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

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Land Model Working Group
6 Feb 2018

Outline

- The interdisciplinary evolution of land models

- CTSM Motivation
  - Land modeling challenges
  - Ad-hoc approaches to model development

- CTSM development
  - Underpinnings and structure
  - Development process

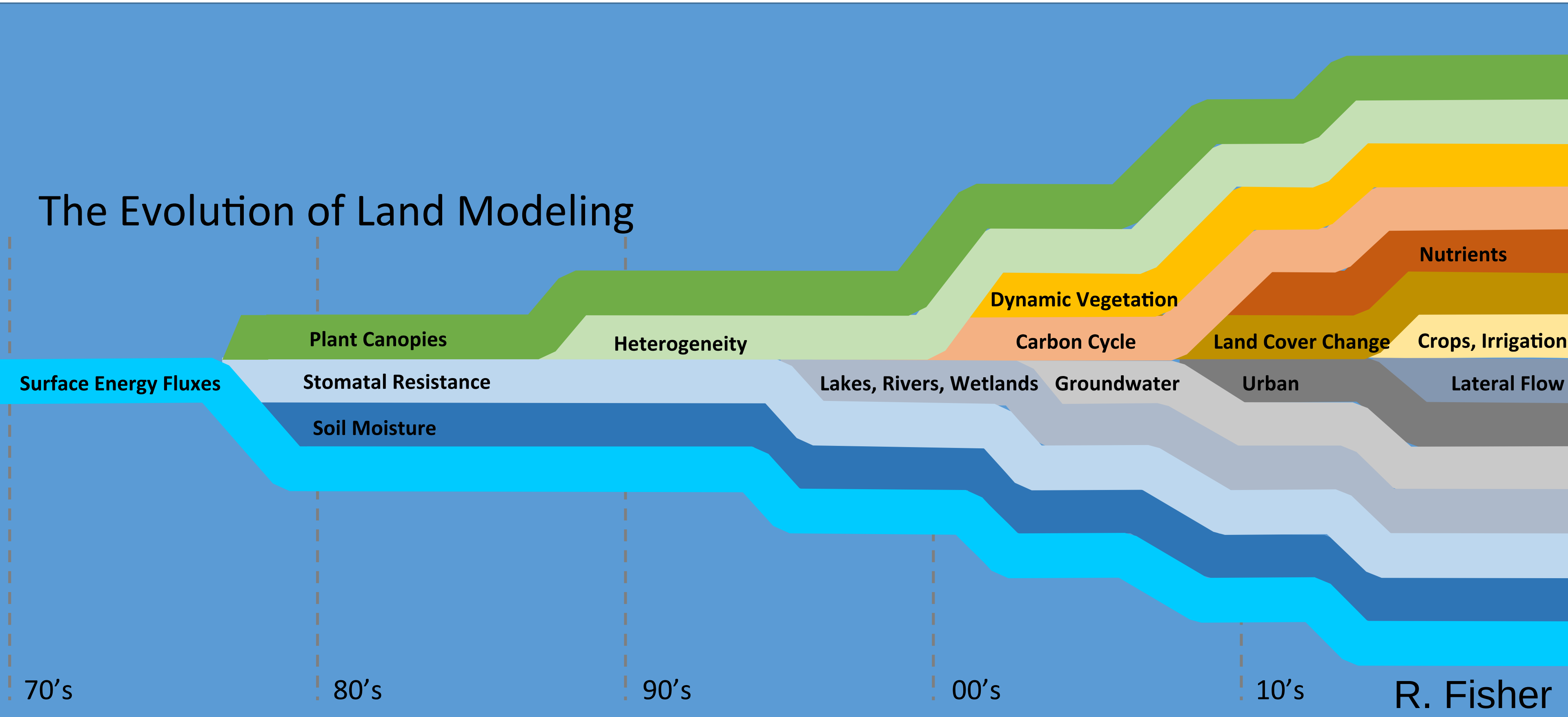
- Summary: Opportunities and challenges

The interdisciplinary evolution of land models

Land as a lower boundary to the atmosphere → **Land as an integral component of the Earth System**

Focus on land-atmosphere energy fluxes → *Mechanistic modeling of land processes* → *Simulate the dynamics of change (e.g., dynamic vegetation)*

Limited representation of land processes & feedbacks → *Properties define processes (focus on short-term fluxes)* → *Processes define properties (feedbacks and interactions across time scales)*



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Motivation

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- Divergence of land modeling efforts
  - Noah-MP, DOE, etc.
- Convergence of land modeling efforts
  - Increasing recognition that many modeling groups are doing the same thing, and are duplicating effort
- 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 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

Two issues: Model proliferation and the shantytown syndrome

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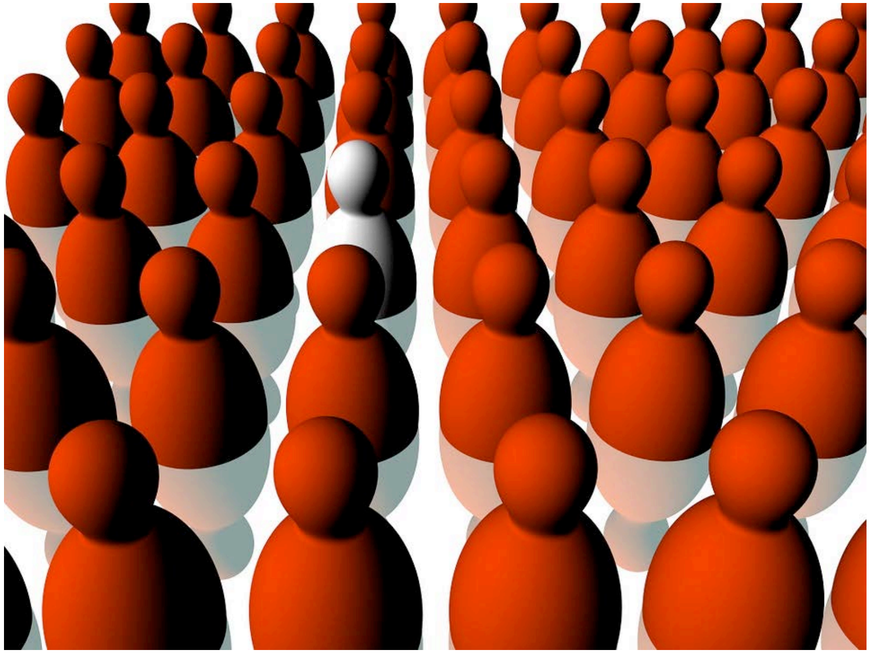
- **Model proliferation**: Every hydrologist has their own model, making different decisions at different points in the model development process

- **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)***



Benefits of a unified land model

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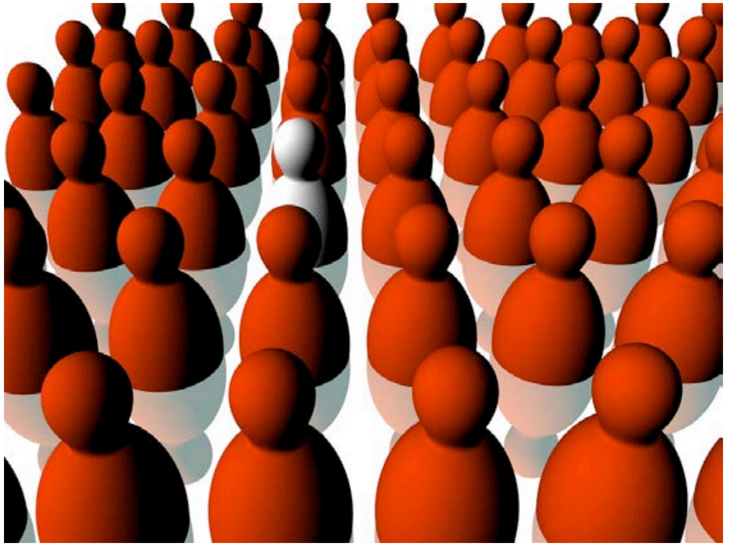
- Improve understanding of differences among models (debate about processes)
  - Model inter-comparison experiments flawed because too many differences among participating models
- Improve understanding of model limitations
  - Most models not constructed to enable a controlled and systematic approach 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

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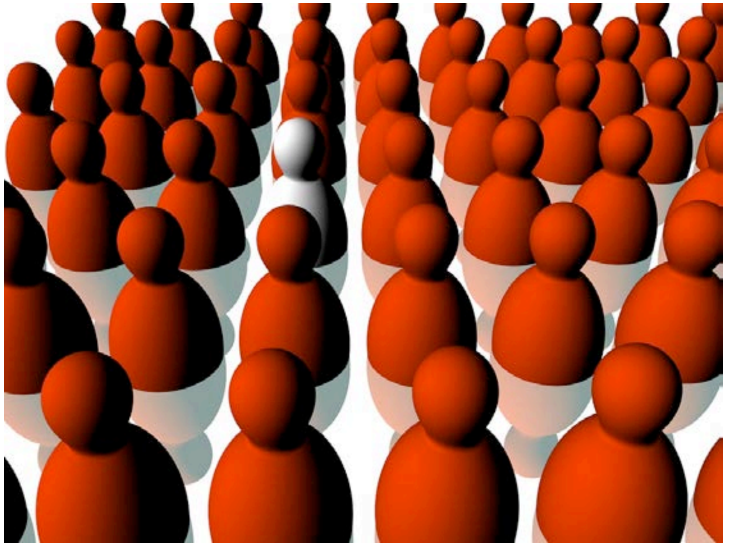
- Simplifies sharing of code and concepts across different model development groups
  - Separating physics from numerics (the “structural core”) and modularity at the flux level accelerates the process of adding/testing new capabilities
- Enables users to include/exclude specific processes
  - Model 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



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Development of a unifying model framework

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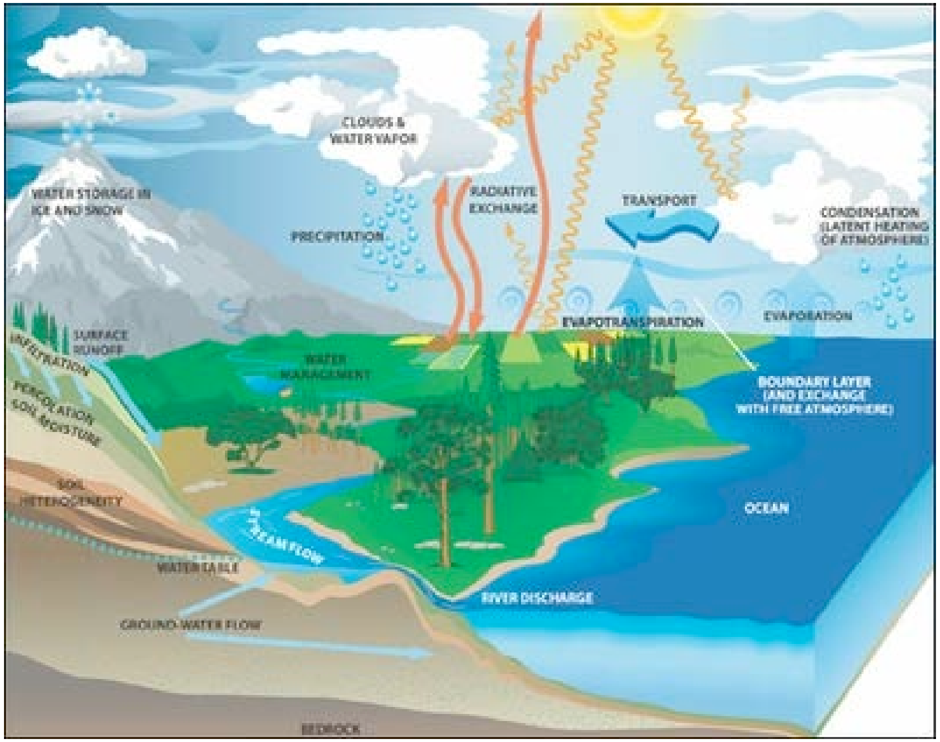


General schematic of the terrestrial water cycle, showing dominant fluxes of water and energy

Conceptual basis:

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

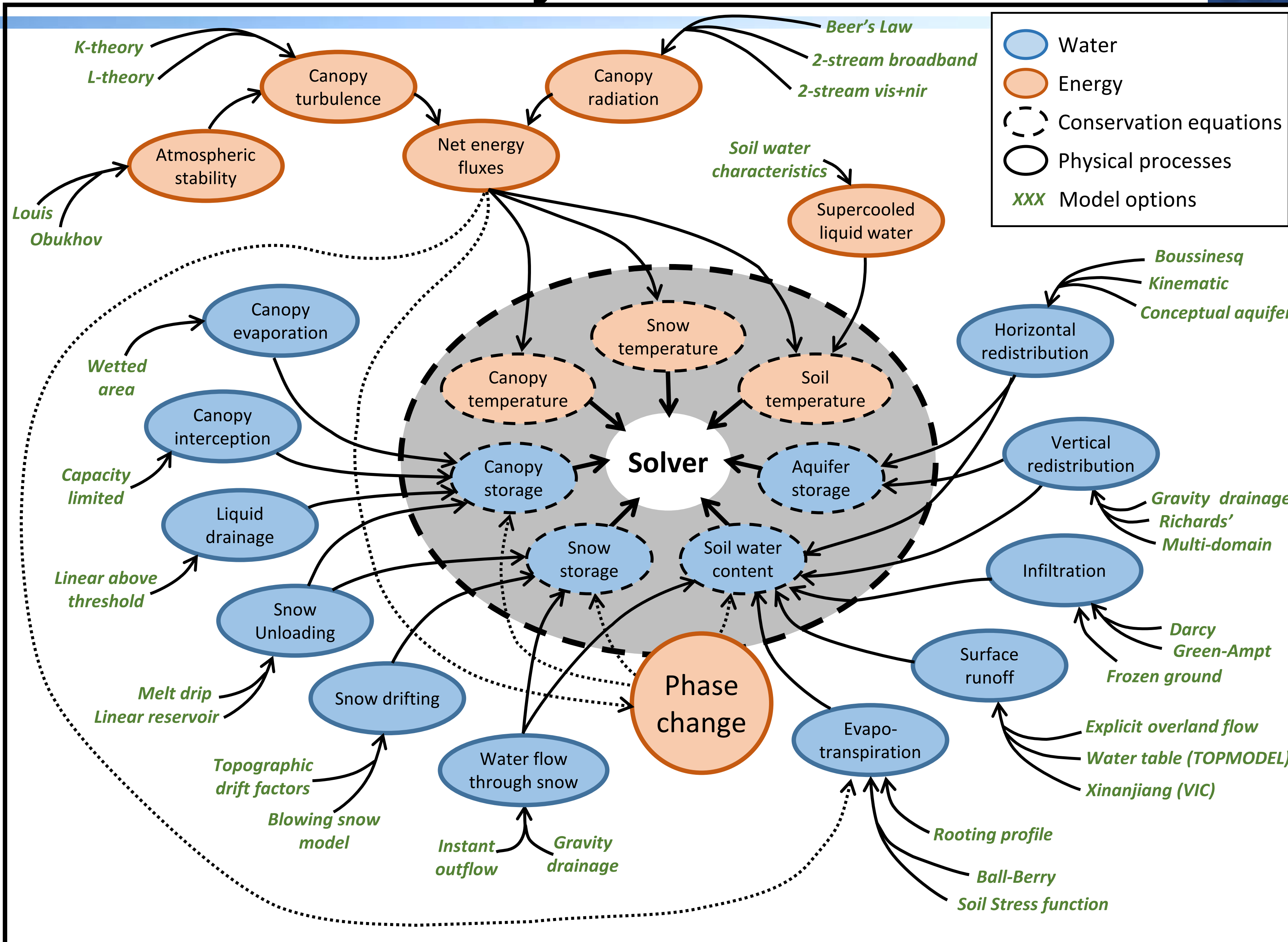
2. Differences among models relate to
   a) the spatial discretization of the model domain;
   b) the approaches used to parameterize individual fluxes (including model parameter values); and
   c) the methods used to solve the governing model equations.

The Structure for Unifying Multiple Modeling Alternatives (SUMMA):

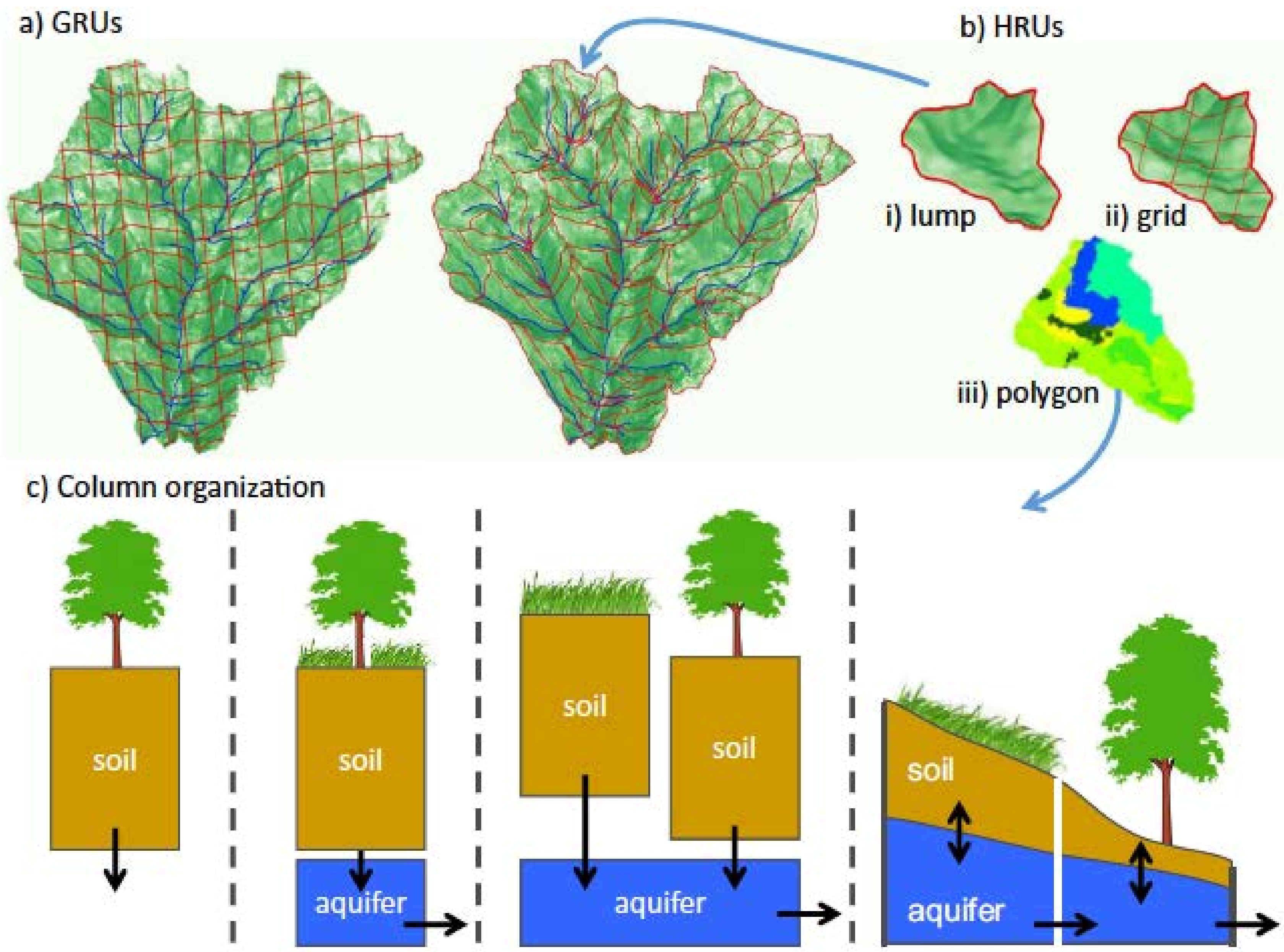
Defines a single set of conservation equations for land biogeophysics, with the capability to use different spatial discretizations, different flux parameterizations and model parameters, & different time stepping schemes

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

Process flexibility



Spatial flexibility



The Community Terrestrial Systems Model

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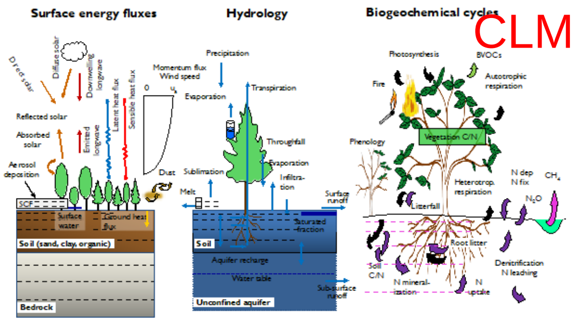
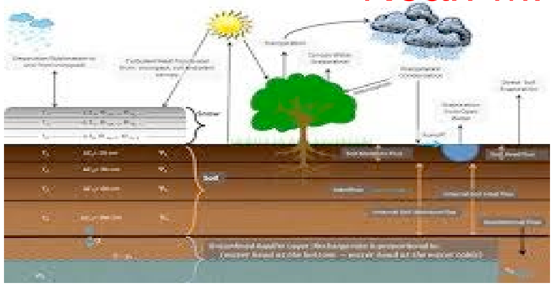
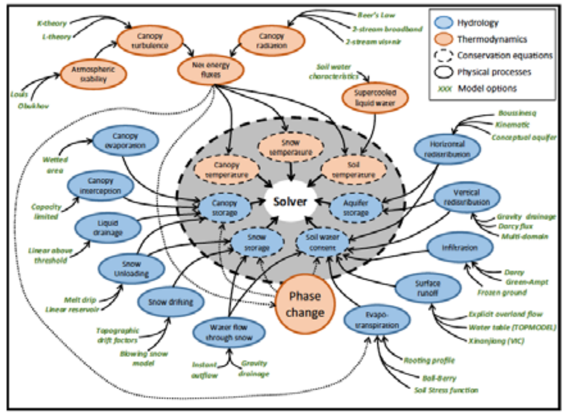
CLM

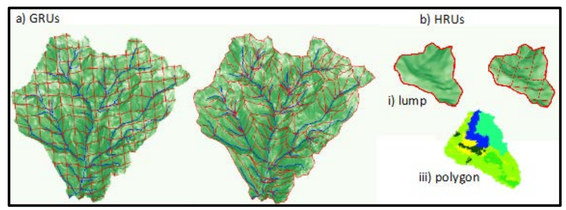


Noah-MP

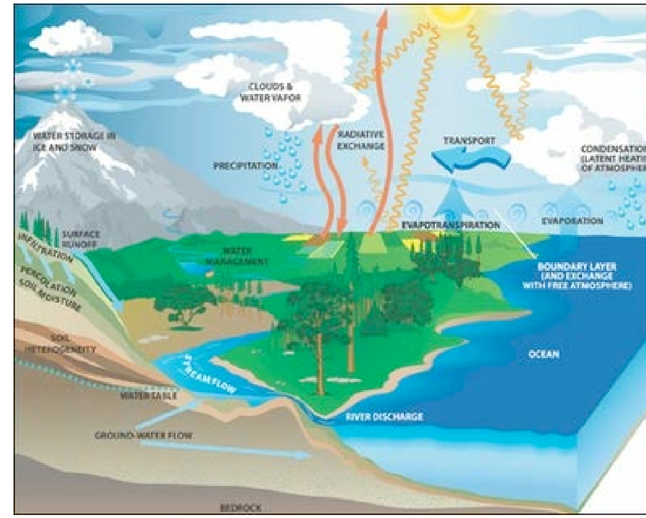


SUMMA





The Community Terrestrial Systems Model (CTSM)



Conceptual basis

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

Formulates master model template which multiple models can be derived

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

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

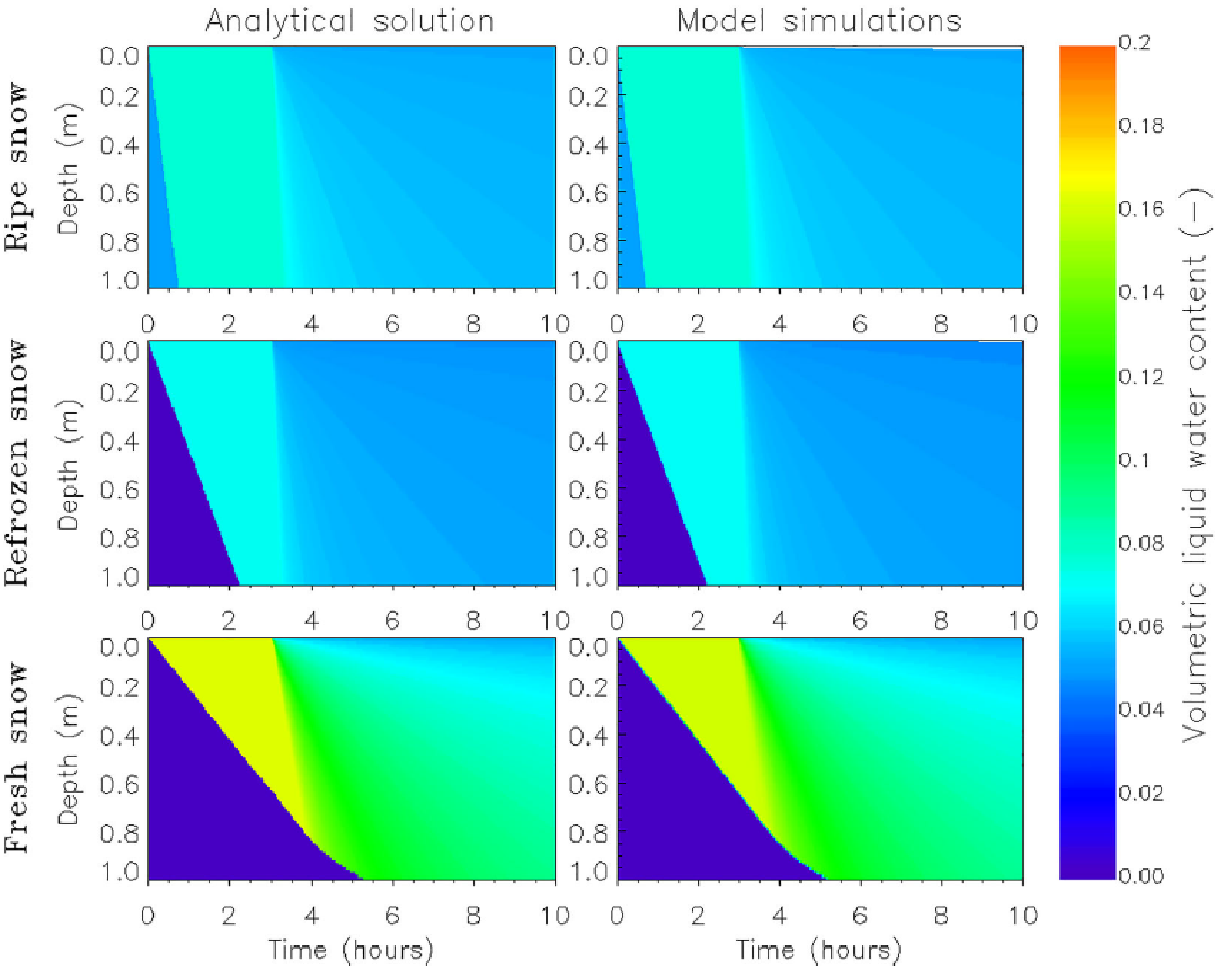
- Multiple configurations
- Easy to modify/use
- Centralized support

A controlled approach to model development

Laugh tests for land models

Constant precip for three hours at top of a 1-m snowpack

Analytical solution



CTSM development process

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- Initiated project
  - Developed white paper (RAL&CGD)
  - Discussions with NCAR leadership
  - Presentation to NSF Site Visit Team
- Developed strategic plan
  - Vision; Requirements and challenges
- Developed implementation plan
  - Path forward for model development
- Model development
  - Collaborative coding environment
  - Unify data requirements
  - Develop/refine design
  - Understand efficiency
- Model applications (early adopters)
  - Isotopes

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Summary of CTSM development

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- 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 transition
  - Existing land models (e.g. Noah-MP) are a special case CTSM (pool resources across NCAR and beyond)
  - Short-term parallel development efforts: Existing models (Noah-MP, SUMMA, 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

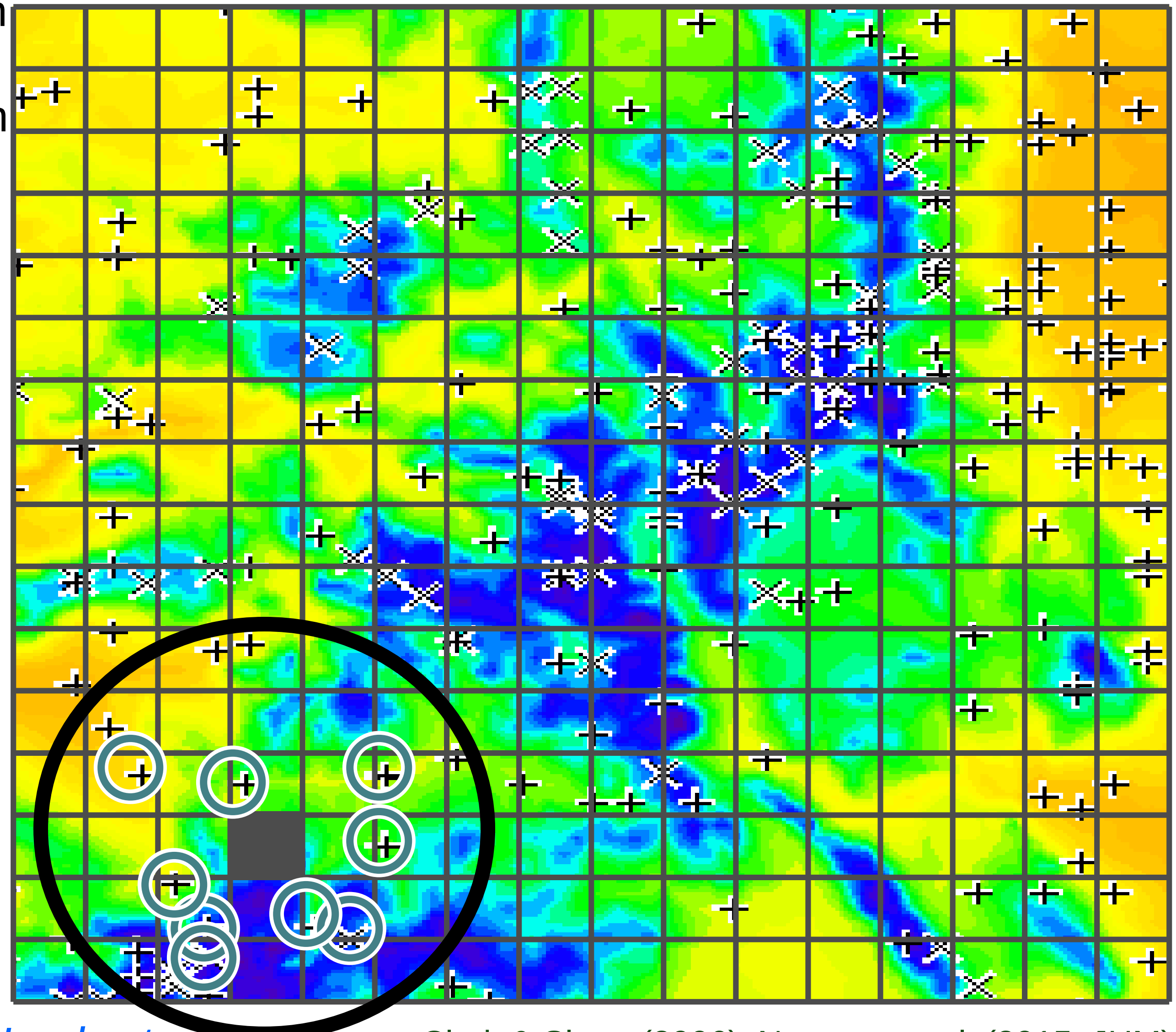
Forcing uncertainty

Step 1:

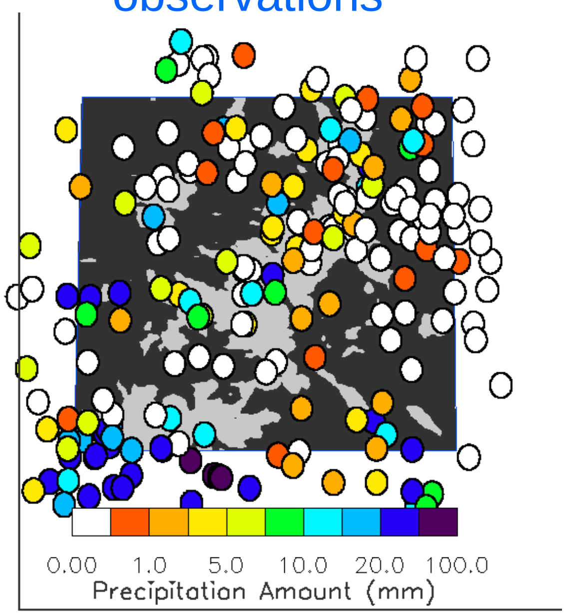
Locally weighted regression at each grid cell:

- Probability of Precipitation via logistic regression
- Amount and uncertainty (least squares mean & residuals)

Example over the Colorado Headwaters



observations

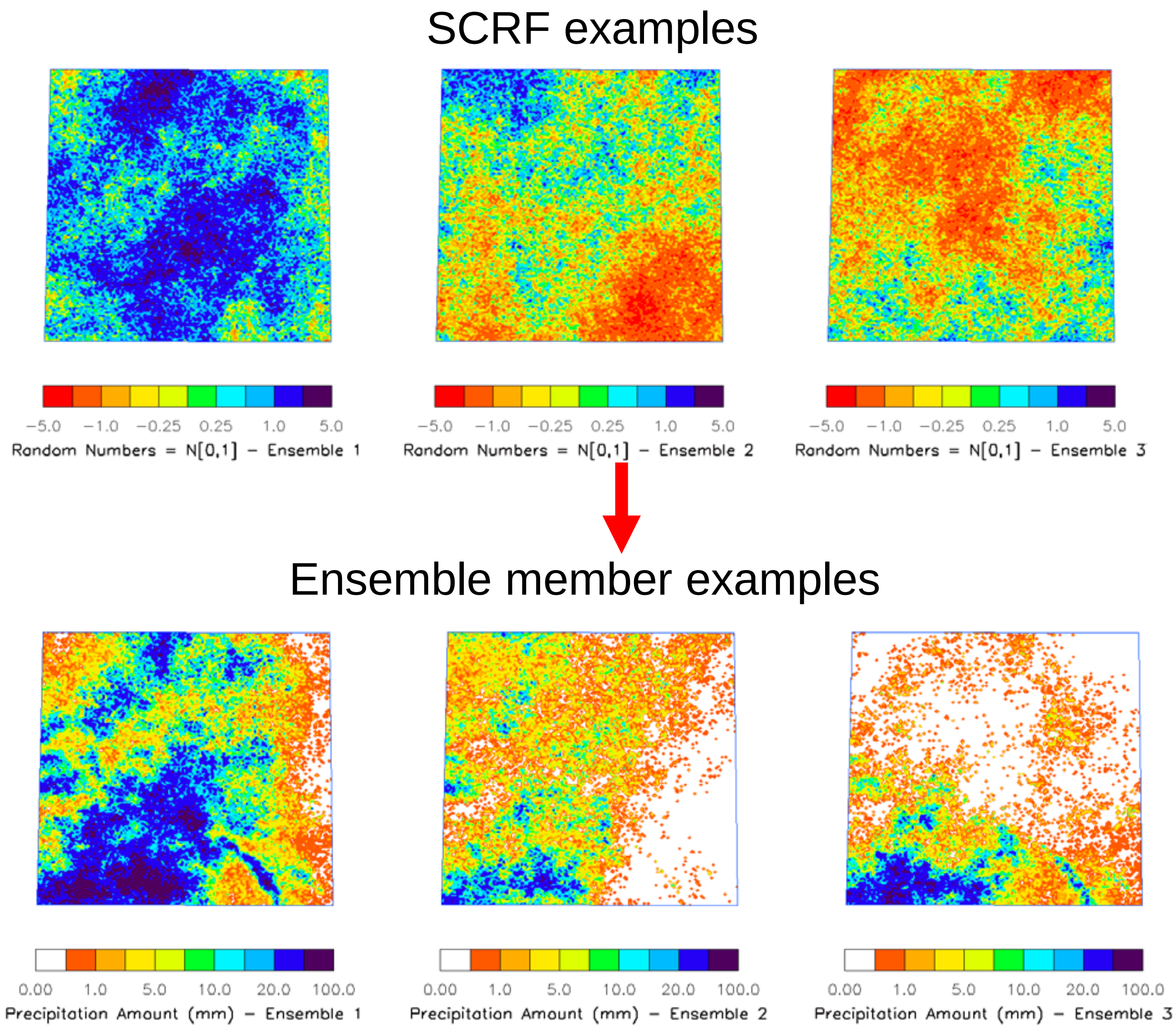


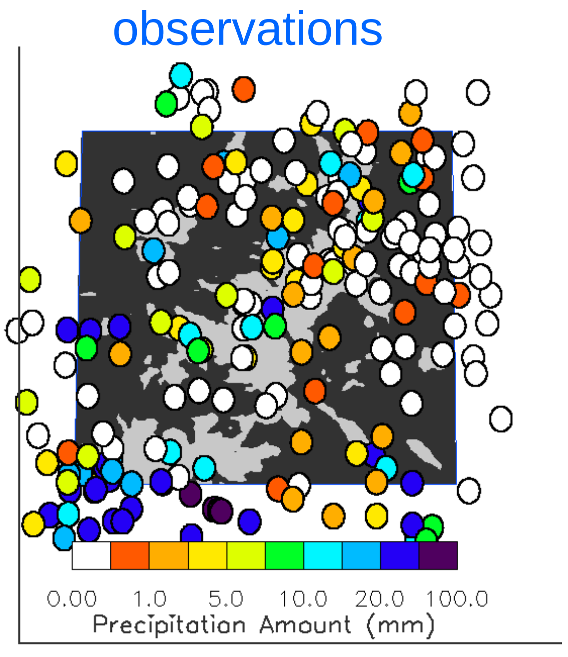
Example over the Colorado Headwaters

Clark & Slater (2006), Newman et al. (2015, JHM)

Forcing uncertainty

Step 2:
Synthesize ensembles using spatially correlated random fields (SCRFs)



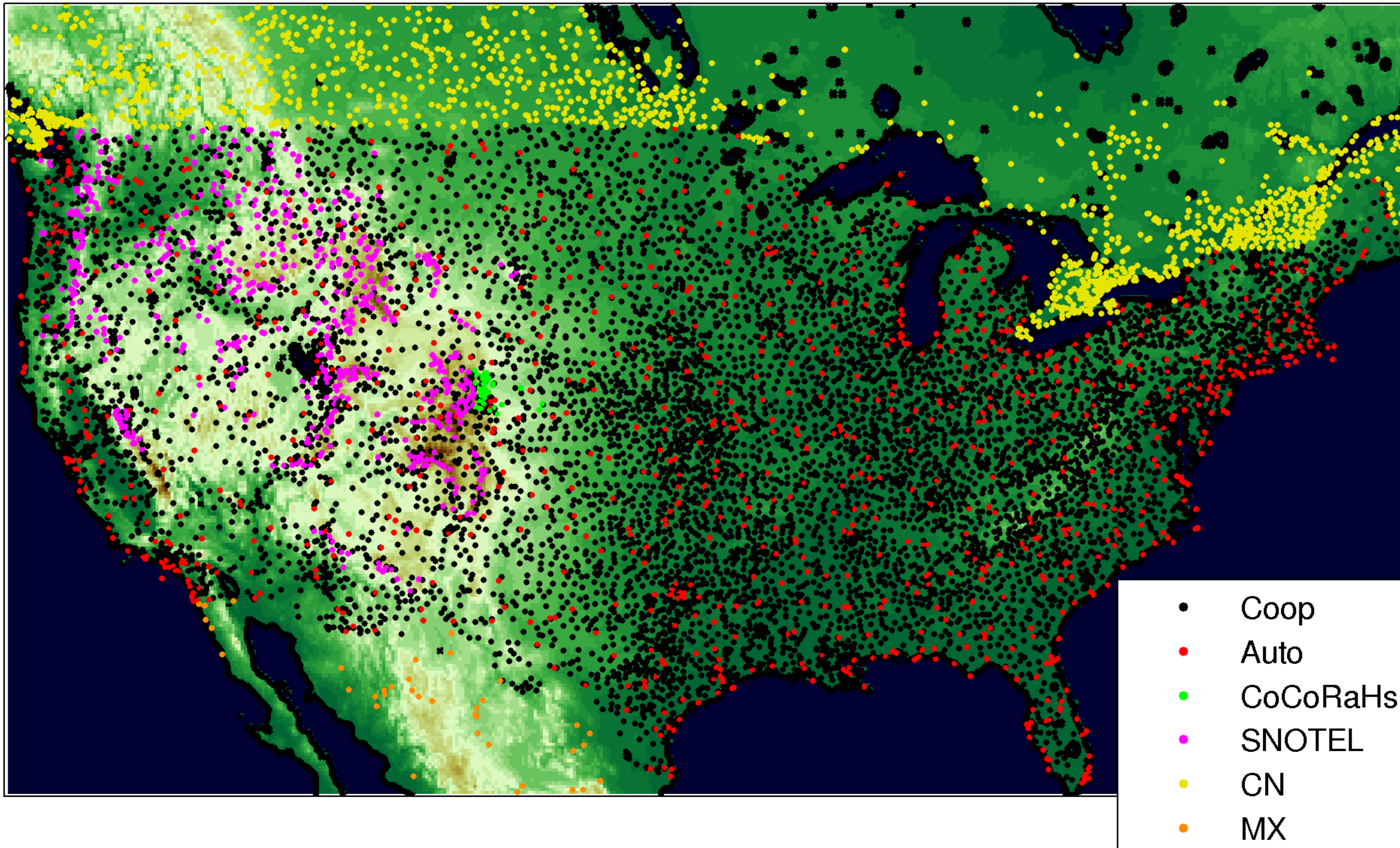


Example over the Colorado Headwaters

Clark & Slater (2006), Newman et al. (2015, JHM)

Ensemble spatial met. fields

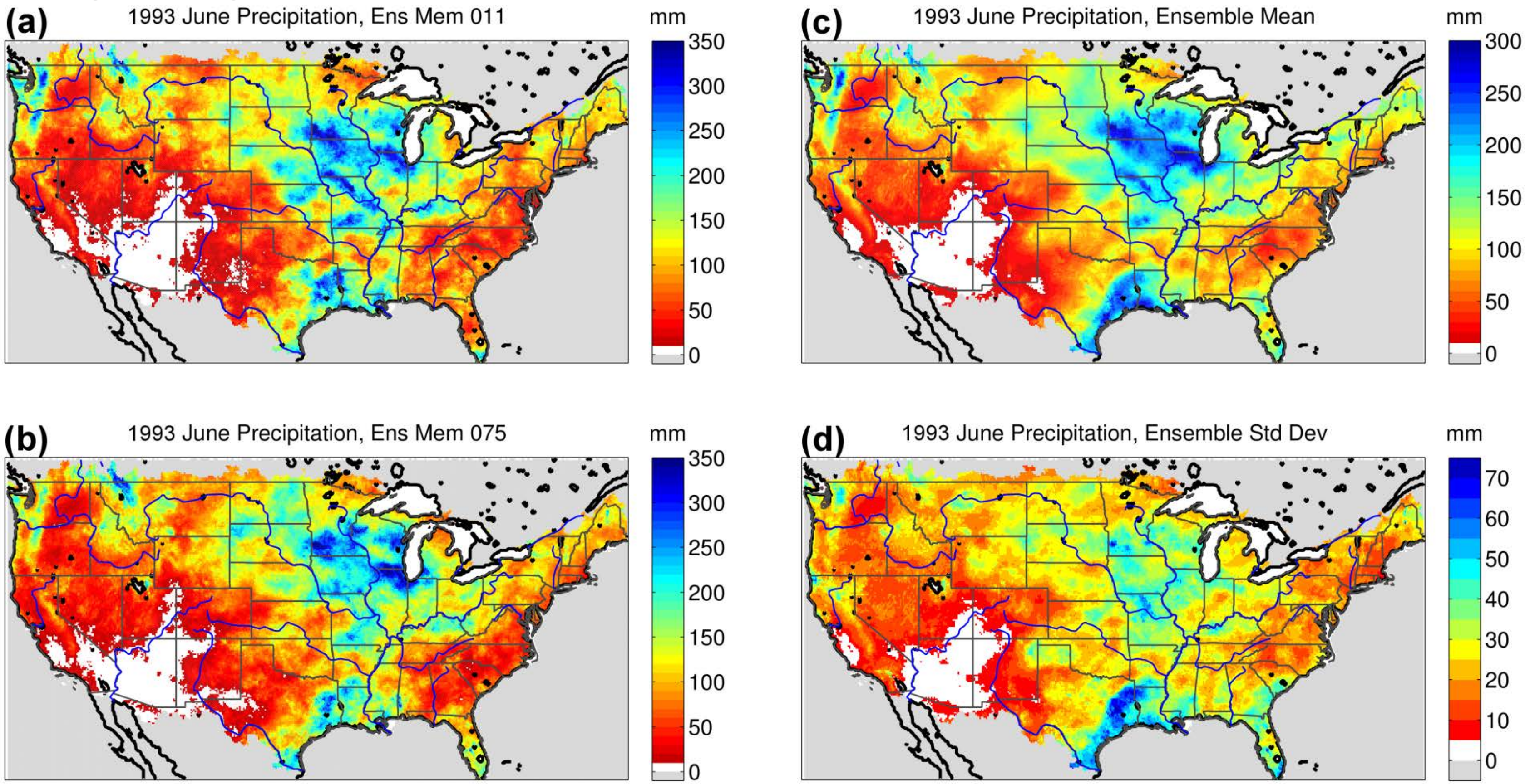
Spatial extrapolation from 12,000+ stations across the CONUS



CONUS product

- Dataset constructed from 1980-2012
- Daily spatial fields of precipitation and temperature
- Dataset freely available

Example output for June 1993



Newman et al., JHM 2015

Application in WRF Evaluation

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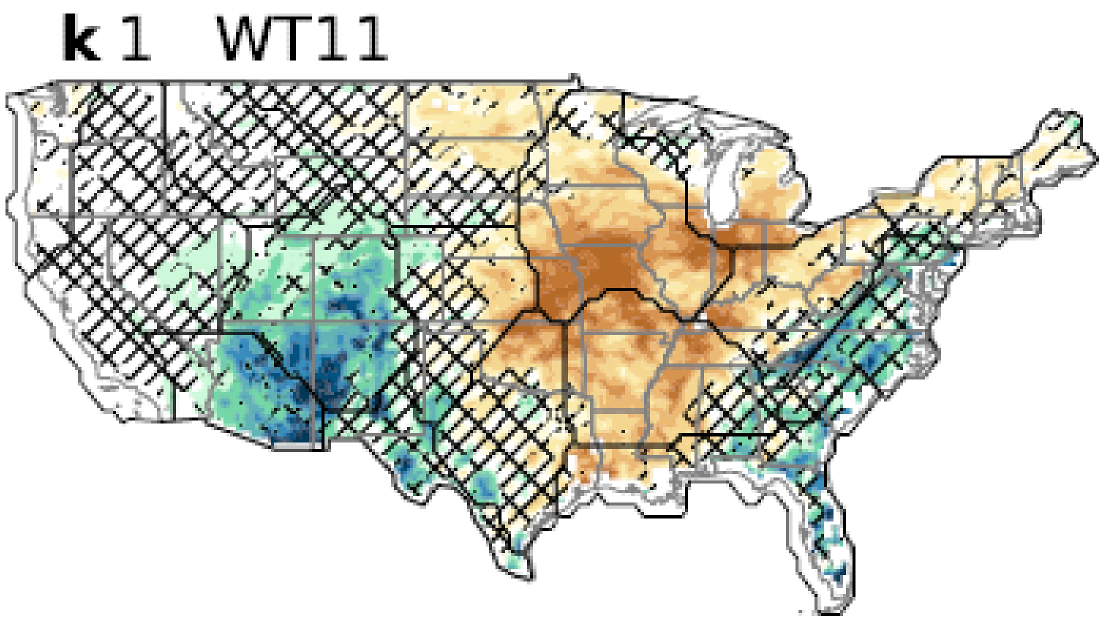
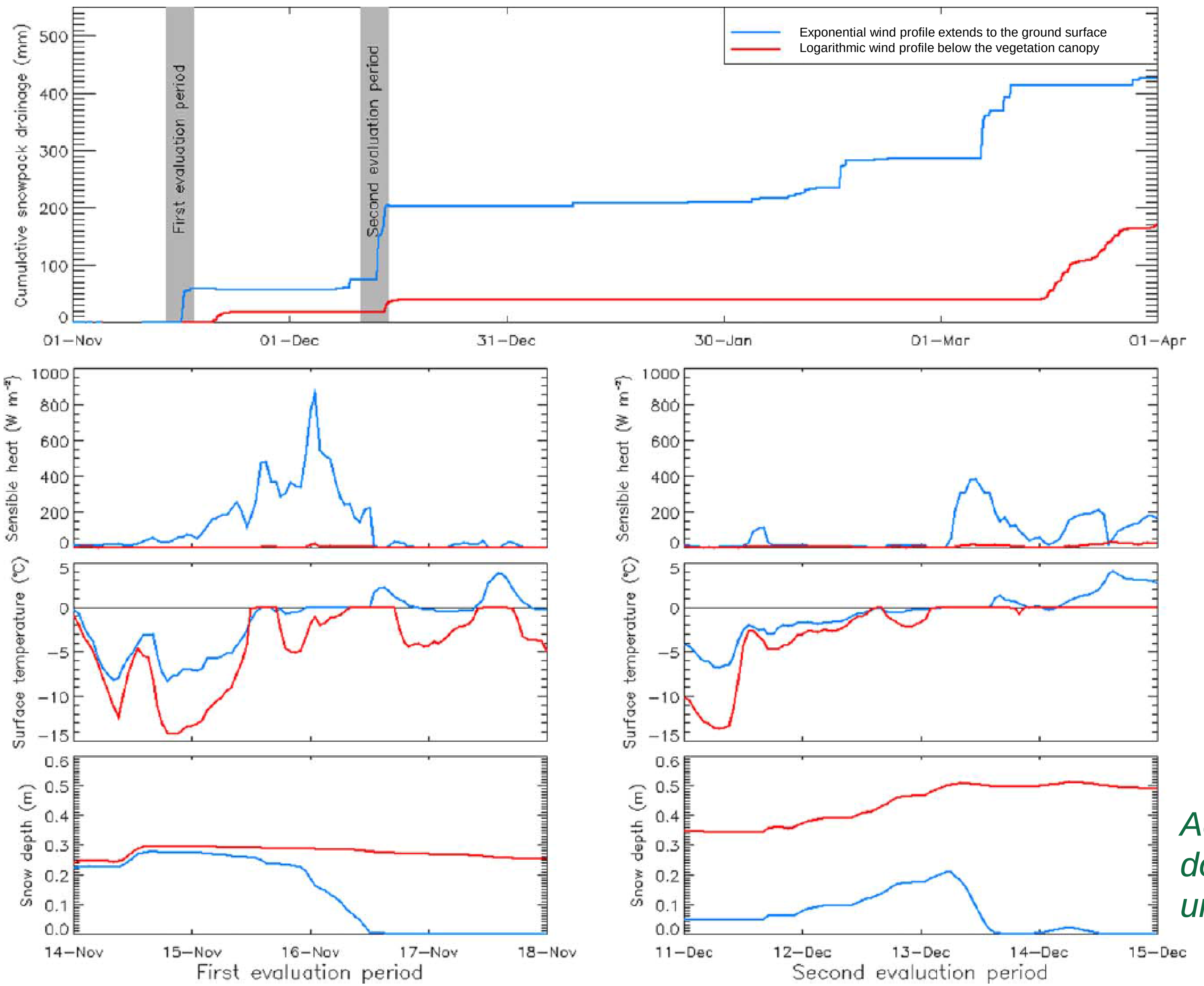
- Conditional bias for specific weather types
  - Example for the North American monsoon:
  - WRF has distinct dipole in mean precipitation – wet in the desert Southwest, dry central US



  - *Unhatched areas are outside the ensemble uncertainty*

Model uncertainty



Adding a bad model doesn't increase uncertainty!

Model uncertainty

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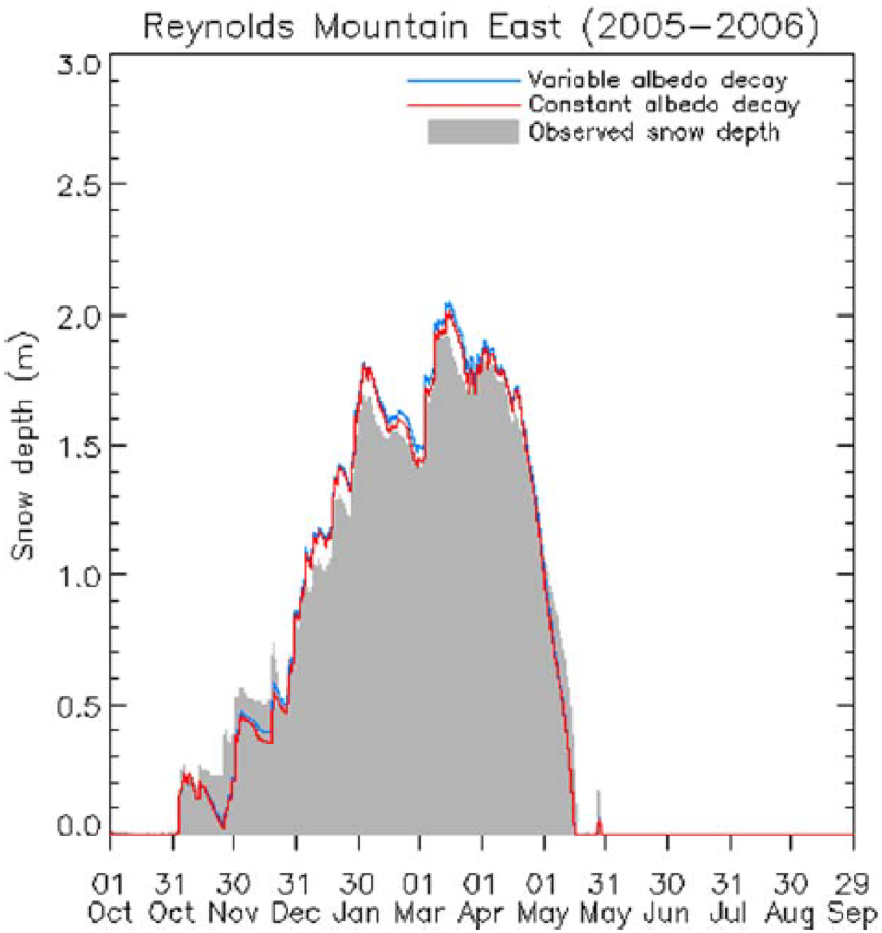
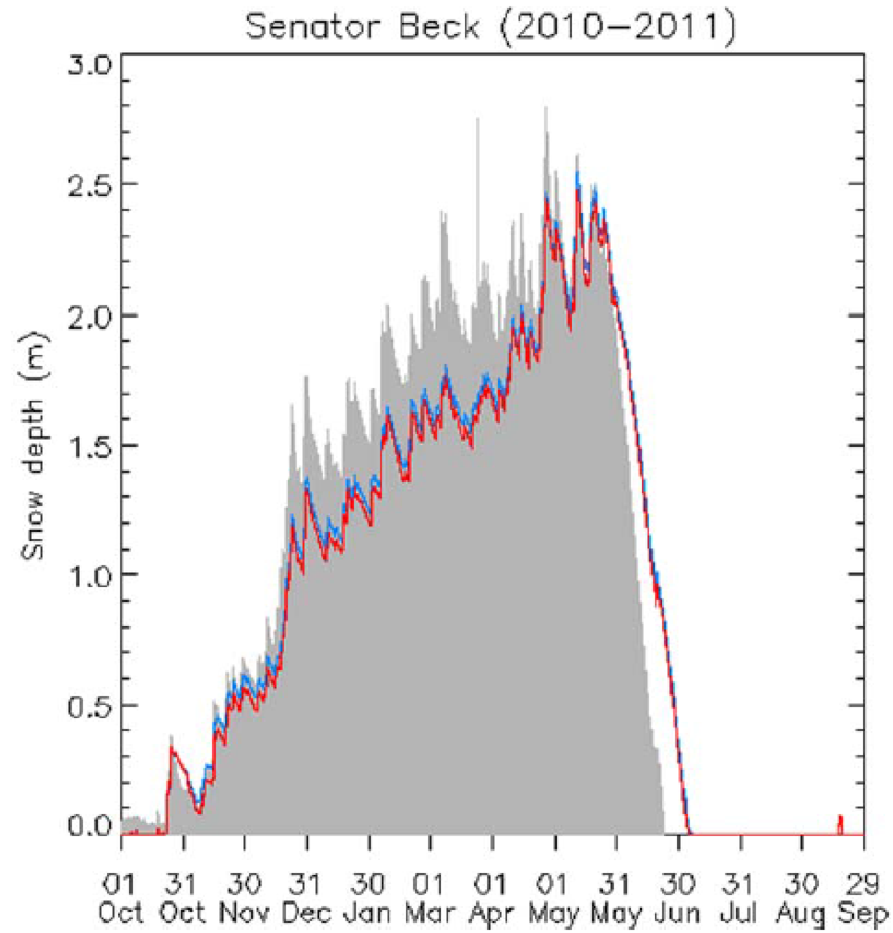




You are not more certain just because models agree!

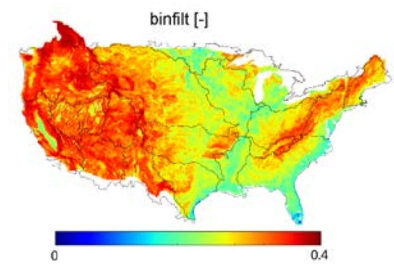
(wrong answers for the same reasons)

Key scientific challenges

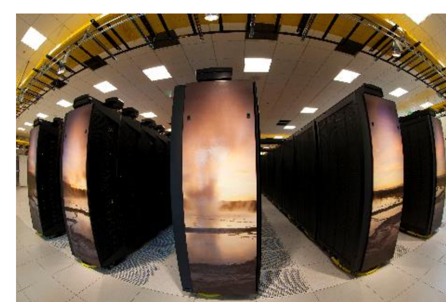
- The choice of modeling approaches arguably stems from personal preferences (physics vs. parsimony, etc.)
- Need a stronger scientific basis for model development/improvement
  - Treat numerical modeling as a subjective decision-making process – *carefully evaluate all modeling decisions in a controlled and systematic way*

- Processes
  - Models do not adequately represent dominant processes – stronger links between theory and model algorithms?
  - Always the key question of what processes are resolved explicitly and what processes are parameterized

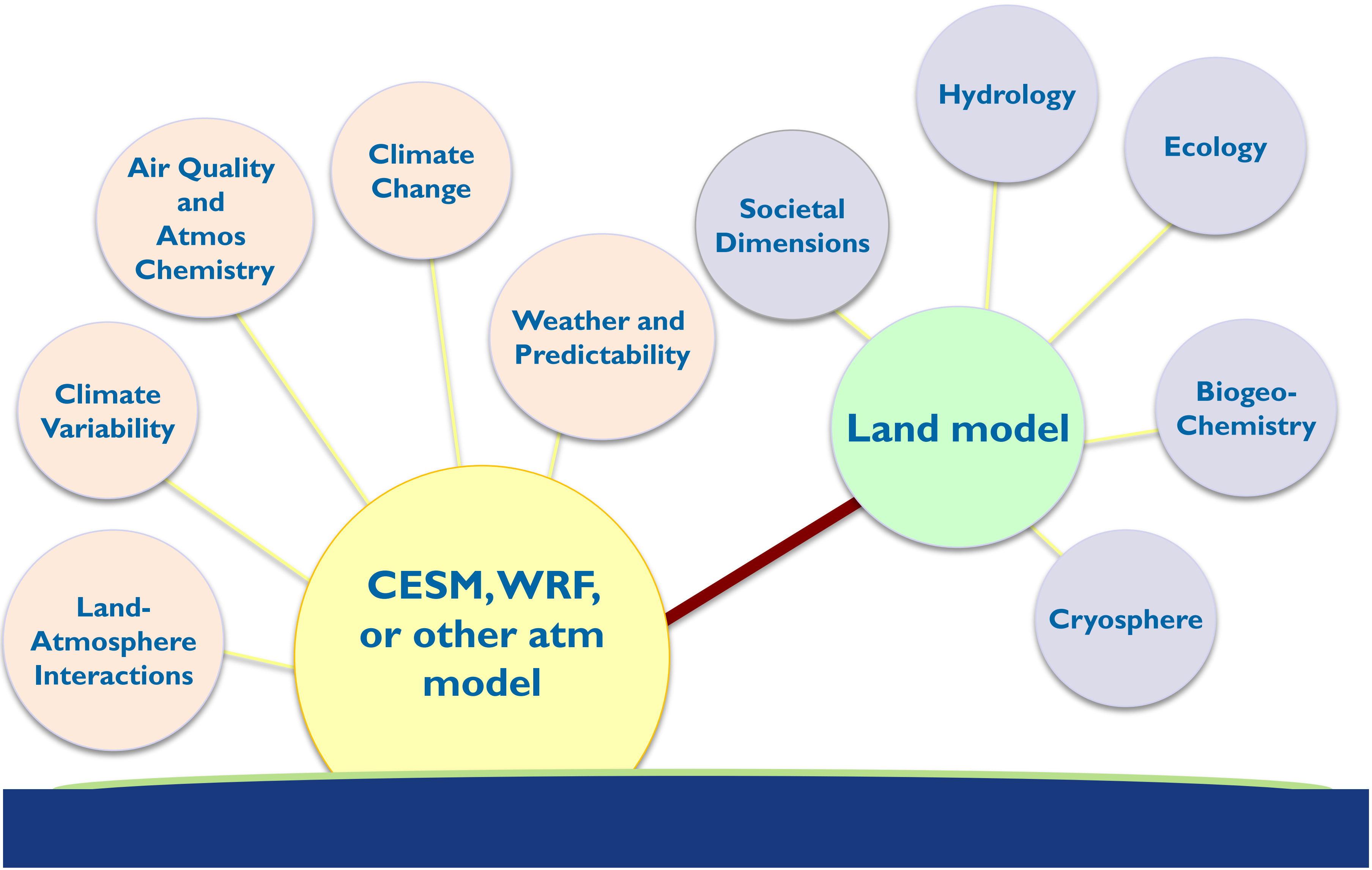
- Parameters
  - Models as mathematical marionettes
  - Vegetation and soils datasets have limited resolution and information content – new datasets / geophysical information?



- Computing
  - The rapid advances in computing are revolutionizing capabilities for simulations with large domain size, more detailed process representation, fine horizontal resolution, and large ensembles
  - The expense of complex models can sacrifice opportunities for model analysis, model improvement, and uncertainty characterization



The interdisciplinary challenge of land modeling



Plans for the next-generation land model

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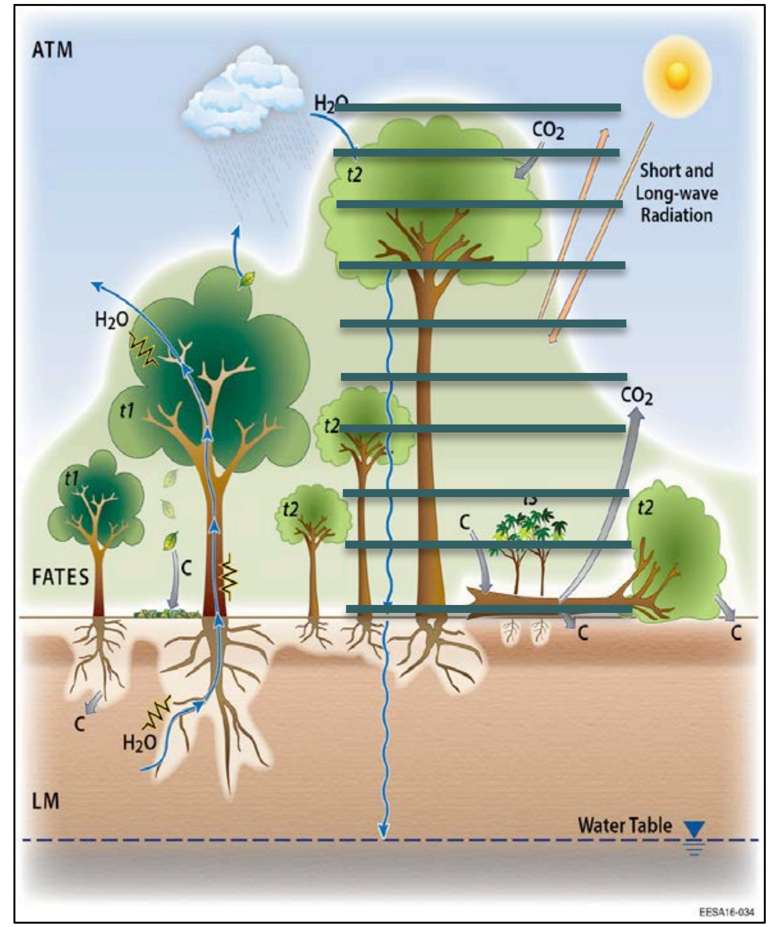
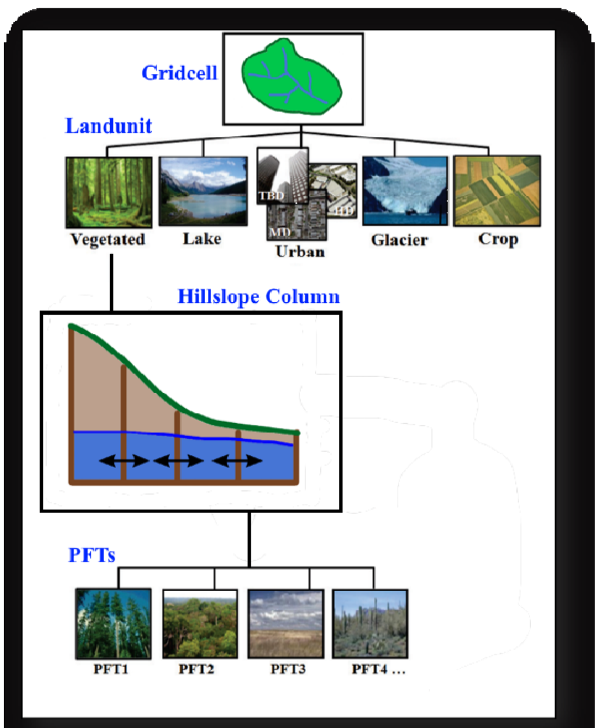
- Ecosystem vulnerability and impacts on carbon cycle and ecosystem services
- Sources of predictability from land processes
- Impacts of land use and land-use change on climate, carbon, water, and extremes
- Water and food security in context of climate change, climate variability, and extreme weather

Ecosystem Demography / Multi-layer canopy





Lateral fluxes of water

Water and land management

Key challenges (not scientific!)

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- Parallel development
  - Existing models currently used across multiple projects
  - Initially the effort is diffuse (e.g., individuals developing code for both Noah-MP and CTSM)
  - Need to accelerate early applications for different model use cases
- Modularity
  - Need to support contributions at multiple levels of granularity
    - One extreme (e.g., LIS) – multiple land models in a common framework
    - Another extreme (e.g., CTSM) – granularity at the level of individual fluxes
    - Common desire – granularity for model component (e.g., crop model, snow model)
  - Coarse-grain modularity has challenges with process responsibility (e.g., is the crop model "responsible" for stomatal conductance) as well as the numerical solution
  - Need to move towards community standards for model development, to simplify sharing code/concepts across model development groups
- Funding
  - Support the interdisciplinary challenge of land modeling


QUESTIONS??