Unifying land modeling across NCAR:
The Community Terrestrial System Model (CTSM)

Martyn Clark, Dave Lawrence, Bill Sacks, Michael Barlage, Mariana Vertenstein, Gordon Bonan, Rosie Fisher, Fei Chen, Andy Wood, David Gochis, Ned Patton, and Roy Rasmussen

Land model working group meeting
2 March 2017

Outline

- CTSM Motivation
  - Land modeling challenges
  - Ad-hoc approaches to model development
- CTSM development
  - Underpinnings and structure
  - Development process
- Summary

Motivation

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- Divergence of land modeling efforts

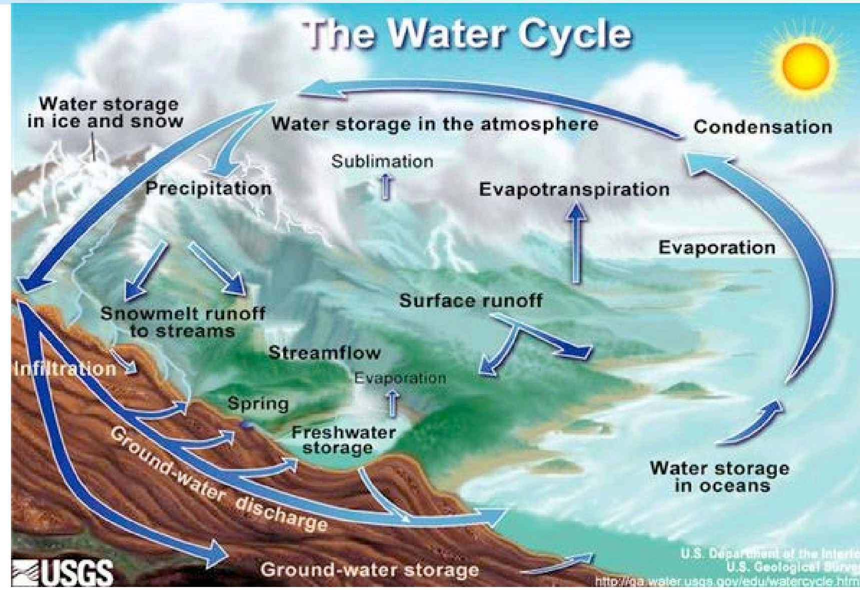
- Development of a community hydrologic model
  - CUAHSI experience
  - CUAHSI project to improve hydrology in CLM
  - CUAHSI community modeling workshop (July 2016)
    (moving beyond the John F. Kennedy philosophy)

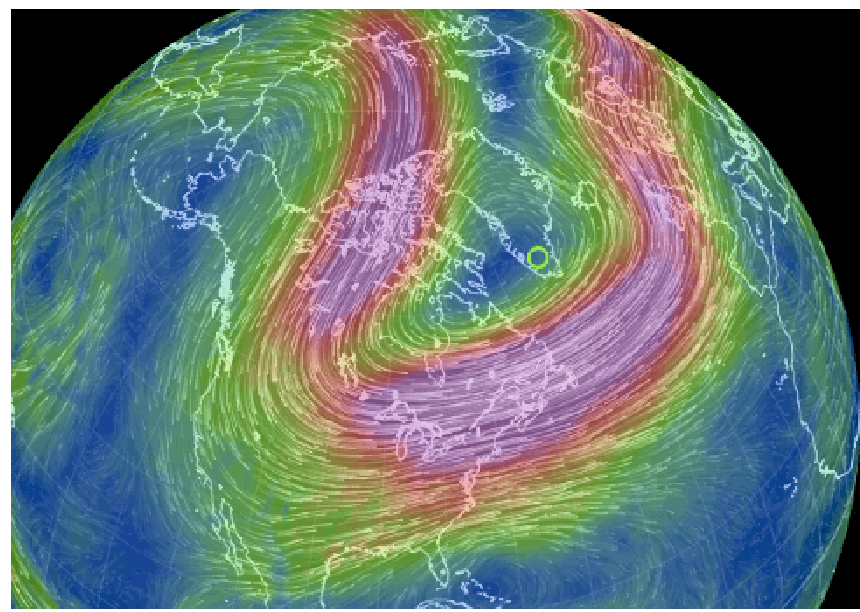
- Increasing recognition that many modeling groups are doing the same thing, and are duplicating effort

- Increasing recognition that classical MIPs are a failure
  - Too many differences across models to attribute inter-model differences to specific modeling decisions
  - Haven't learned much from MIPs, and model development decisions based on the inspiration and experience of individual modelers

Land vs. atmospheric modeling

- Modeling the terrestrial system depends on the (unknown) details of the landscape
- Increases in horizontal resolution often do not lead to improvements in land model performance (especially at larger scales)
- Need creativity in spatial discretization of the model domain
- Land modelers have developed a glut of models that differ in almost every aspect of their conceptualization and implementation

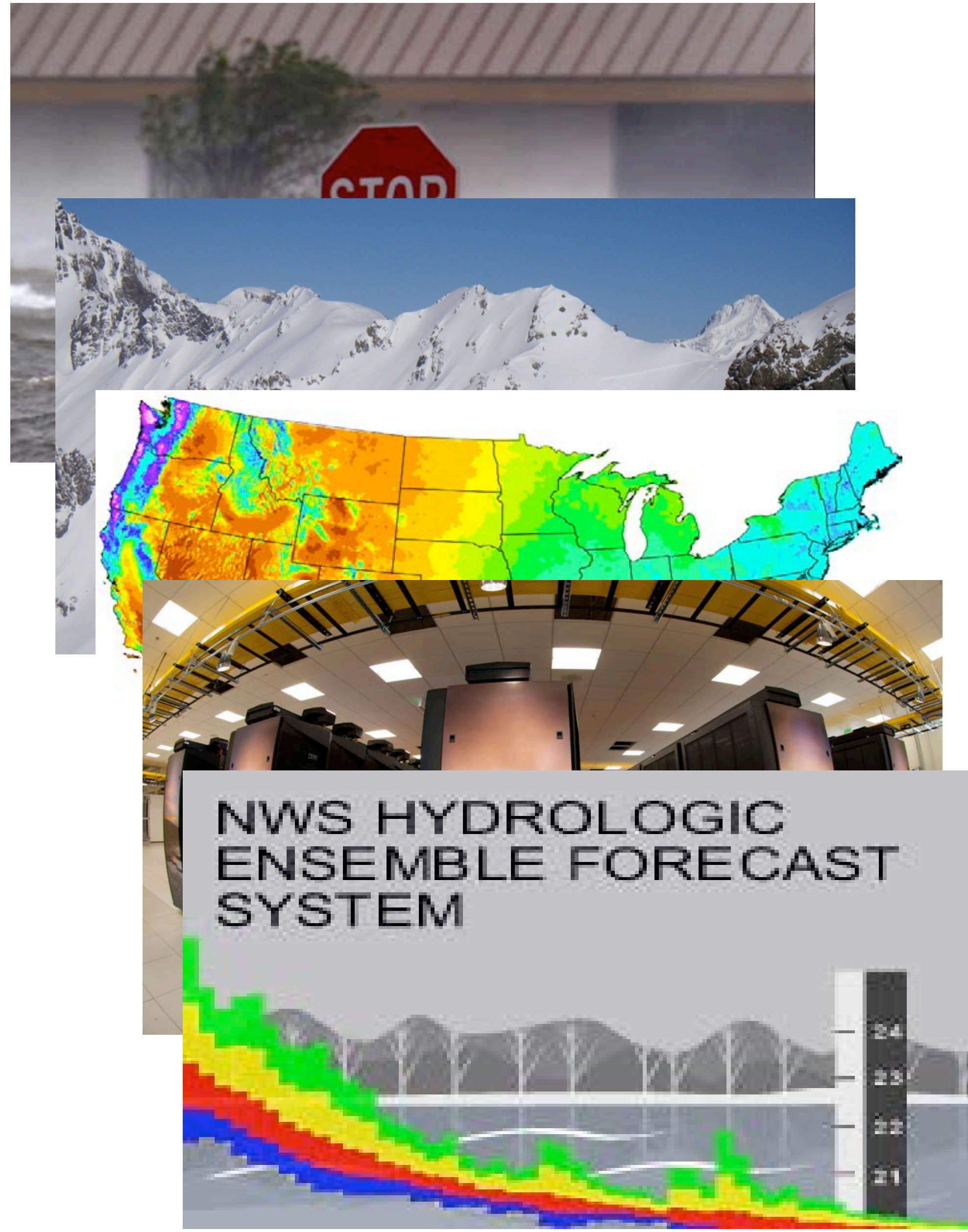




Land modeling challenges

- Define equations to simulate fluxes of water, energy, momentum, and carbon for the different sub-systems within the model domain
- Represent spatial variability across a hierarchy of scales
- Generate information on met. forcing data and model parameters
- Solve the model equations (temporally integrate model eqns)
- Characterize model uncertainty

- *Different modelers have addressed different model development decisions in different ways*
- *This has created a plethora of models that differ in almost every aspect of their conceptualization and implementation*



Two issues: Model proliferation and the shantytown syndrome

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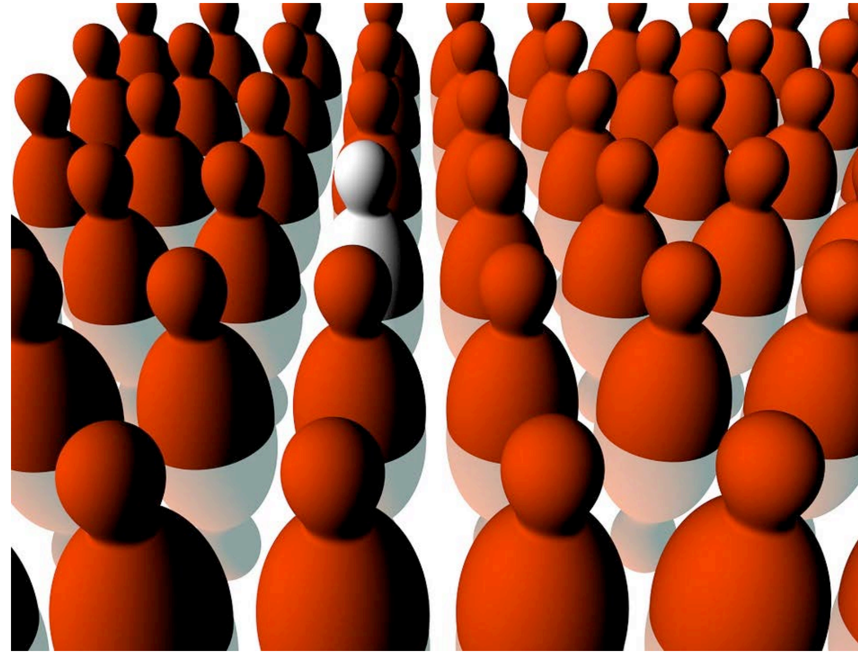
- **Model proliferation**: Every hydrologist has their own model, making different decisions at different points in the model development process

- **The shantytown syndrome**: Ad-hoc approach to model development

- Model proliferation & the shantytown syndrome make it difficult to test underlying hypotheses and identify a clear path to model improvement

- With current model structures, it is easy to incorporate new equations for a given process, ***but very difficult to incorporate new approaches that cut across multiple model components (multi-layer canopy example)***



Two issues: Model proliferation and the shantytown syndrome

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Water Resources Research

COMMENTARY

10.1002/2014WR016731

Do we need a Community Hydrological Model?

Markus Weiler[1] and Keith Beven[2,3,4]

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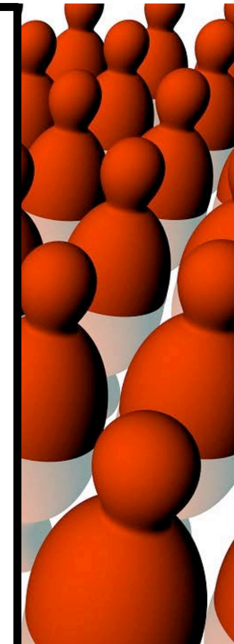
Abstract We believe that there are too many models in hydrology and we should ask ourselves the question, if we are currently wasting time and effort in developing another model again instead of focusing on the development of a Community Hydrological Model. In other fields, this kind of models has been quite successful, but due to several reasons, no single community model has been developed in the field of hydrology yet. The concept, strength, and weakness of a community model were discussed at the Chapman Conference on Catchment Spatial Behaviour and Complex Organisation held in Luxembourg in September 2014. This discussion as well as our own opinions about the potential of a community models or at least the ... are debated in this commentary.



A unifying framework is needed

- Define a "master modeling template" from which multiple existing models can be derived
- Step back, consider what we have learned in the last few decades, and develop the next-generation hydrologic/land model adopting best modeling practices and modern programming standards

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CTSM underpinnings

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Water Resources Research

RESEARCH ARTICLE

10.1002/2015WR017198

Companion to *Clark et al.* [2015], doi:10.1002/2015WR017200.

A unified approach for process-based hydrologic modeling: 1. Modeling concept

Martyn P. Clark[1], Bart Nijssen[2], Jessica D. Lundquist[2], Dmitri Kavetski[3], David E. Rupp[4],
Ross A. Woods[5], Jim E. Freer[6], Ethan D. Gutmann[1], Andrew W. Wood[1], Levi D. Brekke[7]

Key Points:
- Modeling template formulated u
  a general set of conservation equations
- Evaluation focuses on flux parameterizations and spatial variability/connectivity
- Systematic approach helps impro
  model fidelity and uncertainty characterization

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Water Resources Research

RESEARCH ARTICLE

10.1002/2015WR017200

Companion to *Clark et al.* [2015], doi:10.1002/2015WR017198.

A unified approach for process-based hydrologic modeling: 2. Model implementation and case studies

Martyn P. Clark[1], Bart Nijssen[2], Jessica D. Lundquist[2], Dmitri Kavetski[3], David E. Rupp[4], Ross A. Woods[5], Jim E. Freer[6], Ethan D. Gutmann[1], Andrew W. Wood[1], David J. Gochis[1], Roy M. Rasmussen[1], David G. Tarboton[7], Vinod Mahat[8], Gerald N. Flerchinger[9], and Danny G. Marks[9]

Key Points:
- Flexible model implementation enables evaluation of key modeling decisions
- Case studies illustrate capabilities t
  identify preferable modeling approaches
- Accelerates improvements in mode
  fidelity & uncertainty characterizati

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REVIEW ARTICLE

10.1002/2015WR017096

Special Section:
The 50th Anniversary of Water Resources Research

Improving the representation of hydrologic processes in Earth System Models

Martyn P. Clark[1], Ying Fan[2], David M. Lawrence[1], Jennifer C. Adam[3], Diogo Bolster[4], David J. Gochis[1], Richard P. Hooper[5], Mukesh Kumar[6], L. Ruby Leung[7], D. Scott Mackay[8], Reed M. Maxwell[9], Chaopeng Shen[10], Sean C. Swenson[1], and Xubin Zeng[11]

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Key Points:
- Land model development can benefit from recent advances in hydrology
- Accelerating modeling advances requires comprehensive benchmarking activities
- Stronger collaboration is needed between the hydrology and ESM modeling communities

Development of a unifying model framework

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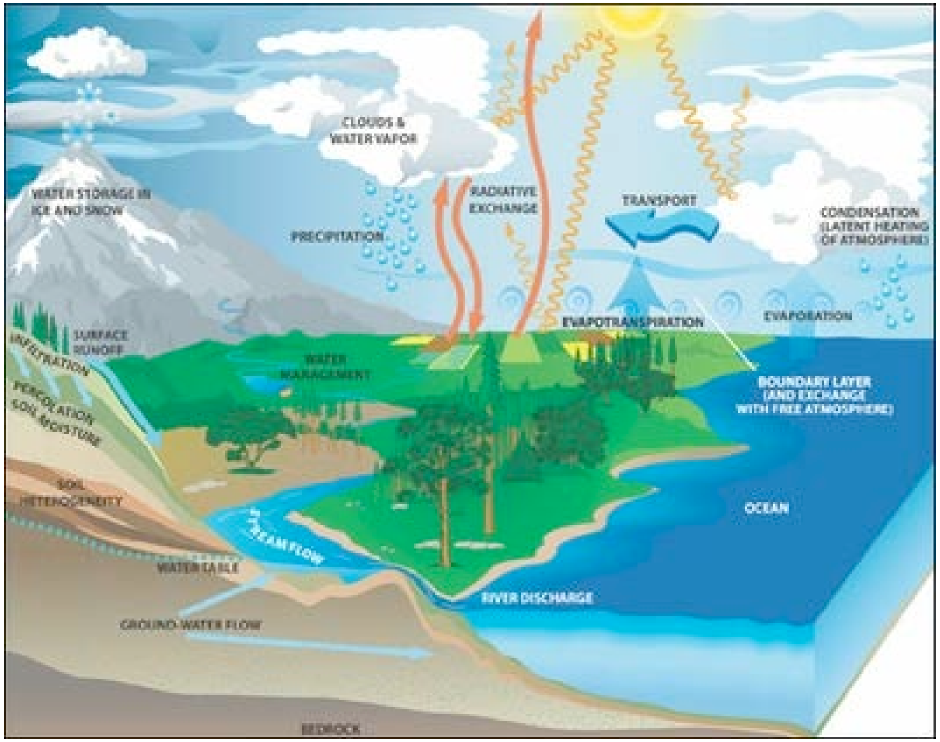


General schematic of the terrestrial water cycle, showing dominant fluxes of water and energy

<u>Conceptual basis</u>:

1. Most modelers share a common understanding of how the dominant fluxes of water and energy affect the time evolution of model states

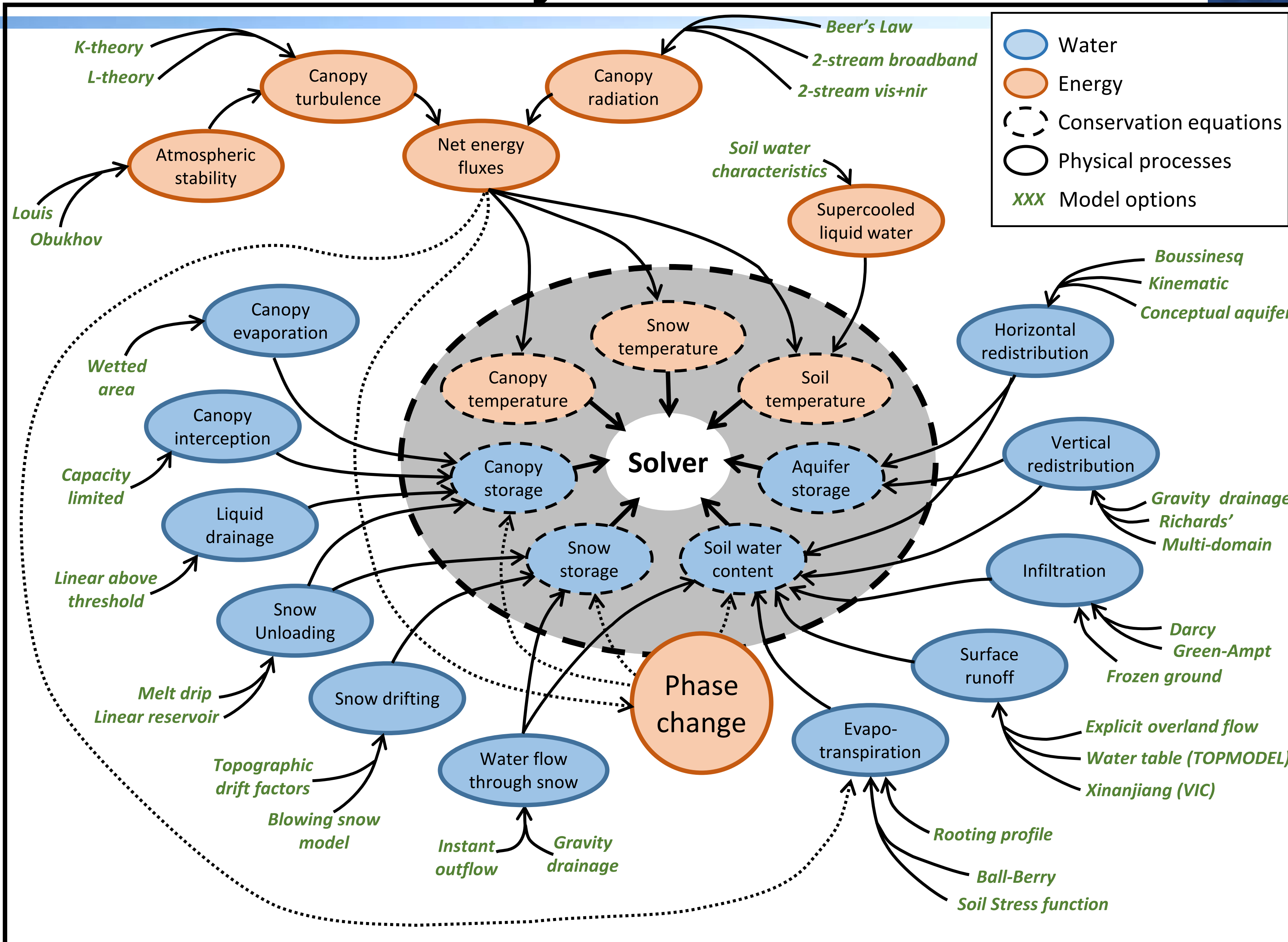
2. Differences among models relate to
   a) the spatial discretization of the model domain;
   b) the approaches used to parameterize individual fluxes (including model parameter values); and
   c) the methods used to solve the governing model equations.

The Structure for Unifying Multiple Modeling Alternatives (SUMMA):

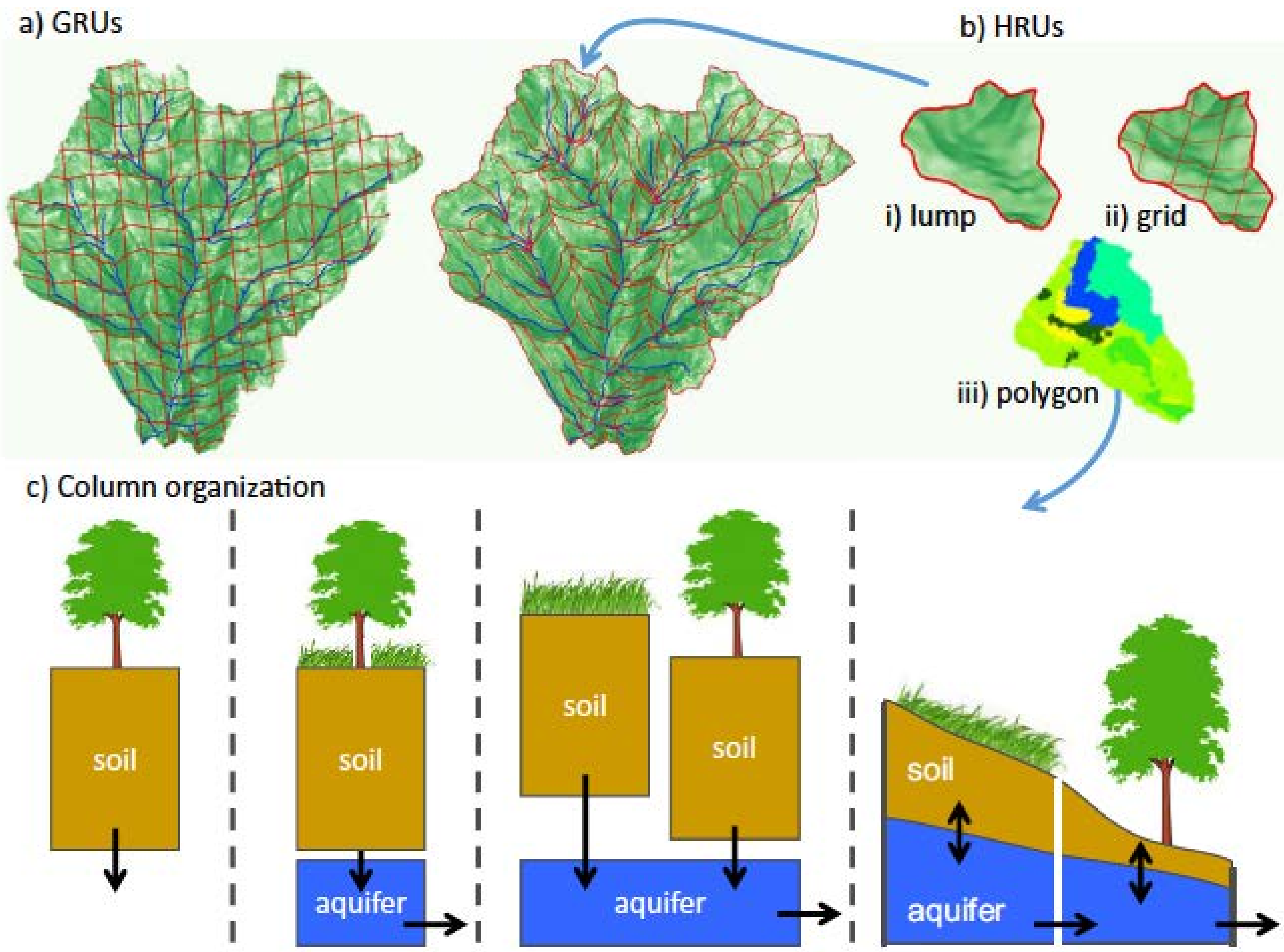
Defines a single set of conservation equations for land biogeophysics, with the capability to use different spatial discretizations, different flux parameterizations and model parameters, & different time stepping schemes

Clark et al. (WRR 2011); Clark et al. (WRR 2015a; 2015b)

Process flexibility

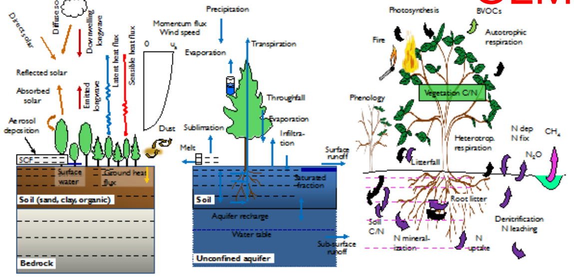


Spatial flexibility

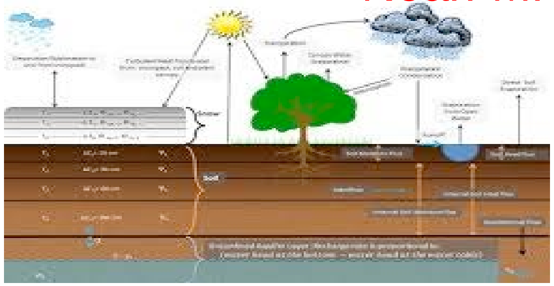


The Community Terrestrial Systems Model

CLM



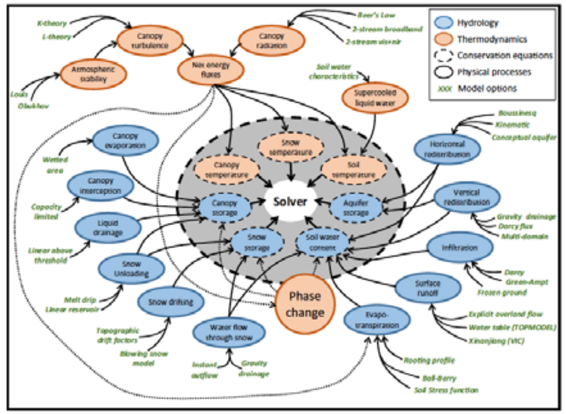
Noah-MP

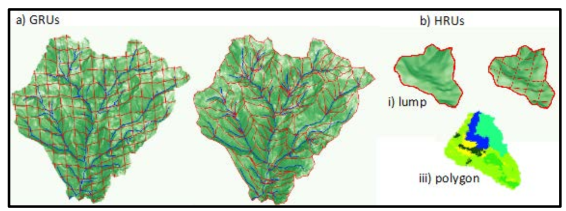


Conceptual basis

- Modelers agree on many aspects of terrestrial system science
- Differences among models relate to
  - *Flux parameterizations*
  - *Spatial discretization*
  - *Numerical solution*

SUMMA

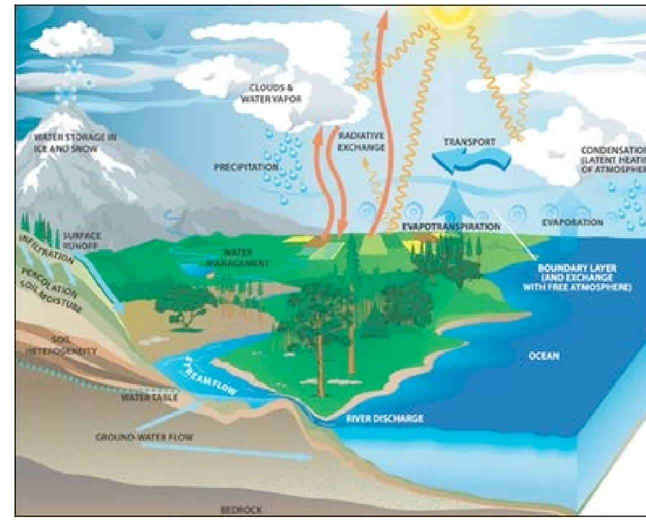




Formulates master model template which multiple models can be derived

- Existing models (*CLM, Noah-MP, WRF-Hydro, etc.*) as a special case

The Community Terrestrial Systems Model (CTSM)

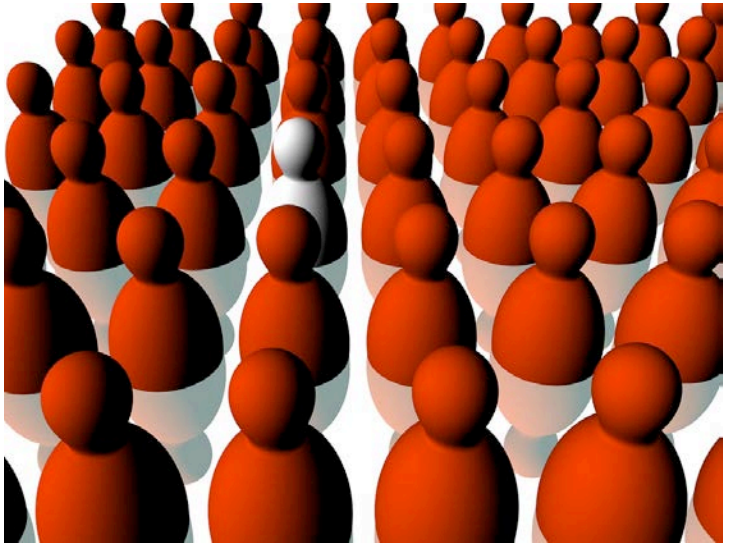


Unifies land models across climate, weather, water, and ecology

- Multiple configurations
- Easy to modify/use
- Centralized support

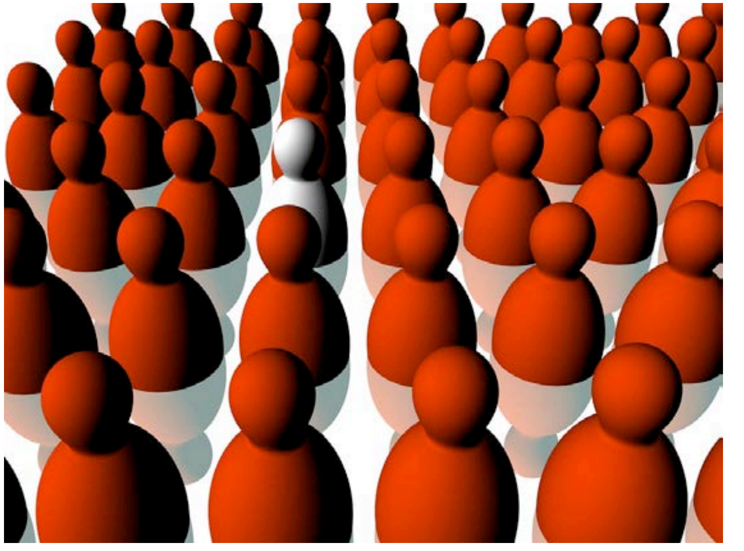
Benefits of a unified land model

- Improve understanding of differences among models (debate about processes)
  - Model inter-comparison experiments flawed because too many differences among participating models
- Improve understanding of model limitations
  - Most models not constructed to enable a controlled and systematic approach to model development and improvement
- Improve characterization of model uncertainty
  - Explicitly characterize uncertainty in individual modeling decisions
  - Enables shift from small-ensemble to large-ensemble framework
- Unite disparate (disciplinary) modeling efforts
  - Without a unified modeling framework the community cannot effectively work together, learn from each other, and accelerate model development
- Reduce duplication of effort



Benefits of the proposed model structure

- Simplifies sharing of code and concepts across different model development groups
  - Separating physics from numerics (the “structural core”) and modularity at the flux level accelerates the process of adding/testing new capabilities
- Enables users to include/exclude specific processes
  - Model can be tailored to suit multiple applications
  - Model simplification opens up new possibilities for teaching and research
- Simplifies data assimilation efforts
  - Formalizes the input-state-output relationships, meaning land model construction matches data assimilation methods
- Reduces development costs
  - Modular structure and separating physics from numerics reduces the in-person cost of modifying CLM, a cost borne by NCAR scientists and software engineers and university collaborators



CTSM development process

<u>April 2016</u>: Grass-roots effort on concept
- *RAL and CGD developed a white paper*

<u>23 May 2016</u>: Discussions w/ NCAR mgmt

<u>7 June 2016</u>: Presentation to the NSF SVT

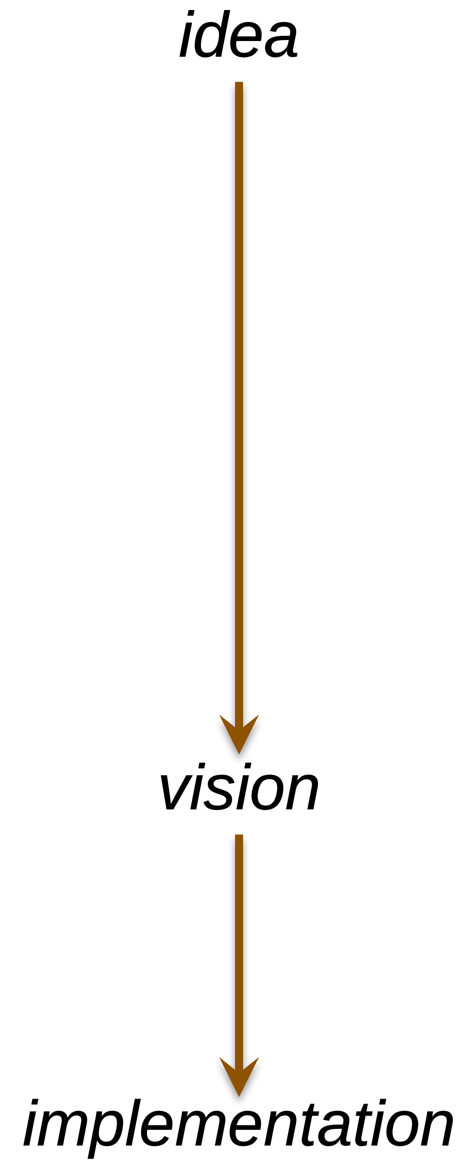
<u>13 June 2016</u>: Cross-NCAR kickoff meeting
- *History and vision*
- *Requirements and challenges*
- *Path forward for model development*
- *Formation of working groups*

<u>29 September 2016</u>: Synthesis meeting
- *Refine requirements/challenges*
- *Refine model design*

<u>October 2016</u>: Develop implementation plan

<u>17 November 2016</u>: Implementation meeting

<u>January 2017</u>: Coding begins!



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Summary of CTSM development

- Model development
  - Use SUMMA concepts to refactor CLM, and integrate capabilities from Noah-MP
  - Major focus on supporting datasets, documentation, user support, etc., to make the model easier to use/modify
  - Model will necessarily be more complex than individual models since it must meet a broader range of objectives
- Model governance
  - Existing land model applications (e.g. Noah) a special case CTSM (pool resources across NCAR and beyond)
  - Effectively manage multiple applications with different time scales of development
  - Short-term parallel development efforts: Existing model derivatives (Noah-MP, etc.) will continue to evolve, and shift to the CTSM once capabilities exist for specific applications
- It's the right time for a unified land model
  - The community is ready for it – dissatisfaction with model divergence and duplication of effort
  - We know how to do it – recently developed proof-of-concept for land biogeophysics
  - Appropriate time in the CLM development cycle


QUESTIONS??