Developing the Next-Generation Land Surface Models: Challenges and Achievements

Zong-Liang Yang

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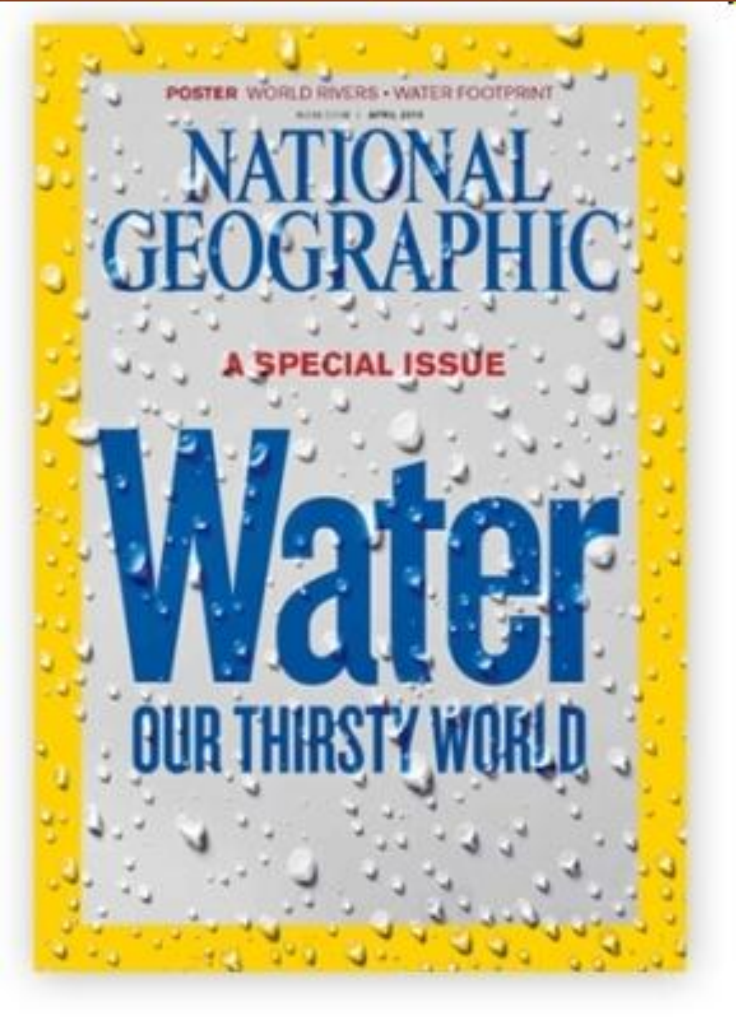
Presentation at the Institute of Atmospheric Physics,
Chinese Academy of Sciences, Beijing,26 May 2011

Why Land

- Land has direct societal relevance: we live on land!
- Land provides us food, clothing, shelter, and infrastructure.
- Land is at the central stage for extreme weather/climate events (droughts, floods, dust storms, bush fires).
- Land processes are complex, highly heterogeneous, multi-disciplinary, and multi-scale!



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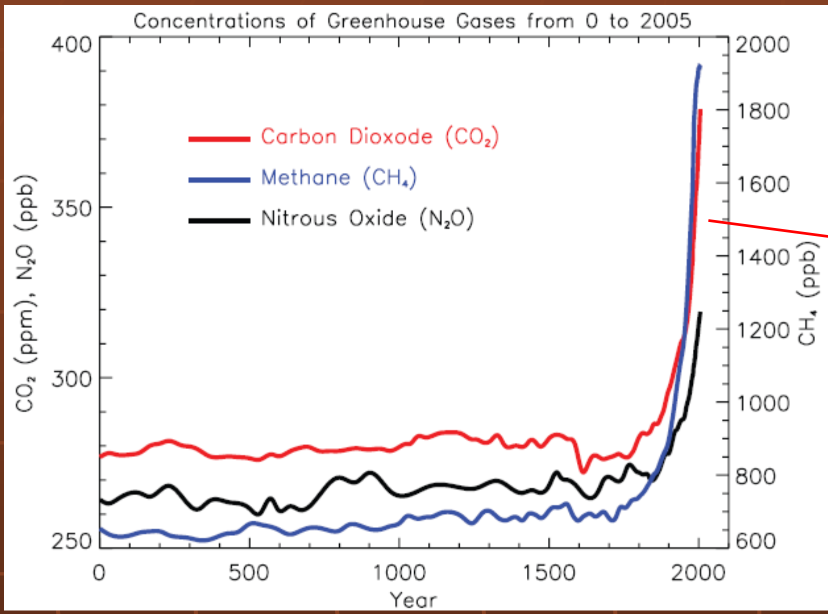
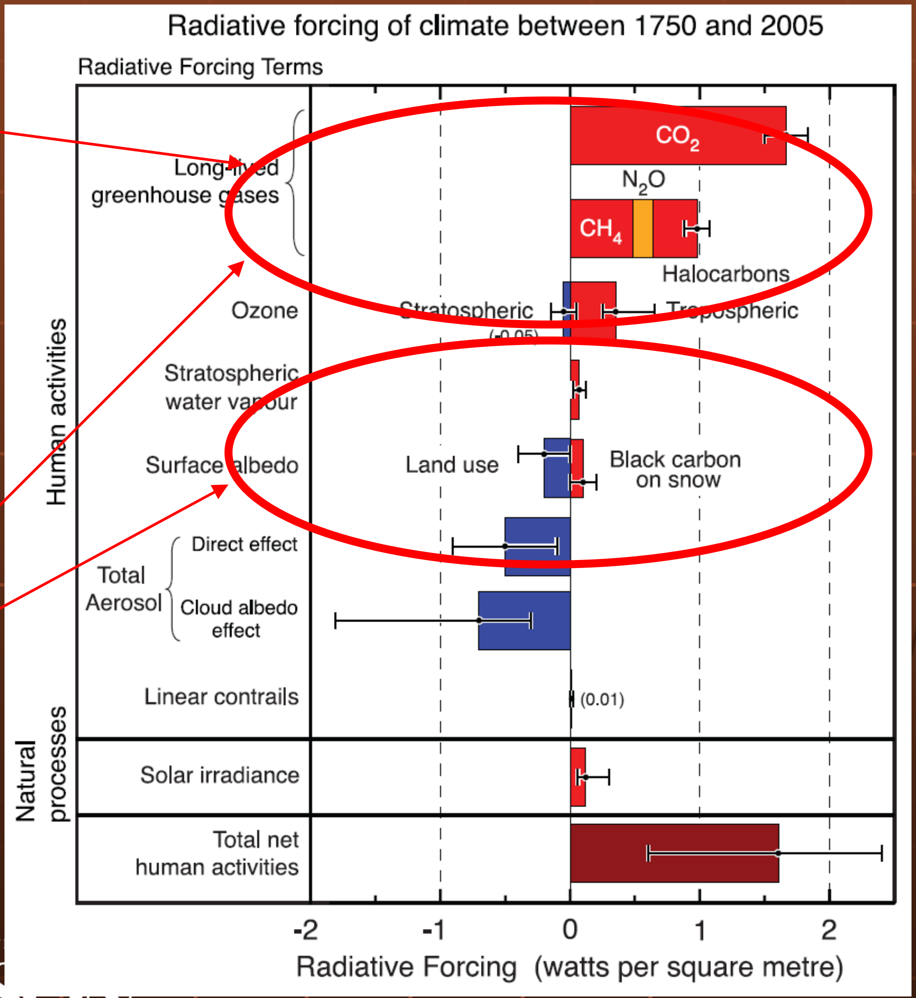
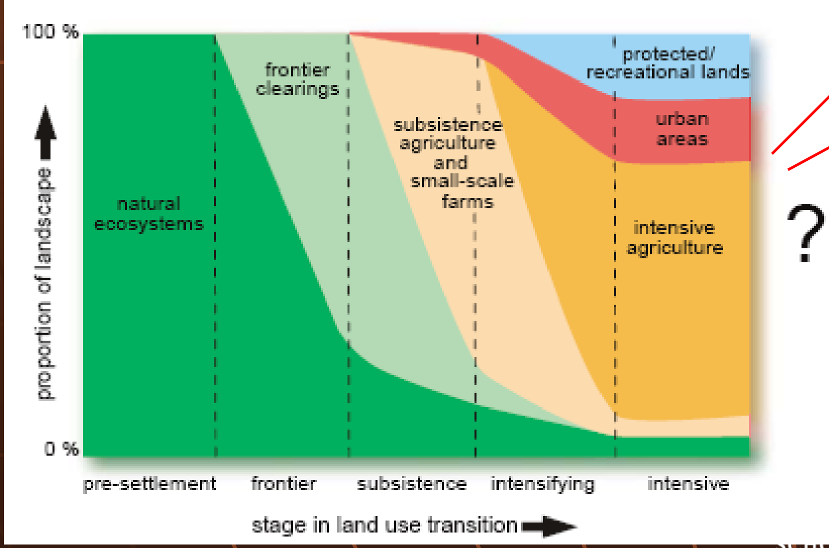
Climate Change:

Greenhouse Gases versus Land Use and Land Cover Change



IPCC 2007





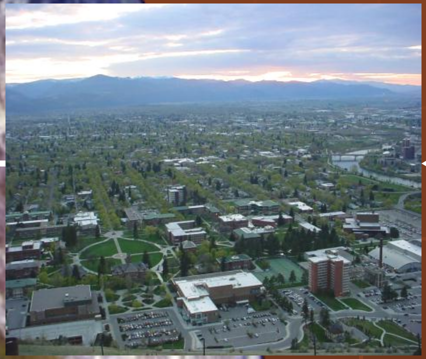
?

Foley et al. 2005

DYNAMIC GLOBAL LAND TRANSITIONS

LANDUSE ⟷ **LANDCOVER**

[Human control] — [Biophysically controlled]



Human Systems

- **Institutions**
- **Culture**
- **Technology**
- **Population**
- **Economic**

HUMAN DECISION MAKING

political/economic choices

Ecological Systems

- **B**iogeochemistry
- Genetic bank
- Water
- Air

Economic Problems

-poverty
-unequal wealth
-war
-globalization

Ecological Problems

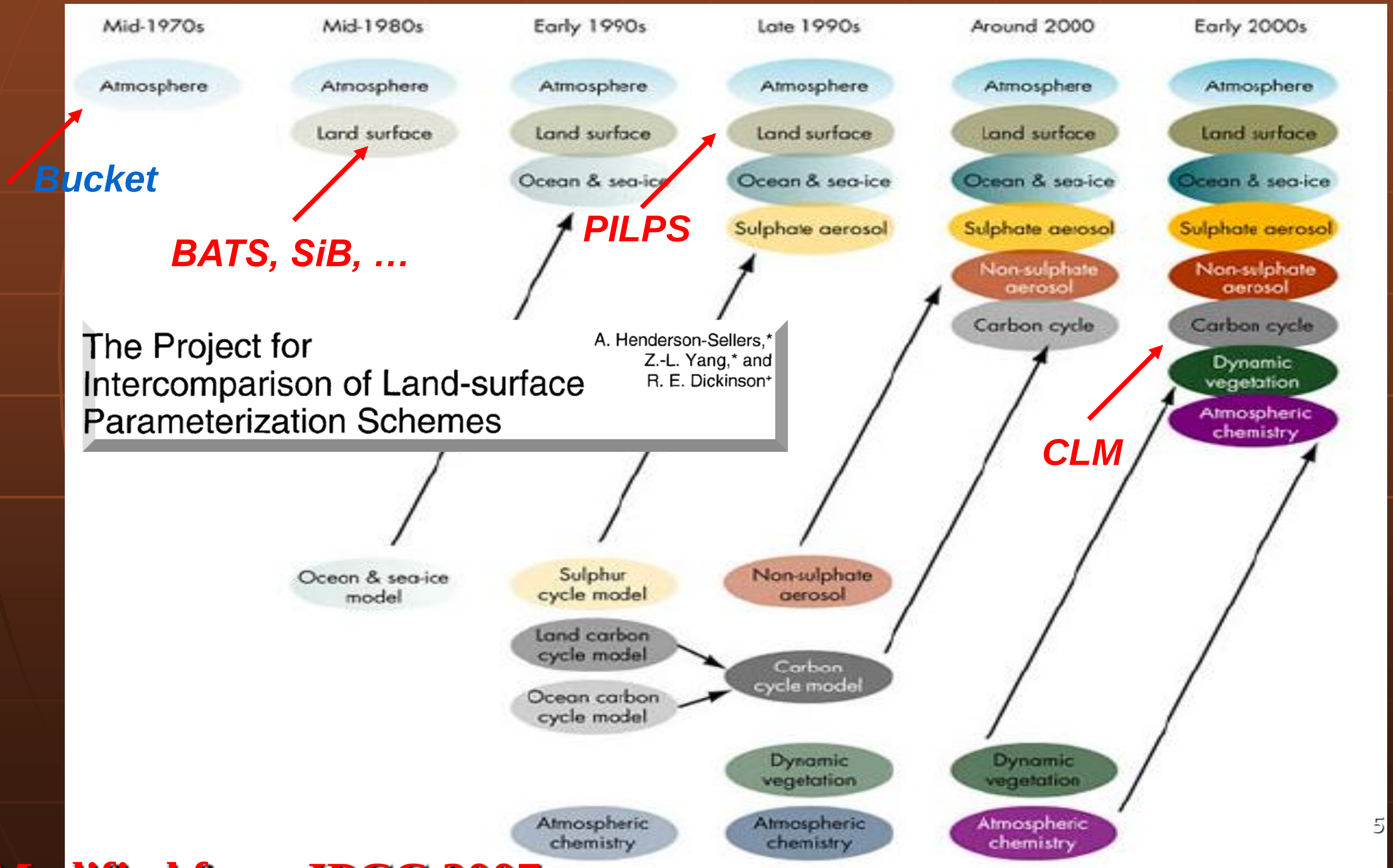
-pollution
-diseases
-food/fibre/fuel shortages
-overcrowding

Ecosystem goods & services

-clean air/water
-waste recycling
-food/fibre/fuel
-recreation

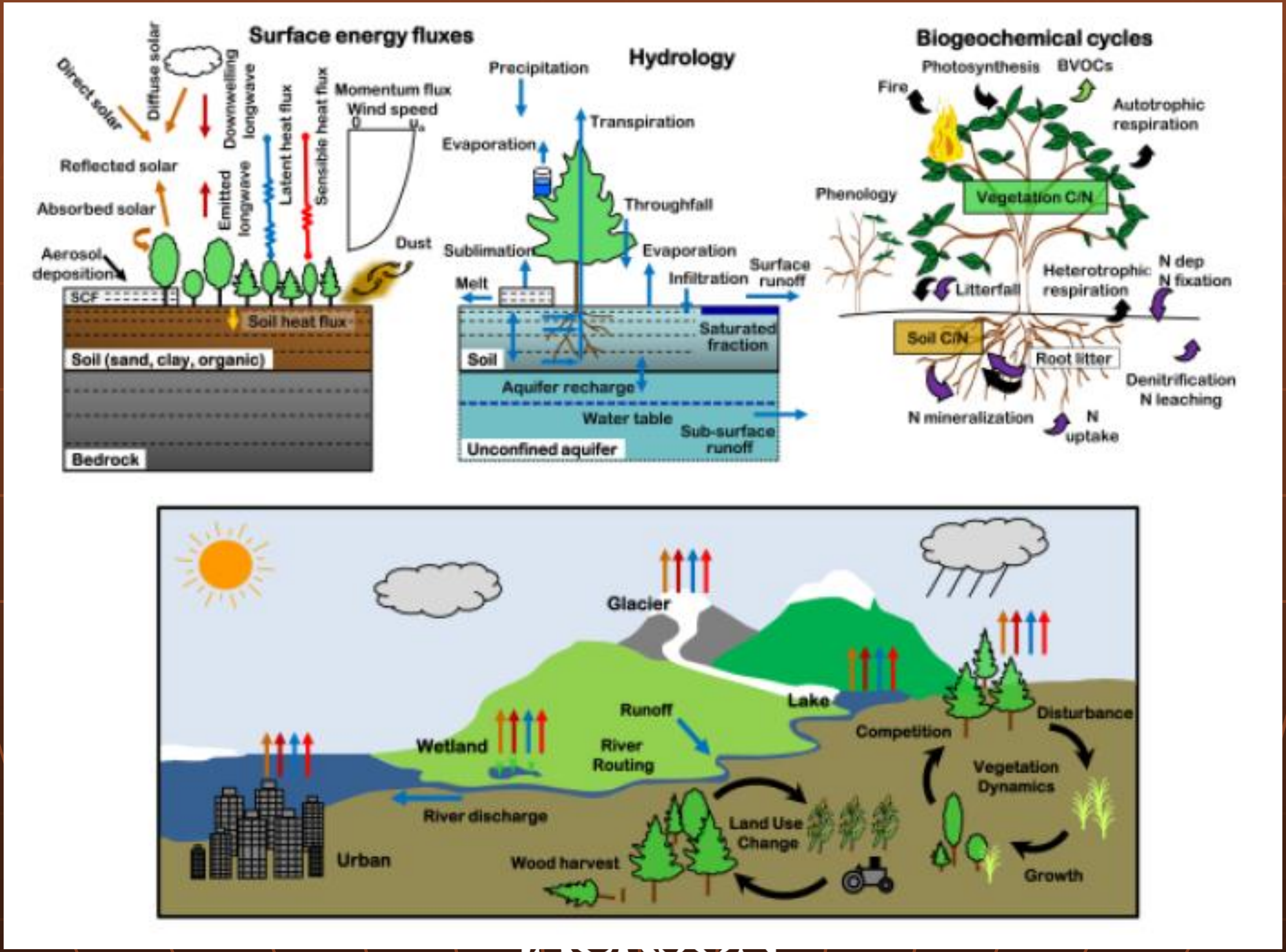
Running 2006

History: Land has been an important component in weather and climate models



Modified from IPCC 2007

Community Land Model (CLM4): 2010→



Lawrence et al. (2011)

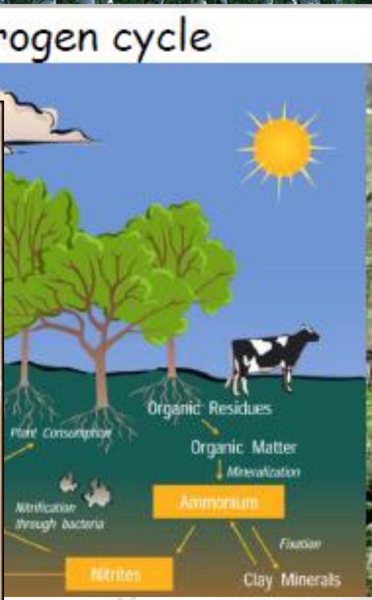
Co-Chairs: David Lawrence (NCAR), Zong-Liang Yang (Univ of Texas at Austin)

CLM4

- Evolved from CLM3.5 (released in 2008 by Oleson *et al*.). CLM3.5 improves over CLM3 (released in 2004)
  - Surface runoff (Niu, Yang *et al*., 2005)
  - Groundwater (Niu, Yang, *et al*., 2007)
  - Frozen soil (Niu and Yang, 2006)
  - Canopy integration, canopy interception scaling, and pft-dependency of the soil stress function (Lawrence *et al*., 2007)
- CLM4 (released in 2010) improves over CLM3.5
  - Prognostic in carbon and nitrogen (CN) as well as vegetation phenology; the dynamic global vegetation model is merged with CN
  - Transient landcover and land use change capability
  - **Urban canopy (Oleson *et al*.)**
  - **BVOC component (MEGAN2) (Guenther *et al*.)**
  - **Dust emissions**
  - Updated hydrology and ground evaporation
  - New density-based snow cover fraction, snow burial fraction, snow compaction
  - Improved permafrost scheme: organic soils, 50-m depth (5 bedrock layers)
  - Conserving global energy by separating river discharge into liquid and ice water streams

Reality Check




Outline

- Introduction
- Vegetation
- Water
- Data Assimilation
- Landscape to Coast
- Summary: Take Away Messages
- Future Work

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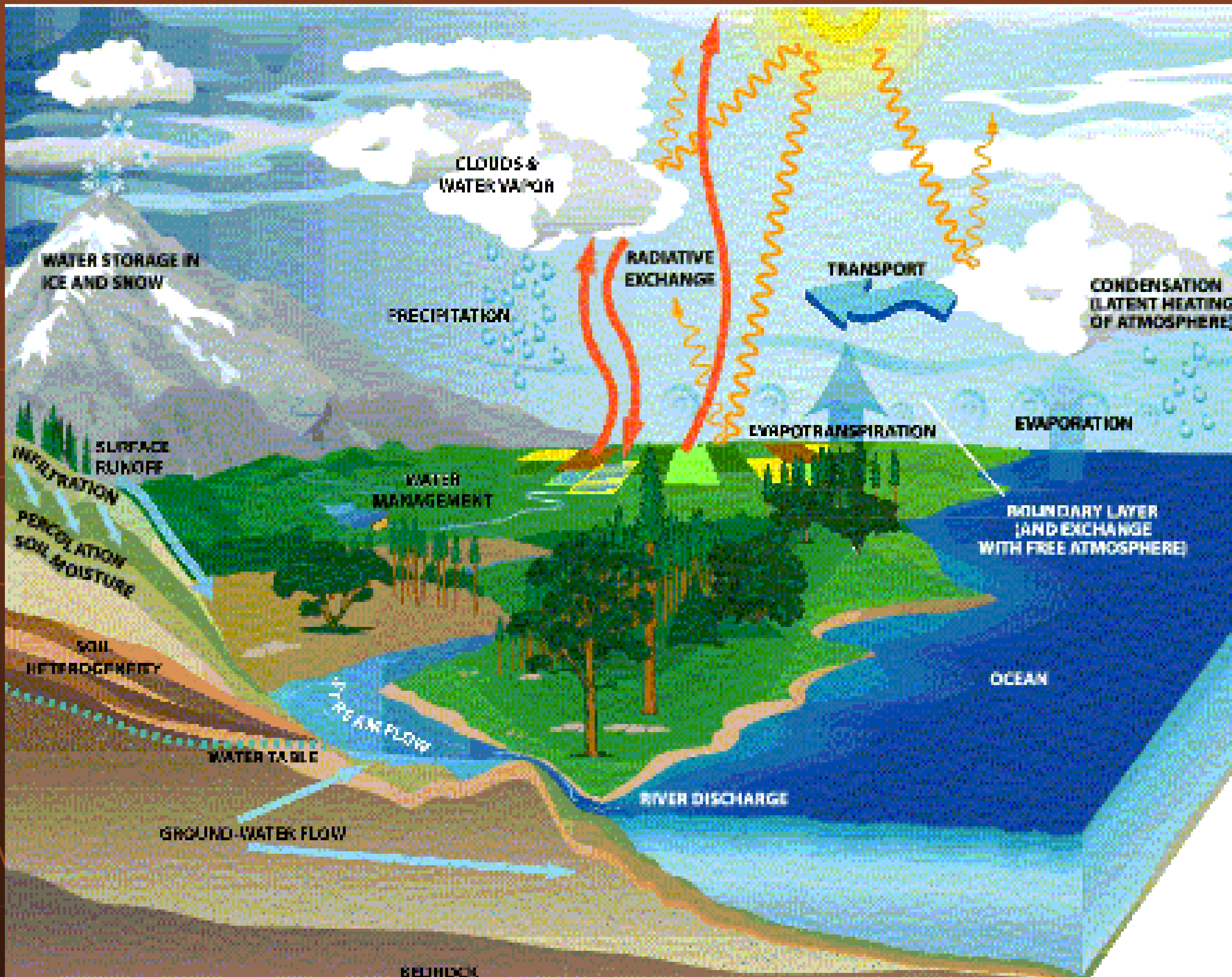
Land Surface Processes



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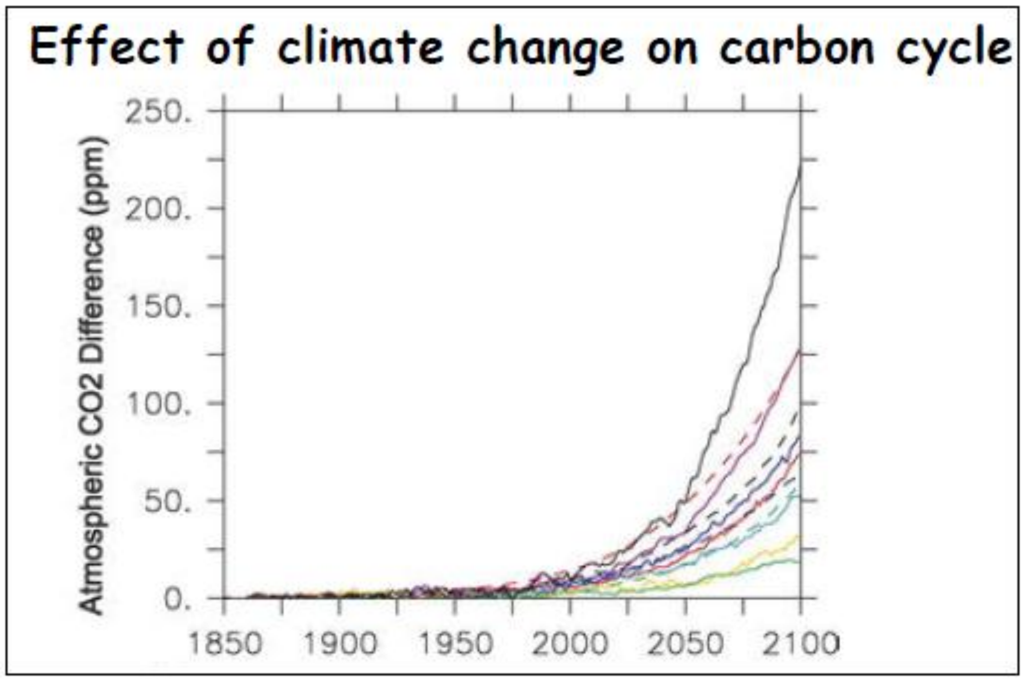
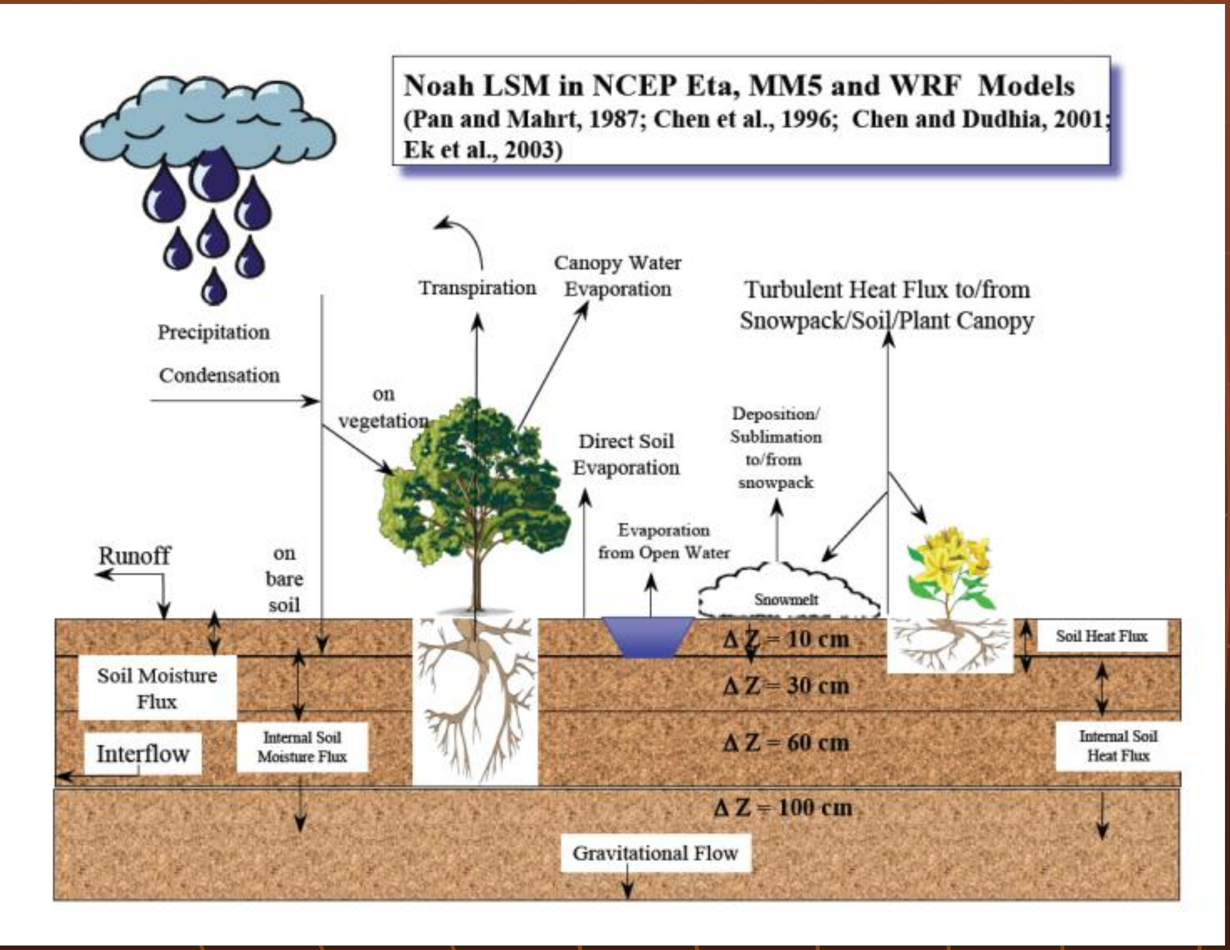
Issues in Vegetation Research

Short-term weather, climate, and atmospheric chemistry models lag behind climate change models in treating interactive canopy and biogeochemistry.



Friedlingstein et al. (2006) J Climate 19:3337-3353

Noah Land Surface Model



- Noah is a default LSM in NCEP Eta, MM5, and WRF models.
- Leaf area index (LAI) and % vegetation cover are prescribed from satellite data.
- Intra-seasonal to inter-annual prediction requires an interactive vegetation canopy or prognostic phenology.

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Interactive Vegetation Canopy

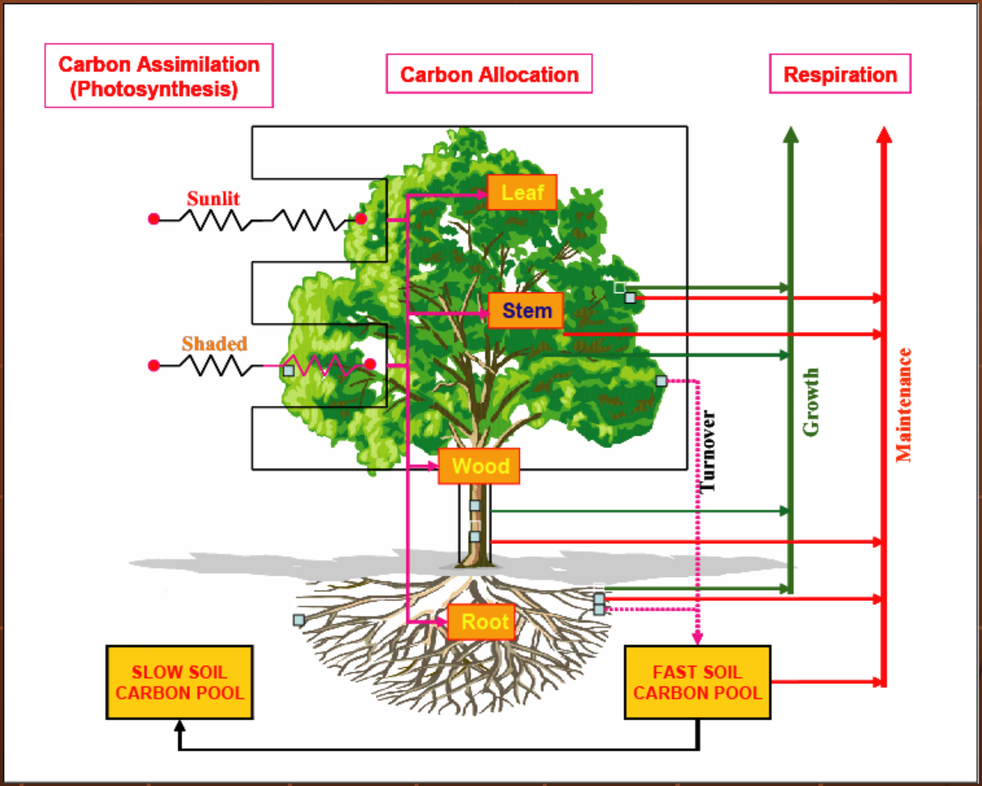
The model includes a set of carbon mass ($g\ C/m^2$) balance equations for:

1. Leaf mass
2. Stem mass
3. Wood mass
4. Root mass
5. Soil carbon pool (fast)
6. Soil carbon pool (slow)

Processes include:

1. Photosynthesis ($S\downarrow$, T, θ, e_{air}, CO_2, O_2, N …)
2. Carbon allocation to carbon pools
3. Respiration of each carbon pool (T_v, θ, T_{root})

$$\frac{\partial M_{leaf}}{\partial t} = R_{gain} - R_{loss}$$

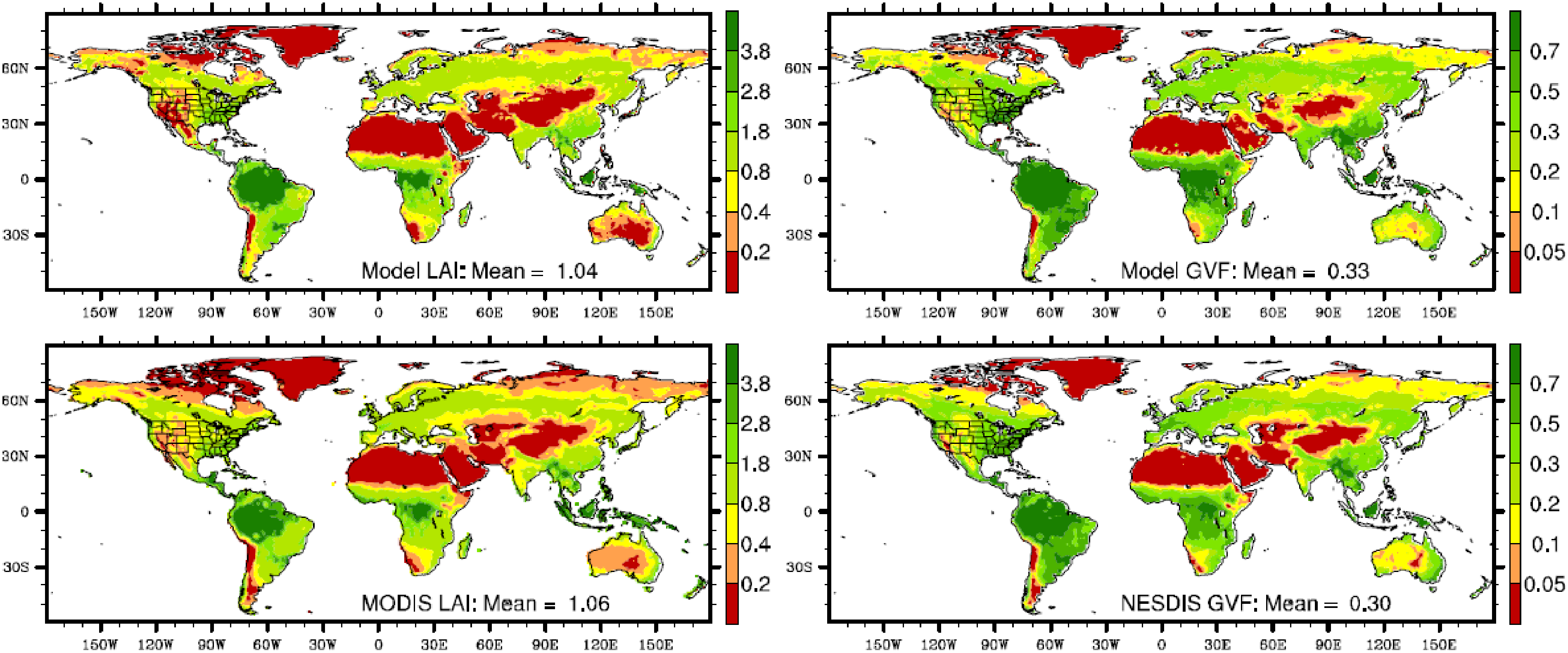


Dickinson et al. (1998),
Yang and Niu (2003)

Carbon gain rate: photosythesis * fraction of carbon partition to leaf
Carbon loss rate: leaf turnover (proportional to leaf mass)
respiration: maintenance & growth (proportional to leaf mass)
death: temperature & soil moisture

$LAI = M_{leaf} * C_{area}$ *where* C_{area} *is area per leaf mass* (m^2/g).

Comparison of Noah-MP and Satellite LAI and % Vegetation Cover (GVF)



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Yang et al. (2011a)

WRF Simulated & Observed Monthly and Seasonal Mean Precipitation in Central Great Plains

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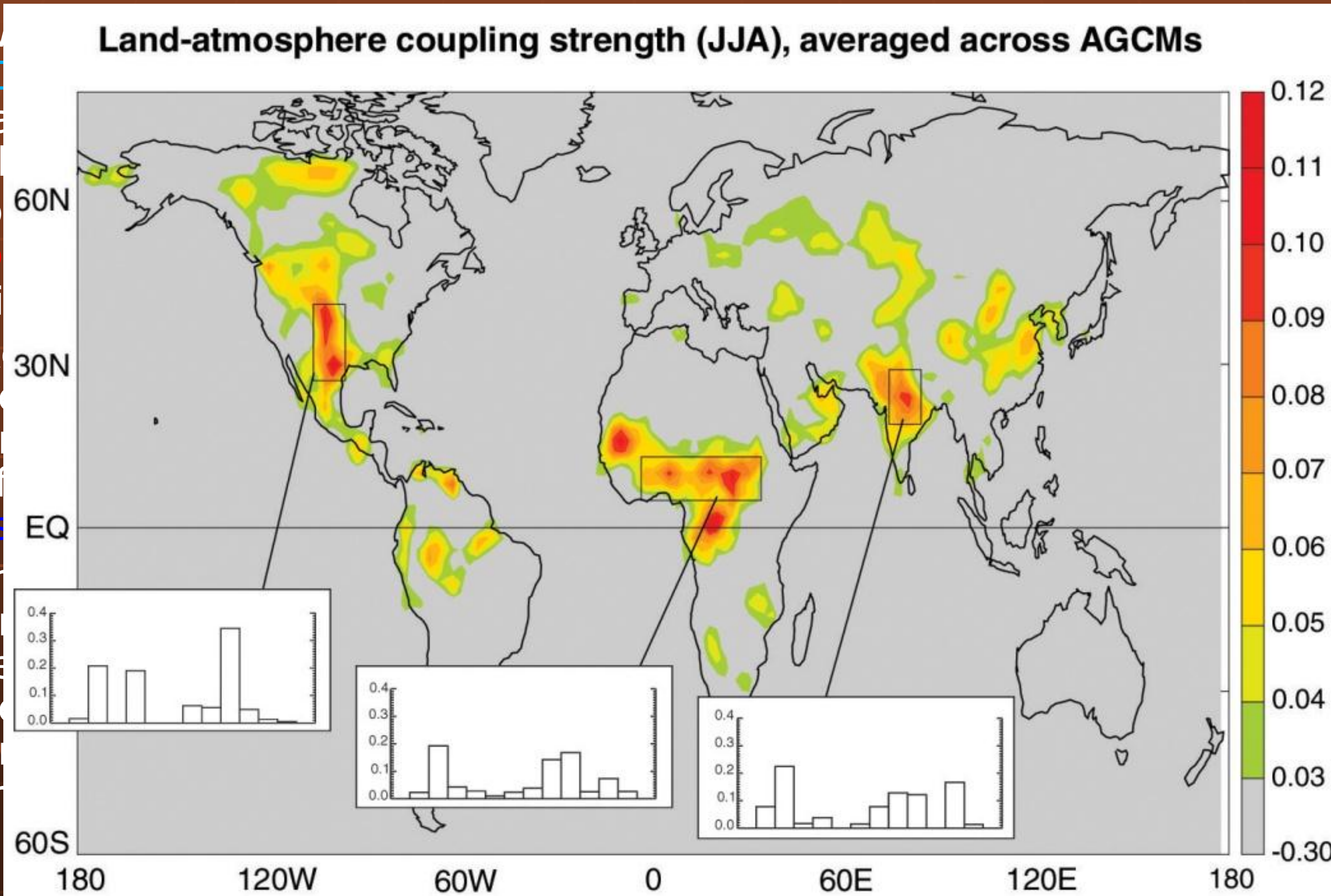

Jiang et al. (2009) *J. Geophys. Res.*

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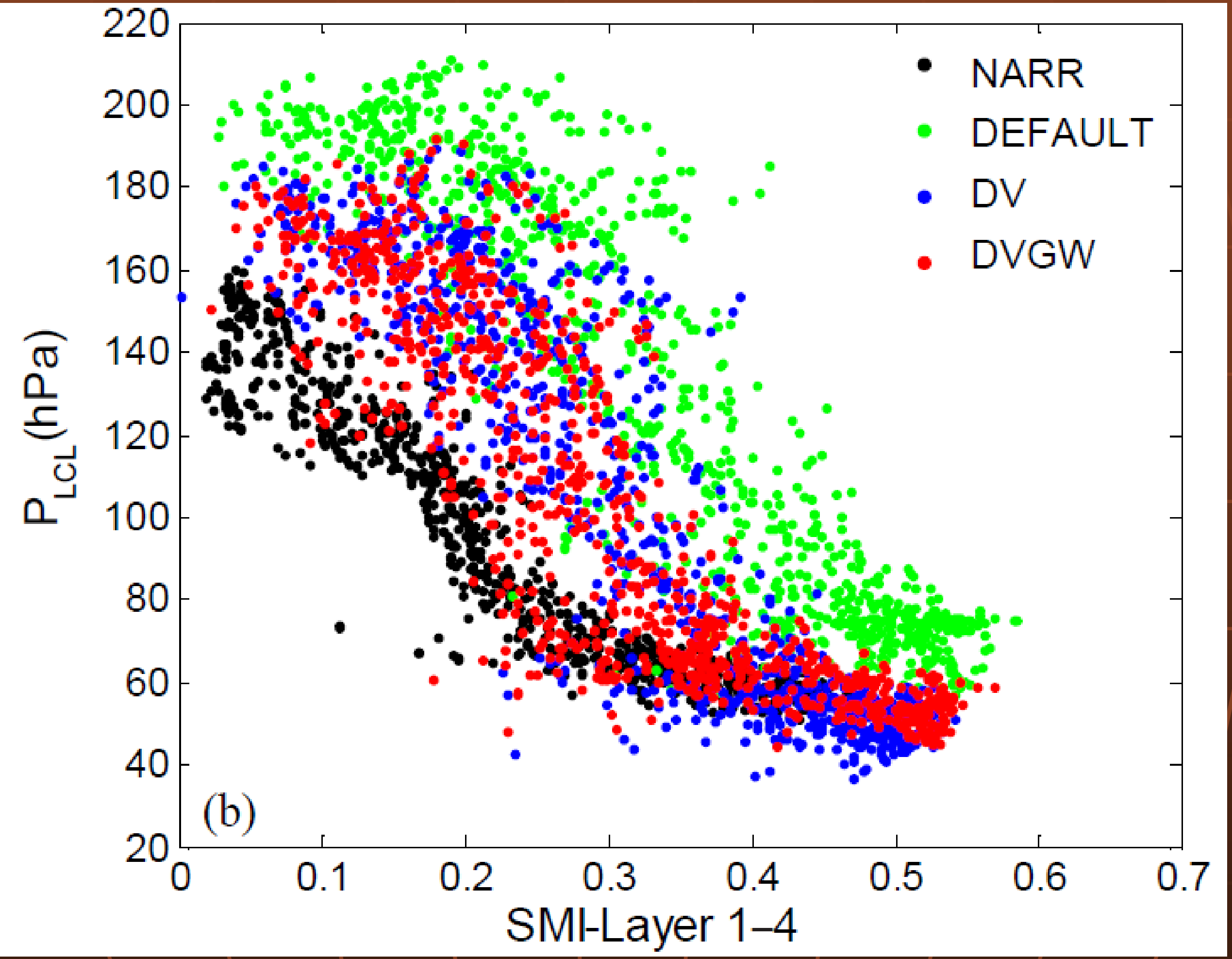
Lifting condensation level (LCL) height versus soil moisture index (SMI) in the soil layers



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Jiang et al. (2009) *J. Geophys. Res.*

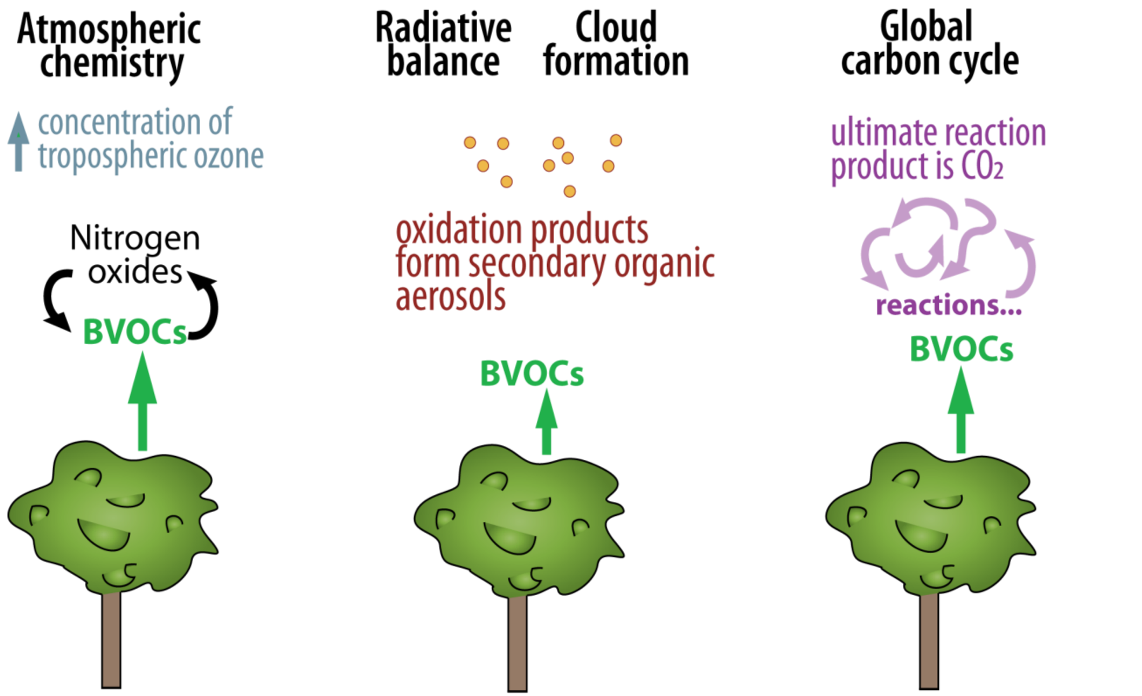
Biogenic emissions of volatile organic compounds (BVOCs)

Isoprene (C_5H_8 异戊二烯), monoterpene ($C_{10}H_{16}$单萜烯), other reactive VOCs

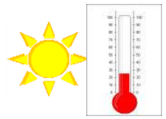
Trace gases in the air

Important roles

BVOCs = 90% VOCs



Climate Change and BVOC Emissions



BVOCs + NO_x → O_3

BVOC emissions vary by species

Live Oak

American Elm

1. **Climate change** affects BVOC emissions:
   - **directly:** by altering incident solar radiation, precipitation, temperature, etc.
   - **indirectly:** by altering leaf area index, species composition and density

2. **Anthropogenic land-cover change** alters species composition → affects BVOC emissions

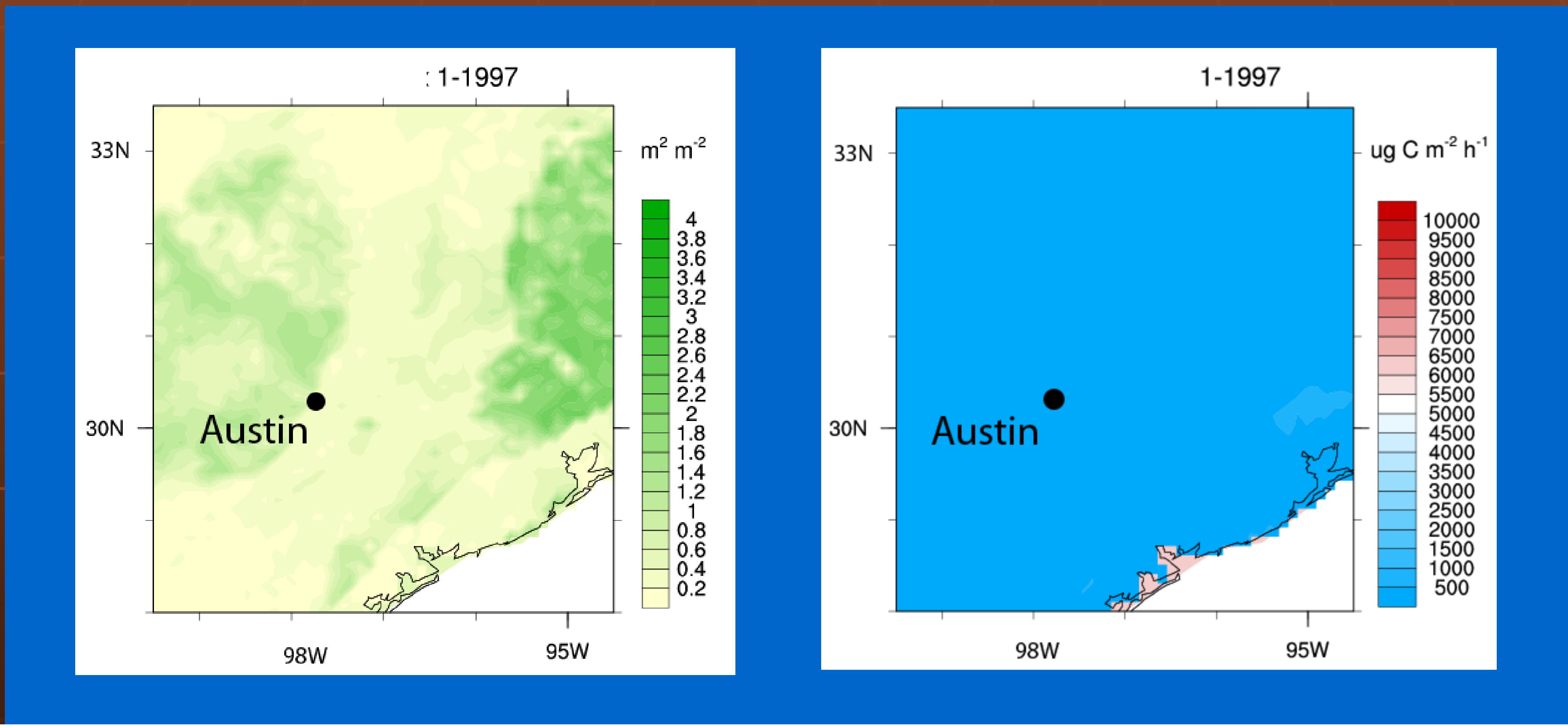
Some challenges:

Climate models have a high uncertainty in simulating key weather variables

Land-surface models represent vegetation as mosaics of plant functional types, not species

Precipitation Variability Drives Year-to-year Changes in Leaf Biomass and Biogenic Emissions (movie)

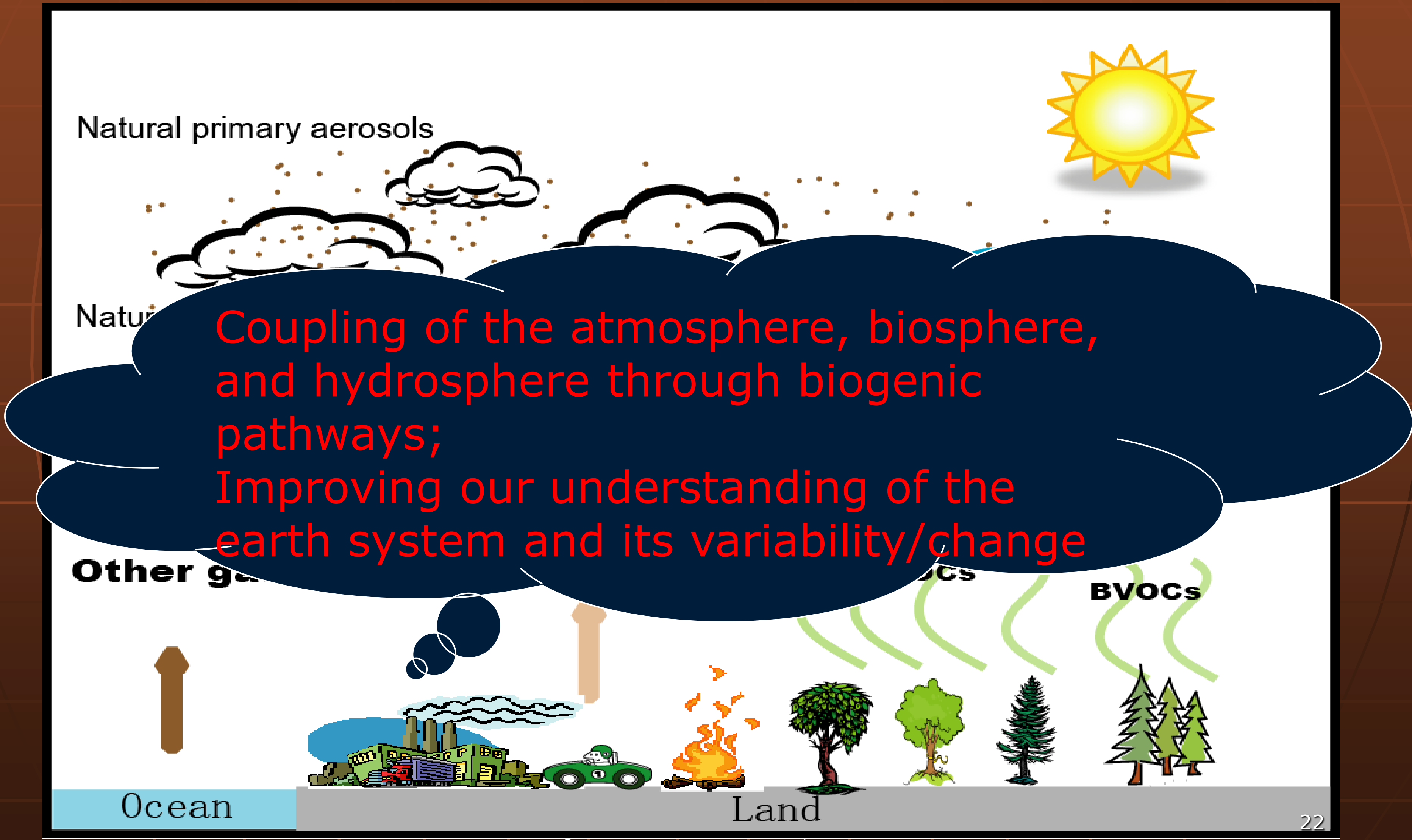
Leaf area index in Texas | **Biogenic emissions in Texas**



Gulden, L. E., Z.-L. Yang and G.-N. Niu, 2007, *J. Geophys. Res.*, **112** (D14), D14103, 10.1029/2006JD008231.

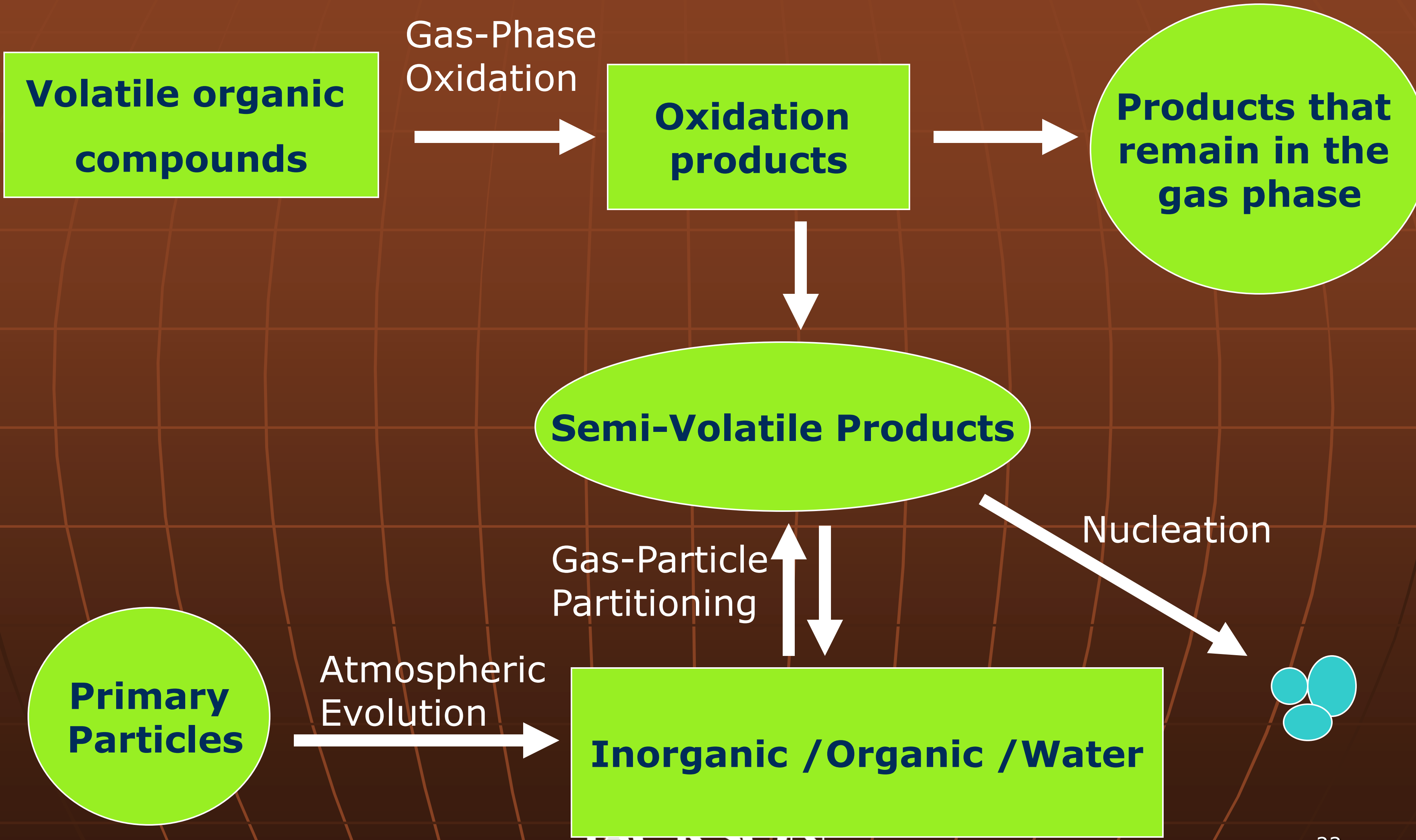
Gulden, L.E. and Z.-L. Yang, 2006, *Atmospheric Environment*, **40(8)**, 1464-1479.

Biogenic Volatile Organic Compounds (BVOCs) and Secondary Organic Aerosols (SOAs)



Jiang, Yang et al. (2010), Atmospheric Environment

Route of SOA formation



Seinfeld and Pankow (2003)

SOA formation

Partitioning between gas and particle phases

$$A_i = K_i G_i \mathrm{M_o}$$

M_o : pre-existing aerosols
A_i :Aerosol concentration

(*Pankow*, 1994)

Semi-Volatile reactive organic gases (*G_i*)

Monoterpenes+ OH/NO3/O3 → $\alpha_1 G_1 + \alpha_2 G_2$
Isoprene + OH → $\alpha_1 G_1 + \alpha_2 G_2$

Stoichiometric yields (α_i)

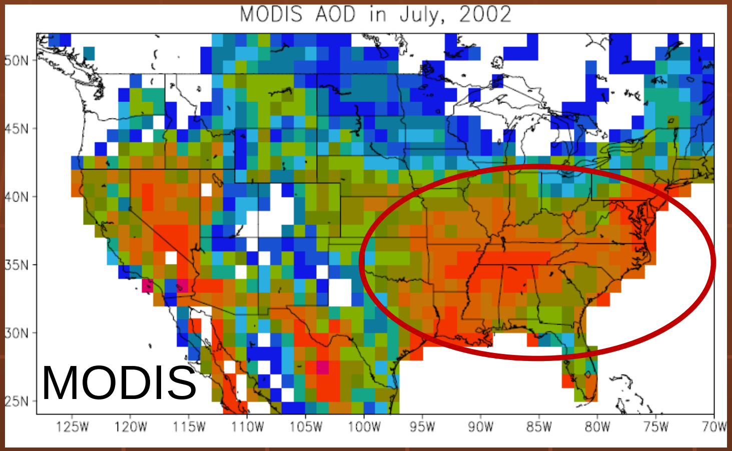
2-product model (Odum et al., 1996)

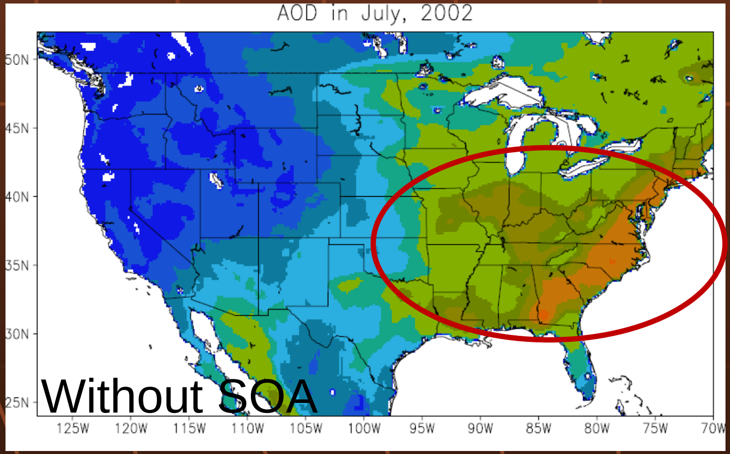
Also include temperature effect

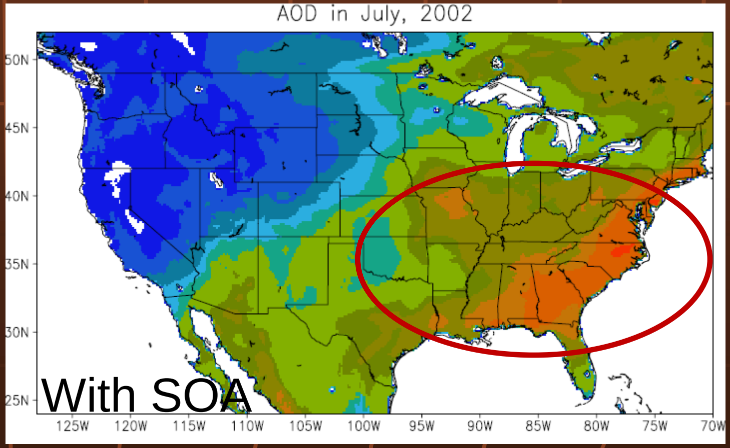
$$c^*(T) = c(T_{ref})(\frac{T_{ref}}{T})\exp(\frac{\Delta H_{vap}}{R}(\frac{1}{T_{ref}} - \frac{1}{T}))$$

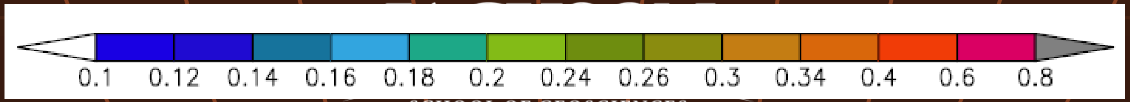
Jiang, Yang et al. (2010), Atmospheric Environment

MODIS and WRF-CHEM simulated aerosol optical depth (AOD) at 550nm



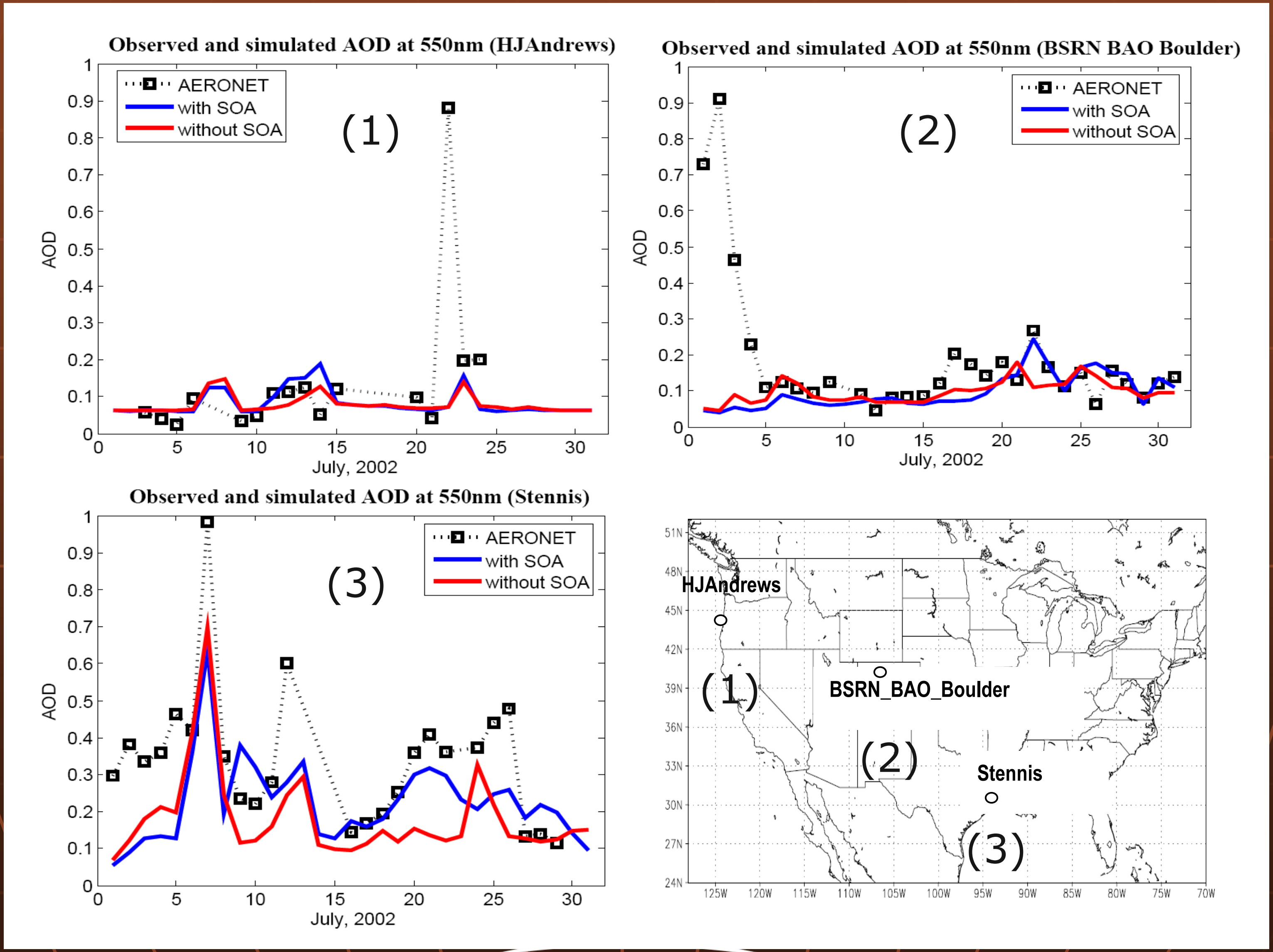






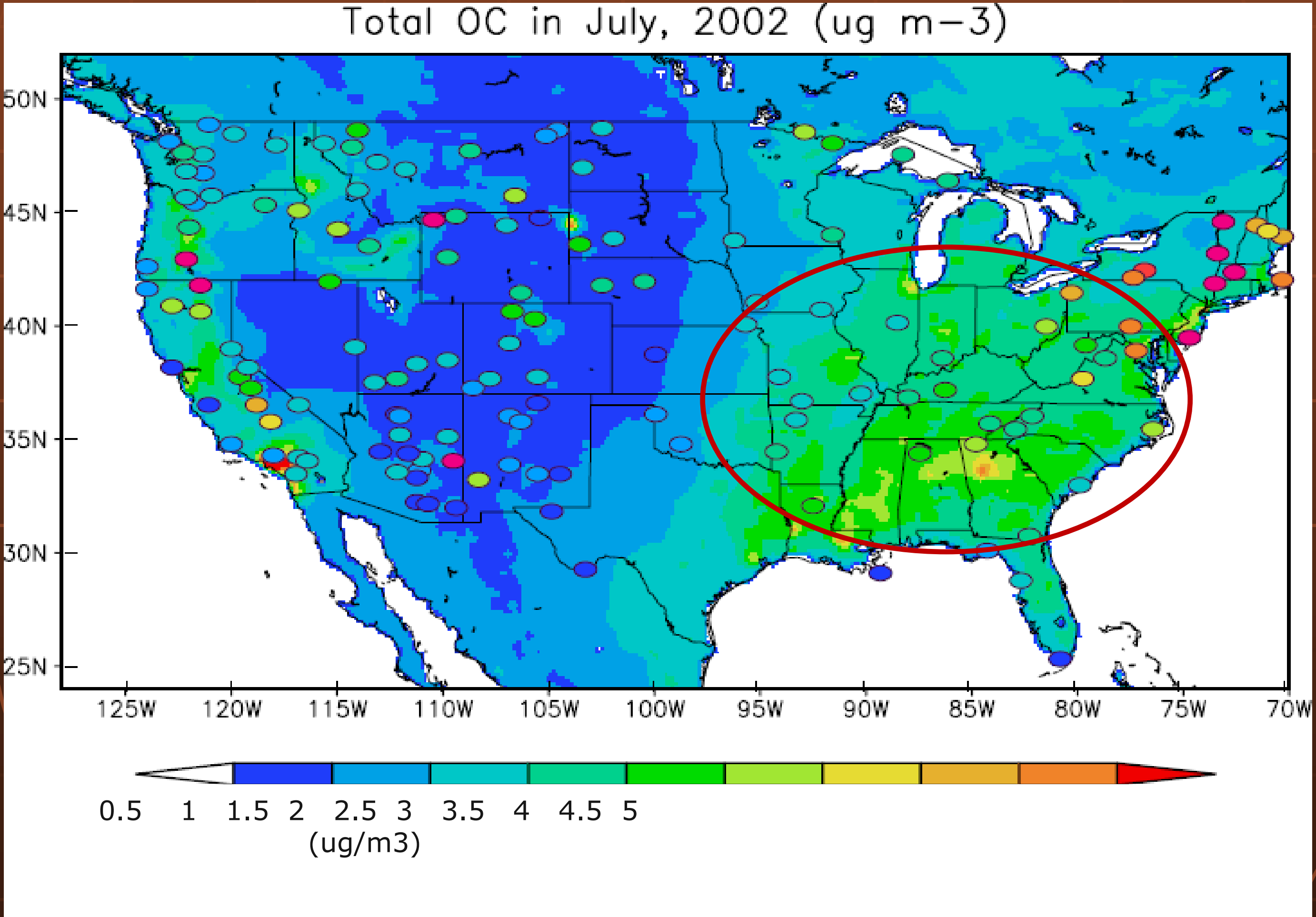
Jiang, Yang et al. (2010), Atmospheric Environment

Comparison of simulated AOD with AERONET data



Jiang, Yang et al. (2010), Atmospheric Environment

Comparison of simulated OC concentrations with IMPROVE data



OC

Jiang, Yang et al. (2010), Atmospheric Environment

Summary

Augmenting land surface models with interactive vegetation canopy and groundwater

- Improves intra-seasonal to inter-annual predictive skills;
- Increases temporal and spatial variability of biogenic emissions;
- Allows better understanding of atmosphere, biosphere and hydrosphere coupling through biogenic pathways.

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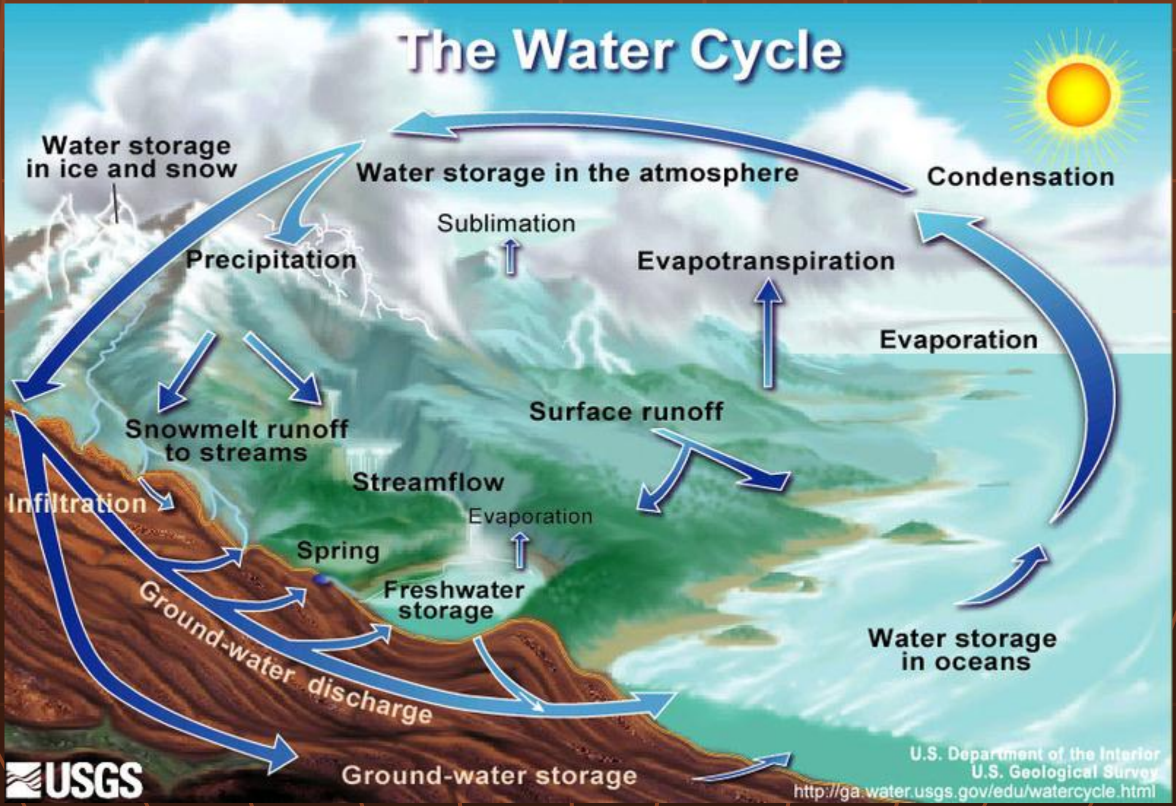
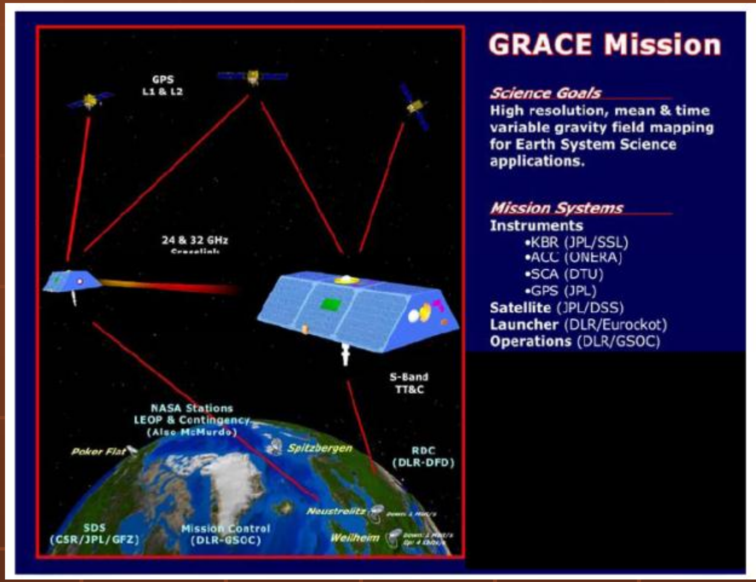
Issues in Water Cycle Research

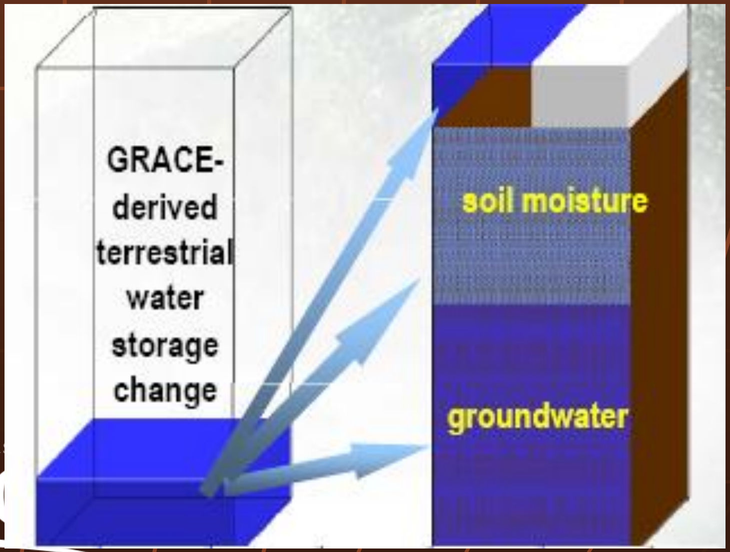
- How can we improve, assess, and evaluate hydrological models on regional to global scales?



Gravity Recovery and Climate Experiment (GRACE)

- 8+ years of mission operation (Tapley et al., 2004)
- First-time global data of gravity (~100 km, monthly to 10-day)
- Unprecedented accuracy of mass variations
- Allowing a better understanding of the global water cycle





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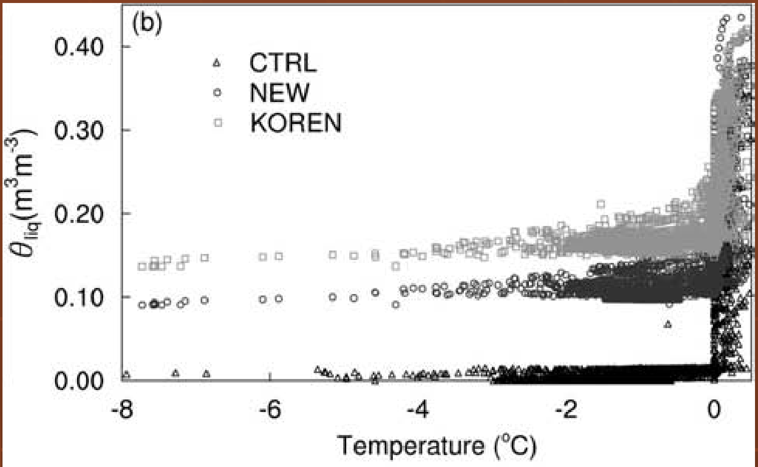
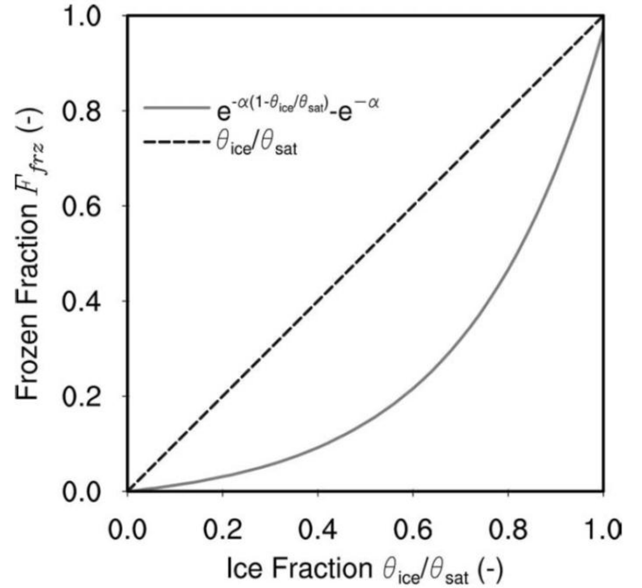
Improving Frozen Soil Process in CLM2

Original model: no super-cooled water for below freezing soil temperatures

New model: allowing super-cooled water and percolation in the frozen soil

Results: improving infiltration of snowmelt; improving timing of runoff, and a shift of water storage by one month in good agreement with GRACE data





Niu and Yang (2006) J. Hydrometeorology.

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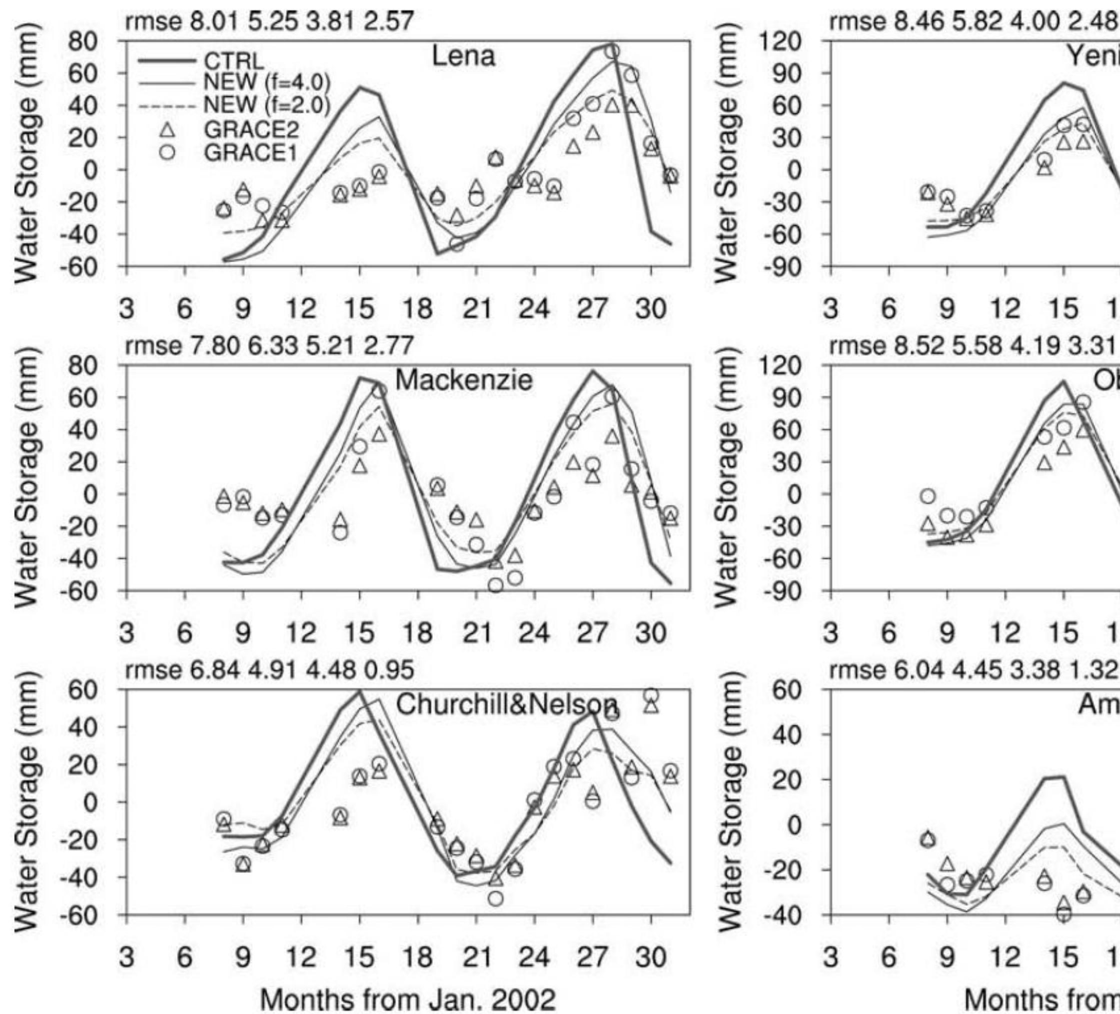
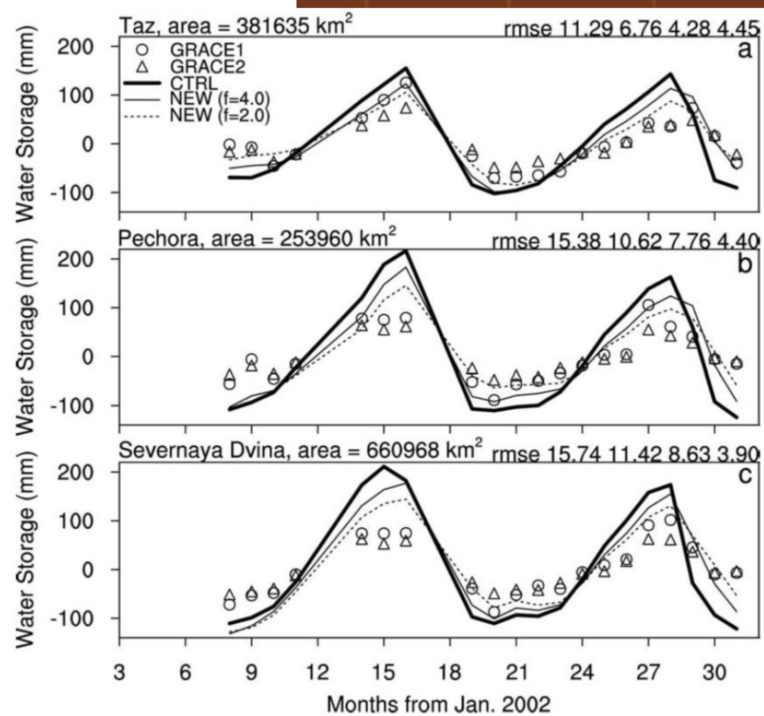
Improving Frozen Soil Process in CLM2



Results: a shift of seasonal maximum water storage by one month in good agreement with GRACE data



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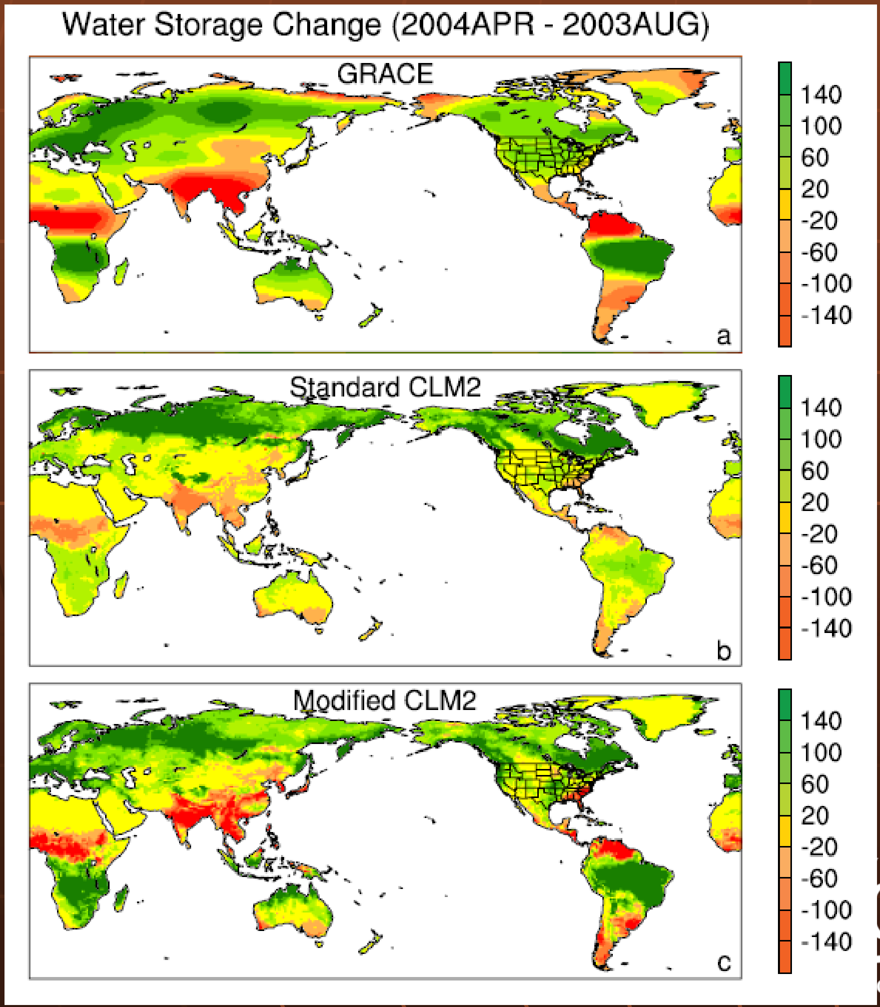
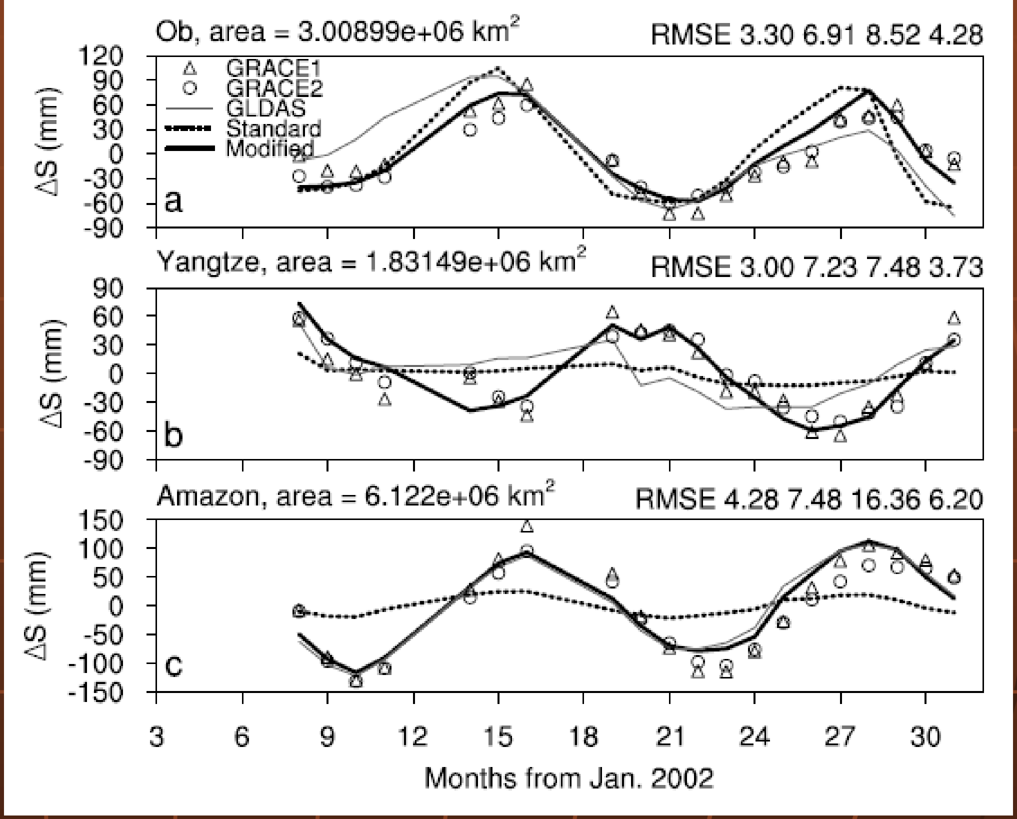
Niu and Yang (2006) J. Hydrometeorology.

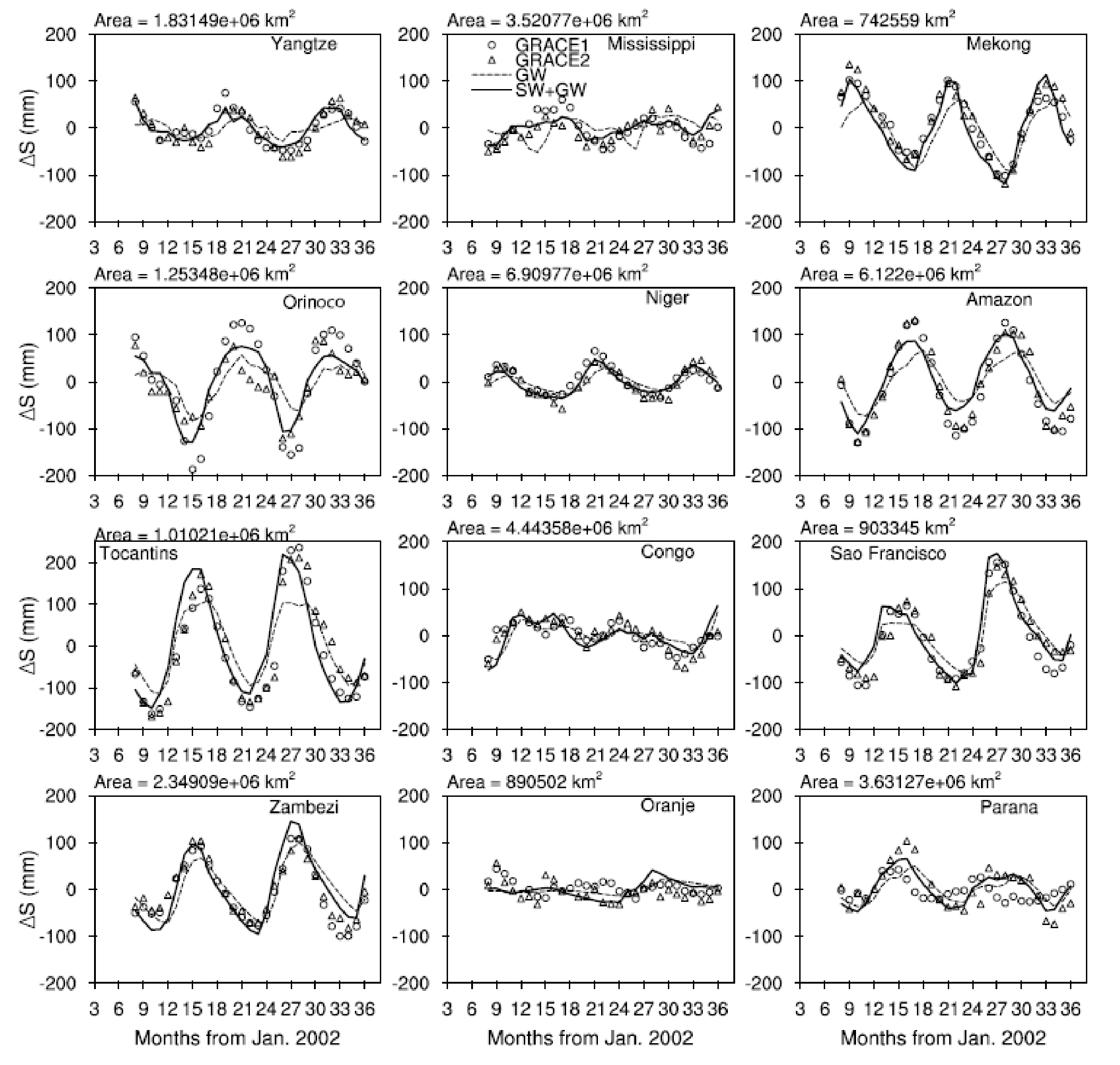
Improving Interception, Runoff, and Frozen Soil Process in CLM2





Niu and Yang (2006) GRL

Improving Groundwater Dynamics in CLM2



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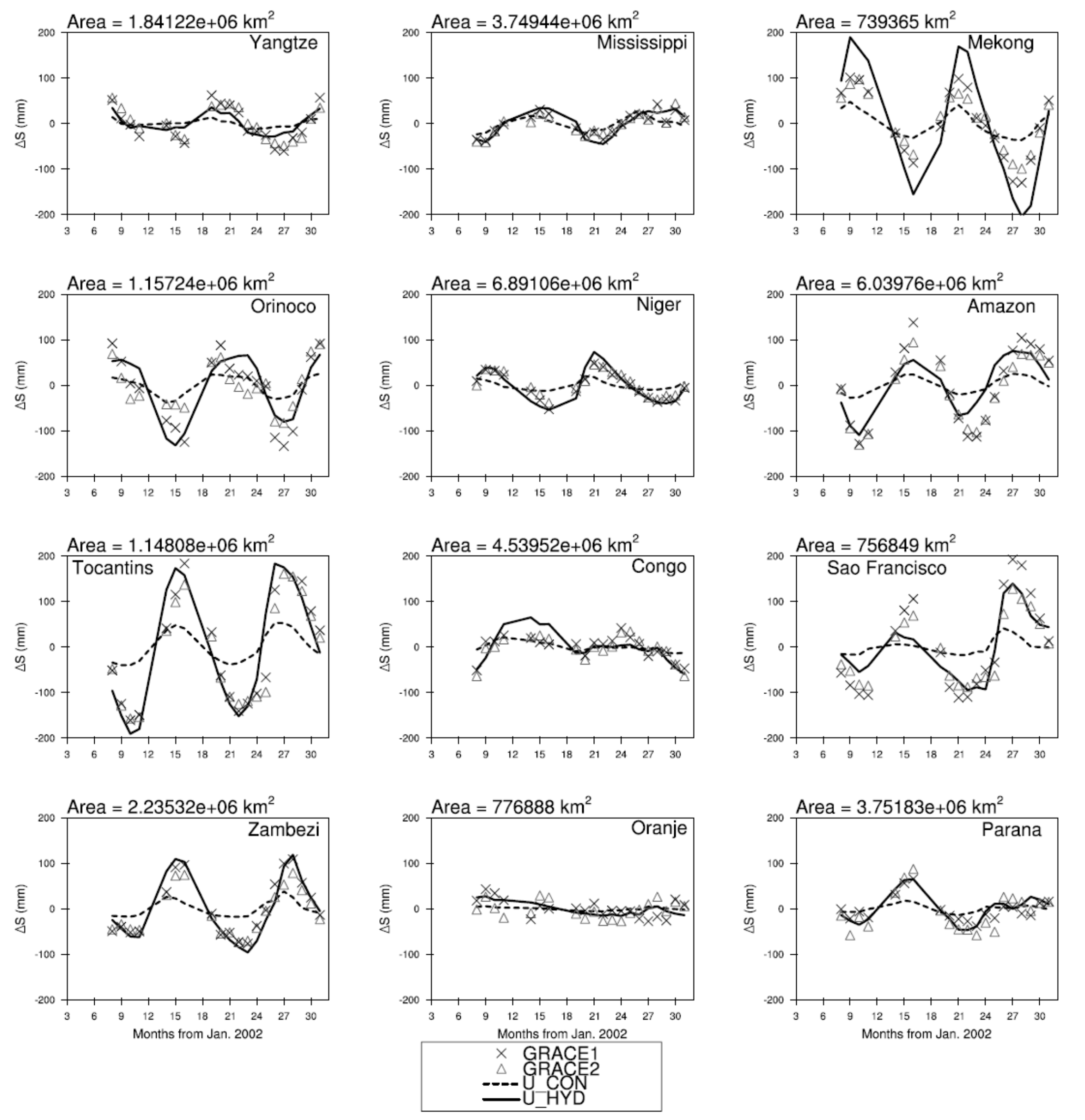
Niu, Yang, et al. (2007) JGR

Improved hydrological schemes in CLM3.5

Oleson, K. W., G.-Y. Niu, **Z.-L. Yang**, D. M. Lawrence, P. E. Thornton, P. J. Lawrence, R. Stöckli, R. E. Dickinson, G. B. Bonan, S. Levis, A. Dai, and T. Qian, 2008: Improvements to the Community Land Model and their impact on the hydrological cycle, *J. Geophys. Res.*, **113**, G01021, doi:10.1029/2007JG000563.



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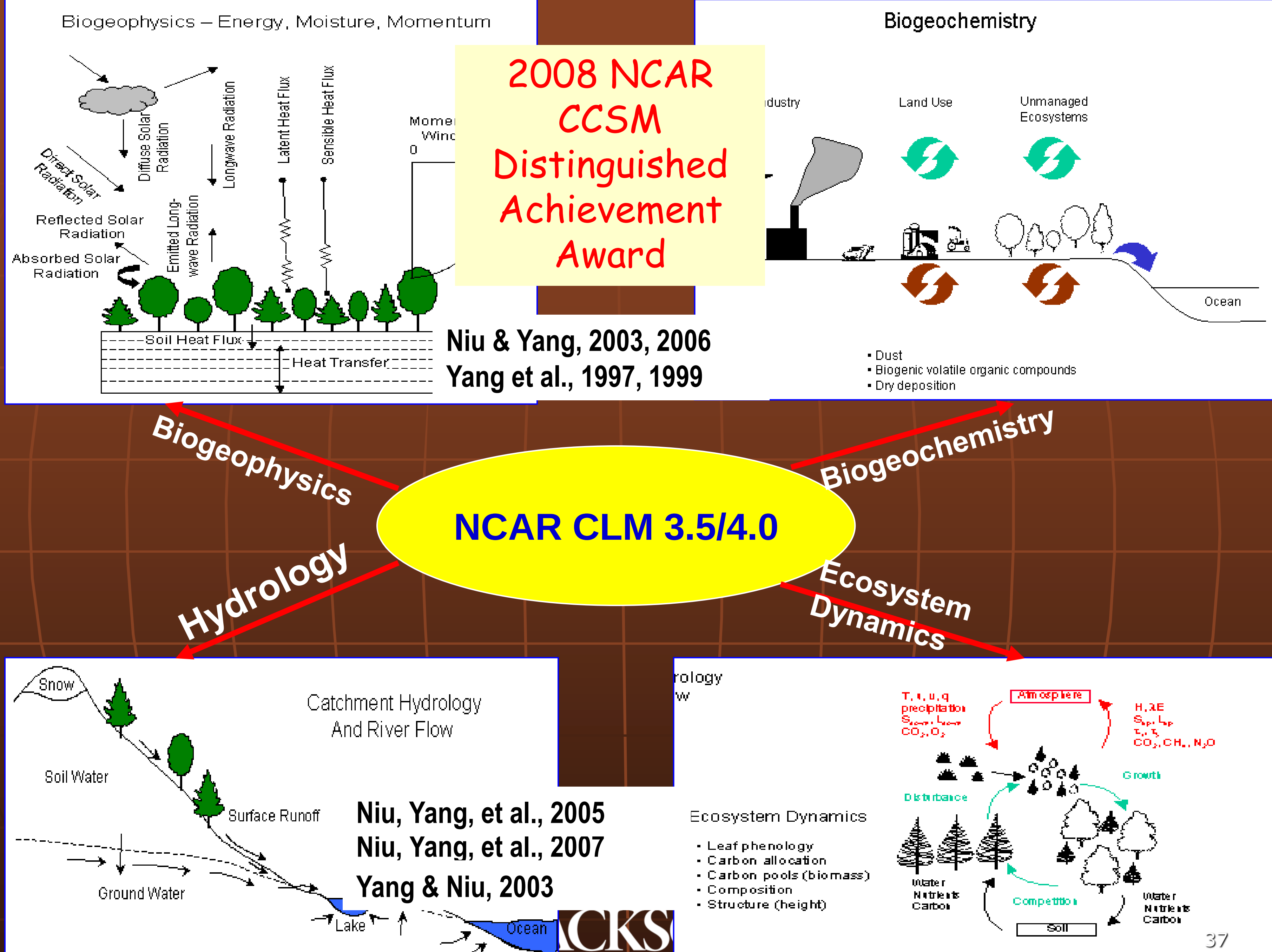
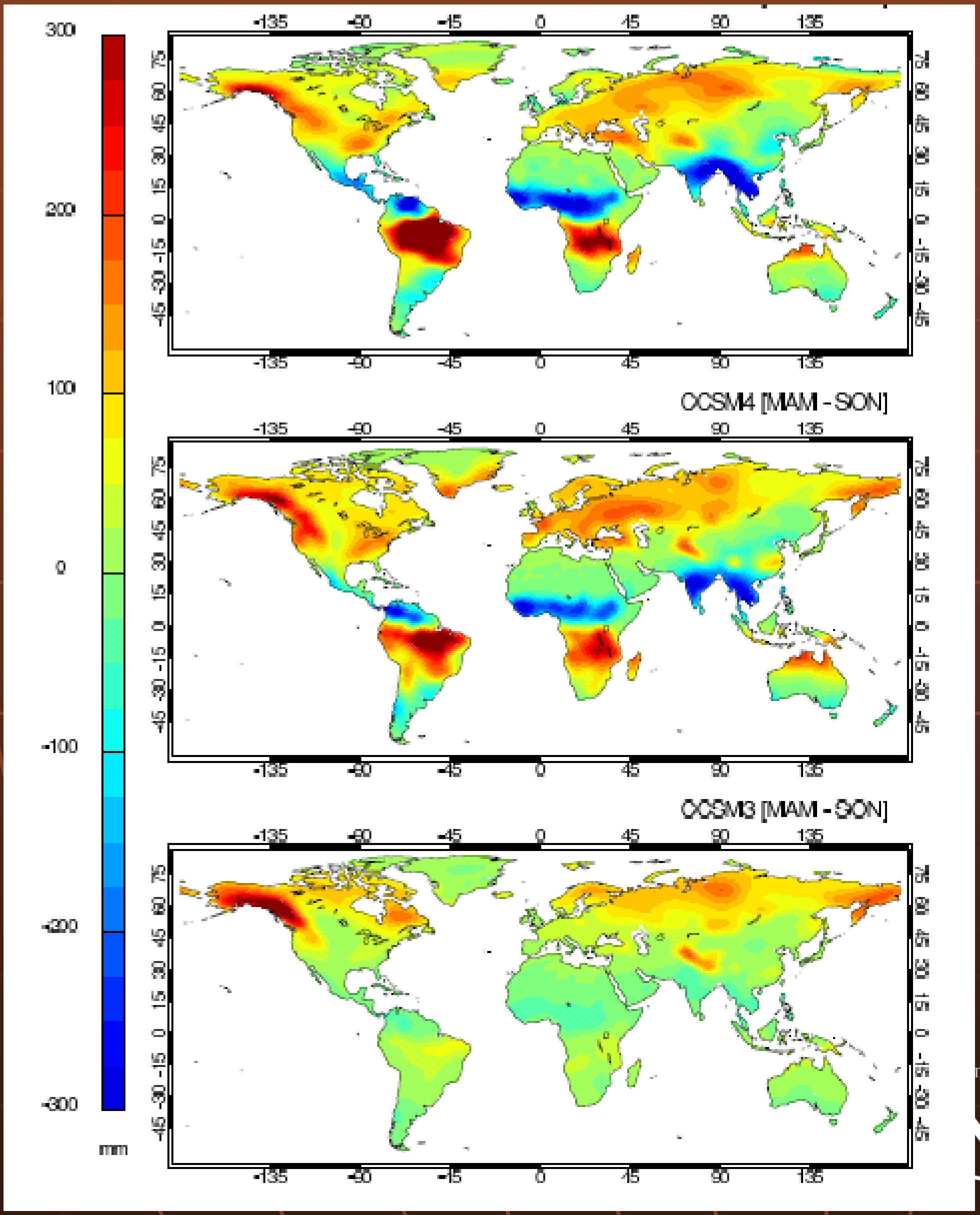


Collaborators: UT (Yang, Niu, Dickinson), NCAR (Bonan, Oleson, Lawrence) and others

Terrestrial Water Storage Change



GRACE (MAM – SON)

CCSM4 (MAM – SON)
(Fully coupled global land, atmosphere, ocean, ice climate model)

CCSM3 (MAM – SON)

Gent et al. (2011)

Summary

GRACE data have been successfully used to improve, assess, and evaluate the NCAR Community Land Model, perhaps the first GRACE-tested model used in IPCC AR5 global climate or earth system models.

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Issues in Snow Data Assimilation

- Direct insertion (using observations to replace model calculations)
- Limited domain size (watershed scale mostly)
- Unrealistic snow depletion curves
- Limitations in radiometric data assimilation
  - Infrared/visible bands: clouds contamination
  - Microwave bands: low accuracy for wet snow

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Multi-sensor Snow Data Assimilation

MODIS | GRACE

Hypothesis:

GRACE/MODIS multi-sensor data assimilation algorithm can achieve more accurate SWE data than MODIS and open loop at continental scale.

MODIS	GRACE
Geometric property: snow area	Integral of water storage (vertically)
Weather sensitive	Weather insensitive

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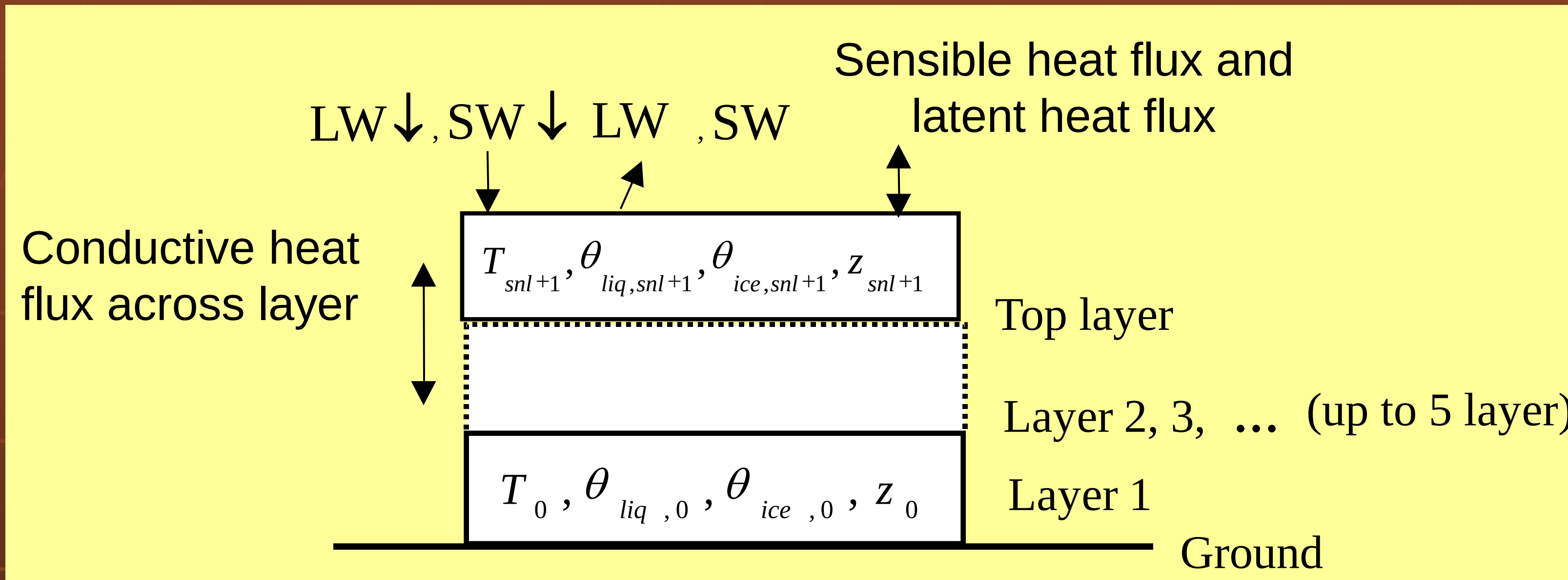
Multi-layer Snow Model in Community Land Model



$$C\frac{\partial T}{\partial t} = \frac{\partial}{\partial z}(\lambda \frac{\partial T}{\partial z}) + \rho_{ice} L_f \frac{\partial \theta_{ice}}{\partial t} + S$$

Snowpack heat diffusion

$$G + LH + SH = LW_g + SW_g$$

Surface energy balance

$$X_{SWE,t} = X_{SWE,t-1} + P_t - Q_t - E_t$$

System function

The Ensemble Kalman Filter (Monte Carlo)

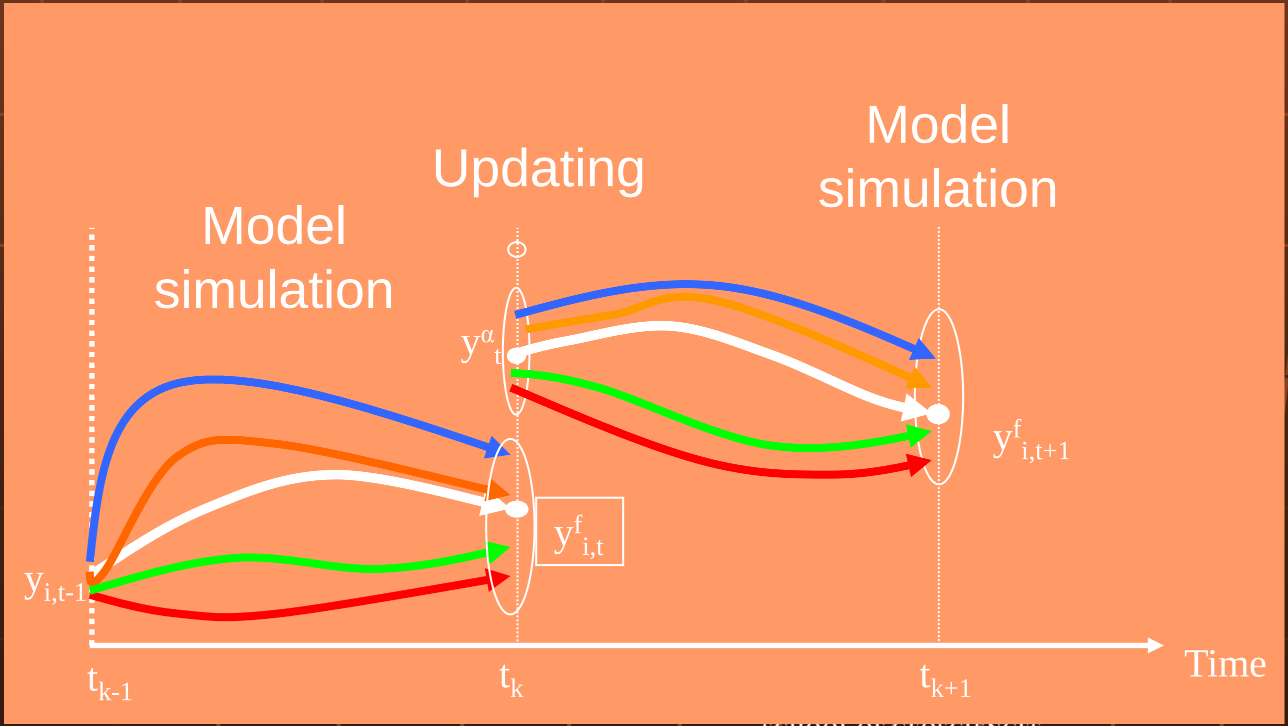
$$x_{i,t}^{f} = f\left(x_{i,t-1}, u, \alpha, w\right)$$

$$P_t^{f} = \frac{1}{N-1} D_t D_t^{T}$$

$$D_t = [x_{1,t}^{f} - \overline{x}_t, x_{2,t}^{f} - \overline{x}_t, \ldots, x_{N,t}^{f} - x_t]$$

$$x_{i,t}^{a} = x_{i,t}^{f} + K_t\left(y_t - Hx_{i,t}^{f} + v_i\right)$$

$$K_t = P_t^{f} H^{T}\left(HP_t^{f} H^{T} + R\right)^{-1}$$

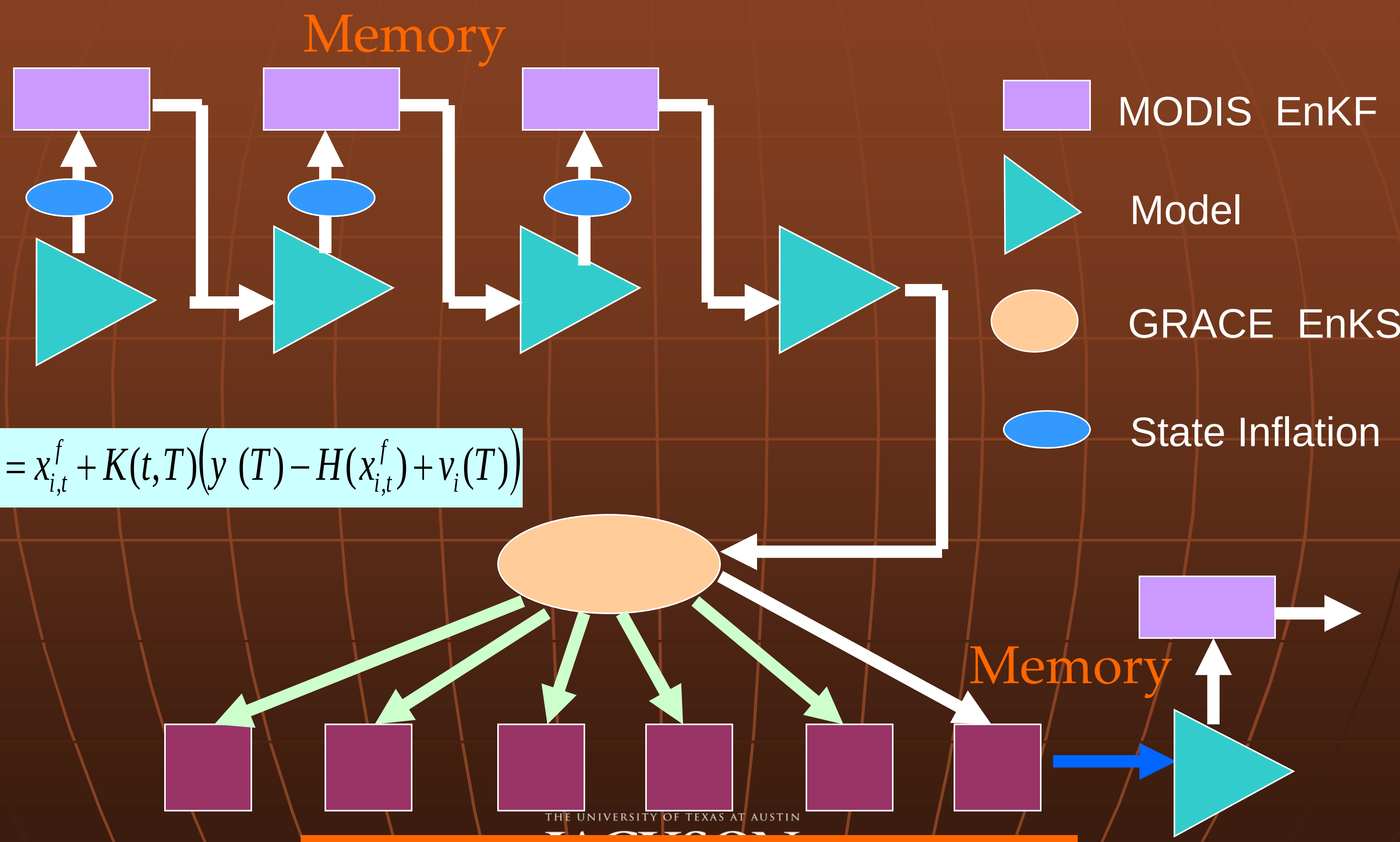


Computationally competitive

Resolve nonlinear observation function

Resolve forcing and initialization uncertainties

Multi-sensor Data Assimilation of MODIS and GRACE

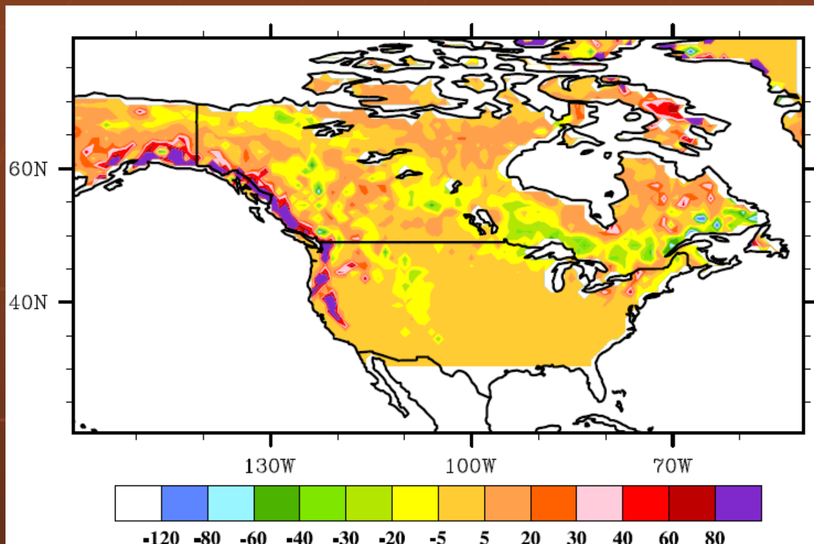


$$x^a_{i,t} = x^f_{i,t} + K(t,T)\left(y\,(T) - H(x^f_{i,t}) + v_i(T)\right)$$

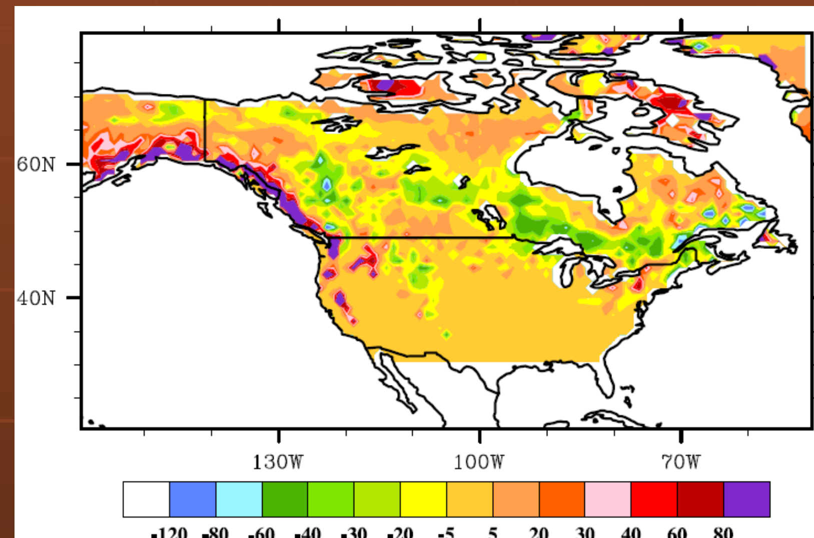
Daily average of the simulation results

Monthly SWE Difference (mm) MOD_GRACE - MOD

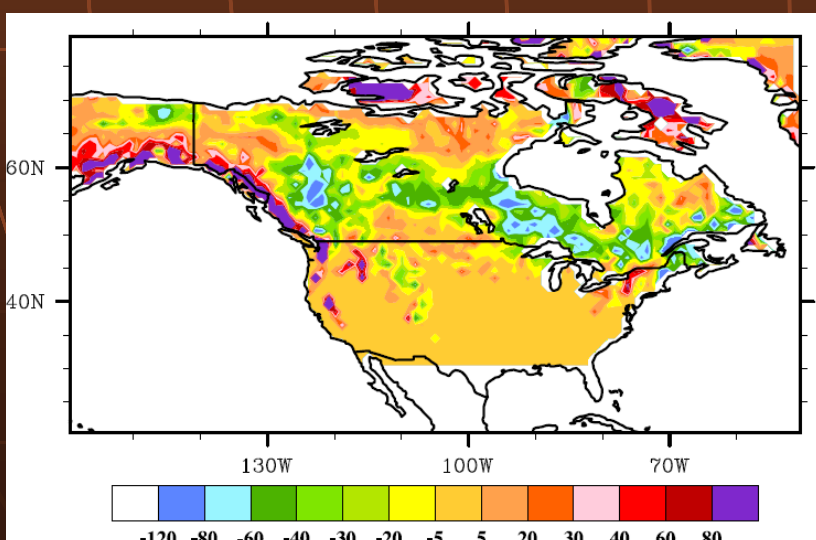
Jan



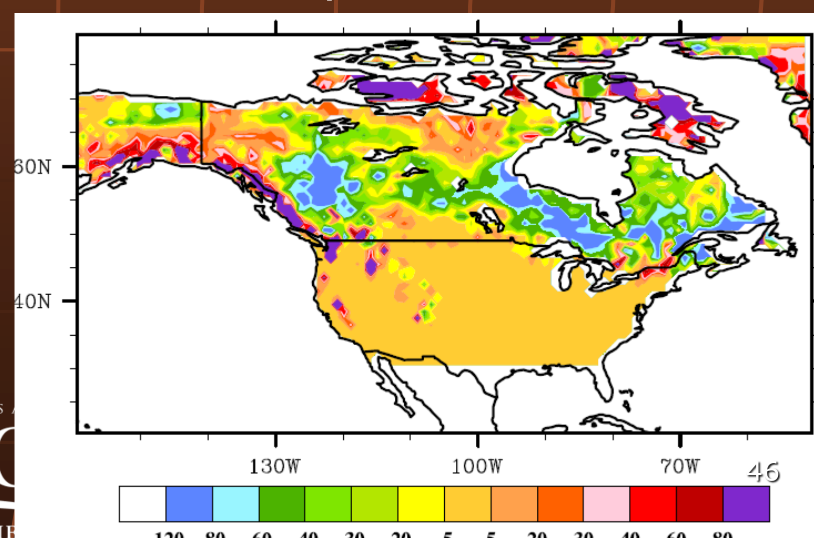
Feb



Mar



Apr



Summary

- Efforts are being made to retrieve continental-scale snow water equivalent using multi-sensor data assimilation methods.
- The combined EnKF-EnKS approach accomplished multi-sensor data assimilation, with GRACE TWS information largely complementing MODIS estimates in many regions.

Su, H., Z.-L. Yang, G.-Y. Niu, and R. E. Dickinson (2008), Enhancing the estimation of continental-scale snow water equivalent by assimilating MODIS snow cover with the ensemble Kalman filter, JGR, 113, D08120, doi:10.1029/2007JD009232.

Su, H., Z.-L. Yang, R. E. Dickinson, C. R. Wilson, and G.-Y. Niu (2010), Multi-sensor snow data assimilation at continental scale: the value of GRACE TWS information, JGR, 115, D10104, DOI: 10.1029/2009JD013035.

Outline

- Introduction
- Vegetation
- Water
- Data Assimilation
- Landscape to Coast
- Summary: Take Away Messages
- Future Work

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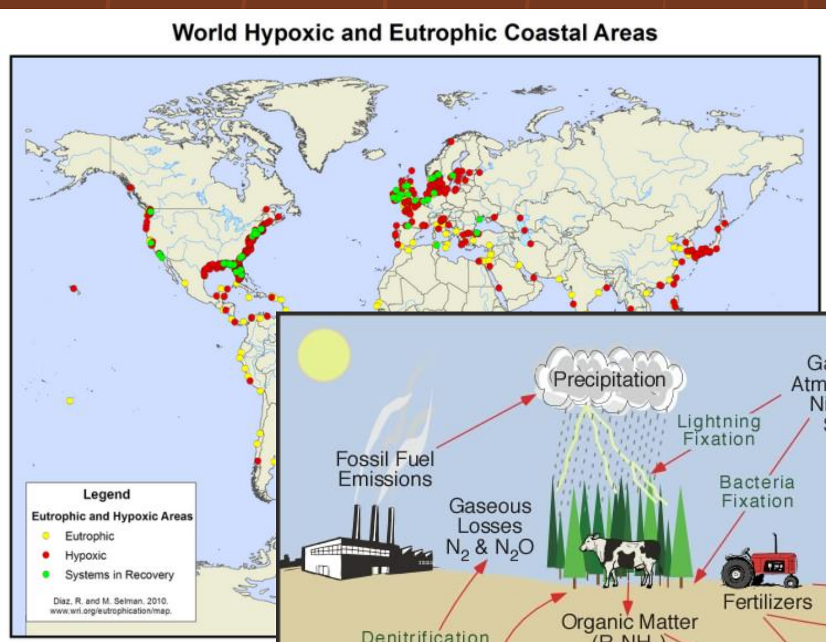
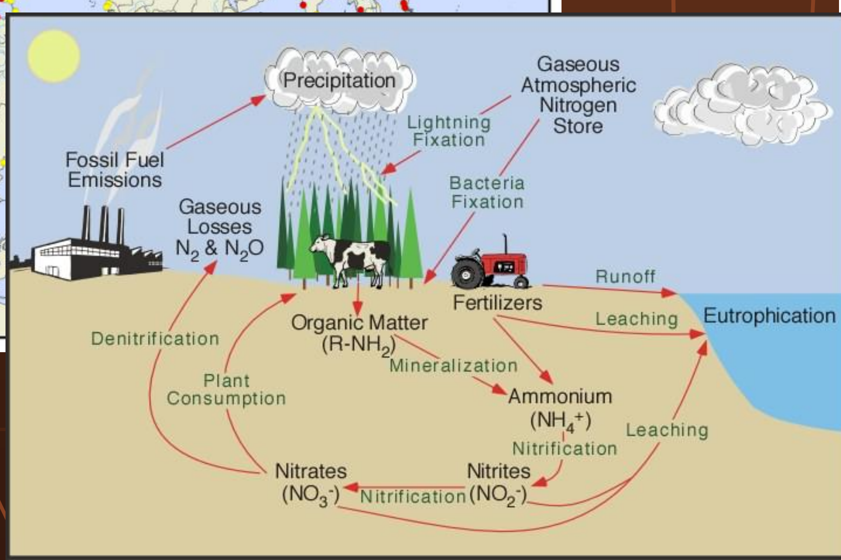
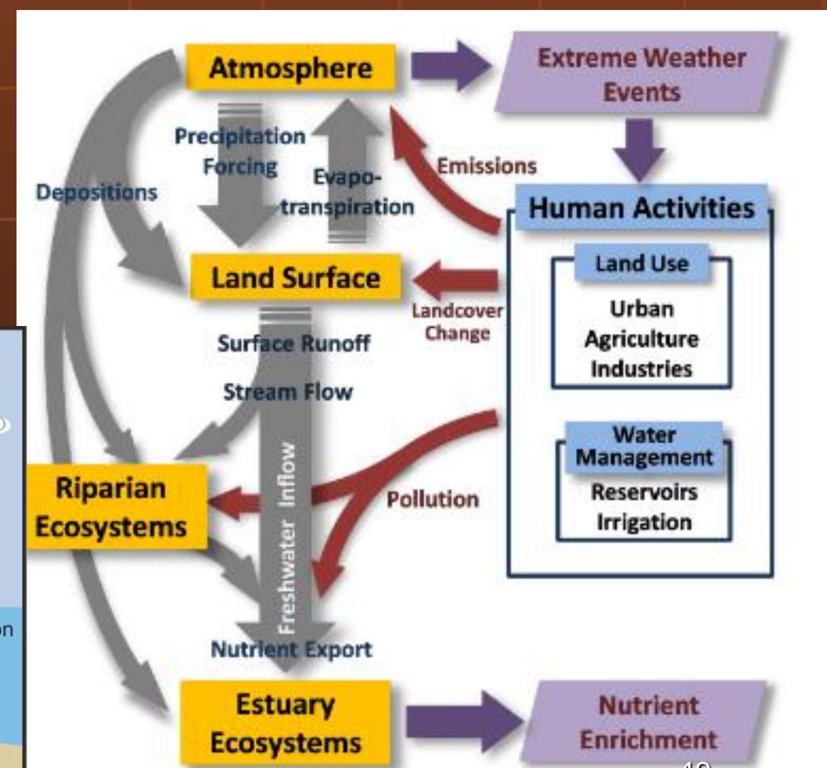
Issues in Riverine Nutrient Export Research

- Lacking integrated climate, extreme weather, land surface, river flow, biogeochemistry, and ecological models.







Yang (2011)

Noah LSM with multi-physics options

1. Leaf area index (prescribed; predicted)
2. Turbulent transfer (Noah; NCAR LSM)
3. Soil moisture stress factor for transpiration (Noah; BATS; CLM)
4. Canopy stomatal resistance (Jarvis; Ball-Berry)
5. Snow surface albedo (BATS; CLASS)
6. Frozen soil permeability (Noah; Niu and Yang, 2006)
7. Supercooled liquid water (Noah; Niu and Yang, 2006)
8. Radiation transfer:
   - Modified two-stream: Gap = F (3D structure; solar zenith angle; …) ≤ 1-GVF
   - Two-stream applied to the entire grid cell: Gap = 0
   - Two-stream applied to fractional vegetated area: Gap = 1-GVF
9. Partitioning of precipitation to snowfall and rainfall (CLM; Noah)
10. Runoff and groundwater:
    - TOPMODEL with groundwater
    - TOPMODEL with an equilibrium water table (Chen&Kumar,2001)
    - Original Noah scheme
    - BATS surface runoff and free drainage

More to be added

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Niu et al. (2011)

Collaborators: Yang, Niu (UT), Chen (NCAR), Ek/Mitchell (NCEP/NOAA), and others

Maximum # of Combinations

1. Leaf area index (prescribed; predicted) 2
2. Turbulent transfer (Noah; NCAR LSM) 2
3. Soil moisture stress factor for transp. (Noah; BATS; CLM) 3
4. Canopy stomatal resistance (Jarvis; Ball-Berry) 2
5. Snow surface albedo (BATS; CLASS) 2
6. Frozen soil permeability (Noah; Niu and Yang, 2006) 2
7. Supercooled liquid water (Noah; Niu and Yang, 2006) 2
8. Radiation transfer: 3
   - Modified two-stream: Gap = F (3D structure; solar zenith angle; …) ≤ 1-GVF
   - Two-stream applied to the entire grid cell: Gap = 0
   - Two-stream applied to fractional vegetated area: Gap = 1-GVF
9. Partitioning of precipitation to snow- and rainfall (CLM; Noah) 2
10. Runoff and groundwater: 4
    - TOPMODEL with groundwater
    - TOPMODEL with an equilibrium water table (Chen&Kumar,2001)
    - Original Noah scheme
    - BATS surface runoff and free drainage

2x2x3x2x2x2x2x3x2x4 = 4608 combinations

Process understanding, probabilistic forecasting, quantifying uncertainties

36 Ensemble Experiments

Table 3. The first group of 12 experiments and their corresponding options of schemes.

Exp.	Dynamic vegetation	r_s	β	Runoff schemes
EN1	On	Ball-Berry	Noah	SIMGM
EN2				SIMTOP
EN3				Schaake96
EN4				BATS
EN5			CLM	SIMGM
EN6				SIMTOP
EN7				Schaake96
EN8				BATS
EN9			SSiB	SIMGM
EN10				SIMTOP
EN11				Schaake96
EN12				BATS

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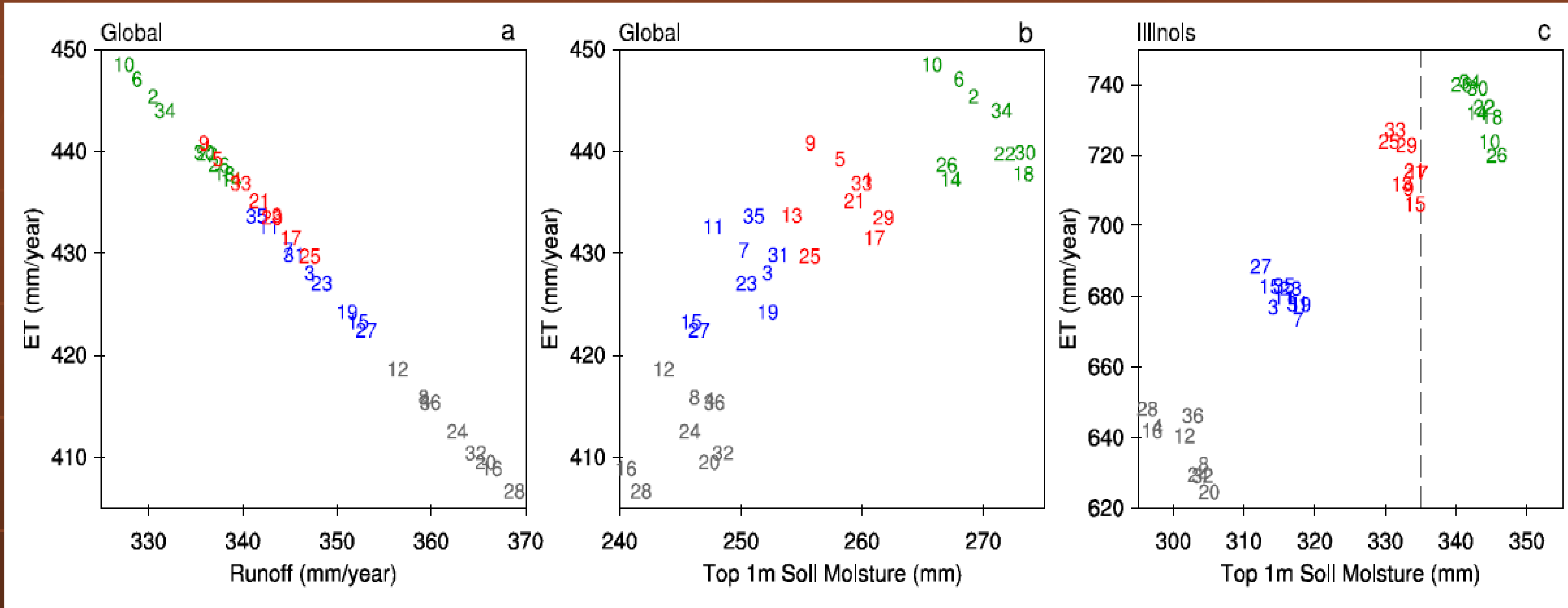
Yang et al. (2011a)

36 Ensemble Experiments



Runoff scheme is shown as the dominant player in the SM-ET relationship: SIMTOP (bottom sealed; green) produces the wettest soil and greatest ET; BATS (greatest surface runoff: grey) produces the driest soil and smallest ET.

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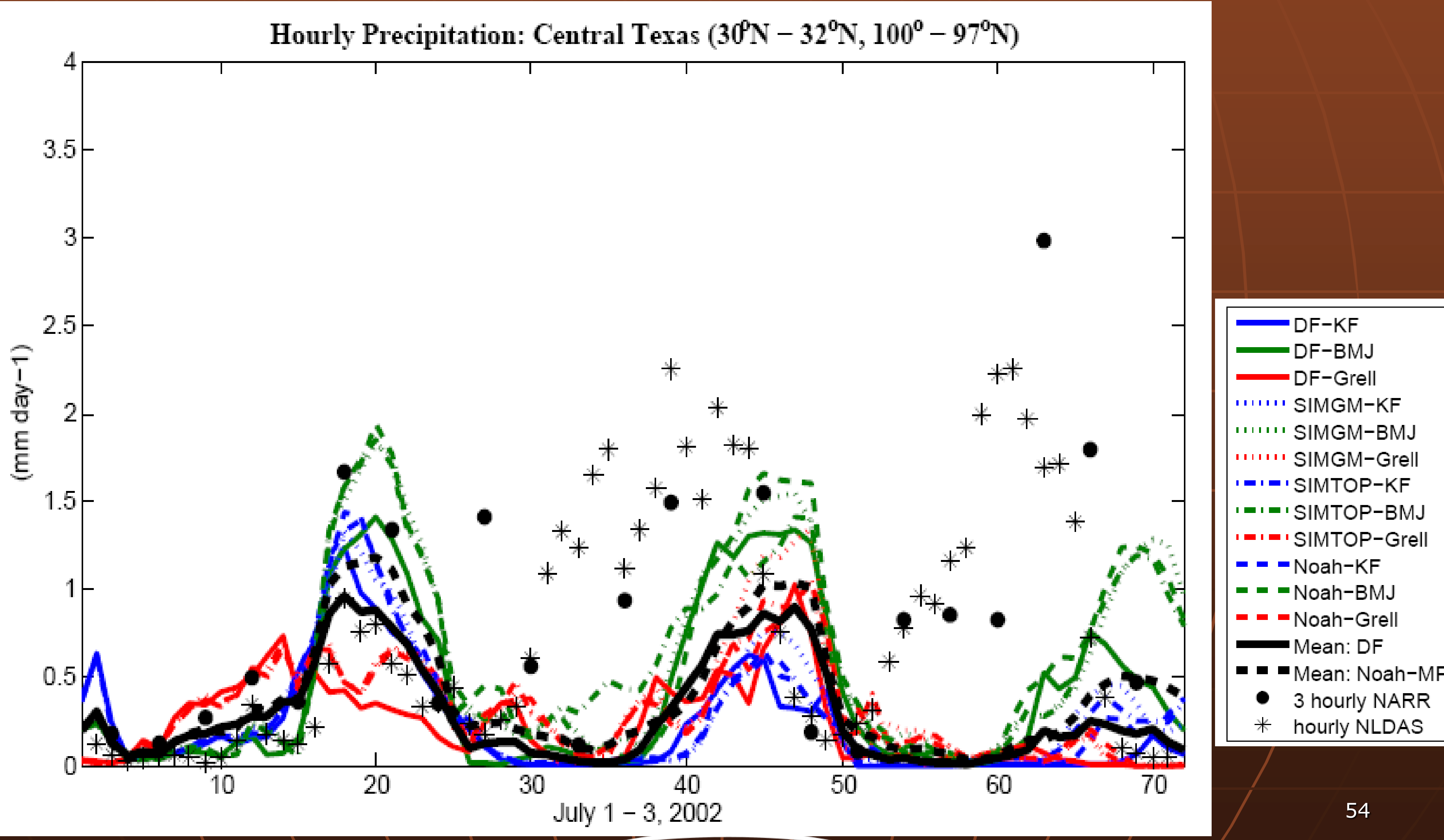
Yang et al. (2011a)

Hourly Precipitation (mm/hour) from July 1 to 3, 2002 for Various Convection & Runoff Runs



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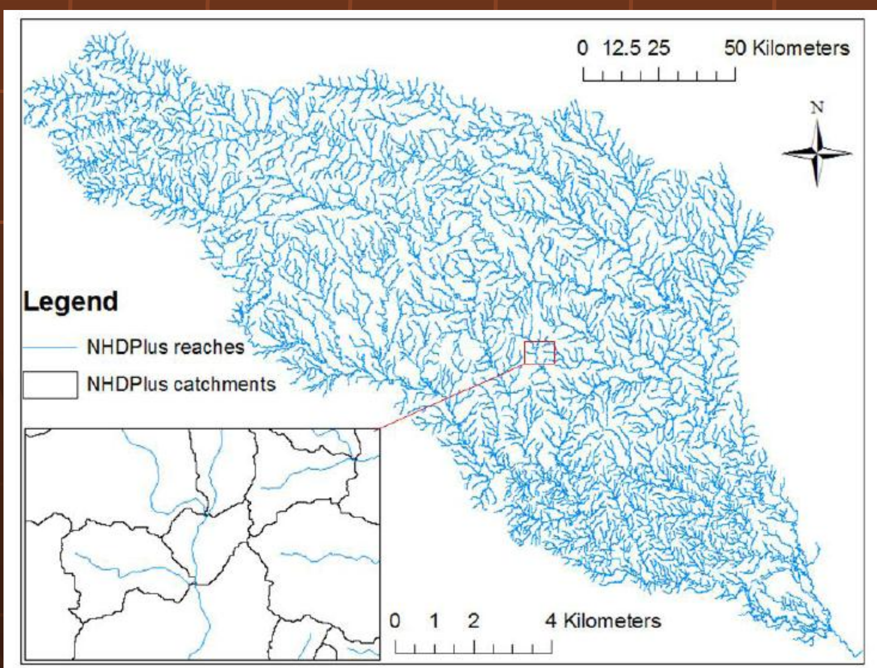
Yang et al. (2011b) in preparation

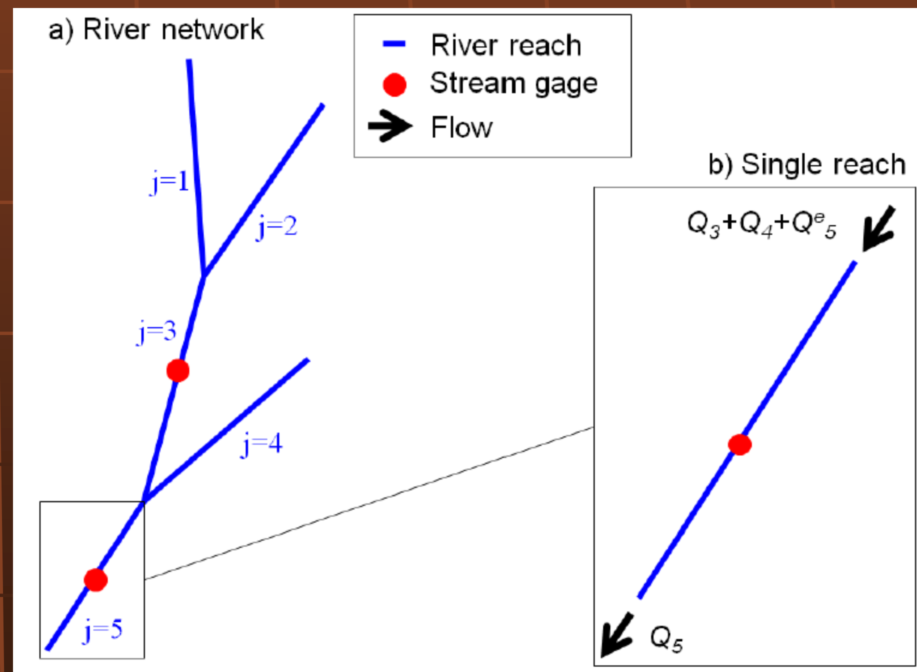
River network model: RAPID

- Routing Application for Parallel computatIon of Discharge

$$(\mathbf{I}-\mathbf{C}_1\cdot\mathbf{N})\cdot\mathbf{Q}(t+\Delta t)=\mathbf{C}_1\cdot\mathbf{Q}^e(t)+\mathbf{C}_2\cdot\left[\mathbf{N}\cdot\mathbf{Q}(t)+\mathbf{Q}^e(t)\right]+\mathbf{C}_3\cdot\mathbf{Q}(t)$$

$$\mathbf{V}(t+\Delta t)=\mathbf{V}(t)+\left[\mathbf{N}\cdot\mathbf{Q}(t)+\mathbf{Q}^e(t)\right]\cdot\Delta t-\mathbf{Q}(t)\cdot\Delta t$$





David et al. (2011)

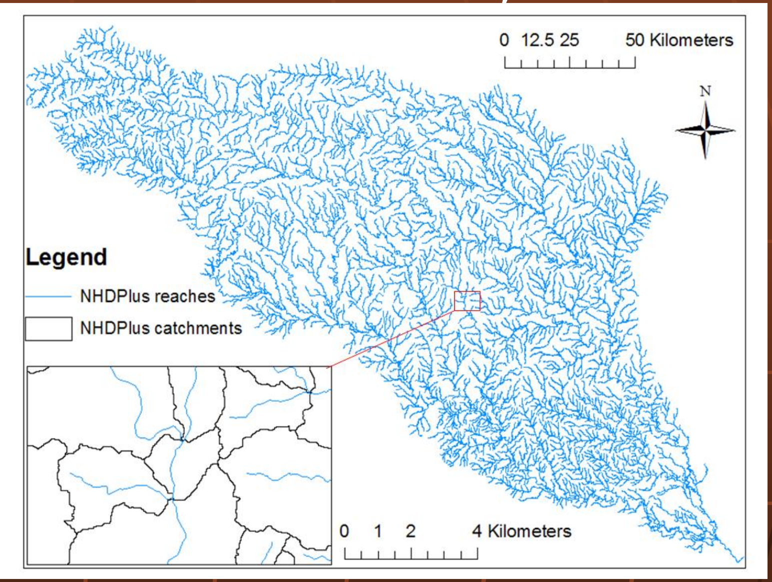
NHDPlus – River and Catchment Network for the Nation

Entire dataset

3 million river reaches

Connectivity information

Guadalupe and San Antonio Basins, TX



5,175 river reaches
26,000 km^2

Integration of the National Hydrography Dataset, National Elevation Dataset and National Land Cover Dataset completed by EPA in 2006

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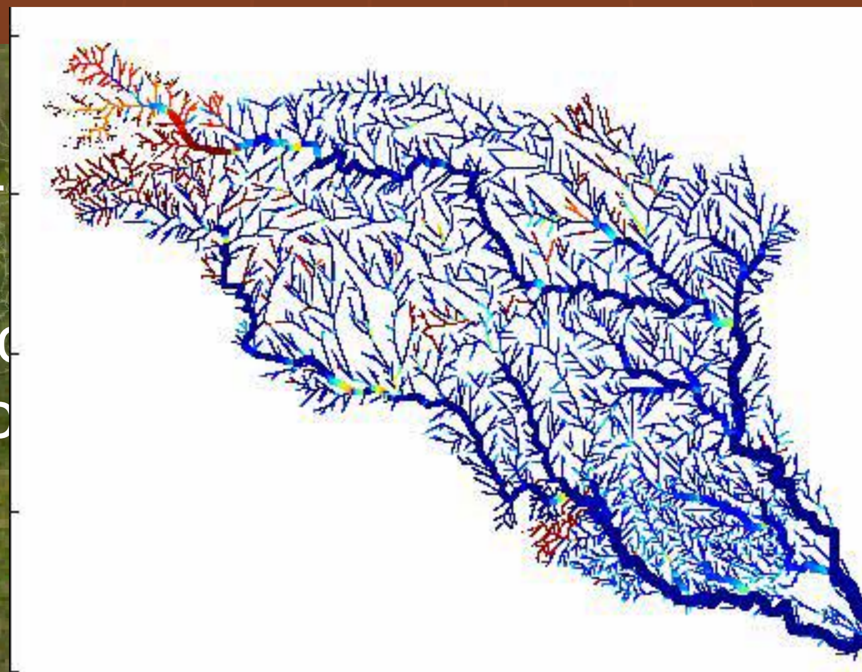
How can we build a river network model for the nation?

Texas Rivers Draining to the Gulf of Mexico

http://www.geo.utexas.edu/scientist/david/rapid.htm



- 01/01/2004 – s
- 4-km grid
- NARR meteoro rainfall
- Noah-MP runo

- facilitate modeling of nutrient loading, transport, and export to coastal waters

Thanks to Cedric David, Bryan Hong, David Maidment, Ben Hodges, Ahmad Tavakoly, and Adam Kubach of Texas Advanced Computing Center and Frank Liu of IBM

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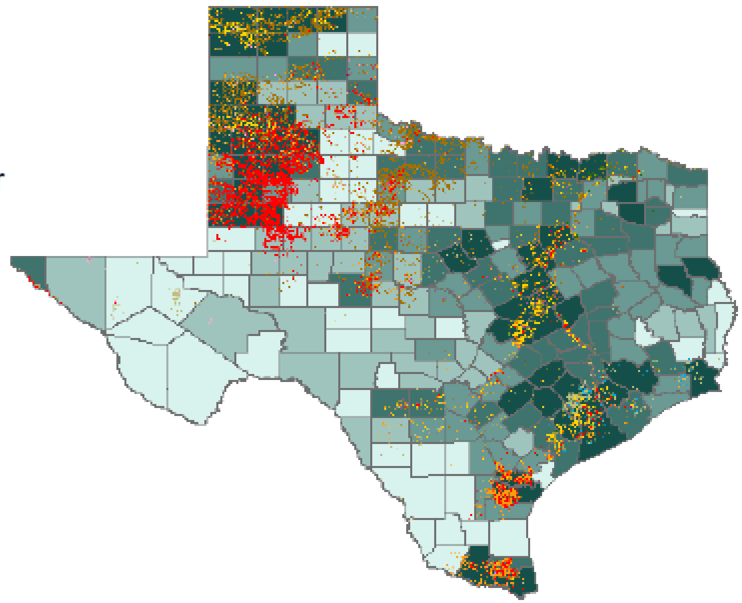
Developing a Comprehensive N Database

Texas Nitrogen Inputs with Spatial Crop Distribution (Livestock and Fertilizer)

Crop Data

- USDA National Agriculture Statistics Service Data (Part of USDA Crop Land Data Layer Project)
- 56 meter resolution
- Only crop information is plotted (excludes NLCD other land cover types)
- Based on NASS USDA-CLD from 2008



Legend

Total N inputs (Tons) 2007

- 0 - 327
- 328 - 1,261
- 1,262 - 2,843
- 2,844 - 5,402
- 5,403 - 36,945

Alfalfa, Aquaculture, Background, Barley, Canola, Christmas Trees, Citrus, Clover/Wildflowers, Corn, Cotton, Dry Beans, Fallow/Idle Cropland, Herbs, Millet, Oats, Onions, Other Crops, Other Small Grains, Other Tree Nuts, Peaches, Peanuts, Rye, Safflower, Sorghum, Soybeans, Spring Wheat, Sugarcane, Sunflowers, Sweet Potatoes, W. Wht./Soy. Dbl. Crop, Watermelon, Winter Wheat, Misc. Vegs. _Fruits, Peas, Potatoes, Rice

Nitrogen Input Data

- Livestock Input
  - Livestock population data from 2007 Census of Agriculture
    - Beef Cows
    - Dairy Cows
    - Pigs & Hogs
    - Turkeys
    - Sheep
    - Goats
    - Horses
    - Chickens (broilers)
  - Livestock N excretion rates for animals chosen from *Boyer et al. 2002*, which were taken from U.S. study by *van Horn et al. 1998*
- Fertilizer Input
  - Texas State Chemist Office County Fertilizer Distribution Data
  - From 2007 (to match with Census)
  - This data is available for 2005-2010, and variations in input concentrations is present as seen in Figure 6

Helper (2010)

Summary

- We have developed a multi-physics (MP) framework for the land surface. Together with the MP framework for the atmosphere, this MP framework is useful for probabilistic forecasts of the mesoscale extreme events. More research and experiments are warranted.
- We have developed a new river routing scheme (RAPID) that utilizes the NHDPlus river network, operates on supercomputing platforms, and optimizes parameters.
- We are developing a comprehensive nitrogen database for water quality and nutrient export modeling.
- We are extending the Texas-regional prototype landscape-to-coast study to the entire Mississippi River Basin, with a goal towards CONUS and global applications.

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Outline

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- Water
- Data Assimilation
- Landscape to Coast
- Summary: Take Away Messages
- Future Work

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Summary: Take Away Messages

Traditionally, land surface modeling

- treats land as a lower boundary condition in weather and climate models;
- determines the coupling strength and land–atmosphere interactions and feedbacks;
- calculates, in both coupled and offline modes, latent heat (ET), sensible heat, reflected solar radiation, upward longwave radiation, runoff, and state variables (soil moisture, snow water equivalent, soil temperature).

Driven by IPCC & regional/local applications, land surface models

- have evolved greatly in the past three decades;
- are becoming more complex as we are facing emerging needs to
  - understand climate variability and change on all time/space scales,
  - quantify the climatic impacts on energy/water resources, agriculture, ecosystems, and environmental conditions for decision making.
- demand cross-cutting efforts from multi-disciplinary groups.

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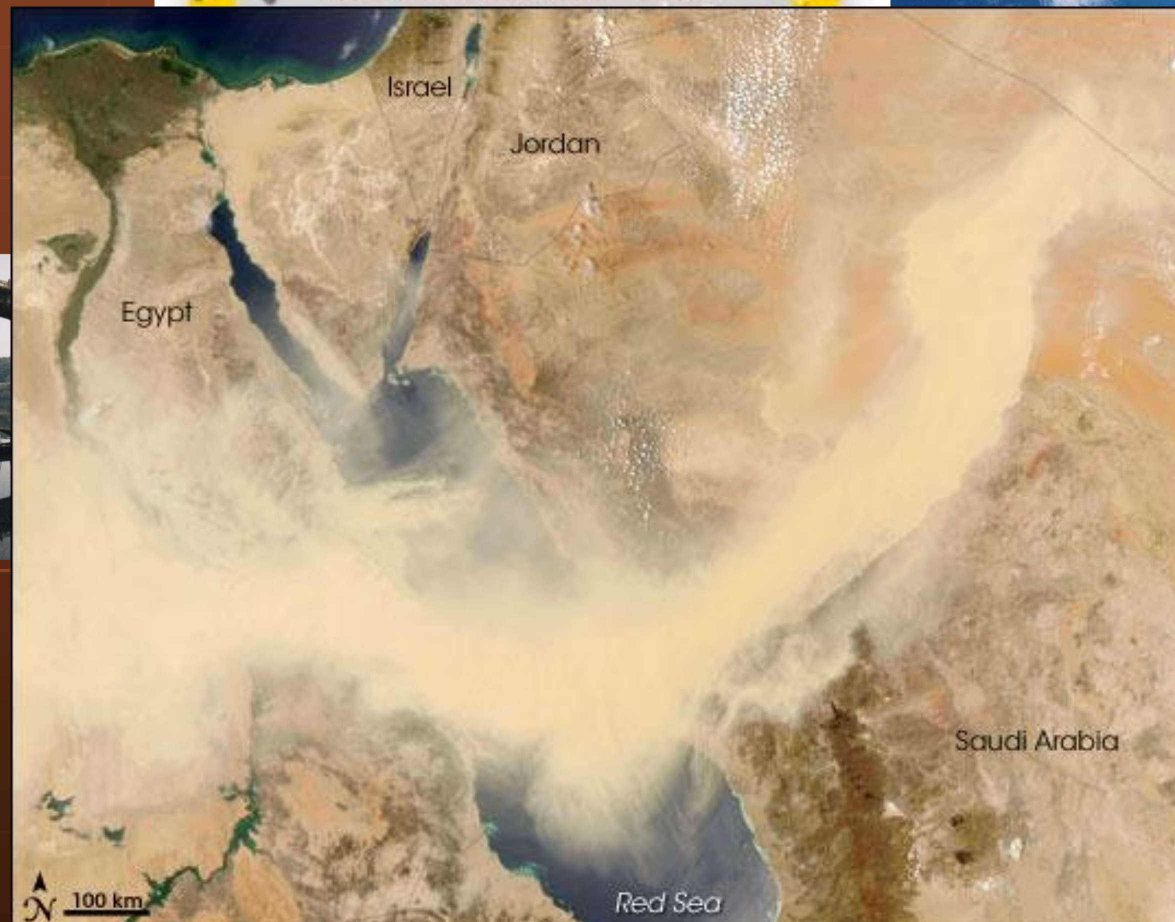
Beyond Land–Atmosphere Interaction

- Land provides us food, clothing, shelter, and infrastructure.
- Land is at the central stage for extreme weather and climate events.
- Land has direct societal relevance and land research is fun.
- Land processes are multi-disciplinary, and multi-scale.

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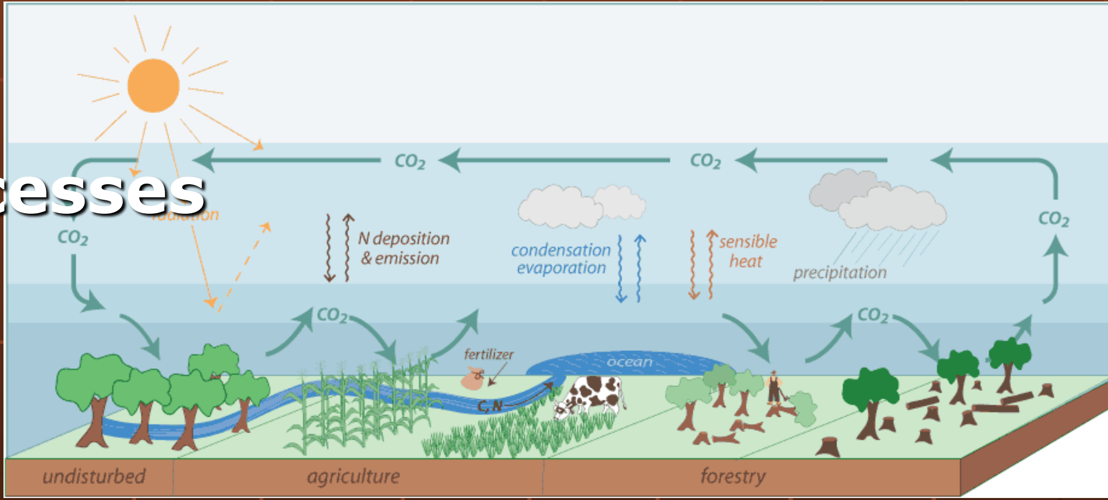
Land Surface Models Must Now Deal with

- **Exchange processes with the atmosphere**
  - Momentum
  - Energy (reflected shortwave, emitted longwave, latent/sensible heat)
  - Water (precipitation, evapotranspiration)
  - Trace gases (CO_2, CH_4, N_2O, BVOCs)/dusts/aerosols/pollutants
- **Exchange processes with the ocean**
  - Fresh water
  - Sediments/nutrients
  - Salinity
- **Land-memory processes**
  - Topography
  - Snow/ice cover
  - Soil moisture
  - Vegetation



- **Human activities**
  - Land use (agriculture, afforestation, deforestation, urbanization, …)
  - Water use (irrigation, human withdraws, dams, …)
  - Air pollution / Water pollution
  - Environmental degradation

New Challenges (1)

- Petascale [$O(10^{15})$] Computing Architectures
  - Massively parallel supercomputers (10^4–10^5 multi-core processors)
  - New challenges in memory management
  - Current codes may be ill-equipped
  - May need significant level of recoding

World's Fastest Supercomputer in 2002

35.6 trillion math operations per second (TFlops)
640 nodes, 5104 processors
Occupies 4 tennis court
Earth Simulator
4/19/2002

World's "Fastest" Supercomputer in 2011

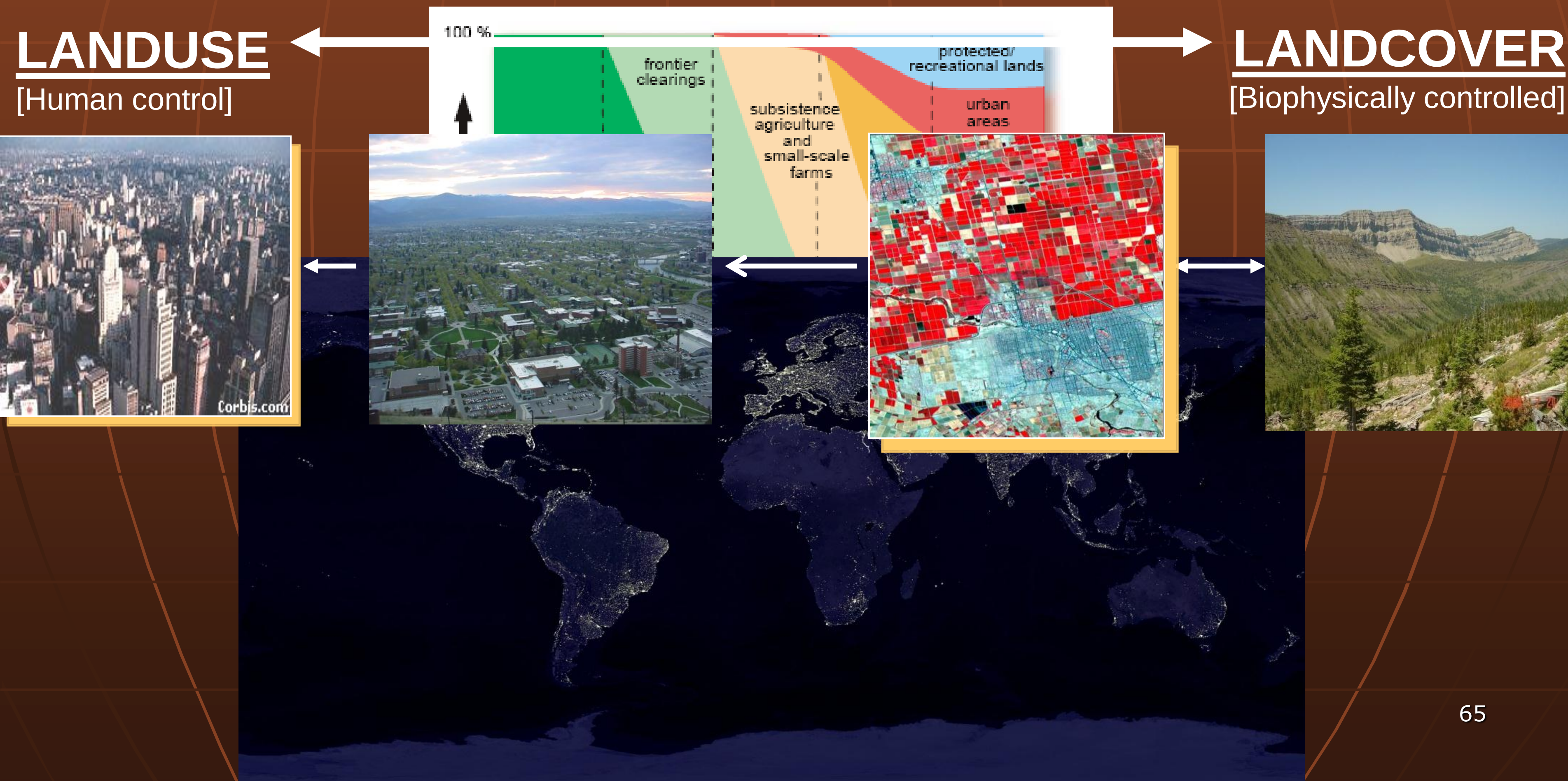
579.4 trillion math operations per second (TFlops)
3936 nodes, 62976 core processors
Texas Advanced Computing Center, UT-Austin
Ranger
5/19/2011

New Challenges (2)

- Rapid Transformation of Landscapes
  - Land surface as a complex system
  - Natural and managed components, and multi-scale interactions
  - Deforestation, Reforestation, Urbanization, Agriculture and Irrigation
  - Living organisms

LANDUSE
[Human control]

LANDCOVER
[Biophysically controlled]

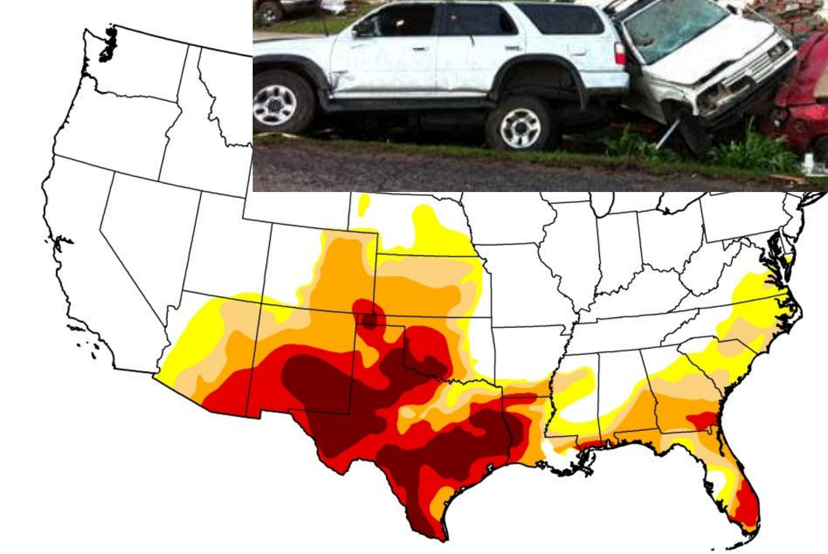


New Challenges (3)

- Increasing Frequency of Extreme Events
  - Heat waves and cold waves
  - Wild fires
  - Floods/droughts
  - Dust storms
  - Tornados/hurricanes

Mississippi River Flood
Hazen, Ark., USA, 5 May 2011

Tornado damages
Alabama, USA, 26-28 April 2011



US Drought Monitor
10 May 2011

Dust storms in Gansu Province, China, 28 April 2011

New Challenges (4)

- Earth System–Society Interactions
  - Integrated assessments: impacts, vulnerability, and resilience
  - Scenario-based decision making
  - Reality check

Human Systems

- **Institutions**
- **Culture**
- **Technology**
- **Population**
- **Economic**

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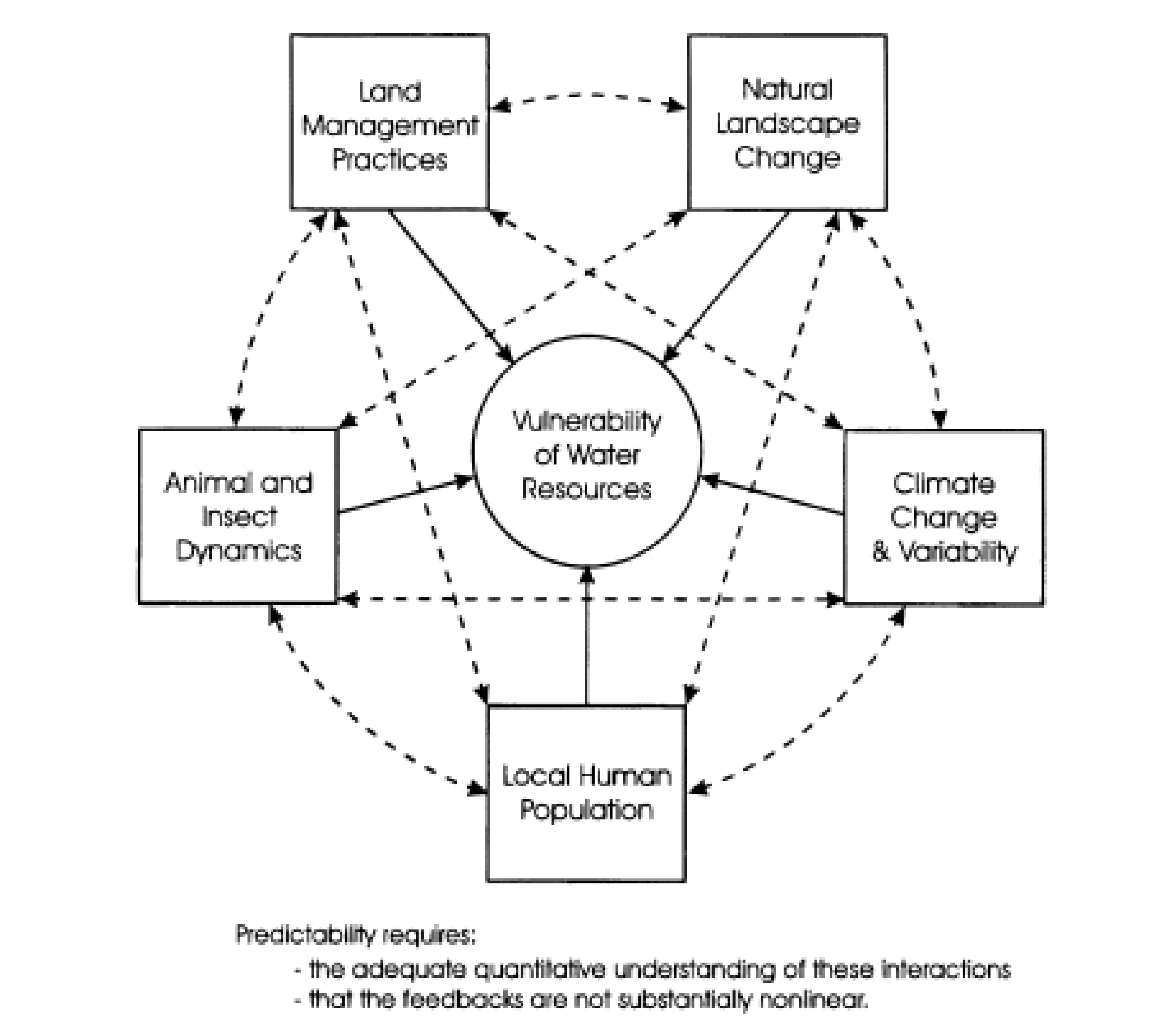
emistry
ank

Economic Problems

-poverty
-unequal wealth
-war
-globalization

ices



Pielke, Sr. (2001)

New Challenges

- Petascale [O(10^{15})] Computing Architectures
  - Massively parallel supercomputers (10^4–10^5 multi-core processors)
  - New challenges in memory management
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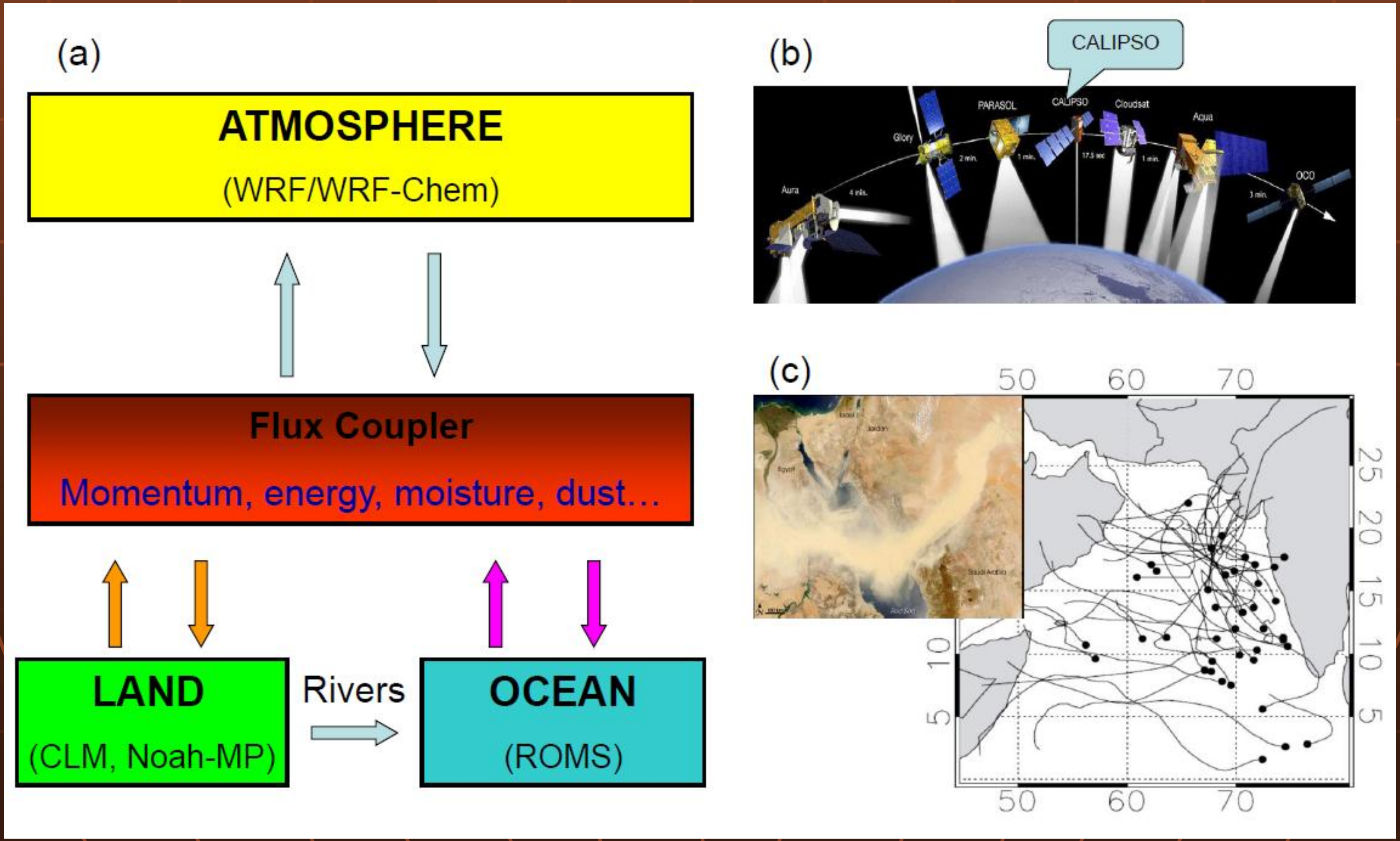
Future Work (1)

- Integrated Earth System Modeling and Analysis

  Putting all pieces together
  Regional Earth System Modeling and Analysis Symposium (Beijing, May 18–22, 2011) and beyond



Observations: FLUXNET, a global network

USED SITES IN OUR STUDY:

- Morgan Monroe (1999-2005)
- Fort Peck (2000-2005)
- Harvard Forest (1994-2003)
- Niwot Ridge (1999-2004)
- Boreas (1994-2005)
- Lethbridge (1998-2004)

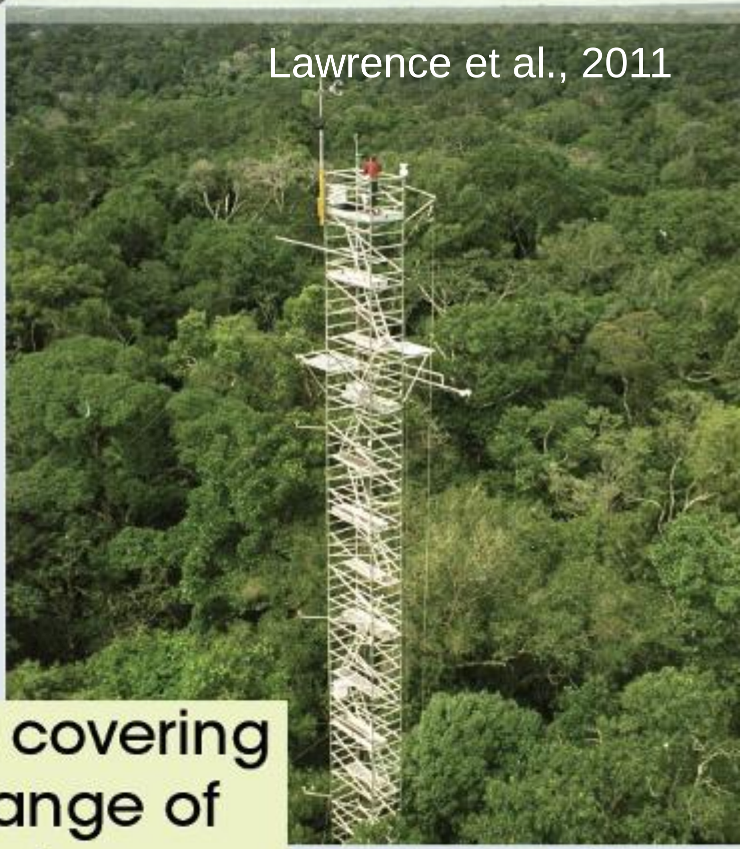
- Santarem KM83 (2001-2003)
- Tapajos KM67 (2002-2005)

- Castelporziano (2000-2005)
- Collelongo (1999-2003)
- El Saler (1999-2005)
- Kaamanen (2000-2005)
- Hyytiälä (1997-2005)
- Tharandt (1998-2003)
- Vielsalm (1997-2005)

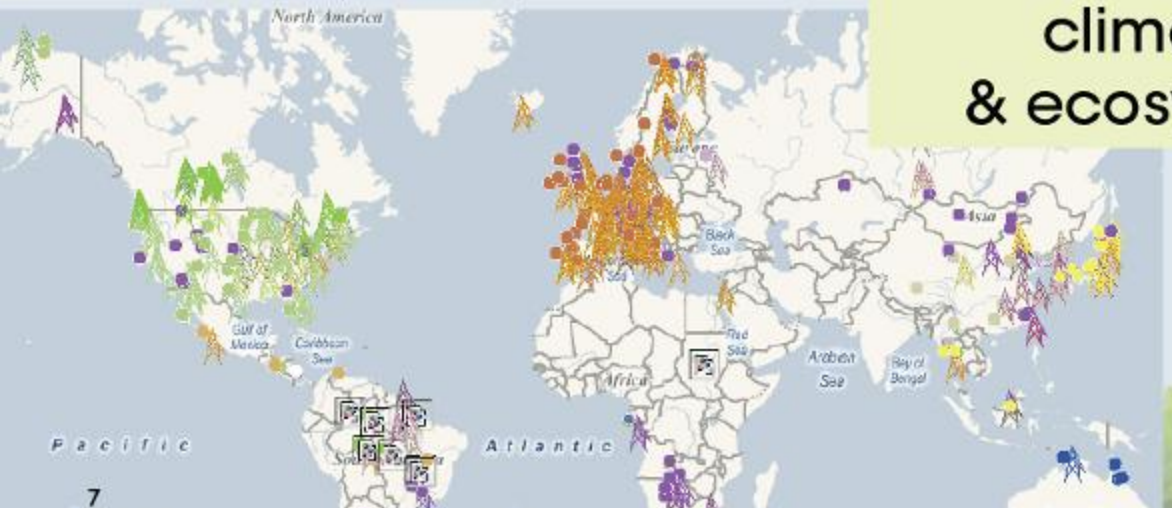
Color Legend:

temperate
tropical
boreal
sub-alpine
north-boreal
mediterranean

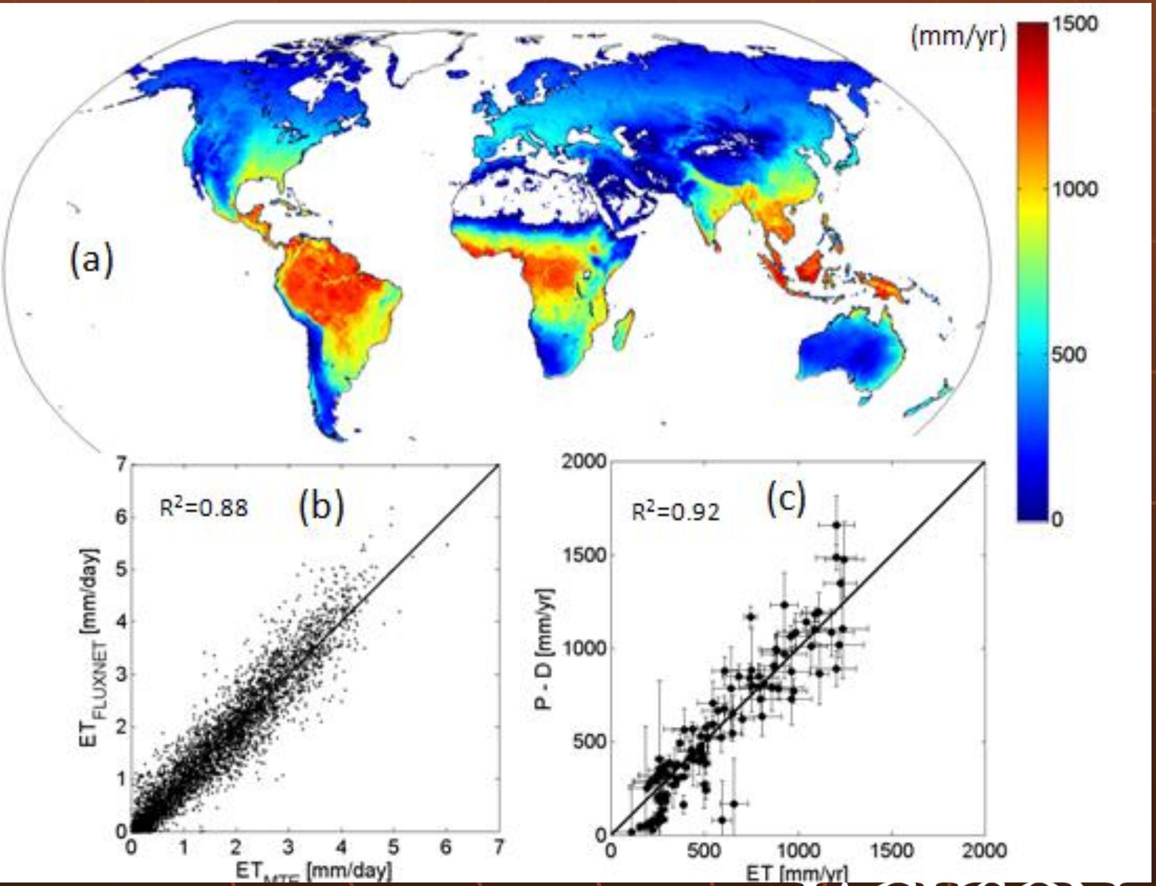
Lawrence et al., 2011



500+ sites covering global range of climates & ecosystems



Evaluation of upscaled global evapotranspiration



(a) Map of mean Evapotranspiration from 1982-2008

(b) Predicted vs. Observed ET at FLUXNET sites (10-fold cross-validation from MTE training)

(c) Corroboration aganist river catchment water balances

(d) Comparison against GSWP-2 land surface model ensemble (16 models) stratified according to bioclimatic zones

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Jung et al. 2010 Nature

FLUXNET Challenges

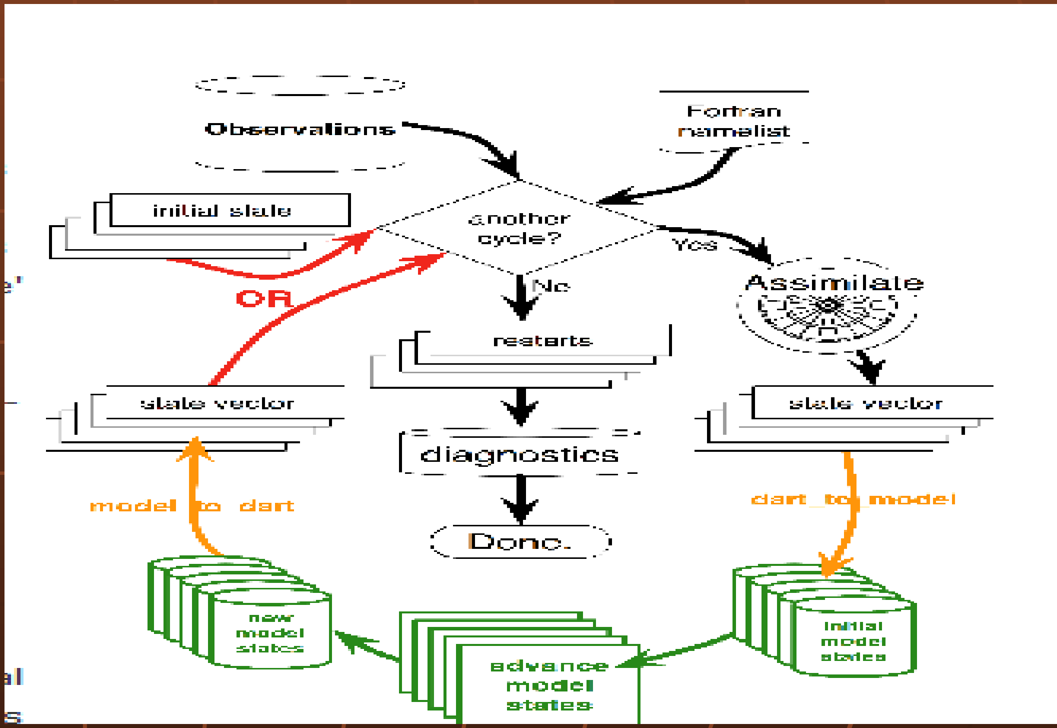
- To Sustain and Grow the Network that ask and answer Network-Scale Questions
  - o To sample representative Climates and Biomes
  - o To sample representative Disturbance Classes
  - o Detect trends in Fluxes as Climate and Land Use Changes
  - o Validate and Parameterize New Generation of Land Surface-Atmosphere Exchange Models
  - o Serve as Critical Partner in Machine Learning Approaches to Flux Upscaling with Satellite Remote Sensing

Baldocchi (2011)

Future Work (2)

- Next Generation Data Assimilation

  Multi-models, multiple datasets (tower fluxes, aircraft measurements, satellite, etc), multiple data assimilation schemes, fine-resolution, and long-term products, in collaboration with NCAR IMAGe



Data Assimilation Research Testbed (DART)

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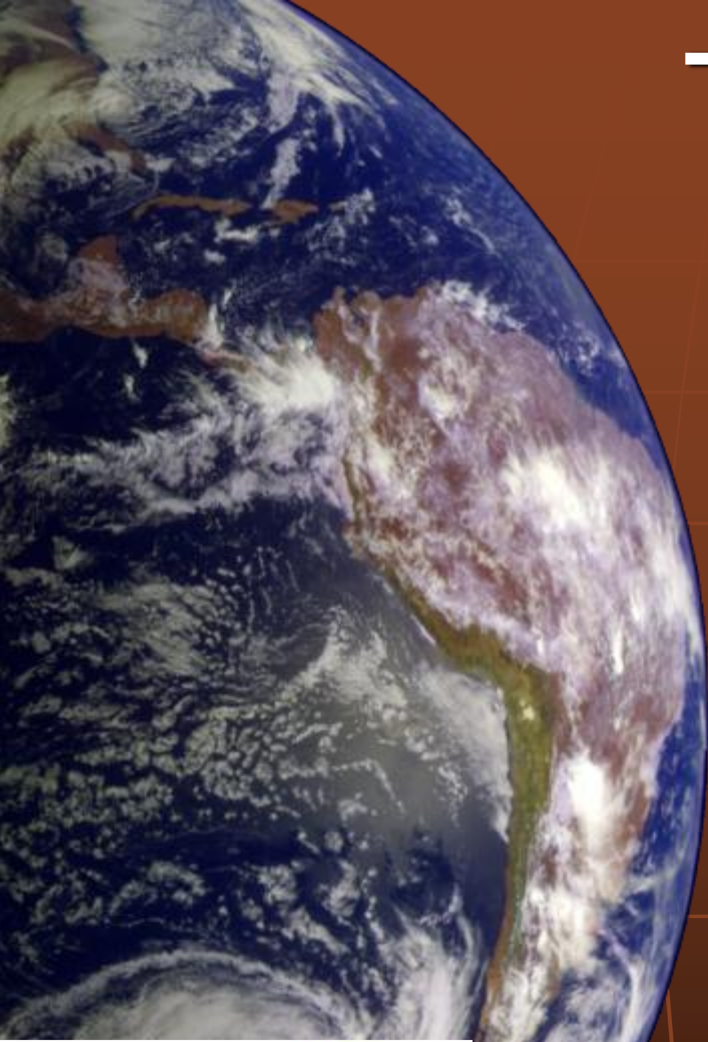
NCAR IMAGe: Data Assimilation Research Section



Thank you!

Xitian Cai, Dr. Cedric David, Dr. Lindsey Gulden
Lisa Helper
Dr. Bryan Hong
Dr. Xiaoyan Jiang, Dr. Marla Knebl
Dr. Jeff Lo
Dr. Guo-Yue Niu
Dr. Enrique Rosero, Dr. Hua Su
Drs. David Allen, Gordon Bonan, Fei Chen, Jianli Chen, Robert Dickinson, Michael Ek, David Gochis, Alex Guenther, David Lawrence, David Maidment, Kenneth Mitchell, Keith Oleson, Roger Pielke Sr., Georgiy Stenchikov, Clark Wilson, Christine Wiedinmyer

King Abdullah University of Science and Technology

KAUST
TACC

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http://www.geo.utexas.edu/climate

Tower flux statistics (15 sites, hourly)

	Latent Heat Flux		Sensible Heat Flux	
	r	RMSE (W/m²)	r	RMSE (W/m²)
CLM3	0.54	72	0.73	91
CLM3.5	0.80	50	0.79	65
CLM4SP	0.80	48	0.84	58

Lawrence et al., 2011

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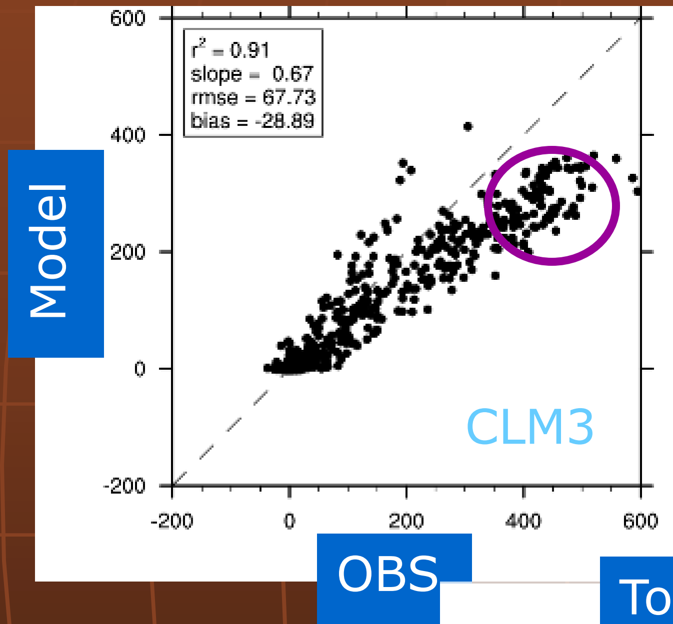
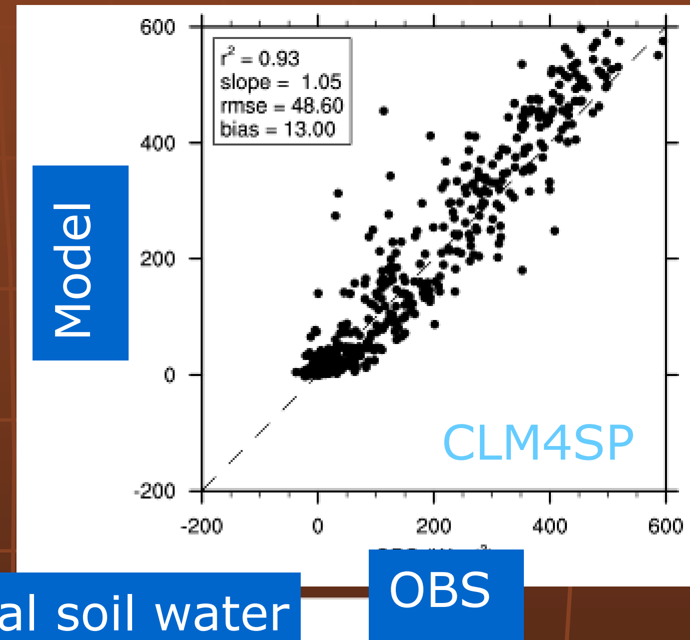
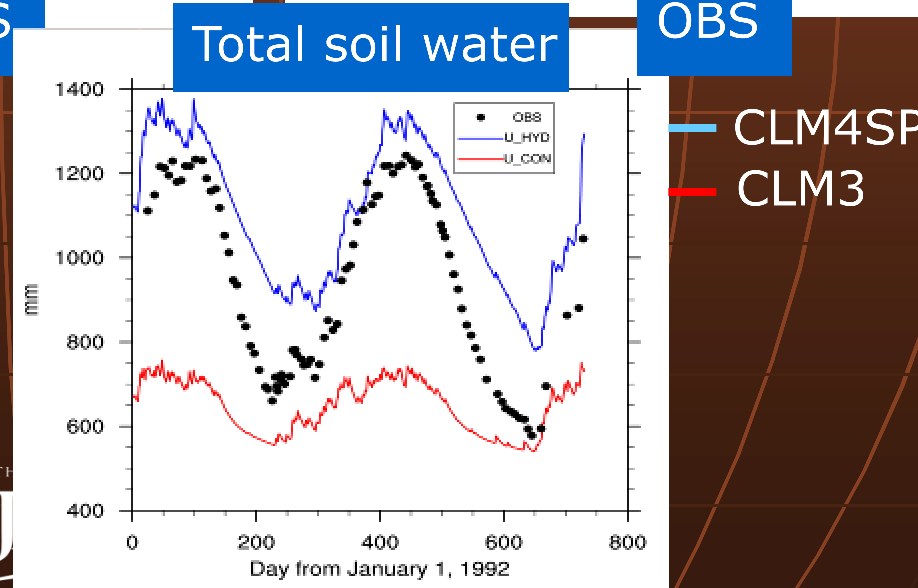
Abracos tower site (Amazon)

Latent Heat Flux



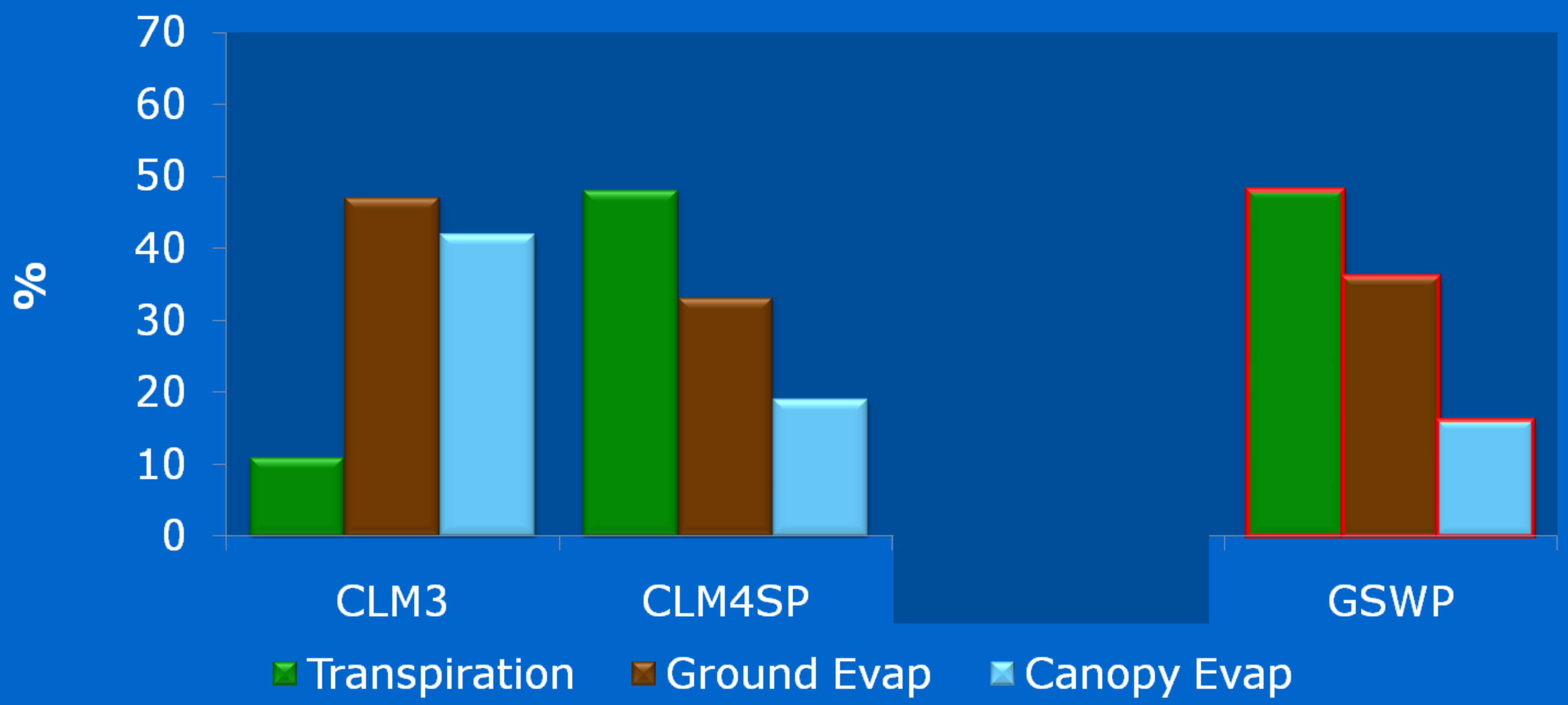
Latent Heat Flux





Lawrence et al., 2011

Global Partitioning of Evapotranspiration



Lawrence et al., 2011

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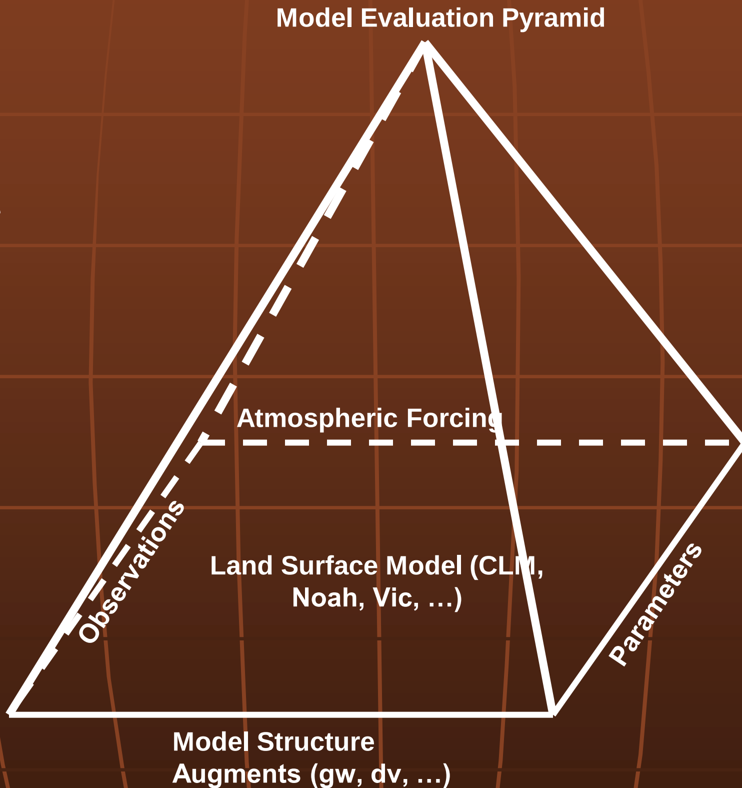
How Can We Use Sophisticated Evaluation Methods To Guide LSM Development?

Two schools of thoughts in LSM development and evaluation

LSM developers consider

1. Increasing realism in representing key processes
2. Understanding feedbacks and interactions
3. Maintaining synergism between LSM and other modules in the host GCM
4. Aiming for past, present, and future climate applications
5. Generalizing parameterizations across sites



LSM evaluators consider

1. Uncertainty in many subsurface parameters and other non-measurable parameters
2. Uncertainty in atmospheric forcing and observations used for evaluation
3. Calibration of the parameters for the augmented part only or for the entire LSM
4. Evaluation in all dimensions
5. Equifinality?

LSM developers do not use automated, sophisticated evaluation tools.

LSM evaluators calibrate/evaluate LSMs that already exist.

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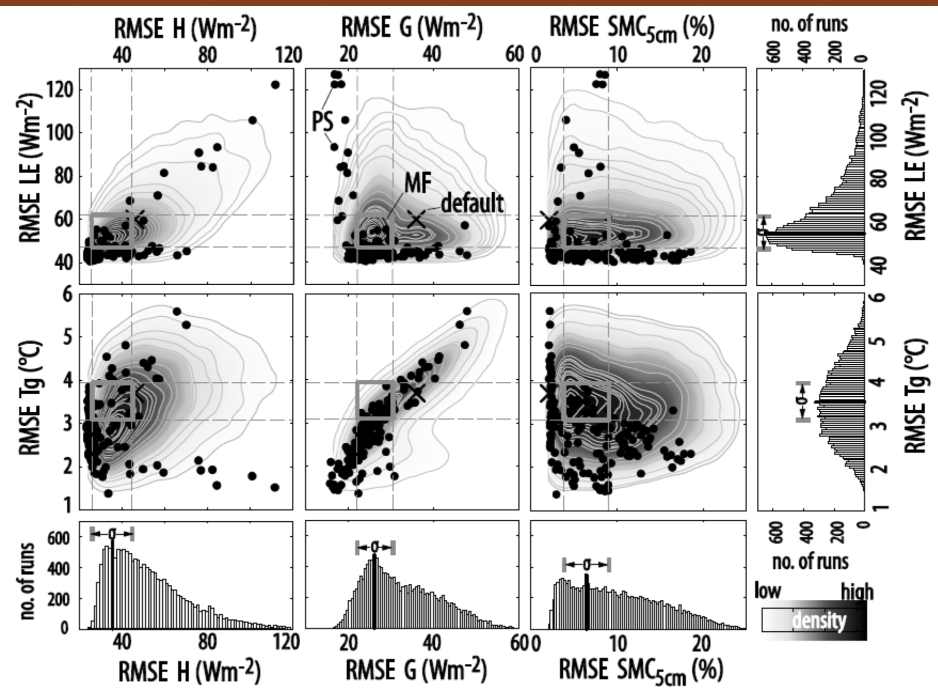
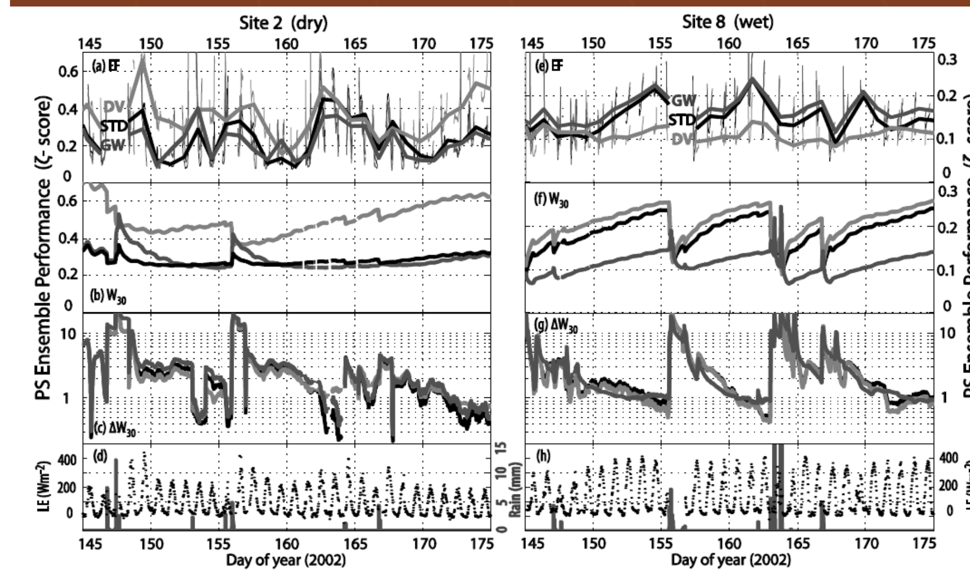
A New Approach to Evaluating LSMs: Ensemble Methods





1) Gulden, L.E., E. Rosero, Z.-L. Yang, et al., 2008: Model performance, model robustness, and model fitness scores: A new method for identifying good land-surface models, *Geophys. Res. Lett*., 35, L11404, doi:10.1029/2008GL033721.
2) Rosero, E., Z.-L. Yang, et al., 2009: Evaluating enhanced hydrological representations in Noah-LSM over transition zones: Implications for model development, *J. Hydrometeorology,* **10**, 600-622. DOI:10.1175/2009JHM1029.1

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Continental River Dynamics and Petascale Computing

High-resolution (30 m – 1 km) coupled atmospheric, hydrologic, and river channel modeling and data assimilation system

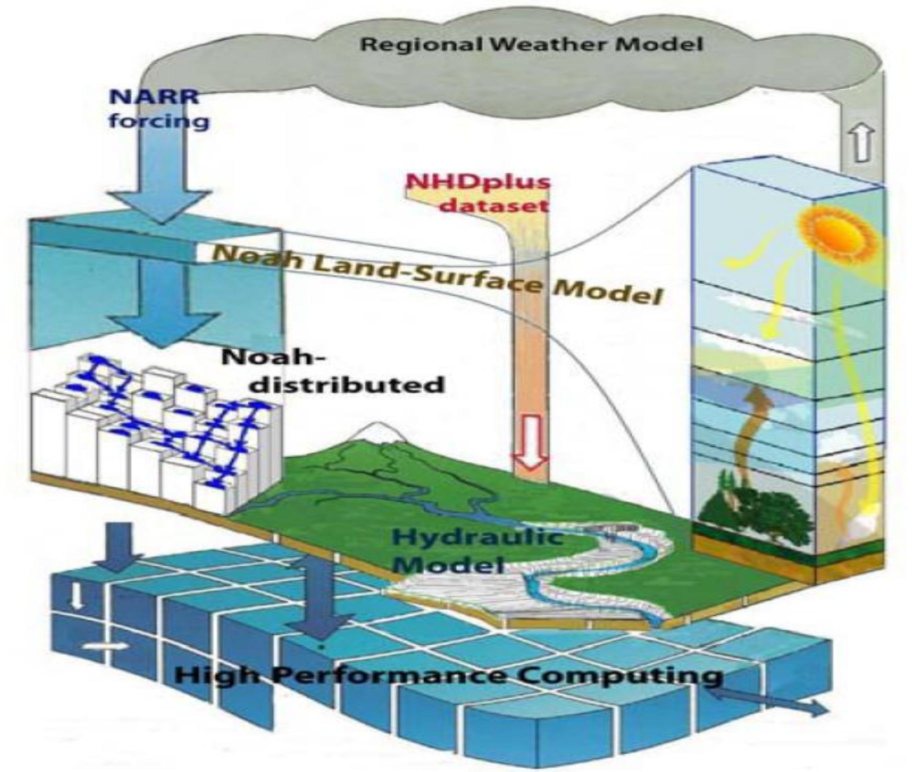
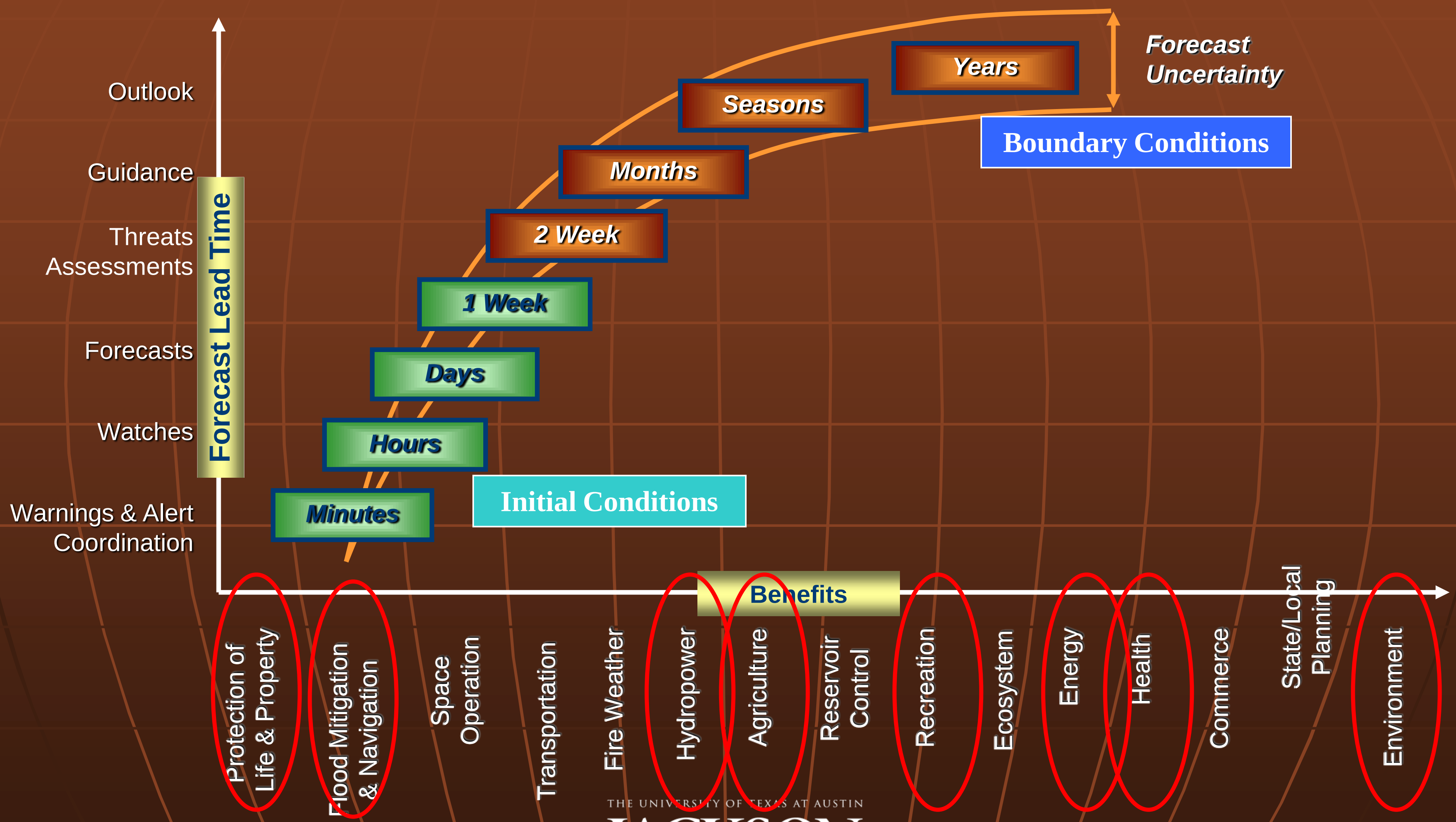


Figure 1: Schematic diagram of components in continental water dynamics

- How much fresh water is available?
- How fast does it move?
- What is its sensitivity to future climate change and land use/land cover change?
- Can we reliably monitor floods and droughts?

Yang, Maidment, Gochis, et al.

Seamless Suite of Forecasts



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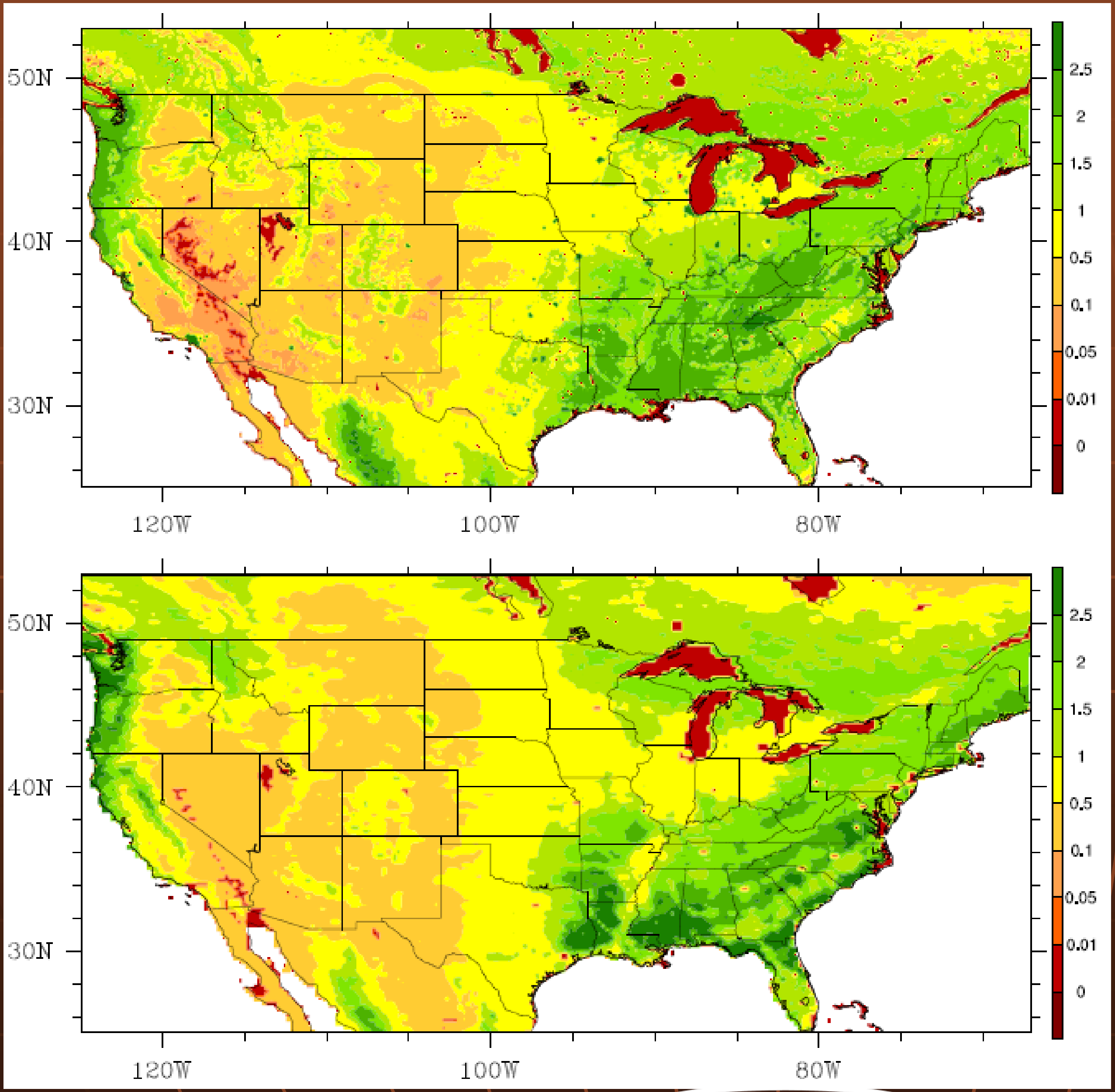
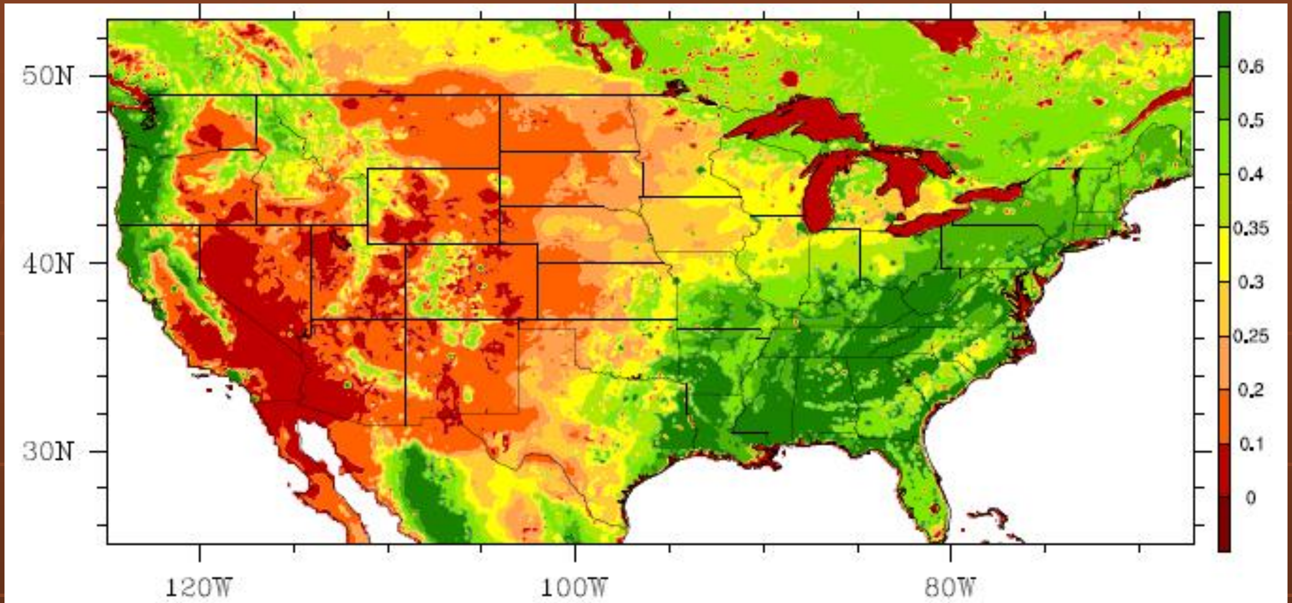
Modeled LAI Using NLDAS



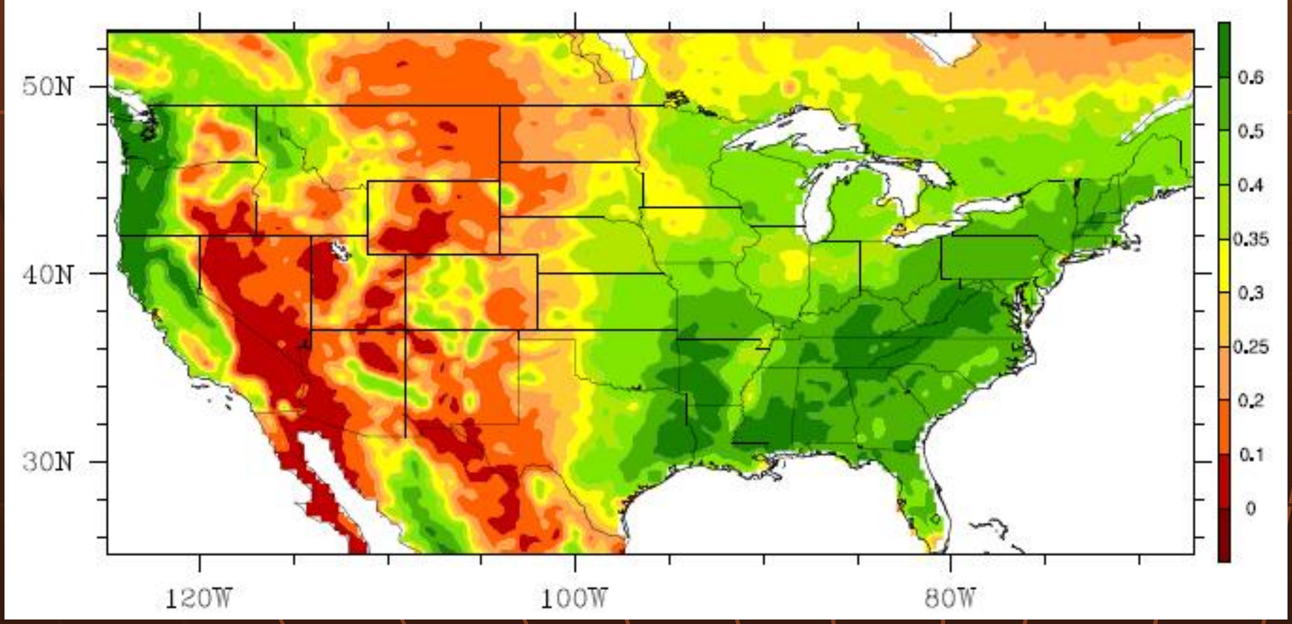
Noah-MP
(2002 – 2007)

MODIS (1/4th degree)
(Mar. 2000 – Jul. 2008)

Modeled GVF Using NLDAS



Noah-MP
(2002 – 2007)



NESDIS (0.144 degree)
(Gutman & Ignatov, 1998)
(5-year mean)

Kalman Filter:

Given R.V. X and its observation y, with noise magnitude of R,

Y=X+v (can be generalized to Y=H(X)+v), X, Y and v are normal distribution

Best estimation of X given Y=y (minimum variance)

Mean of conditional distribution

$$E(X|Y=y) = \int f(X|Y=y)dX = \frac{R}{Var(X)+R}E(X) + \frac{Var(X)}{Var(X)+R}y$$

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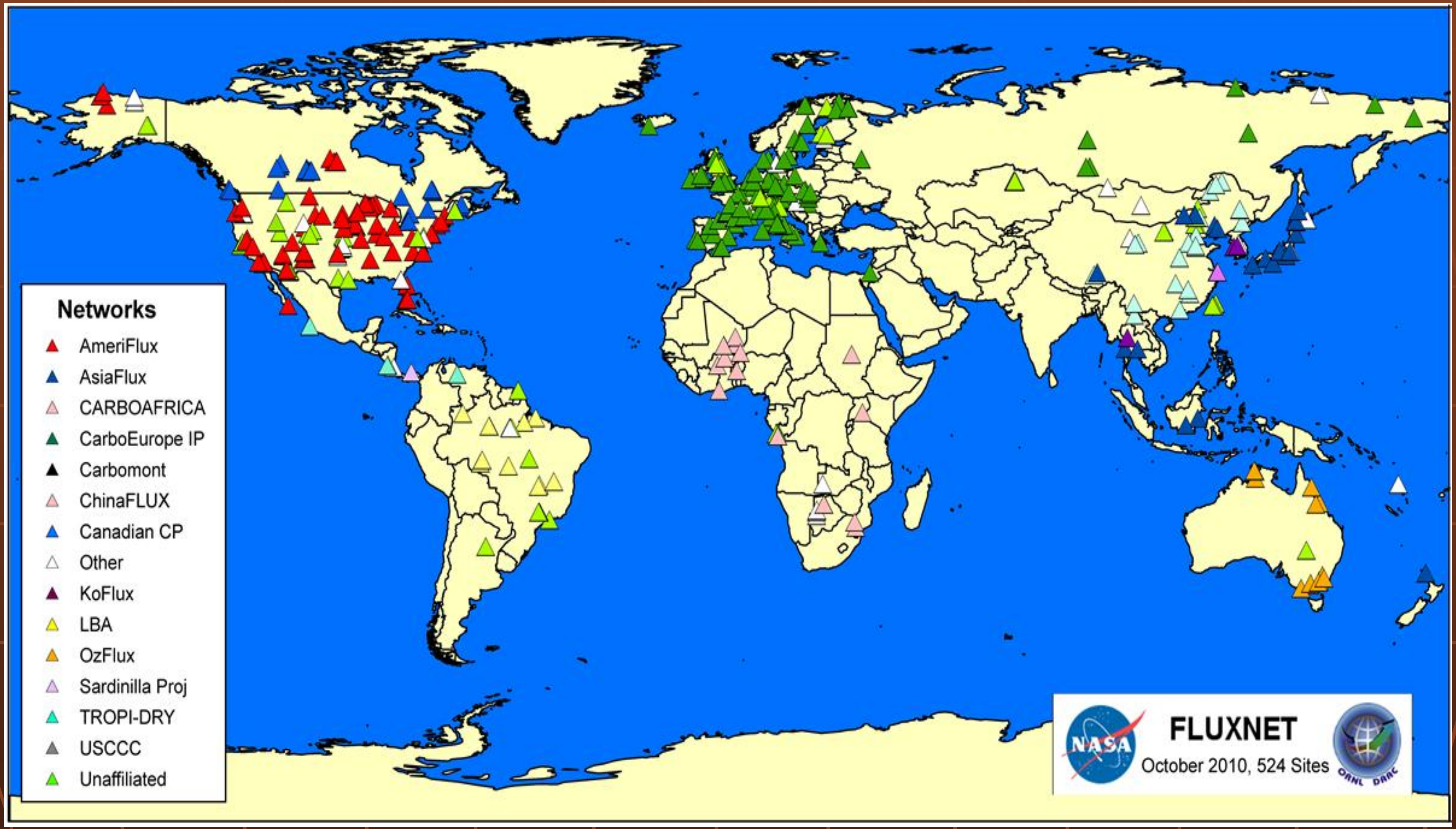
Status of Global Network, 500+ Sites



Being Registered Does not mean Active or Contributing Data

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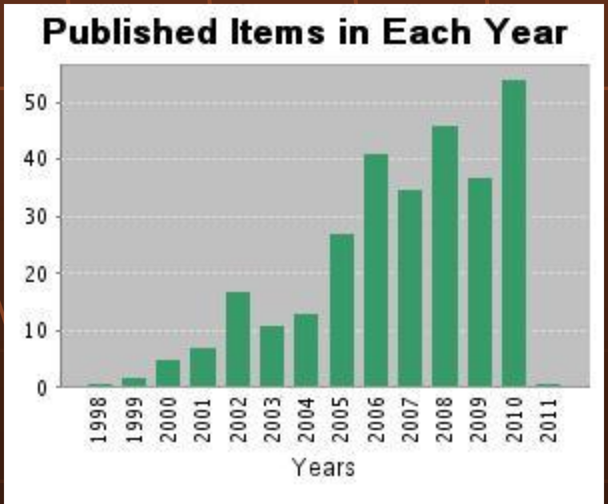
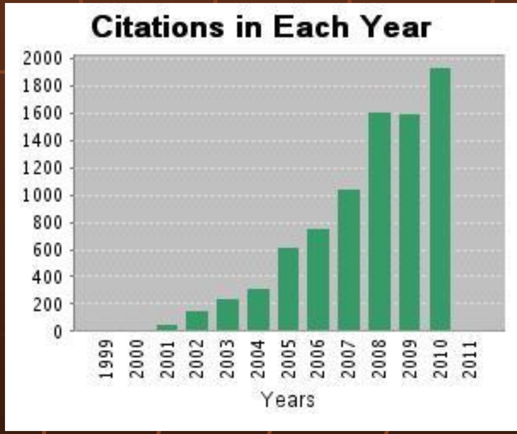
Highlights / Successes

- Papers in Science and Nature
    - o Beer et al; Mahecha et al; Jung et al.
- Explosion of Synthesis Papers
- New Generation of Spatial Upscaling Papers
    - o Xiao et al; Jung et al; Beer et al; Mu et al.
- Citation Count is Growing





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Baldocchi (2011)

Concluding Comments

- We Must Continue to Work Together to Address Important and Contemporary Questions Pertaining to Earth System Science and Climate Change
- A Large and Growing Community of Modelers and Synthesis Scientists are Dependent Upon our Data
- Data are Produced with Govt Support, so it is the Ethical Duty
- Protections are in place to protect Data, PIs and Students in the Short Term, 1-2 years
- It should be the obligation of PIs to Release Data Sets in the Long-Run, e.g. Older Datasets, to Advance Science

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Baldocchi (2011)