Challenges and Progress in Integrated Assessment and Evolution in the Global Change Assessment Model (GCAM)

DOE Climate and Earth System Modeling PI's Meeting

Anthony C. Janetos, Director
Joint Global Change Research Institute
PNNL/UMD

21 September 2011

Outline

- Have been asked to review progress and evolution in IAMs and specifically GCAM
- Will briefly review research community's priorities as articulated for DOE IARP
- Then examine where we are making progress on each of these
- Will show some examples of results and changes in model structures – but most details can be found in individual talks and posters
- Suggest where gaps still exist and therefore some directions for the near future

IA Modeling

IAMs focus on the connection between human systems research and energy.

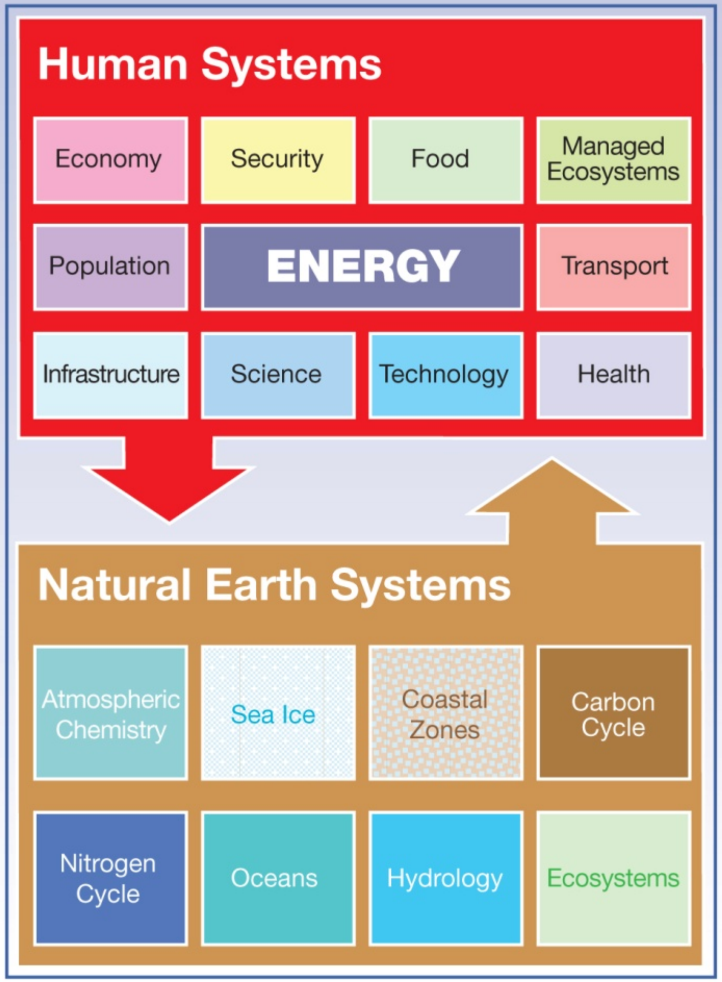
- IAMs provide natural science researchers with information about human systems, such as GHG emissions, land use, and land cover.

IAMs **integrate** natural and human system climate science.

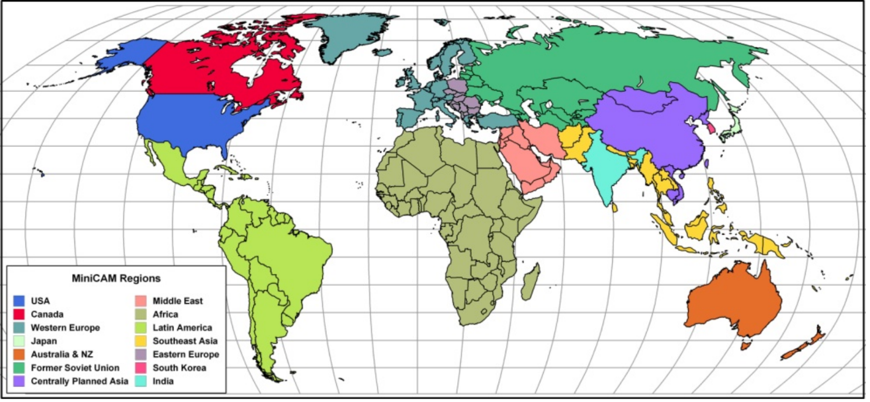
- IAMs provide insights that would be otherwise unavailable from disciplinary research.
- IAMs capture interactions between complex and highly nonlinear systems.

IAMs provide important, science-based decision support tools.

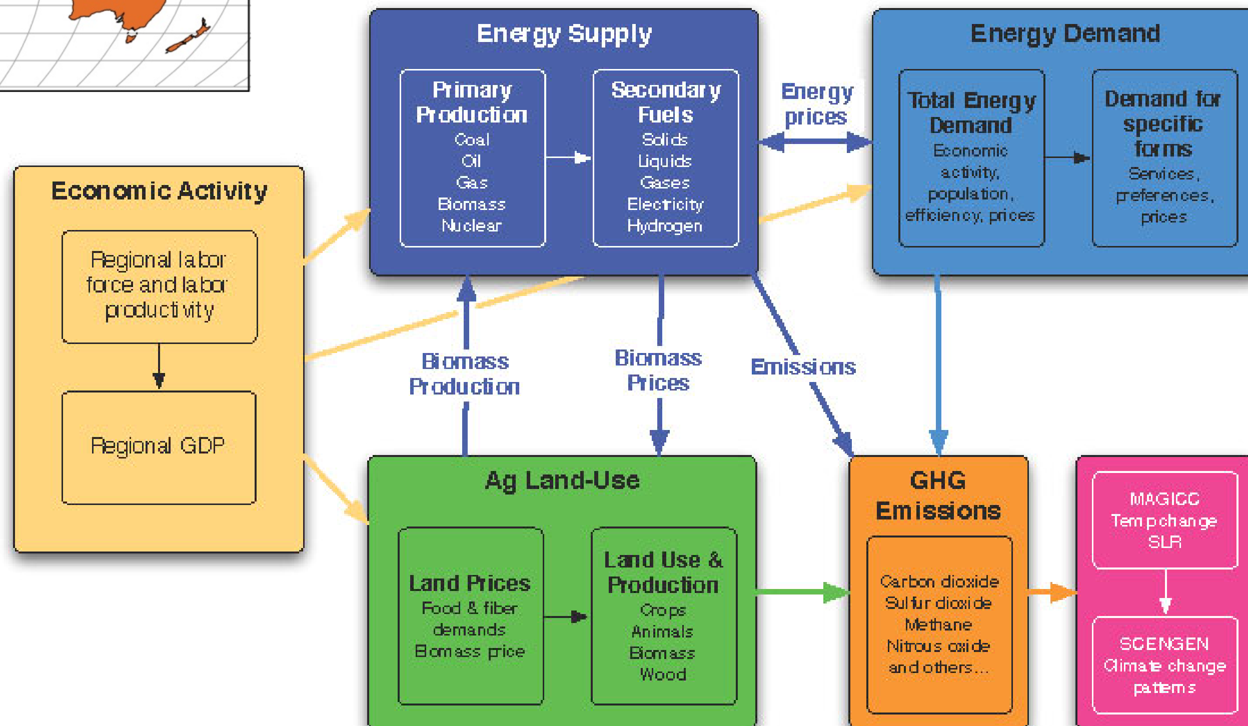
- IAMs support national, international, regional, and private-sector decisions.



The PNNL Global Change Assessment Model (GCAM)



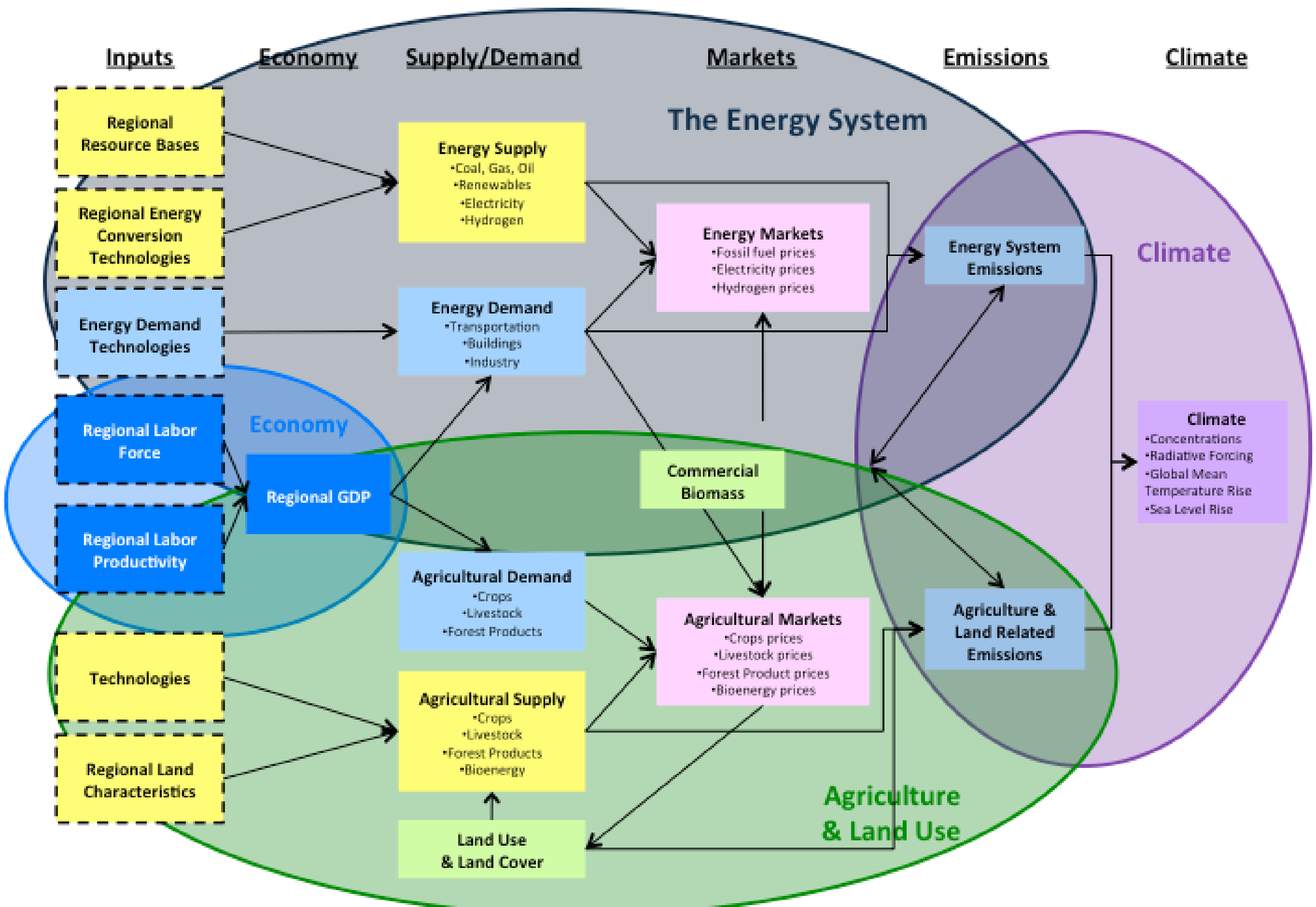
- Energy-Agriculture-Economy Market Equilibrium
- 14 Global Regions – Fully Integrated
- Explicit Energy Technologies – All Regions



- Fully Integrated Agriculture and Land Use Model
  - 15 Greenhouse Gases and Short-lived Species
    - Typically Runs to 2100 in 15-year time steps

Pacific Northwest NATIONAL LABORATORY
Proudly Operated by Battelle Since 1965
UNIVERSITY OF MARYLAND

Another View of GCAM



Context

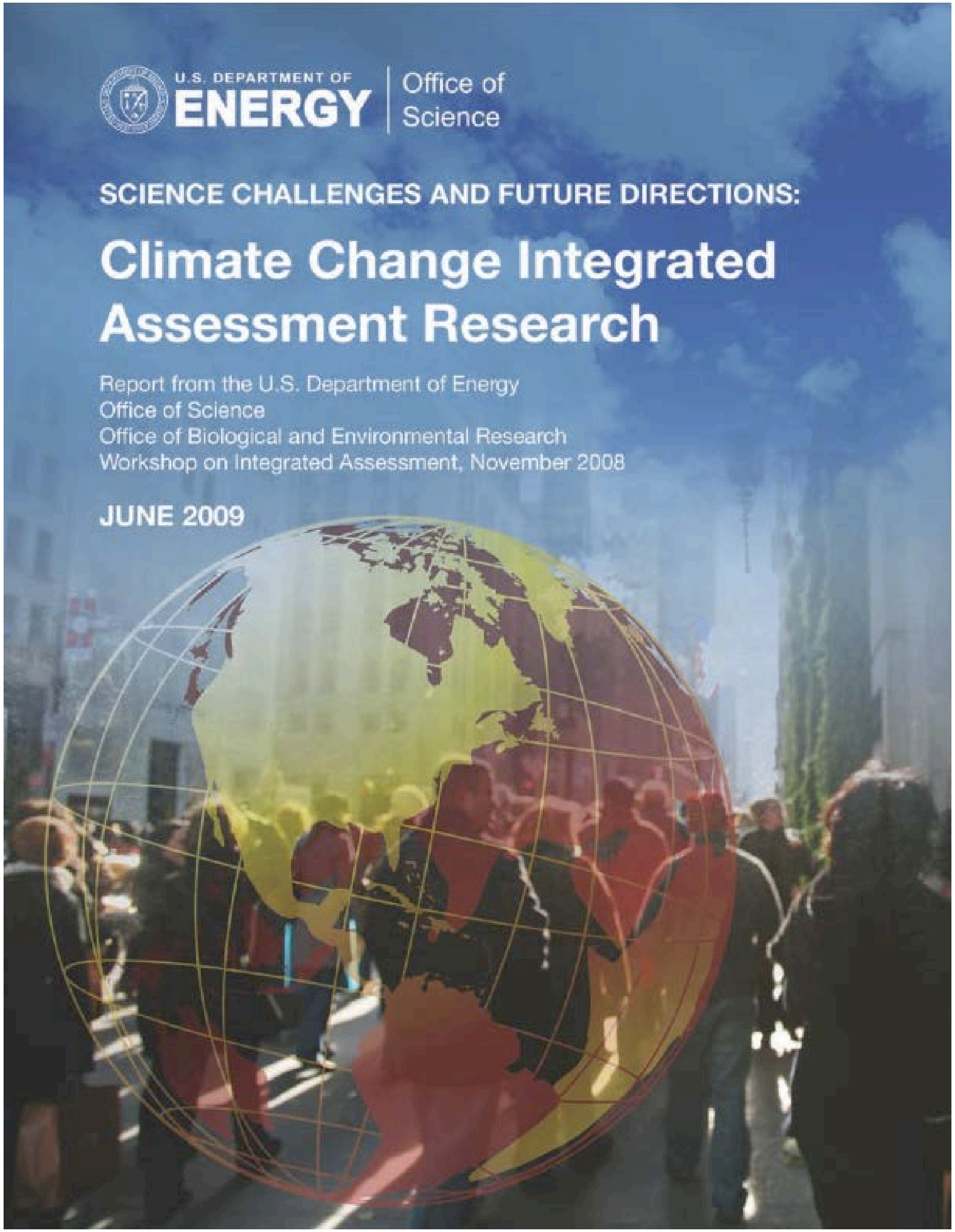
- In the middle of a sea-change for science and decisions about climate change
- A significant desire for integrated modeling and analysis
- DOE initiated a series of activities to understand major research directions

Context and Community Input for this Report

- November 2008 synthesizing workshop: Science Challenges and Future Directions for Climate Change IA Research
- Biological and Environmental Research Advisory Committee review of the IA Research Program – 2007
- 2007 and 2008 annual workshops on IA, Snowmass, Colorado
- Joint Global Change Research Institute and Oak Ridge National Laboratory 2007 Interagency Summer Workshop Series – Impacts, Adaptation, and Frontiers in Science
- Biological and Environmental Research's Climate and Environmental Sciences Division strategic plan for climate change research
- U.S. Climate Change Science Program Interagency Working Group on Human Contributions and Response and Decision Support
- IA Research Program co-sponsored 2008 workshop (and related workshop) on uncertainty methods – Argonne National Laboratory and University of Chicago

DOE Research Directions Workshop

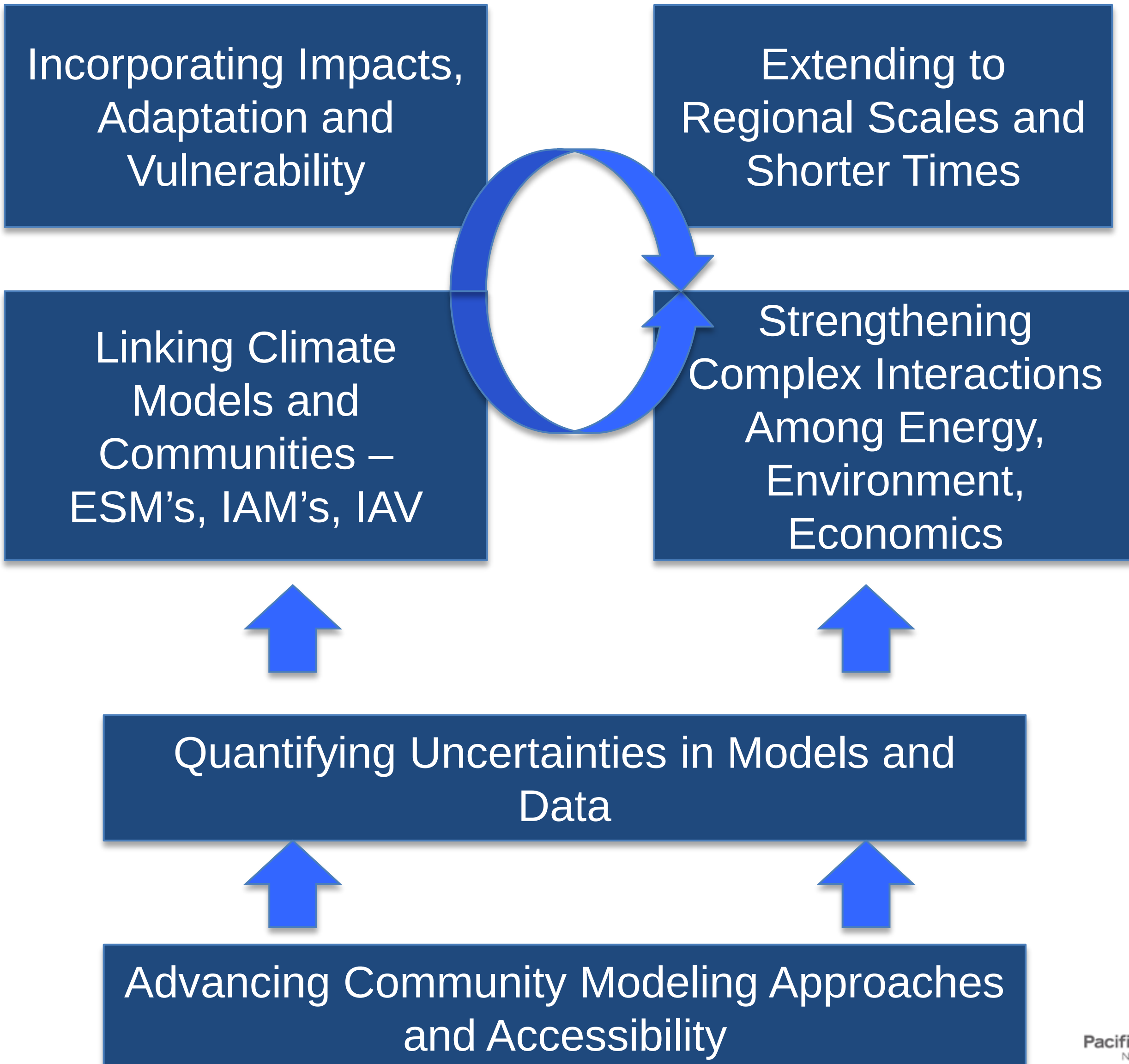
- Members of the scientific communities from integrated modeling, climate modeling, land modeling, energy modeling
- Two days of discussion to find common ground on major priorities for a research agenda
- Report summarizing major conclusions and more detailed scientific questions for each topic



Pacific Northwest
NATIONAL LABORATORY
Proudly Operated by Battelle *Since 1965*

UNIVERSITY OF MARYLAND

Major Challenges



Pacific Northwest NATIONAL LABORATORY
Proudly Operated by Battelle Since 1965
UNIVERSITY OF MARYLAND

Regional Scales and Shorter Time Steps

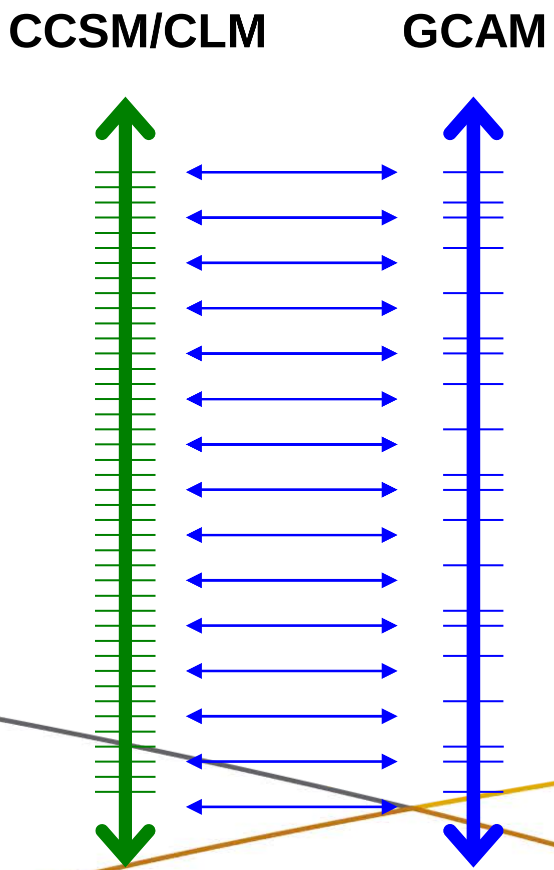
- Global calculations with large geopolitical regions over long time periods are quite reasonable for long-lived GHG's and strategic questions about mitigation strategies that focus on changes in energy technologies
- But provides limited information about regional scales and periods of a few years to a few decades
- Limited insight into how strategies for adaptation to change might interact with mitigation strategies
- Limited insight into possible limiting environmental factors: water supply, good agricultural soils, climate change itself
- So have focused on technical issues of shortening the time step of the model and incorporating significantly more regional specificity

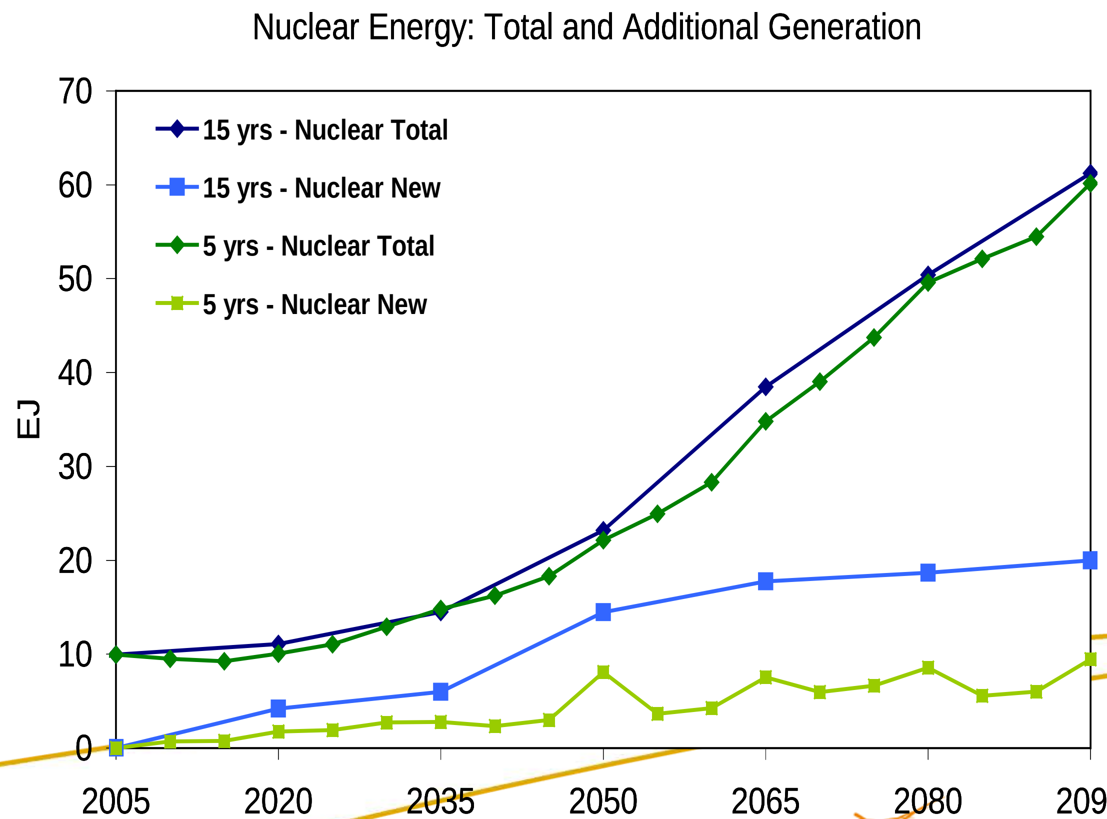
Creation of a variable time-step version of GCAM

- More opportunities to hook into climate models avoids large inconsistencies developing between the models over long time steps
- Better representation of new technologies and their availability
- Better representation of vintage (old) technology and retirement/replacement
- Leading to better representation of total energy consumption and greenhouse gas emissions
- Flexibility means even tighter time steps (to 1 year) are possible

Variable time-step version of GCAM

- From 15 year interval to 5 year interval

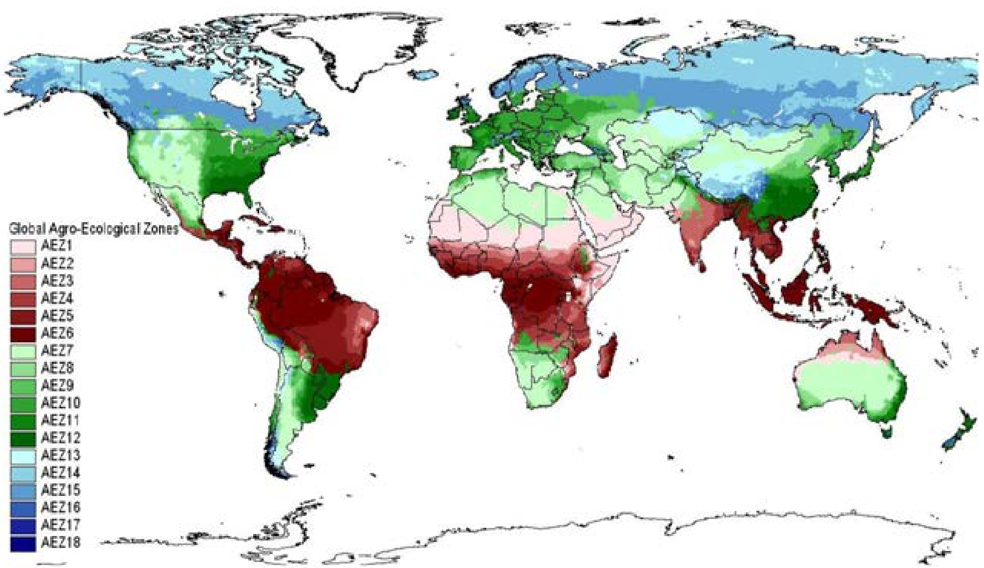




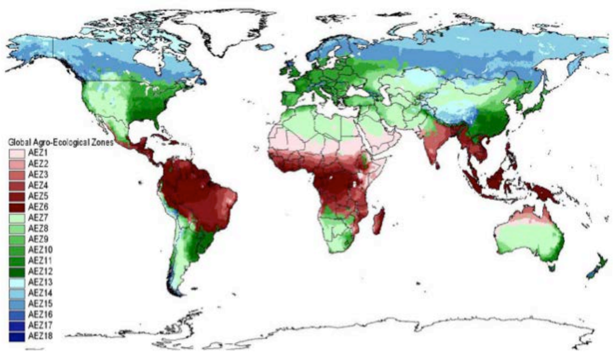
Redevelopment of agriculture and land-use modeling within GCAM

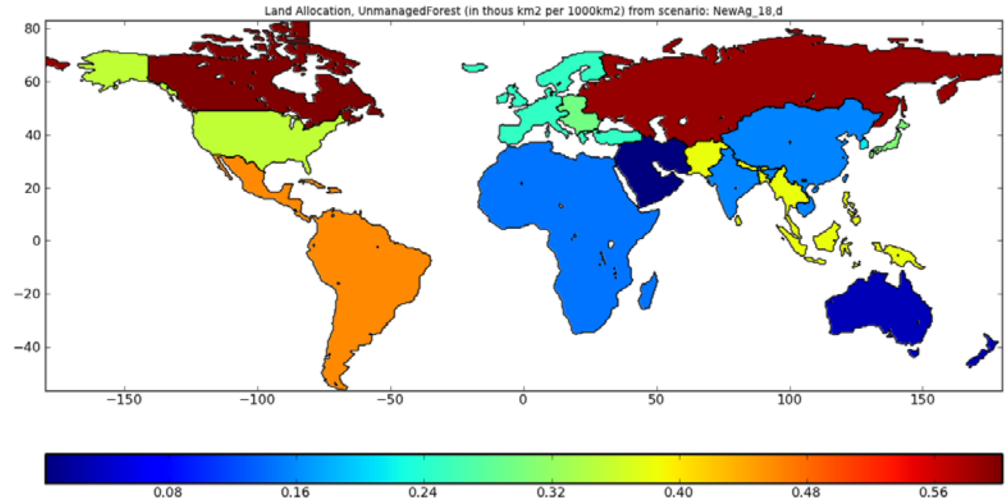
- Objective: Shift from statistically to physically determined land productivity and create a flexible scale model
- Step 1: Develop new GCAM AgLU code that allows for subregionalization based on data inputs
- Step 2: Compile subregionalized input data set

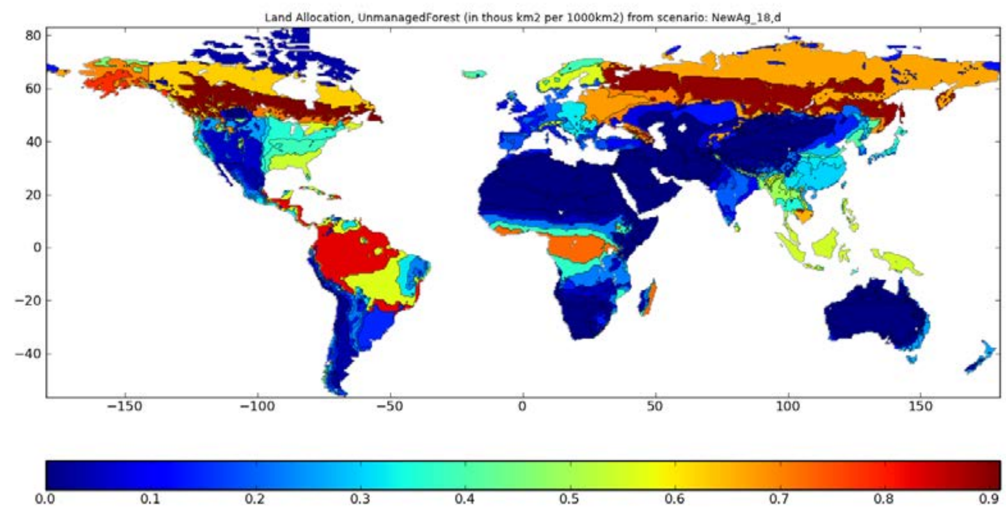
- Data for climate-defined agro-ecological zones (AEZs) selected for first application



AEZ Implementation in GCAM: Where are Forested Lands?



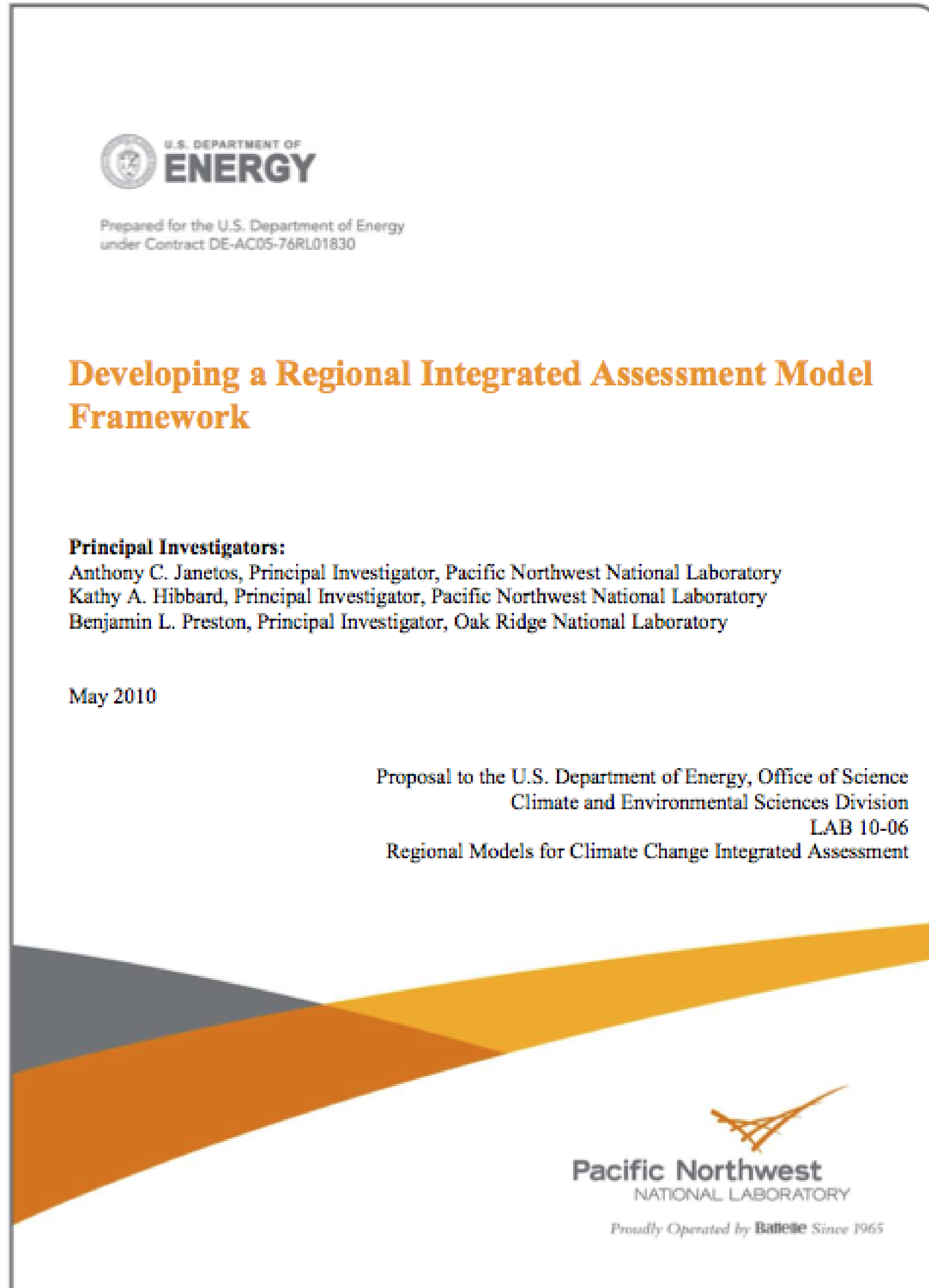




Overarching Questions for Regional IAM Studies

1. What are the regional characteristics and opportunities for mitigation and adaptation strategies? For example, are there physical (e.g., the availability of water or sufficient soil fertility) or economic (e.g., the availability of physical infrastructure) constraints that make the implementation of different energy technologies (e.g., biofuels) or mitigation strategies (e.g., carbon capture and storage) more difficult, but that are only appreciated when simulations are done with greater regional specificity than the national or international strategies that are done today?
2. How do changes in mean climate and climate variability affect adaptation and mitigation strategies?
3. What are the interactions between management decisions and natural processes that contribute to rapid, or nonlinear changes in the environment? Where are such nonlinarities, and how do their consequences contribute to climate feedbacks?
4. How will adaptation and mitigation strategies interact in the next few decades?

Regional Integrated Assessment Modeling: the Southeast and Gulf


U.S. DEPARTMENT OF ENERGY

Prepared for the U.S. Department of Energy under Contract DE-AC05-76RL01830

Developing a Regional Integrated Assessment Model Framework

Principal Investigators:
Anthony C. Janetos, Principal Investigator, Pacific Northwest National Laboratory
Kathy A. Hibbard, Principal Investigator, Pacific Northwest National Laboratory
Benjamin L. Preston, Principal Investigator, Oak Ridge National Laboratory

May 2010

Proposal to the U.S. Department of Energy, Office of Science
Climate and Environmental Sciences Division
LAB 10-06
Regional Models for Climate Change Integrated Assessment

Pacific Northwest NATIONAL LABORATORY

Proudly Operated by Battelle Since 1965

(a) (b)

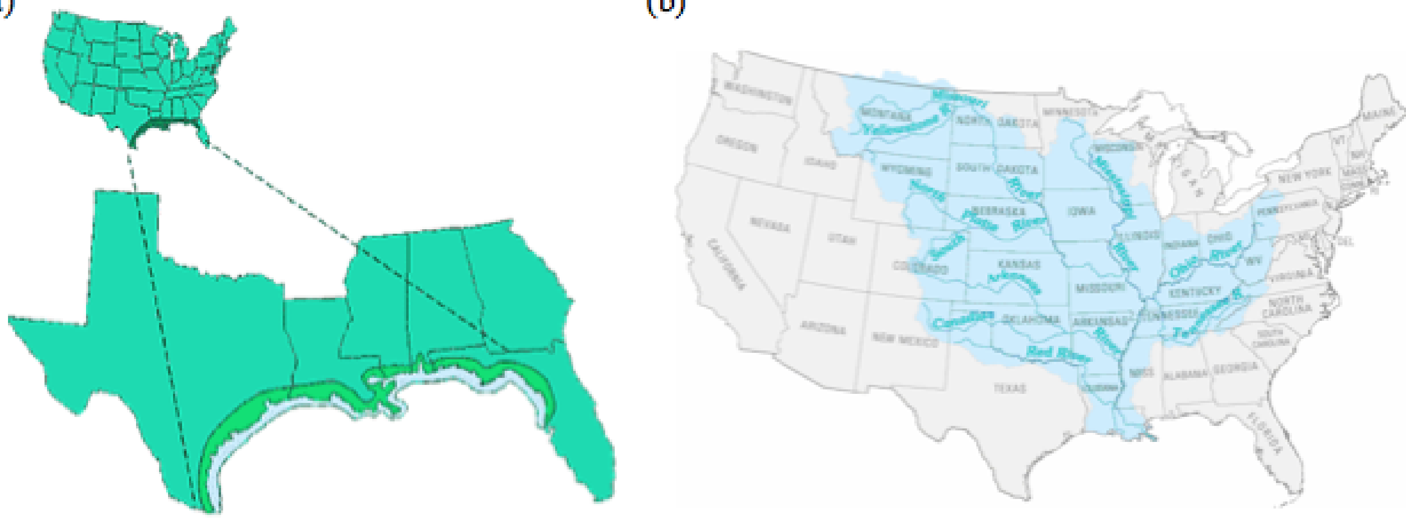


Figure 1: Proposed region of analyses. (a) Six states (Texas, Louisiana, Mississippi, Alabama, Georgia, Florida) that constitute the Gulf Coast as defined by the National Wetlands Research Center in Lafayette, LA. (http://biology.usgs.gov/ecosystems/global_change/aquatic_vegetation.html and (b) The extent and major rivers of Mississippi Atchafalaya River basin for water quality modeling

Two Major Goals

We have two major goals in this proposal.

- We will demonstrate the ability to couple a family of models in a consistent framework for regional integrated modeling and analysis. In so doing, we will demonstrate not only the feasibility of the coupling itself, but will demonstrate the utility of the coupled analyses, and where they differ from single, sectoral analysis.

- We will increase our understanding of the vulnerability of different domains/sectors in the Southeast/Gulf, how that vulnerability is related to different energy and emissions futures, and how adaptive measures may serve to ameliorate potential impacts. Our intent is to perform such simulations to illustrate the consequences of potential actions to a community of regional stakeholders, so that their understanding of potential decisions is increased.

Under existing PNNL initiative funding, an integrated Regional Earth System Model (iRESM) is under development that will link regional climate, integrated assessment, energy, land and hydrologic components to form a spatially flexible and temporally dynamic modeling framework that will be constrained by the global boundary conditions provided by GCAM and the Community Climate System Model (CCSM) from the National Center for Atmospheric Research (NCAR). Key elements of the proposed work are designed to improve the representation of specific Gulf coast electric, oil, coastal processes, land management technologies and plant response to climate change in conjunction with the developing regional integrated models. In the next few sections, we outline the major development tasks in different model components that will leverage on existing funding. We then describe the overall logic of coupled model experiments and their anticipated outcomes. Then we focus on interactions with stakeholder communities and institutions in the region. We finish with a description of the overall task structure, schedule and deliverables, and project management.

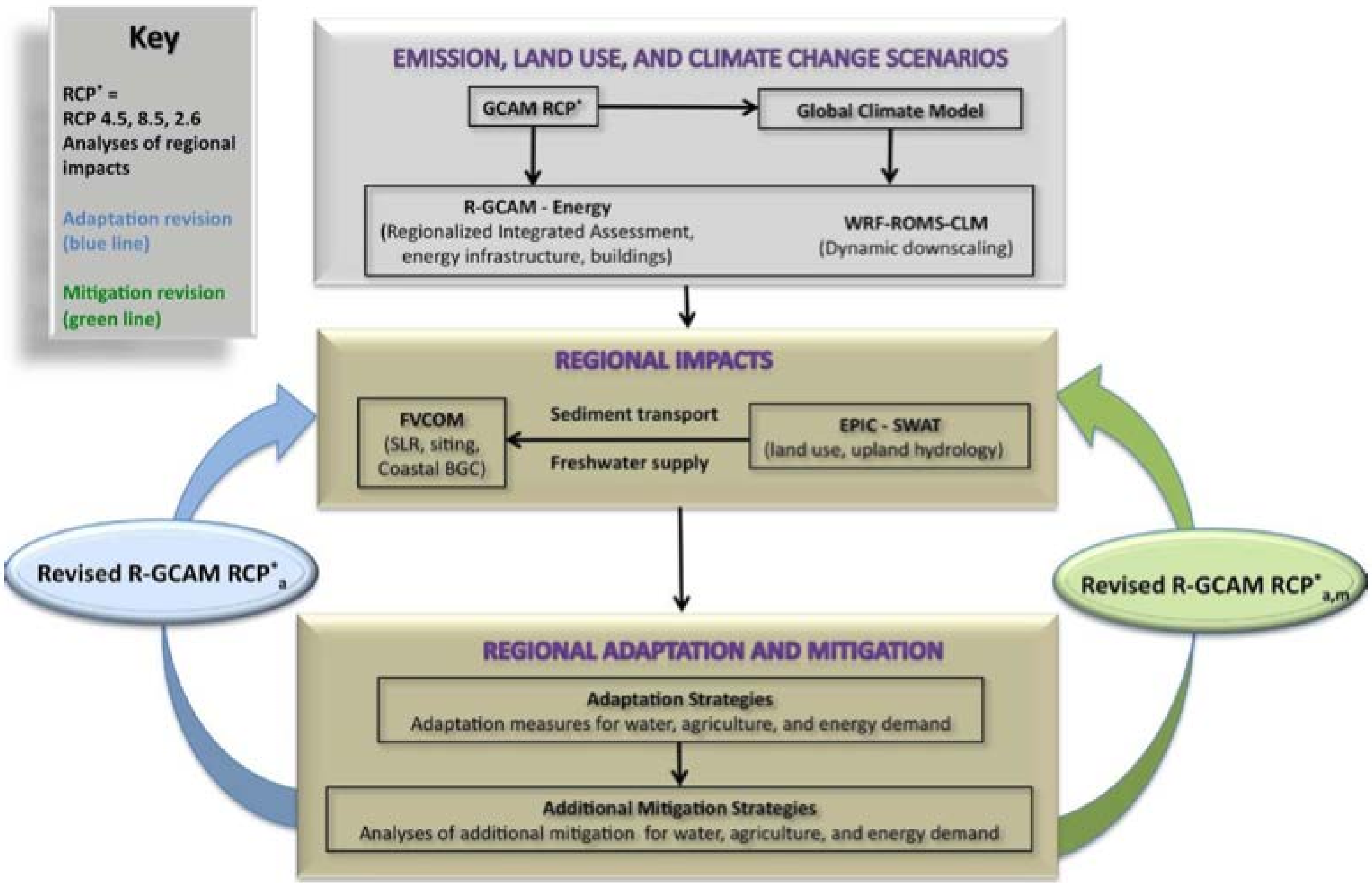


Figure 11. Overview of experimental design and relationship of model and assessment of impact, adaptation and mitigation strategies in the Gulf coast. Representative Concentration Pathways (RCP) 4.5, 8.5 and 2.6 will be used for each cascade of simulations and analysis where RCP* represents the development path for each separate RCP and Revised RCP* is where adaptation/mitigation strategies are allowed to occur.

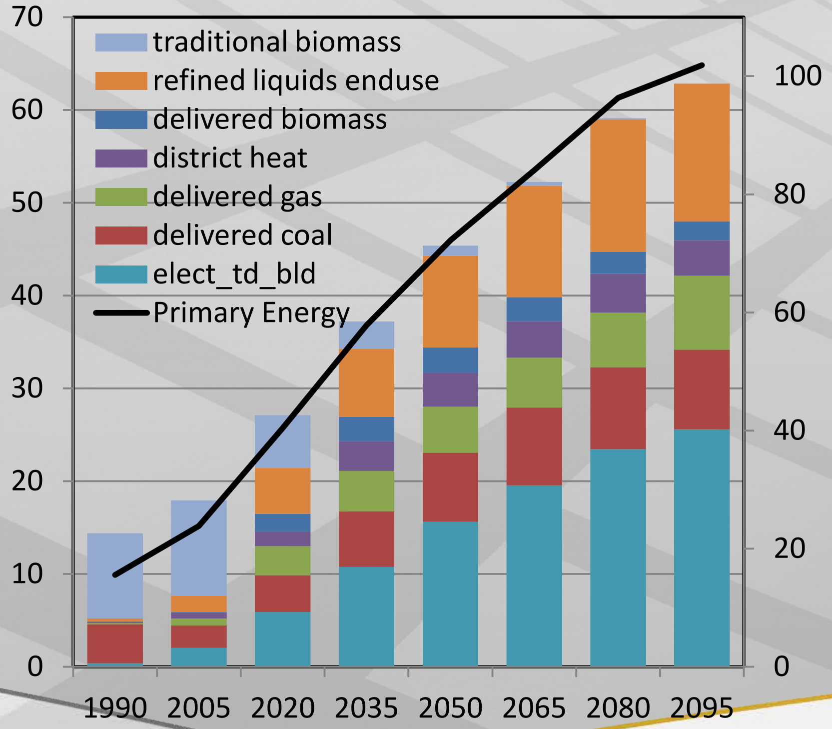
Incorporating IAV

- Integrated models have been “soft-coupled” to impacts models before, often for understanding agricultural impacts
- But in addition, would prefer to examine impacts and potential response strategies to other sectors, some of them of immediate importance to the DOE mission
- Addressing impacts and adaptation strategies can only sensibly be done with more careful attention to geographic specificity and more sophisticated process representation

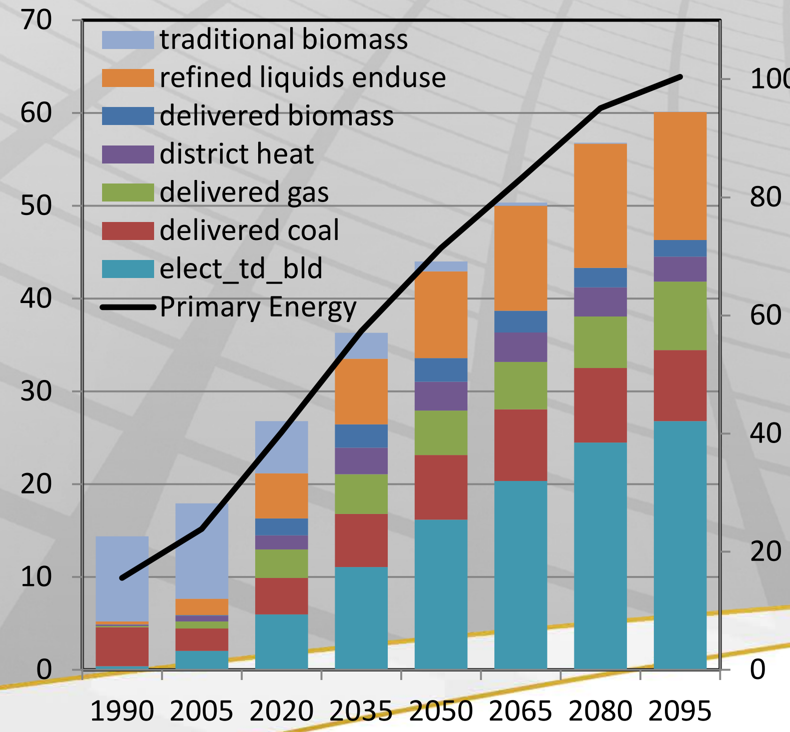
Effects of Changing Degree Days on Chinese Building Energy Consumption:

The Reference Case of China Buildings

Fixed HDD of 2158
Fixed CDD of 1046

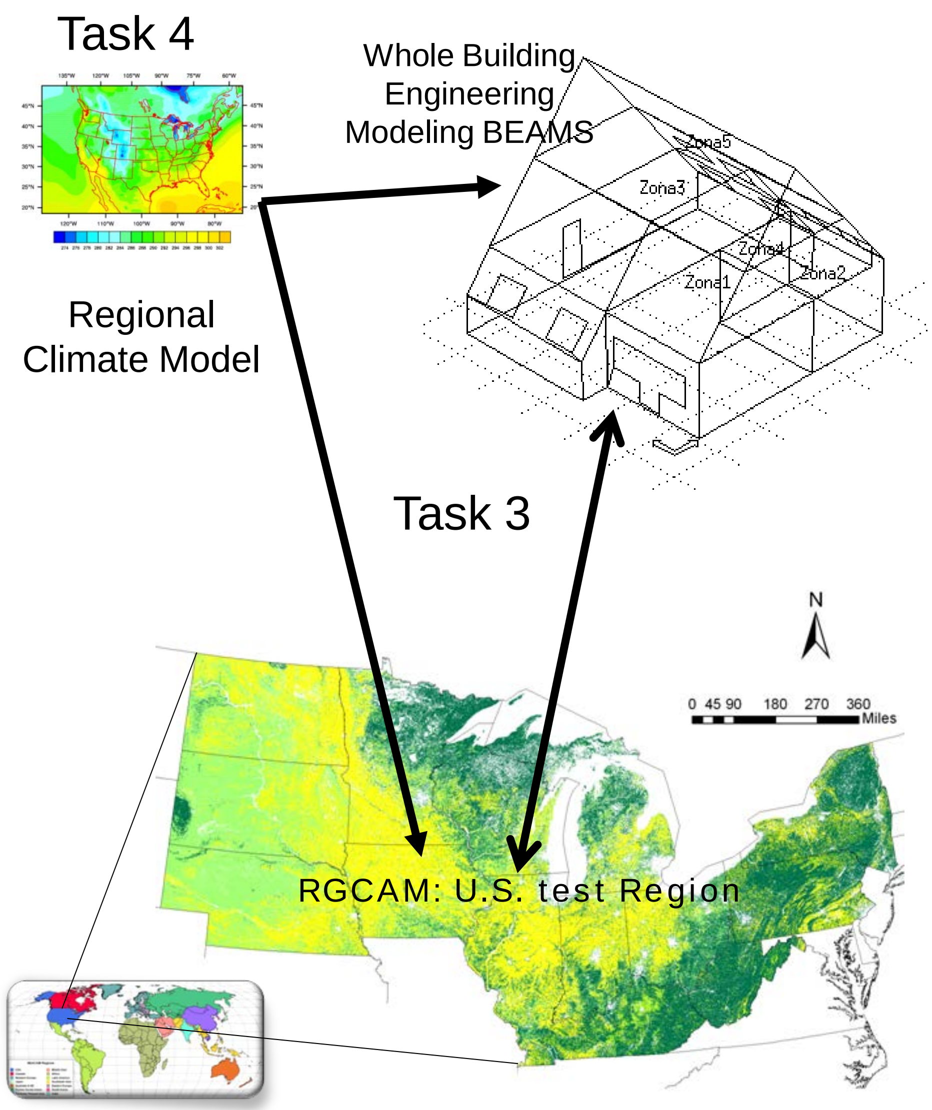


HDD decreasing from 2158 to 1458
CDD increasing from 1046 to 1746



Pacific Northwest NATIONAL LABORATORY
Proudly Operated by Battelle Since 1965
UNIVERSITY OF MARYLAND

Buildings Demand Modeling



BEAMS Model

- ~4000 buildings will be simulated in EnergyPlus to represent the buildings in the RGCAM U.S. test region:
  - 4 climate zones
  - 11 commercial building types
  - 3 residential building types
  - 6-9 sizes within each building type
  - 7-8 vintages of existing buildings and 3 vintages of new buildings
- Building characteristic vary for each combination of attributes
- Hourly (8760 hours) electrical output used to calibrate models and determine building weights based on actual weather and actual hourly electric consumption for test region.
- Our challenge is to pass data back and forth between BEAMS and R-GCAM.

Climate Impacts on Agricultural Ecosystems and Bioenergy

- EPIC is a process-level model of agricultural production
  - Initially developed by USDA, now developed at multiple institutions
  - JGCRI leads development of carbon cycle and greenhouse gases in EPIC
  - Has been applied in many studies of climate impacts on agriculture and is easily linked to climate model projections
- Integration of GCAM and EPIC has a long history
  - Offline hand-offs of data in prior studies
  - Mis-match in scale always limited the interaction
- New developments in both models provide a new opportunity
  - Subregionalization of GCAM AgLU and development of R-GCAM
  - Development of region-wide application system for EPIC through the Great Lakes Bioenergy Research Program

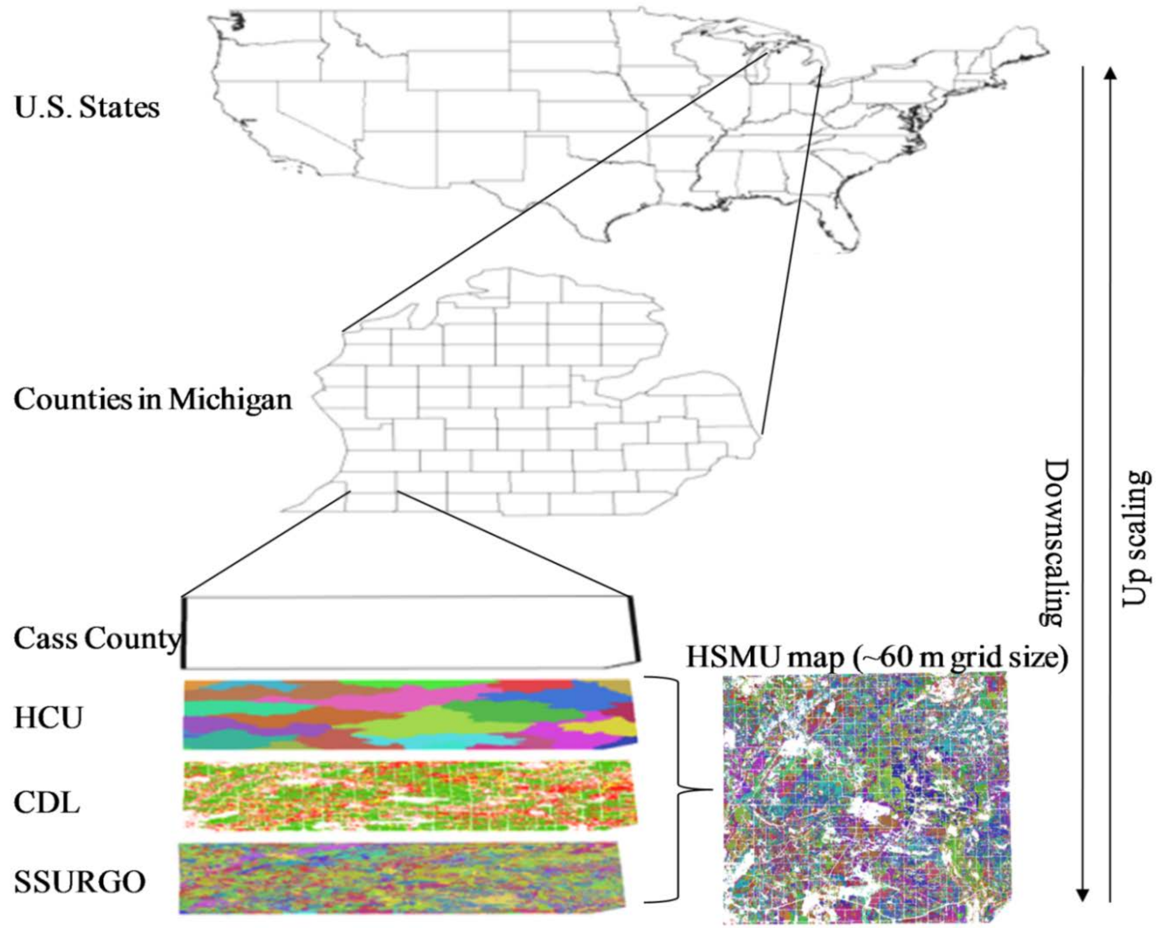
EPIC Application for R-GCAM

EPIC can simulate multiple ***potential*** crops (including bioenergy) and management practices.

Results are scalable to political units in R-GCAM

This approach will

1) Provide an improved, ***consistent*** calibration data set for R-GCAM
2) Establish an approach for ***process-based climate impacts on agriculture*** in R-GCAM



Zhang et al., 2010, GCB Bioenergy, doi: 10.1111/j.1757-1707.2010.01046.x

New Projects on Climate Impacts on Forest Ecosystems and the Implications for Carbon Mitigation

- Couple GCAM with the Ecosystem Demography model
  - How can remote sensing and mechanistic ecosystem models be used to improve integrated assessments of coupled human-forest dynamics?
  - Evaluate afforestation and bioenergy mitigation opportunities
- Ecosystem disturbance in GCAM
  - How could disturbance, such as from hurricanes and forest fires, influence the carbon cycle and the ability of ecosystems to supply fiber and bioenergy?
  - Will change in such disturbances influence mitigation from terrestrial systems?

Linking Climate Models and Other Communities

- Challenge of beginning to incorporate climate feedbacks on both energy and land processes within the framework of an integrated model
- Moving from a one-way pass of information (IAM to GCM) to an evaluation of feedbacks in the evolution of the energy-land-climate system
- Requires moving from reduced form representation of the climate system in IAM frameworks to a sophisticated representations, including coupling with full GCMs/ESMs

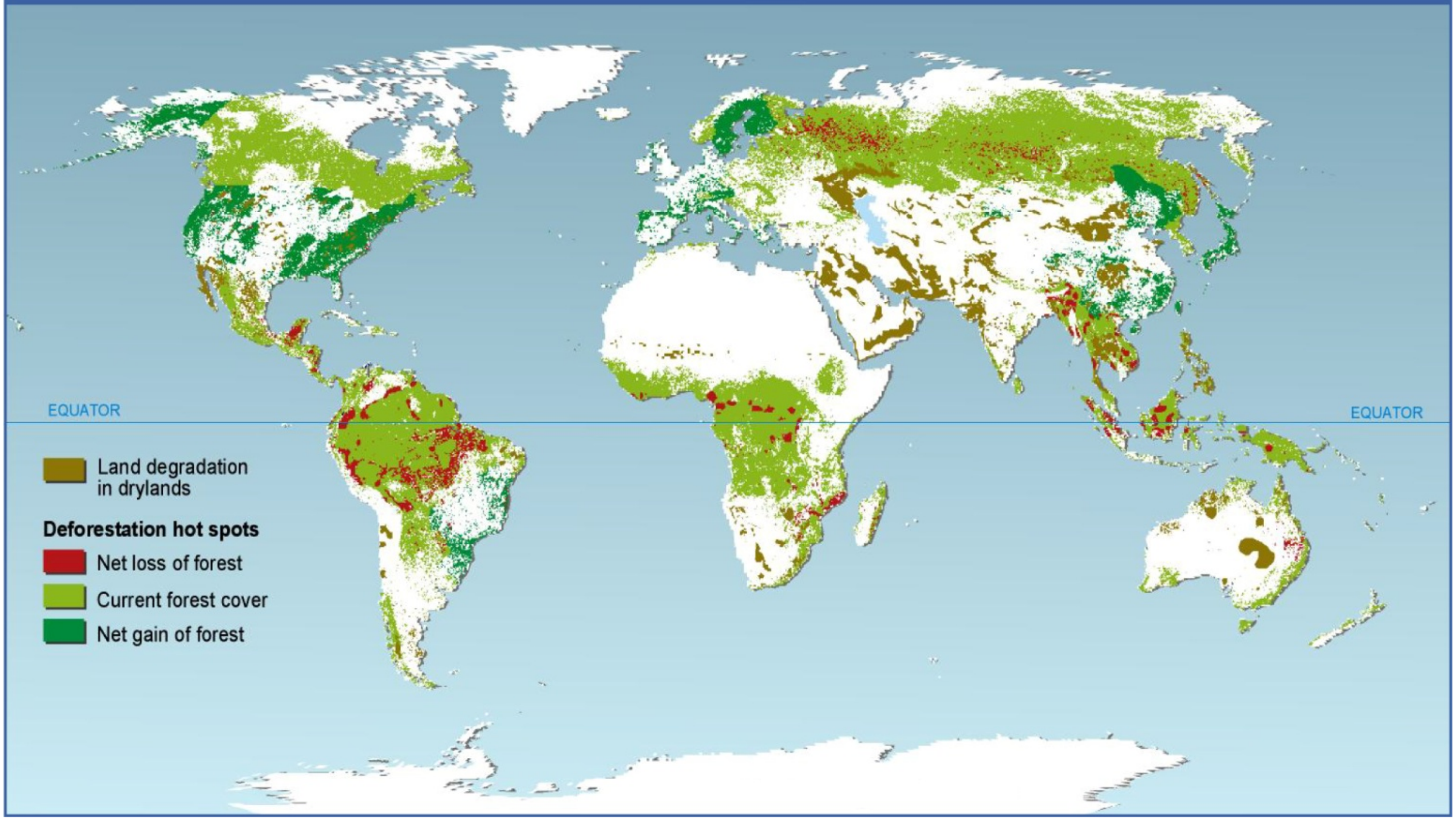
Coupling with Earth System Models: Why Would We Do This?

- Existing Earth System Models are already enormous complex
- Fully coupled AOGCM's with interactive C (and N) cycles, DGVM's, including some aspects of disturbance
- Although there is a growing literature on individual models, as a group, their performance is not yet well understood
- CMIP5 process really the first major community effort to begin to understand their performance in a systematic way
- But these models still are specifying initial land-cover, and at most are simulating changes in potential natural vegetation over time
- And they continue to specify the energy and land-use contributions to increasing CO_2 concentrations in the atmosphere

Why is Specifying Land-Cover and Land-Use a Problem?

- The effects of human activities are the largest direct driver of changes and processes on most of the terrestrial biosphere
  - About half of original forest area converted to agricultural production
  - Roughly doubled the amount of biologically available nitrogen
  - Increases in atmospheric concentrations of CO_2
  - Biggest contribution to loss of biological diversity
- We understand in general terms why many of the transformations have happened
- We can document and observe many of the recent changes

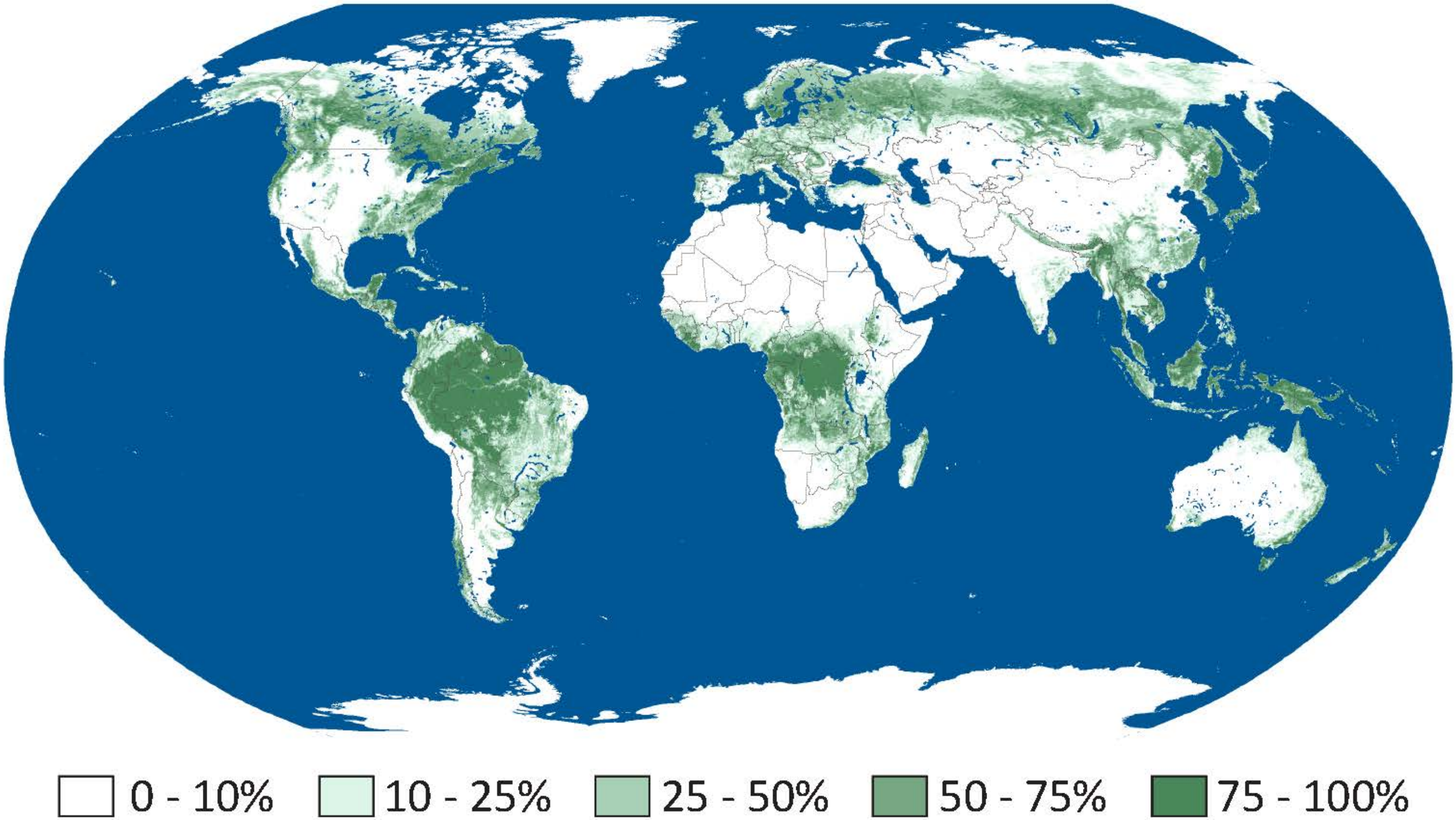
Forest Cover and Land Degradation Change from 1980-2000



Observation

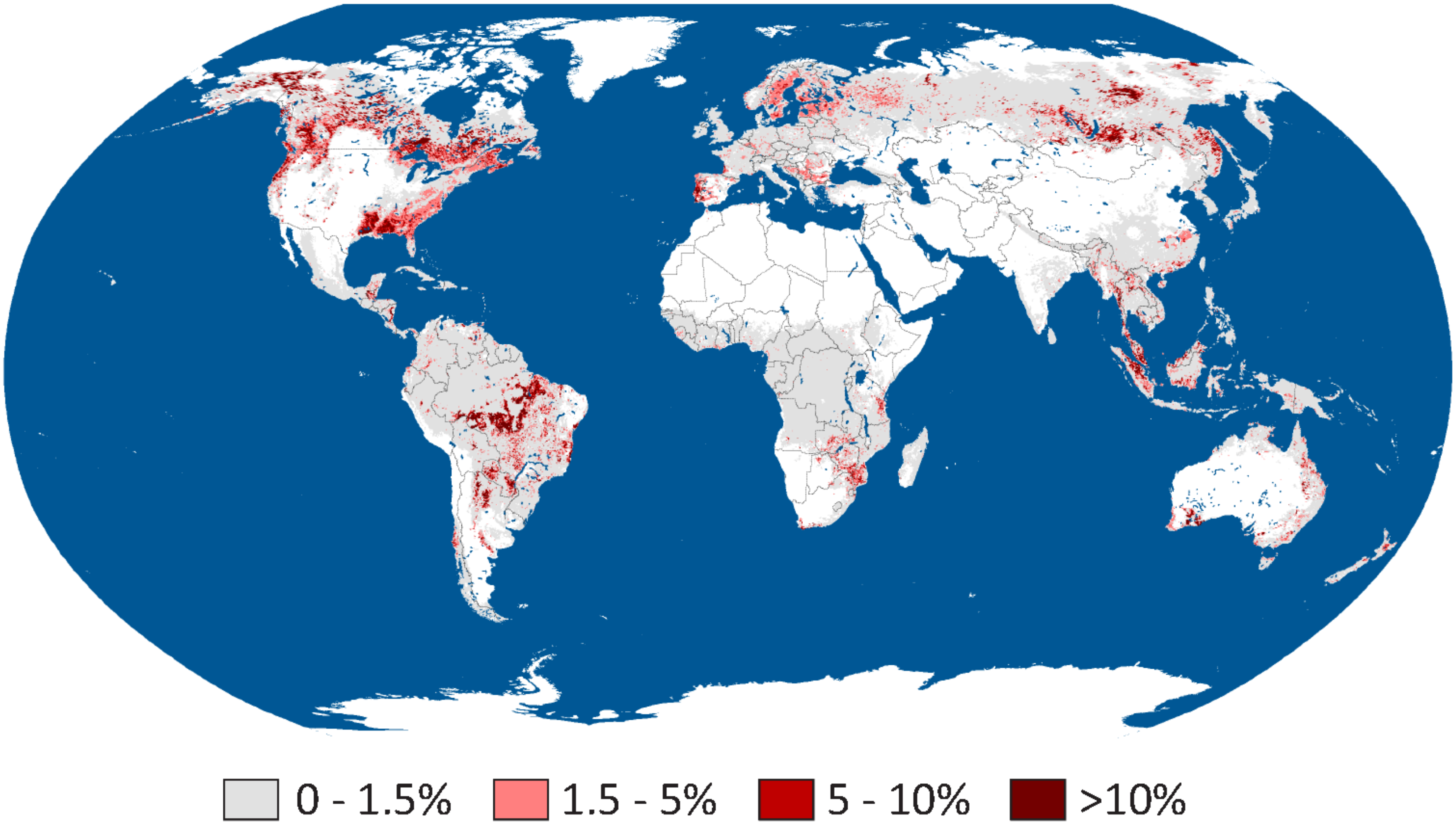
- Our ability to document land-cover change in a quantitative, replicable way is improving very quickly
- Better for forested systems than agricultural systems
- But the community can now do time series analyses and changes very quickly

Percent forest cover, 2000



Pacific Northwest NATIONAL LABORATORY
Proudly Operated by Battelle Since 1965
UNIVERSITY OF MARYLAND

Percent forest cover loss, 2000 to 2005



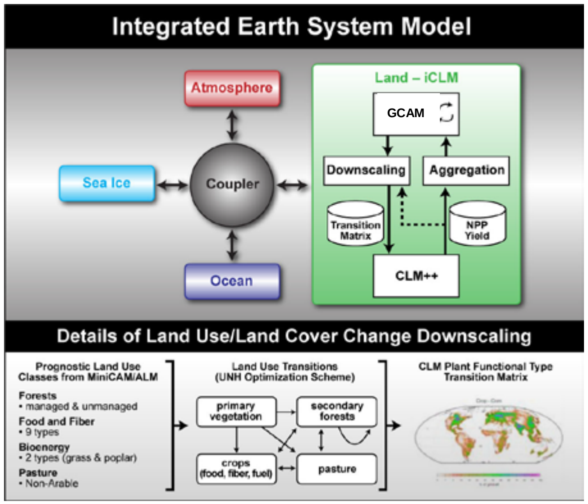
Pacific Northwest NATIONAL LABORATORY
Proudly Operated by Battelle Since 1965

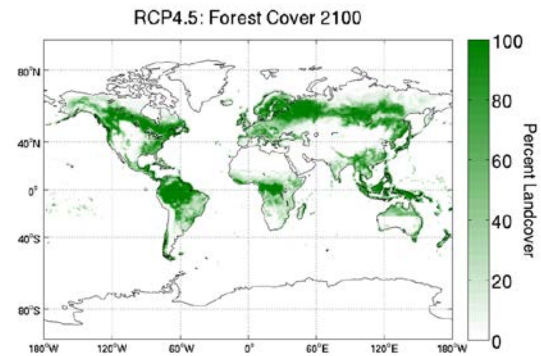
UNIVERSITY OF MARYLAND

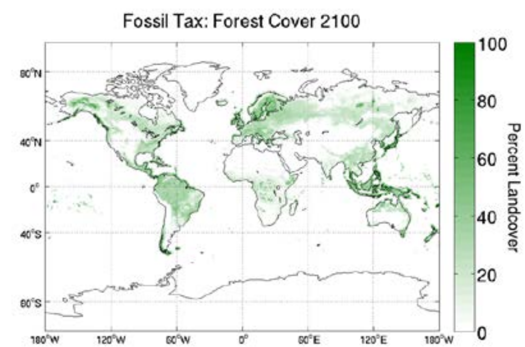
Where Do ESM Projections Come From?

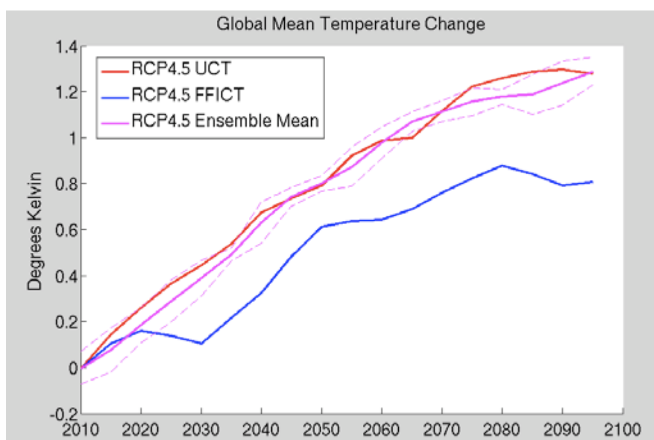
- Either very simple-minded (1% increase per year, through 2100)
- Or from the output of Integrated Assessment Models
- Simulate the changes in mix of energy technologies regionally and globally as a consequence of different choices about carbon concentrations, energy policy, technology diffusion, etc.
- But at the same time, we know from decades of carbon cycle research that meeting demands for energy and meeting demands for agricultural production are part and parcel of the increases in atmospheric CO_2
- So must increasingly focus on the interaction of land-use and the energy system

iESM Preliminary Results









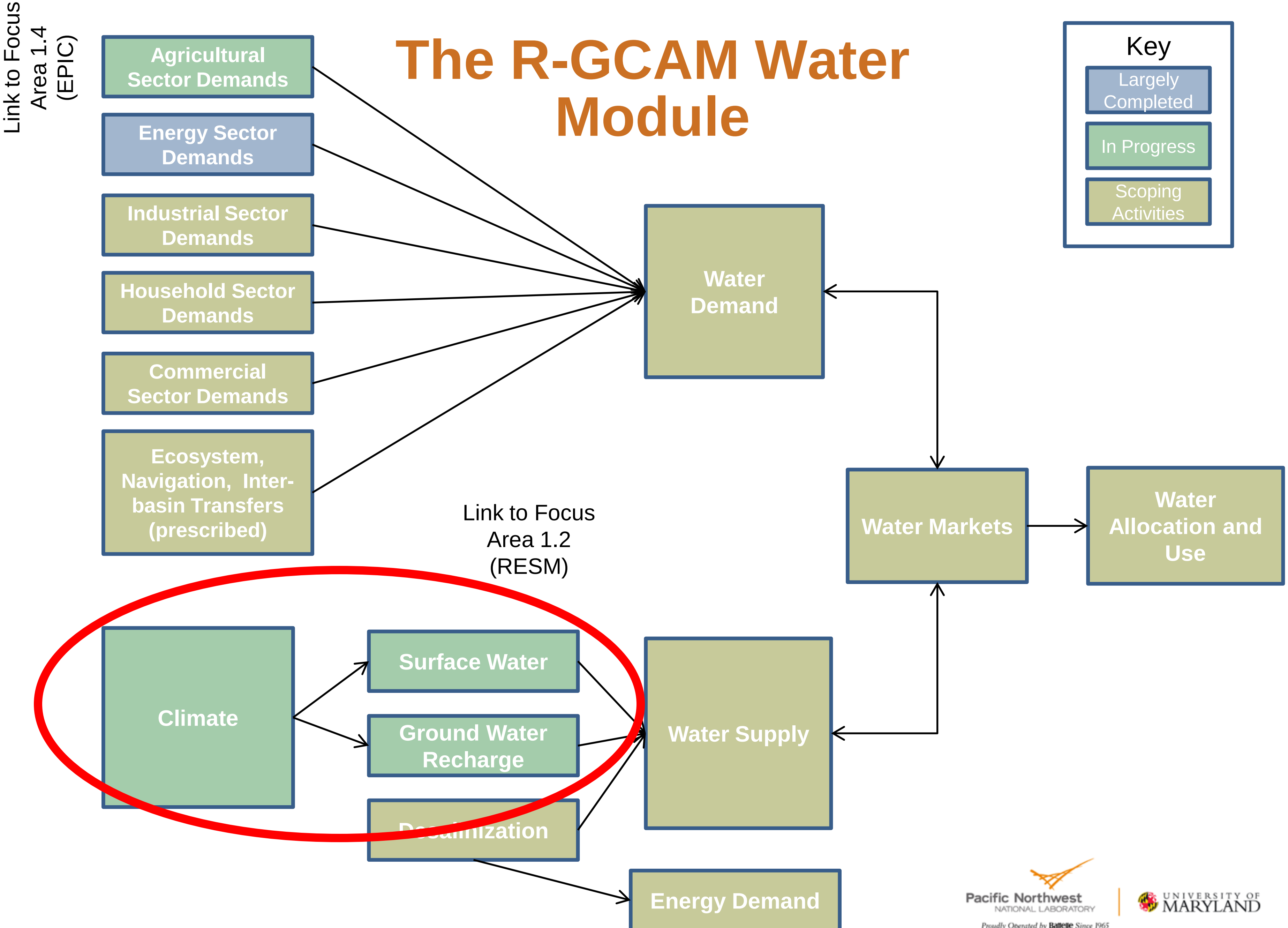
Pacific Northwest NATIONAL LABORATORY
Proudly Operated by Battelle Since 1965

UNIVERSITY OF MARYLAND

Representing Complex Interactions: Energy/Water/Land

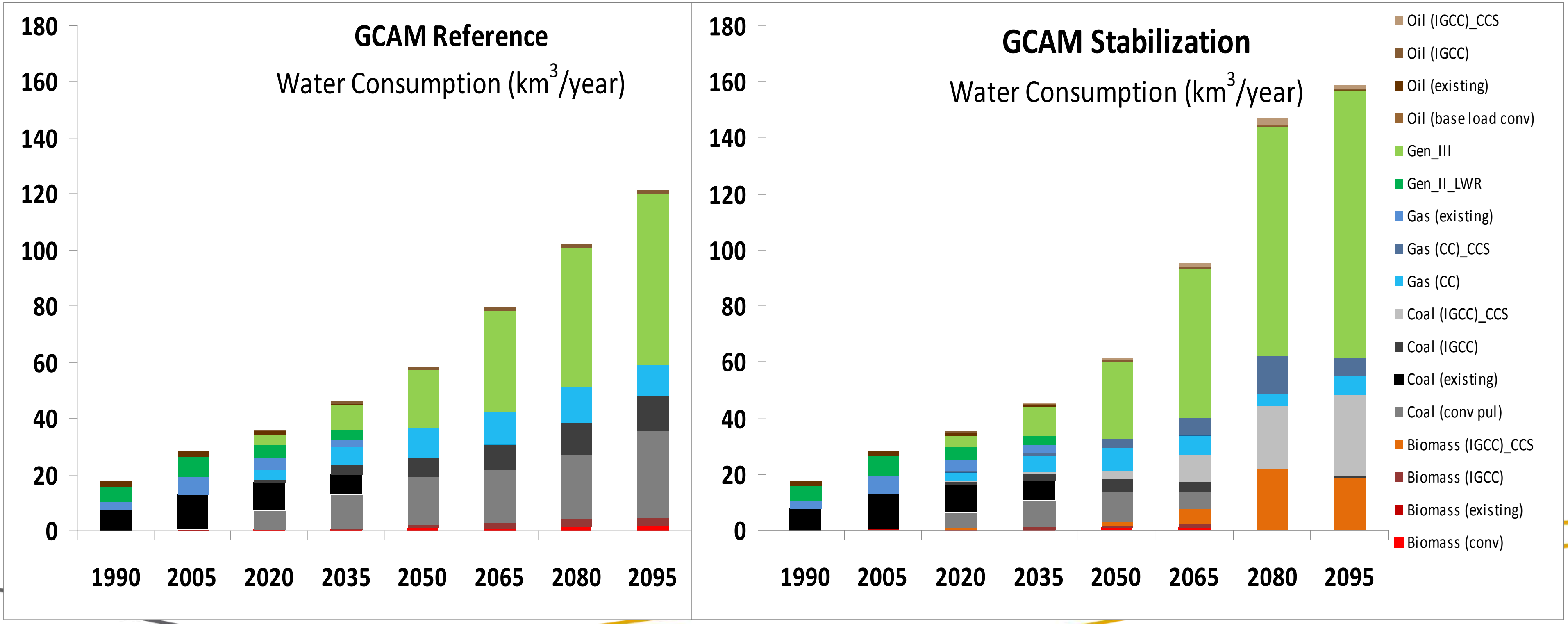
- In the real world, energy demand and use are contingent on the availability of both land and water resources
- Have typically analyzed these as though they were independent of each other and of variation in the climate system – e.g. assumed that there was plenty of water to satisfy energy demand, or have assumed there was plenty of land to satisfy increased demand for agricultural productivity and bioenergy
- But how constraining are these factors? Must be included in the accounting of IAMs to understand how they interact with each other and with the climate system

The R-GCAM Water Module



Development of water use accounting for the energy sector

- Water consumption by energy generation technologies



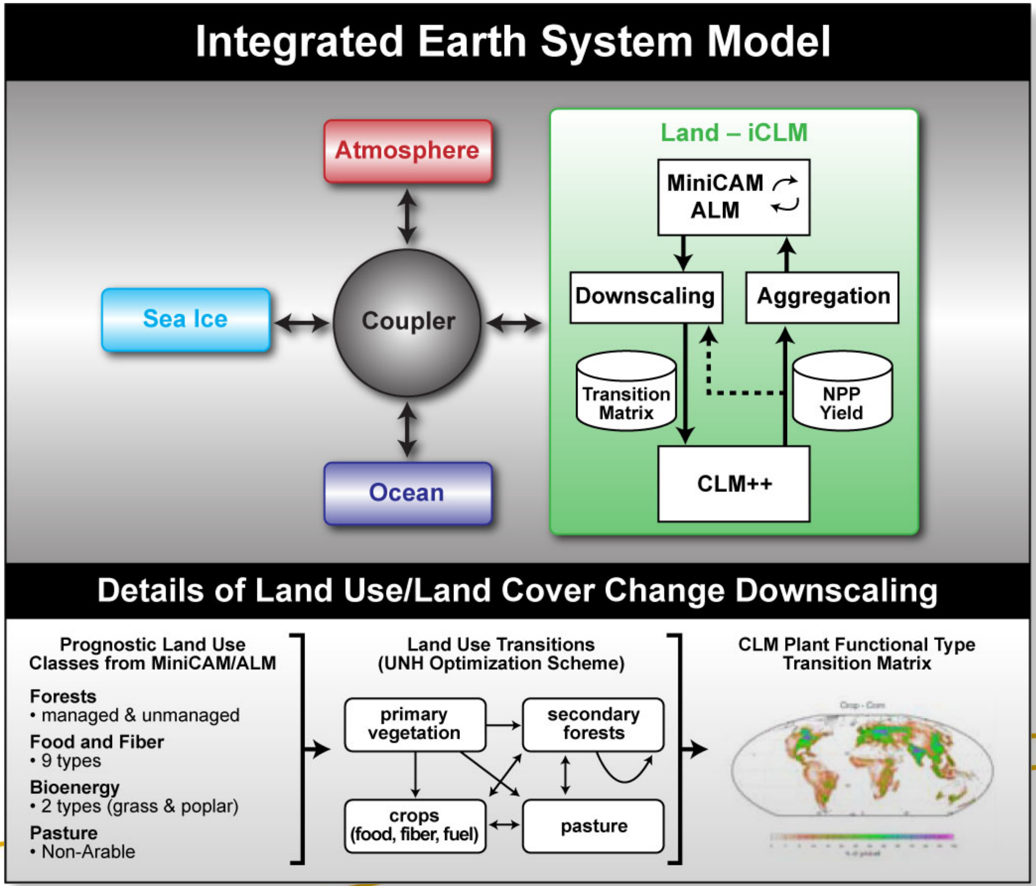
Davies and Kyle, 2009

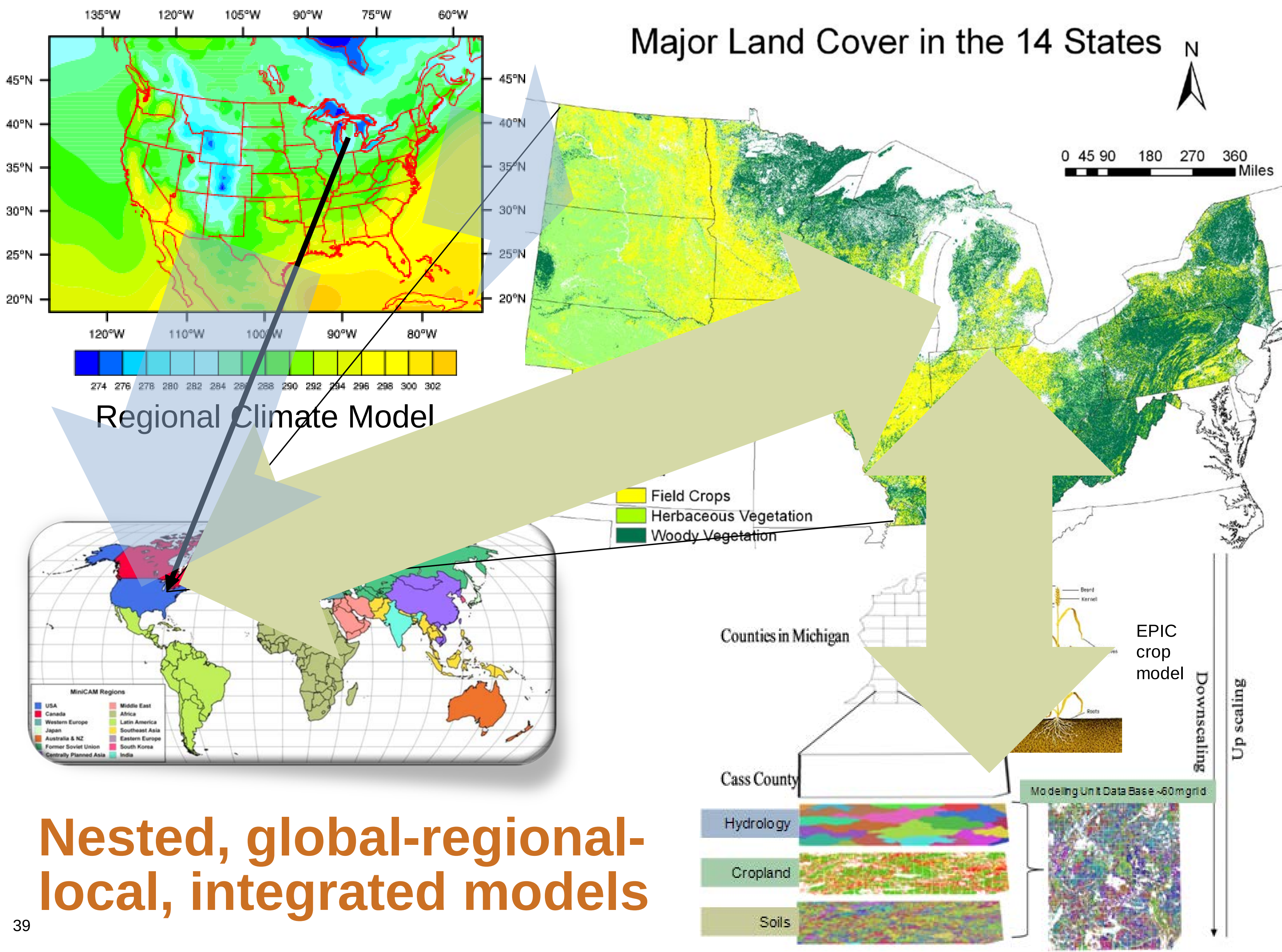
Pacific Northwest National Laboratory
Proudly Operated by Battelle Since 1965
University of Maryland

Integrated modeling biofuels and feedbacks

Objectives of iESM team:

- Investigate biofuel sustainability under future climate change.
- Study feedbacks from climate and CO_2 to the energy markets (phases 2 and 3)
- Quantify irrigation demand/costs for biofuels and energy markets.





Nested, global-regional-local, integrated models

Characterizing Uncertainties

- This is a bigger challenge than the technically demanding problem of parameter estimation in complex models – focus of many UQ efforts
- How do we think about characterizing a variety of uncertainties about the future characteristics of features of integrated energy-land-climate systems that affect the drivers of change?
- How do different models perform on similar tasks?
- How do we map the many possible combinations of parameters in an arbitrary number of scenarios?

FOUR RCPs developed by the IAMC to provide emissions scenarios to the climate/Earth system modeling (ESM) community to jumpstart the assessment process.

▶RCP8.5 (IIASA/MESSAGE)

- >8.5 W/m^2 in 2100,
- Rising

▶RCP6.0 (NIES/AIM)

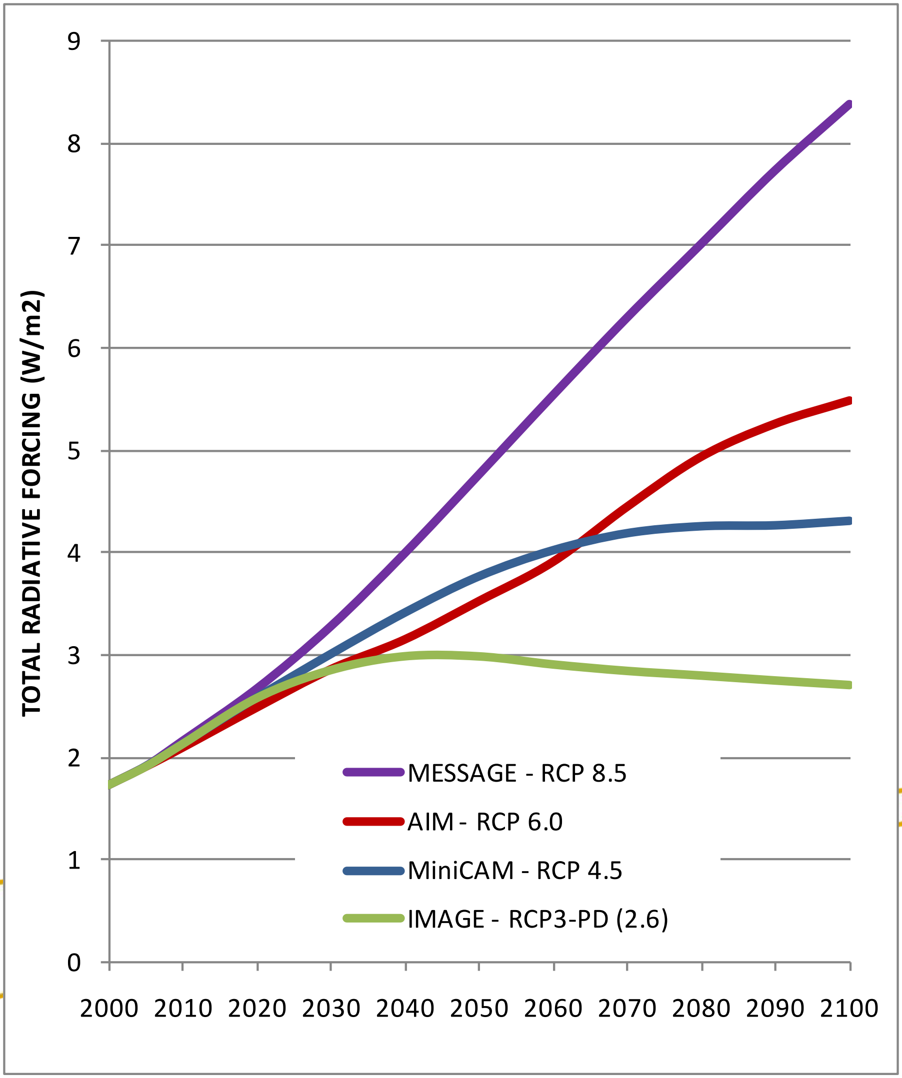
- ~6 W/m^2 at stabilization after 2100
- Stabilization without exceeding target

▶RCP4.5 (PNNL/MiniCAM)

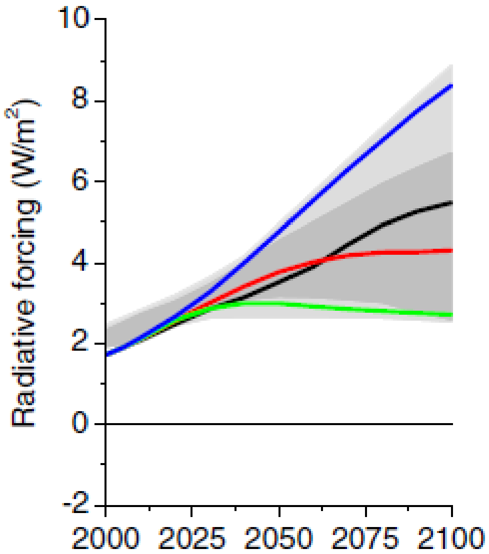
- ~4.5 W/m^2 at stabilization after 2100
- Stabilization without exceeding target

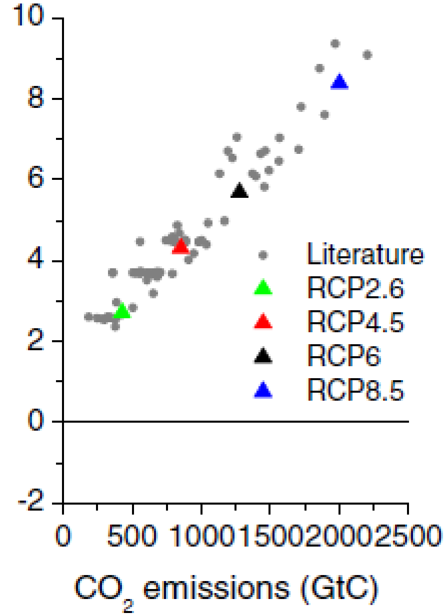
▶RCP2.6 (PBL/IMAGE)

- <3 W/m^2 in 2100
- peak & decline stabilization

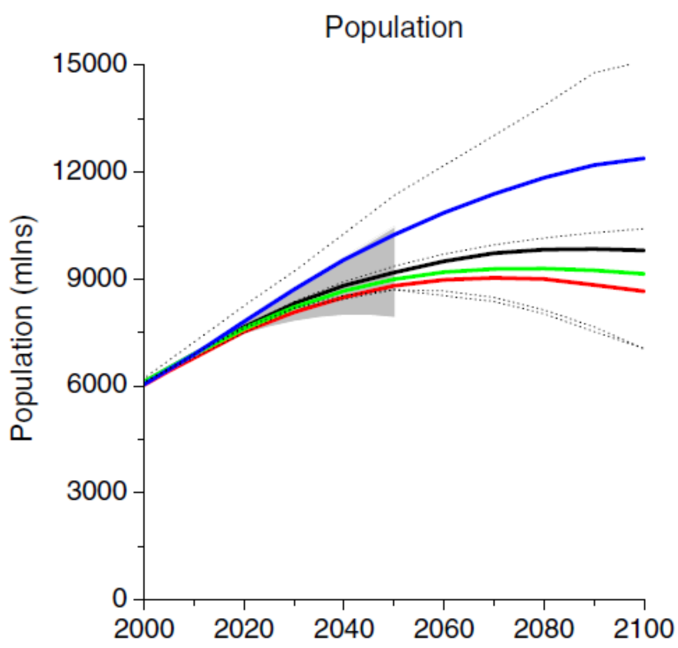


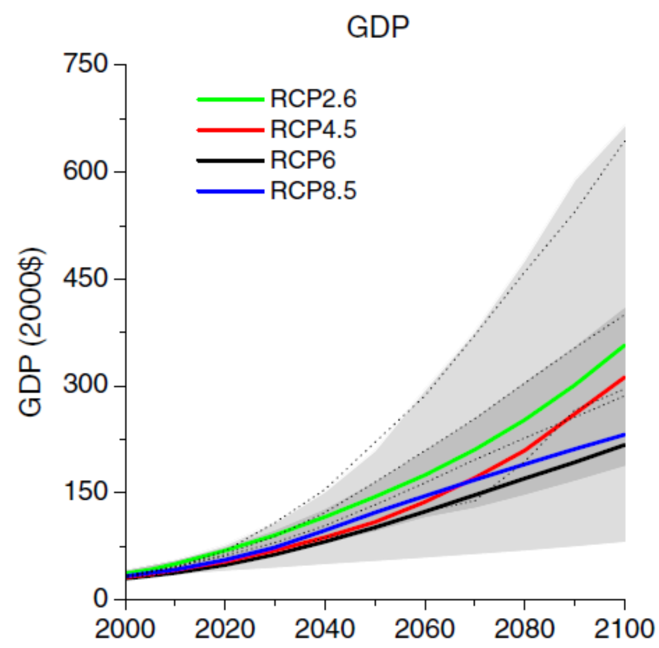
Selected scenarios in context of the literature



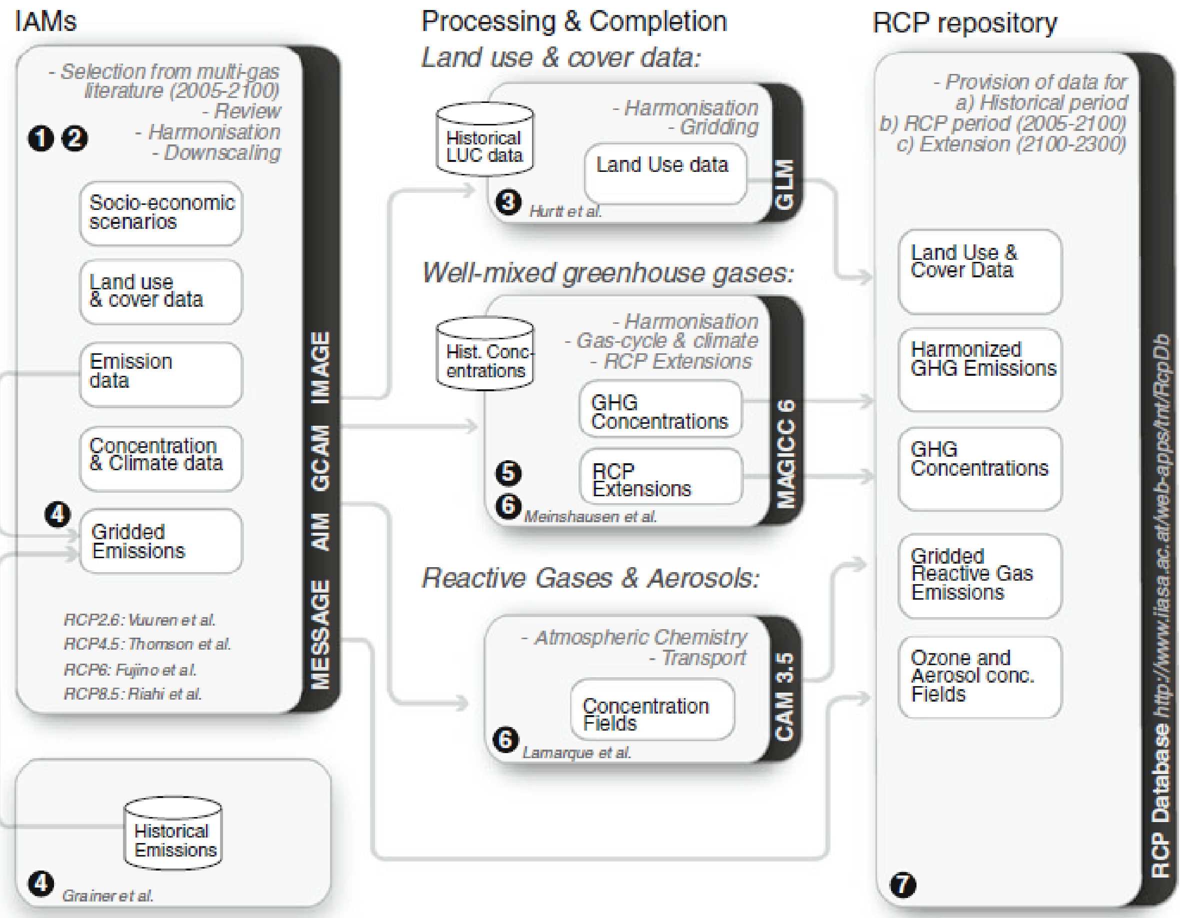


- The RCPs span the range of literature on future radiative forcing
- NOT designed to span range of socio-economic futures





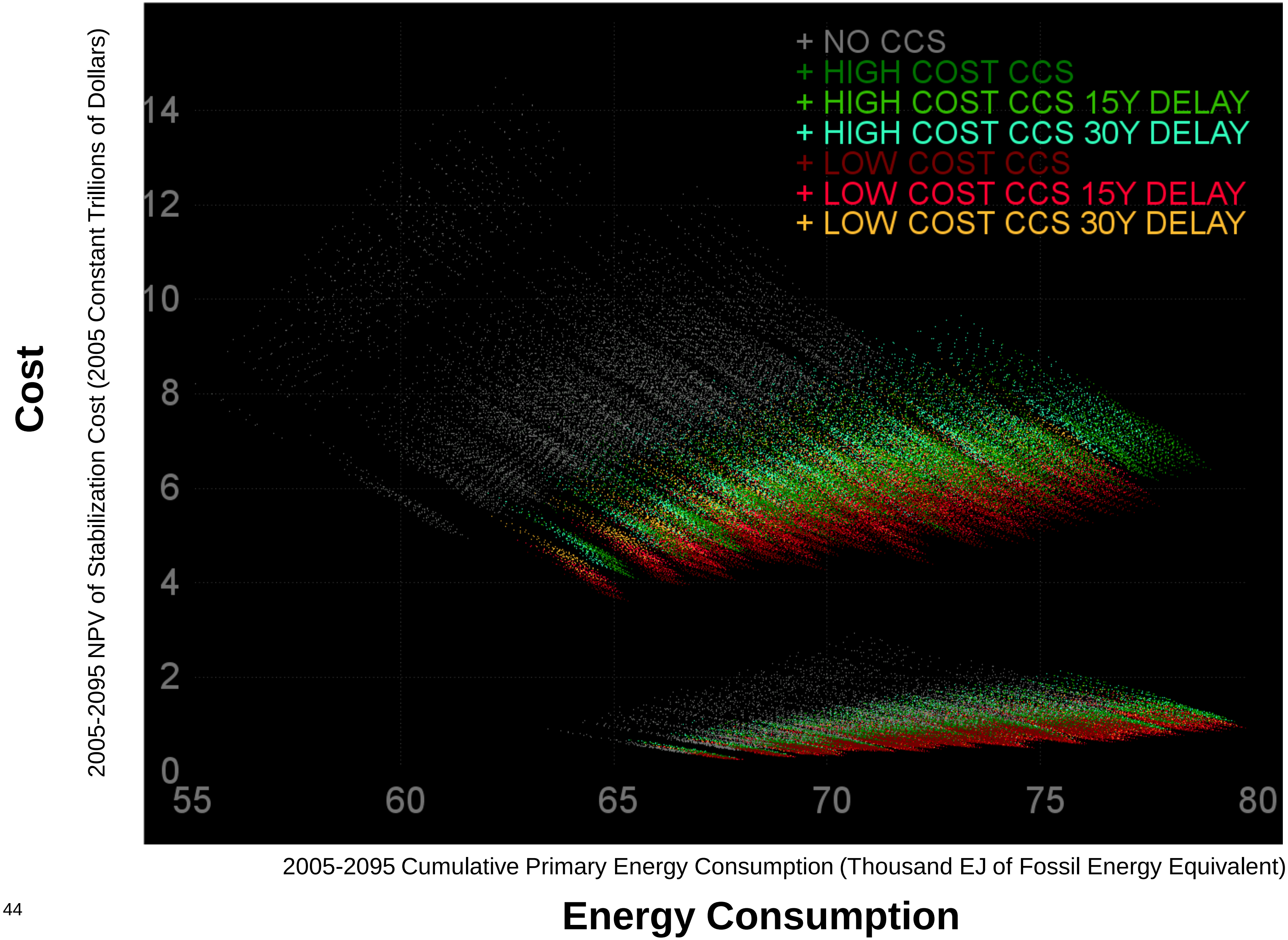
Special Issue on RCPs



1. Overview (van Vuuren et al.)
2. MESSAGE paper (Riahi et al.)
3. AIM paper (Matsui et al.)
4. GCAM paper (Thomson et al.)
5. IMAGE paper (van Vuuren et al.)
6. Land use paper (Hurtt et al.)
7. Emission inventory (Garnier et al.)
8. Atm. Chem. (Lamarque et al.)
9. GHG conc./extension (Meinshausen et al)

Published in *Climatic Change*

The Galaxy of 161k Technology Combinations



Community Modeling

- Have needed to find a way to harness the ingenuity and energy of a broader community
- Have now fully implemented GCAM in a community modeling framework
  - Strict version control of the core model
  - Allowing research versions to proliferate
- Over 70 research groups around the world have already started using GCAM, and tailoring it to their own purposes
- About to have the second International Users Conference

Long term evolution of building energy services and fuel choices in India

•More than 45% of total final energy in India consumed in the residential and commercial building sector (WEO 2007), understanding long term evolution critically important.

•Significant difference in rural and urban energy consumption profiles.

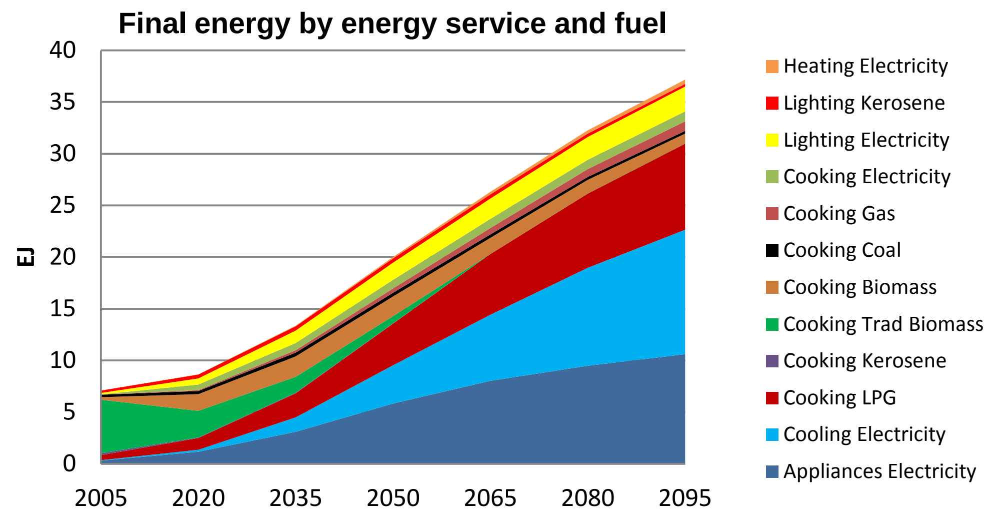
RESULTS

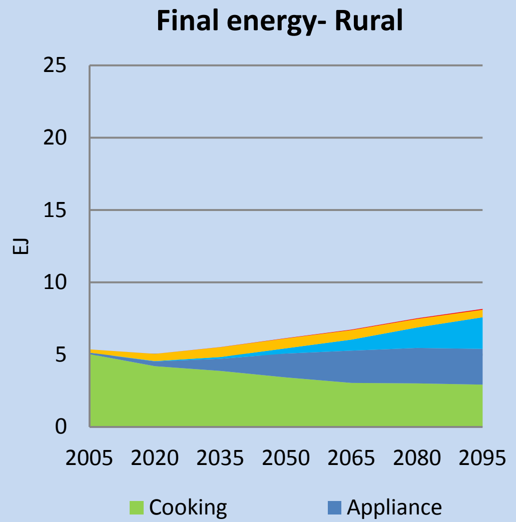
•Cooling energy service and appliances/ equipment energy demand to increase rapidly, especially in urban residential sector. Cooking service will also to take a high share.

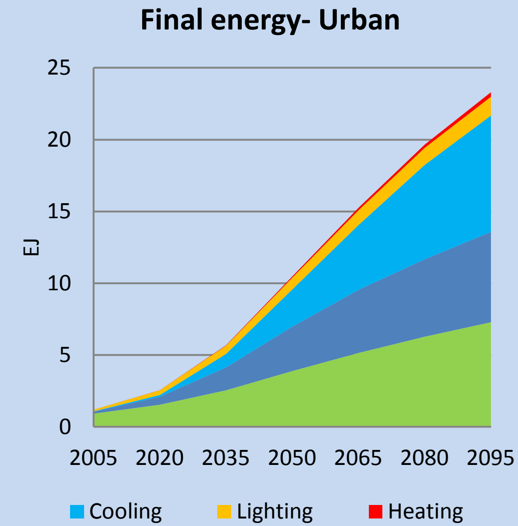
•High reliance on electricity(for cooling, heating and appliances), and gas (particularly LPG, and some NG in urban areas) for meeting cooking energy needs. Limited fuel substitution opportunity exists.

•Low impact of climate policy on reducing final energy demand, as fuel choices limited in Indian building sector unlike other regions of the world.

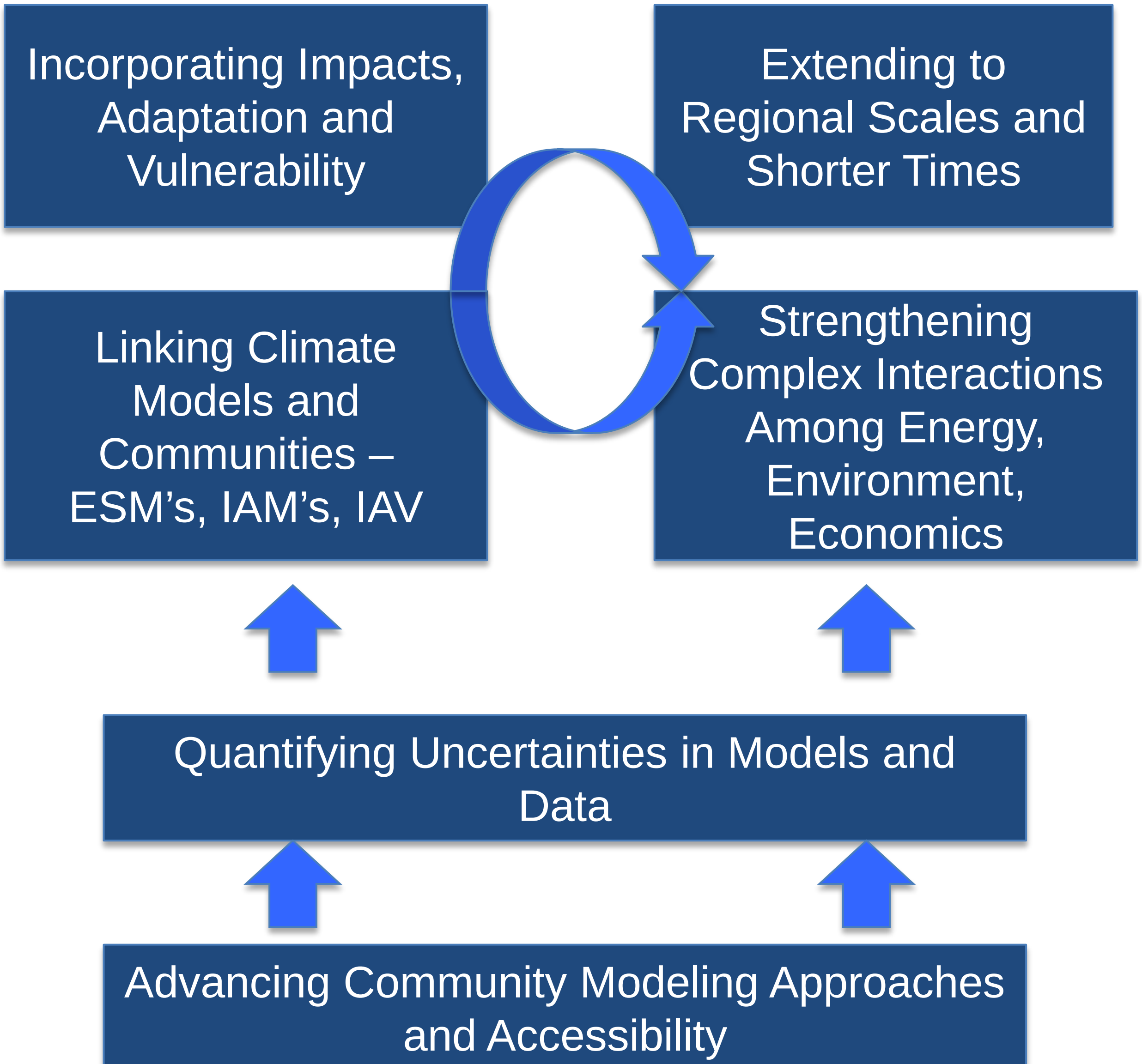
•Alternative energy demand reduction policies needed to significantly reduce demand.







Conclusions



- Significant progress in each area highlighted by the IARP report
- Rapid expansion of capabilities
- Uncovering insights into the interaction of human decision-making and Earth system processes

Pacific Northwest NATIONAL LABORATORY
Proudly Operated by Battelle Since 1965
UNIVERSITY OF MARYLAND