess uncertainty in economic and environmental projections through probabilistic assessments
- Critically and quantitatively analyze environmental management and policy proposals
- Understand and model complex connections among climate, air pollution, food, water, energy, urbanization, economic development…
Broader issues in analysis of evolution of energy, water, land systems and their interaction

- Linkages among complex water, energy, land systems
  - Earth system: Insolation (energy) drives the hydrological cycle (water), with runoff (land surface) into rivers/reservoirs, and lakes to determine spatial availability/flow of freshwater.
  - Human system: Water withdrawals for multiple uses, e.g. power plant cooling (energy), irrigation (agriculture and land use), and domestic and industry uses—supply conflicts and water quality effects.

- Modeling issues
  - Scale (Temporal and spatial)
  - Active feedbacks or altered boundary conditions
  - Explicit modeling of processes or reduced form relationships
  - Stocks and flows (GHG emissions—concentrations, river flows—reservoirs—groundwater, depletable energy—renewable/storage

- Predictability
  - Description of range of outcomes,
  - Quantified as probability

- Adaptation
  - What by whom—national/international level policy and planning or specific investments (public/private, companies/individuals)
  - A problem of investment under uncertainty

http://globalchange.mit.edu/
MIT INTEGRATED GLOBAL SYSTEM MODEL (IGSM): a tool for investigating linkages among complex human and natural systems—convergence of social science, physical and biological sciences and engineering concepts.

Economic Projection and Policy Analysis (EPPA) model

MIT Earth System Model (MESM)

EARTH SYSTEM

Atmosphere: 2-Dimensional Chemical & Dynamical Processes
Urban: Air Pollution Processes
Ocean: 2- or 3-Dimensional Dynamics, Biological, Chemical, and Ice Processes [MITgcm]
Land: Water & Energy Budgets [CLM] Biogeochemical Processes [TEM & NEM]

COUPLLED OCEAN, ATMOSPHERE AND LAND

Examples of Model Outputs

Global mean and latitudinal temperature and precipitation, sea level rise...
Permafrost area, vegetative and soil carbon, Trace gas emissions from ecosystems...
GDP growth, energy use, policy costs, agriculture and health impacts...

Solar Forcing
Volcanic Forcing

Hydrology/water resources
Agriculture, forestry, bio-energy, ecosystem productivity
Climate/energy demand
Trace gas fluxes (CO$_2$, CH$_4$, N$_2$O) and policy constraints
CO$_2$, CH$_4$, CO, N$_2$O, NOx, SOx, NH$_3$, CFCs, HFCs, PFCs, SF$_6$, VOCs, BC, etc.
Land use change
Sea level change

Human Activity (EPPA)
National and/or Regional Economic Development, Emissions, Land Use

Human health effects


http://globalchange.mit.edu/
PROJECT RISKS TO THE NATURAL, MANAGED AND BUILT ENVIRONMENTS FROM HUMAN AND NATURAL FORCES AND THEIR CHANGES. ASSESS MITIGATION AND ADAPTIVE ACTIONS.

http://globalchange.mit.edu/
MODELING WATER MANAGEMENT
OPTIMIZATION AND FLEXIBILITY OF FRAMEWORK

Priorities for Release of Supply
- Environmental Baseflow
- Municipal
- Industrial
- Energy
- Agriculture/Irrigation

WATER STRESS INDEX (WSI) [UNITLESS]
- Measurement of system/environment stress

$$\text{WSI} = \frac{\text{Withdrawal (Dom, Ind, Irr)}}{\text{Supply (Runoff, Inflow)}}$$

UNMET DEMAND (UD) [FRACTION OR %]
- Indicator of the direct human impact

$$\text{UD} = 1 - \frac{\text{Total Consumption}}{\text{Total Demand}}$$

Optimization Algorithm for Each Basin

Qualitatively: Basin Objective
- Maintain highest supply-to-requirement ratio
- Minimal amount of release
- Keep end of year storage high
- High penalty for depleting storage

http://globalchange.mit.edu/
A Water Resource System model for the US
Advantages:
Global simulations of MIT IGSM represents updated BAU impacts of stabilization scenarios as energy and environmental policy changes globally.

Multiple runs/large ensembles (100’s to 1000’s of members) feasible with variation in behavior of multiple GCMS through pattern mapping.

Compare with off the shelf archived GCM runs with fixed concentration paths and inconsistent global economic environment and unable to fully characterize risk space.

Disadvantages:
Effects in the US/North America do not feedback on the globe

Similar detail for the rest of the world would like affect boundary conditions of climate, concentrations, and global trade.
USREP-ReEDs Coverage

• Flexible aggregation of 50 US states + 16 international regions
• Flexible aggregation of 52 sectors of the economy
• Coal, gas, oil, nuclear, hydro, solar and wind electricity generation.
• Solves in 2- or 5-year time steps to 2050
• 9 household types based on income
## USREP-ReEDs Data sources

<table>
<thead>
<tr>
<th>What ?</th>
<th>Where ?</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>International</td>
<td>Global Trade Analysis Project (GTAP, 2008), Version 7</td>
</tr>
<tr>
<td>Final demand</td>
<td>US states</td>
<td>IMPLAN (2008): NIPA and Consumer Expenditure Survey (CES)</td>
</tr>
<tr>
<td></td>
<td>International</td>
<td>GTAP7</td>
</tr>
<tr>
<td>Physical energy flows and prices</td>
<td>US states</td>
<td>State Energy Data System (SEDS), EIA (2009)</td>
</tr>
<tr>
<td></td>
<td>International</td>
<td>IEA/GTAP</td>
</tr>
<tr>
<td>Bilateral trade</td>
<td>Between states</td>
<td>Commodity Flow Survey (Lindall et al., 2006)</td>
</tr>
<tr>
<td></td>
<td>Between states and countries</td>
<td>Origin of Movement (OM) and State of Destination (SD), US Census Bureau (2010)</td>
</tr>
<tr>
<td></td>
<td>Between countries</td>
<td>GTAP7</td>
</tr>
<tr>
<td></td>
<td>Electricity</td>
<td>National Renewable Laboratory’s ReEDS model</td>
</tr>
<tr>
<td>GDP and CO₂ emissions</td>
<td>US states</td>
<td>EIA Annual energy outlook 2015</td>
</tr>
</tbody>
</table>
ReEDS Resolution
(In progress-linkage of ReEDS Canada and Mexico with North America REP)

Chooses least cost electricity deployment with detailed specification of renewable resources with policy constraints or options—minimum renewable requirements, carbon taxation, cap and trade
An application: In a stabilization scenario (L1S), increase in renewable deployment significantly reduces power plant cooling water withdrawals, lessening water stress compared with UCE.

Unconstrained Emission (UCE)

Level 1 Stabilization (L1S)

Change in Cooling Withdrawal (Mgal/day)

Blanc et al., 2013
Evolution of Thermo-electric Water Withdrawals
( Depends on developing Regs. WRT cooling water )

Mga/day

- Unconstrained Emission
- 450 Equivalent CO2

WRS

WICTS
However, water run-off depends strongly on underlying pattern of precipitation and temperature change: E.g. Comparing a relatively “wet” and “dry” pattern

In fact a variety of precipitation patterns depending on underlying GCM

Emergent precipitation pattern changes June-August
With a Range of Annual Runoff Changes (mm/day) Pattern-Mean Forced Response (2040s-2010s)
Seasonality matters—JJA vs Annual: Formulate as CDF
Extend WRS to consider water quality
(Collaboration with Industrial Economics and Tufts)

Boehlert et al. 2015; JAMES; Fant al. 2017; Water; Chapra et al. 2017: ES&T

```
General Circulation Models

Changes in Temperature and Precipitation

Soil characteristics, PET, Crop phenology, Kc, Ky, population projections

Projected Temperature and Precipitation

PET, historical runoff

Historical Temperature and Precipitation

Rainfall Runoff Model
CLIRUN-II

Water Demand Model

Runoff

Demand

Water Resources Systems Model
US Basins

Flows

Volumes

WQ impacts

Water Quality Model
QUALIDAD-HABs

BOD, heat, N, P

Costs, based on visitation or WTP

Reservoirs, hydropower, water management, flow routing

Valuation Model
Willingness To Pay (WTP)
Implications for Recreation
```

http://globalchange.mit.edu/
Water quality model (QUALIDAD)

- Same structure over the Contiguous U.S.

- Scenarios and eras (climate & socioeconomic)
  - Business as Usual (Reference)
  - Mitigation Scenarios

- Water Quality Measures
  - Water Temperature
  - Dissolved Oxygen
  - Organic Carbon
  - Nitrates (Ammonia, Nitrogen & Organic)
  - Phosphates (Organic & Inorganic)
  - Phytoplankton (including HABs)

KEY:
- h: hydrolysis
- s: settling
- df: diffusion
- r: release
- de: death
- re: respiration
- x: oxidation
- n: nitrification
- dn: denitrification
- p: photosynthesis
- sod: sediment O\textsubscript{2} demand
Resolved at 2119 River basins but we often want to report at broader resource regions

- Basin Boundaries
- Total of 2,119 basins (rivers)
  - based on 8-digit HUCs; developed by USGS
Driven by an Ensemble of Climate change scenarios

- Five GCMs, Two RCPs
- Four “eras” (2030, 2050, 2070, 2090)
- Temperatures rise, precipitation varies spatially
- Large differences between GCMs
One Strong Result: Major increases in cyanobacteria concentration in lakes and reservoirs, amplified with dryer and hotter conditions (thousands of cells / ml)

- Large differences between climate scenarios and growth scenarios
- Regardless, HAB occurrence increases, particularly in the northeast and midwest
WATER QUALITY—TEMPERATURE MODELING For THERMAL COOLING

Once-through cooling
Total annual generation (in TWh)

http://globalchange.mit.edu/
### Impacts on Annual Generation in US (lower 48) in 2050

<table>
<thead>
<tr>
<th>Control Gen.</th>
<th>Region</th>
<th>CAM 'CS3REF'</th>
<th>CAM 'POL4.5'</th>
<th>CAM 'POL3.7'</th>
<th>MIROC 'CS3REF'</th>
<th>MIROC 'POL4.5'</th>
<th>MIROC 'POL3.7'</th>
</tr>
</thead>
<tbody>
<tr>
<td>9%</td>
<td>'NE'</td>
<td>3%</td>
<td>-2%</td>
<td>-2%</td>
<td>0%</td>
<td>-4%</td>
<td>-5%</td>
</tr>
<tr>
<td>34%</td>
<td>'SE'</td>
<td>-8%</td>
<td>-11%</td>
<td>-22%</td>
<td>-10%</td>
<td>-11%</td>
<td>-24%</td>
</tr>
<tr>
<td>23%</td>
<td>'MW'</td>
<td>5%</td>
<td>-2%</td>
<td>12%</td>
<td>1%</td>
<td>-4%</td>
<td>9%</td>
</tr>
<tr>
<td>6%</td>
<td>'NP'</td>
<td>-13%</td>
<td>16%</td>
<td>19%</td>
<td>-17%</td>
<td>12%</td>
<td>11%</td>
</tr>
<tr>
<td>16%</td>
<td>'SP'</td>
<td>4%</td>
<td>-1%</td>
<td>-9%</td>
<td>1%</td>
<td>-3%</td>
<td>-10%</td>
</tr>
<tr>
<td>10%</td>
<td>'NW'</td>
<td>2%</td>
<td>1%</td>
<td>-31%</td>
<td>0%</td>
<td>0%</td>
<td>-30%</td>
</tr>
<tr>
<td>2%</td>
<td>'SW'</td>
<td>2%</td>
<td>-12%</td>
<td>101%</td>
<td>1%</td>
<td>-12%</td>
<td>101%</td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td>-1%</td>
<td>-4%</td>
<td>-6%</td>
<td>-4%</td>
<td>-5%</td>
<td>-9%</td>
</tr>
</tbody>
</table>
And Extension to Hydropower
Table 2
Average seasonal change in 2050 hydropower generation from the control for each emissions scenario, at the 2-digit HUC level, under the average across pattern scaled GCM projections. Note: Excludes the Great Lakes 2-Digit HUC.

<table>
<thead>
<tr>
<th>2-Digit HUC</th>
<th>DEC-JAN-FEB</th>
<th></th>
<th></th>
<th>MAR-APR-MAY</th>
<th></th>
<th></th>
<th>JUN-JUL-AUG</th>
<th></th>
<th></th>
<th>SEP-OCT-NOV</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>REF</td>
<td>POL4.5</td>
<td>POL3.7</td>
<td>REF</td>
<td>POL4.5</td>
<td>POL3.7</td>
<td>REF</td>
<td>POL4.5</td>
<td>POL3.7</td>
<td>REF</td>
<td>POL4.5</td>
</tr>
<tr>
<td>New England</td>
<td>18%</td>
<td>11%</td>
<td>10%</td>
<td>2%</td>
<td>1%</td>
<td>1%</td>
<td>-3%</td>
<td>-5%</td>
<td>-4%</td>
<td>0%</td>
<td>-1%</td>
</tr>
<tr>
<td>Mid Atlantic</td>
<td>-7%</td>
<td>5%</td>
<td>5%</td>
<td>-3%</td>
<td>-2%</td>
<td>-2%</td>
<td>-2%</td>
<td>-3%</td>
<td>-8%</td>
<td>-2%</td>
<td>-2%</td>
</tr>
<tr>
<td>South Atlantic Gulf</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>-5%</td>
<td>-4%</td>
<td>-4%</td>
<td>-2%</td>
<td>-1%</td>
<td>0%</td>
<td>-2%</td>
<td>-1%</td>
</tr>
<tr>
<td>Ohio</td>
<td>1%</td>
<td>1%</td>
<td>1%</td>
<td>-2%</td>
<td>-1%</td>
<td>-1%</td>
<td>0%</td>
<td>-1%</td>
<td>-1%</td>
<td>-2%</td>
<td>-1%</td>
</tr>
<tr>
<td>Tennessee</td>
<td>-1%</td>
<td>0%</td>
<td>0%</td>
<td>-2%</td>
<td>-2%</td>
<td>-2%</td>
<td>-1%</td>
<td>-1%</td>
<td>0%</td>
<td>-2%</td>
<td>-1%</td>
</tr>
<tr>
<td>Upper Mississippi</td>
<td>1%</td>
<td>0%</td>
<td>0%</td>
<td>1%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>-1%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
</tr>
<tr>
<td>Lower Mississippi</td>
<td>3%</td>
<td>2%</td>
<td>2%</td>
<td>-18%</td>
<td>-14%</td>
<td>-13%</td>
<td>-18%</td>
<td>-14%</td>
<td>-13%</td>
<td>-6%</td>
<td>-4%</td>
</tr>
<tr>
<td>Souris-Red-Rainy</td>
<td>0%</td>
<td>-4%</td>
<td>-3%</td>
<td>7%</td>
<td>1%</td>
<td>0%</td>
<td>-4%</td>
<td>-5%</td>
<td>-1%</td>
<td>-3%</td>
<td>-4%</td>
</tr>
<tr>
<td>Missouri</td>
<td>-12%</td>
<td>-12%</td>
<td>-10%</td>
<td>14%</td>
<td>6%</td>
<td>5%</td>
<td>-12%</td>
<td>-13%</td>
<td>-10%</td>
<td>-16%</td>
<td>-15%</td>
</tr>
<tr>
<td>Arkansas-White-Red</td>
<td>1%</td>
<td>1%</td>
<td>1%</td>
<td>-8%</td>
<td>-6%</td>
<td>-5%</td>
<td>-6%</td>
<td>-5%</td>
<td>-4%</td>
<td>-5%</td>
<td>-4%</td>
</tr>
<tr>
<td>Texas Gulf</td>
<td>-4%</td>
<td>-1%</td>
<td>-1%</td>
<td>-14%</td>
<td>-10%</td>
<td>-9%</td>
<td>-16%</td>
<td>-9%</td>
<td>-8%</td>
<td>-13%</td>
<td>-9%</td>
</tr>
<tr>
<td>Rio Grande</td>
<td>-8%</td>
<td>-6%</td>
<td>-6%</td>
<td>-8%</td>
<td>-7%</td>
<td>-7%</td>
<td>-16%</td>
<td>-12%</td>
<td>-11%</td>
<td>-7%</td>
<td>-6%</td>
</tr>
<tr>
<td>Upper Colorado</td>
<td>-8%</td>
<td>-9%</td>
<td>-9%</td>
<td>7%</td>
<td>3%</td>
<td>2%</td>
<td>-15%</td>
<td>-12%</td>
<td>-12%</td>
<td>-10%</td>
<td>-10%</td>
</tr>
<tr>
<td>Lower Colorado</td>
<td>32%</td>
<td>14%</td>
<td>9%</td>
<td>33%</td>
<td>10%</td>
<td>7%</td>
<td>42%</td>
<td>26%</td>
<td>21%</td>
<td>3%</td>
<td>1%</td>
</tr>
<tr>
<td>Great Basin</td>
<td>14%</td>
<td>4%</td>
<td>3%</td>
<td>28%</td>
<td>16%</td>
<td>12%</td>
<td>-14%</td>
<td>-11%</td>
<td>-11%</td>
<td>-14%</td>
<td>-15%</td>
</tr>
<tr>
<td>Pacific Northwest</td>
<td>23%</td>
<td>13%</td>
<td>12%</td>
<td>14%</td>
<td>9%</td>
<td>8%</td>
<td>-14%</td>
<td>-12%</td>
<td>-9%</td>
<td>-5%</td>
<td>-5%</td>
</tr>
<tr>
<td>California</td>
<td>10%</td>
<td>6%</td>
<td>5%</td>
<td>7%</td>
<td>4%</td>
<td>3%</td>
<td>-6%</td>
<td>-4%</td>
<td>-4%</td>
<td>-11%</td>
<td>-8%</td>
</tr>
<tr>
<td>TOTAL</td>
<td>13%</td>
<td>7%</td>
<td>6%</td>
<td>9%</td>
<td>5%</td>
<td>4%</td>
<td>-9%</td>
<td>-8%</td>
<td>-7%</td>
<td>-5%</td>
<td>-5%</td>
</tr>
</tbody>
</table>
Current water Stress (unit-less ratio of use to annual availability) simulated average 2001-2020
Implications: For 2050 (2041-2060)
(% change in WSI index from present (2001-2020))

Simulated for two climate patterns (M and N) and two levels of climate sensitivity. Much of stress increase is due to increased demand from growth, but climate often an aggravating factor.

http://globalchange.mit.edu/
Simulated for two climate patterns (M and N) and two levels of climate sensitivity. Run-off changes isolate one the climate effect on water supply.
Climate Impact: Irrigation demand changes for 2050 (2041-2060) (% change from present (2001-2020))

Simulated for two climate patterns (M and N) and two levels of climate sensitivity. Run-off changes isolate one the climate effect on water supply.
Global modeling—some Caveats

• A small sample of possible climate (and growth) scenarios so caution in specific regional results.

• As many have found, climate not necessarily the biggest concern but often one that aggravates other stresses.

• No adaptation measures were considered...projection suggest a call to focus on adaptation.

• Climate effects on both run-off (water supply) and irrigation requirements (water demand) both mostly appear to aggravate potential water stress.

• Greater resolution needed to assess specific adaptation needs along with need to consider predictability of climate and for highly resolved geography.
COMBINING MITIGATION AND ADAPTATION: RISK REDUCTION SEEN IN UNMET WATER DEMANDS.

CHANGE (%) IN UNMET DEMAND BY 2050

Schlosser et al. (2017, forthcoming)

Adaptation Scenarios
Adapt-C: UCE with lined canals
Adapt-C-IE: Adapt-C with high efficiency sprinklers

Total Cost (Billions 2000 US$)

<table>
<thead>
<tr>
<th></th>
<th>China</th>
<th>India</th>
</tr>
</thead>
<tbody>
<tr>
<td>Adapt-C</td>
<td>35</td>
<td>23</td>
</tr>
<tr>
<td>Adapt-C-IE</td>
<td>142</td>
<td>114</td>
</tr>
</tbody>
</table>

http://globalchange.mit.edu/
Future Yields of major crops—ultimately implications for land requirements in 4 “bread basket” regions

We have used a technique to “train,” statistically a simple model to replicate results of major Globally Gridded Crop Model (GGCM) results archived as part of the AGMIP (LPJ-GUESS, LPJmL, PEGASUS, DSSAT, GEPI C)
Maize in North America (averaged over climate scenarios) assessed with a yield emulator of major globally gridded crop models.

Mostly positive trend, but suggested poleward shift, significant differences among the models.

http://globalchange.mit.edu/
Soybeans in Brazil (averaged over climate scenarios)

Significant differences among the models both in pattern and overall impact.
Maize in North America

Mostly positive trend, suggested poleward shift, significant differences among the models
Upland rice in South and Southeast Asia (averaged over climate scenarios)

Increases but wide differences among the models with suggested geographic shifts in production
Methods to explicitly represent irrigated agriculture in the MIT Integrated Global System Model (IGSM)

• Develop supply functions for additional irrigable land for 126 water regions using WRS

• Irrigable land supply curves are built on water region-level estimates of water availability, and the costs of (1) improving irrigation efficiency and (2) increasing water storage

• Irrigable land supply curves are included in the MIT Economic Projection and Policy Analysis (EPPA) model

• Irrigable land supply curves can be adjusted to account for changes in water availability estimated by the IGSM–Water Resource System (IGSM-WRS) model
Irrigable land supply curves

- Supply curves for additional irrigable land are estimated for 126 water regions, built on 282 large river basins (Assessment Sub-Regions) identified by the International Food Policy Research Institute (IFPRI)

Large river basins (lines) and water regions (colors)
Supply curve for an additional irrigable land built up from estimates of cost to increase storage (up to 10 separate additions) reduce conveyance loss, and improve efficiency of water use.
Example: Under growth in food demand, population regions coming up against irrigable land supply constraints (no climate change).

Water regions operating at maximum irrigation potential in 2050.
A modeling framework for decision making under uncertainty

1. Uncertainty Categorization
   - Level of Uncertainty
   - Deep Statistical
   - Scenarios
   - Learning Potential
     - High
     - Multistage decision analysis with simulation
     - Simulation
     - Low

2. Modeling
   - Infrastructure Alternatives
   - Water System Model
   - Decision Model
     - Multistage decision analysis with simulation
     - Simulation
     - Scenarios

3. Risk Profile
   - Cost
   - Water Shortages

http://globalchange.mit.edu/
Another way to look at the problem: Choice may depend on desire to avoid bad outcomes.

Risk Ranking by Infrastructure Option

Example: Water Supply investment options in Melbourne depend strongly on assumptions social cost of water (i.e., value of water shortage).

Thank You

http://globalchange.mit.edu