Improving Hydrological Representation in the Community Noah Land Surface Model for Intra-seasonal to Interannual Prediction Studies

PI: **Zong-Liang Yang**
Co-I: **G.-Y. Niu, F. Chen, D. Gochis**
Collaborator: **K. E. Mitchell, Mike Ek**
Graduate Research Assistants: L.E. Gulden, X.Y. Jiang, E. Rosero
Postdocs: **Bryan Hong, Cedric David**

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Objectives

To investigate how Noah LSM’s augmentation with additional land memory processes (e.g. snow, groundwater and dynamic vegetation) influences its soil moisture memory.

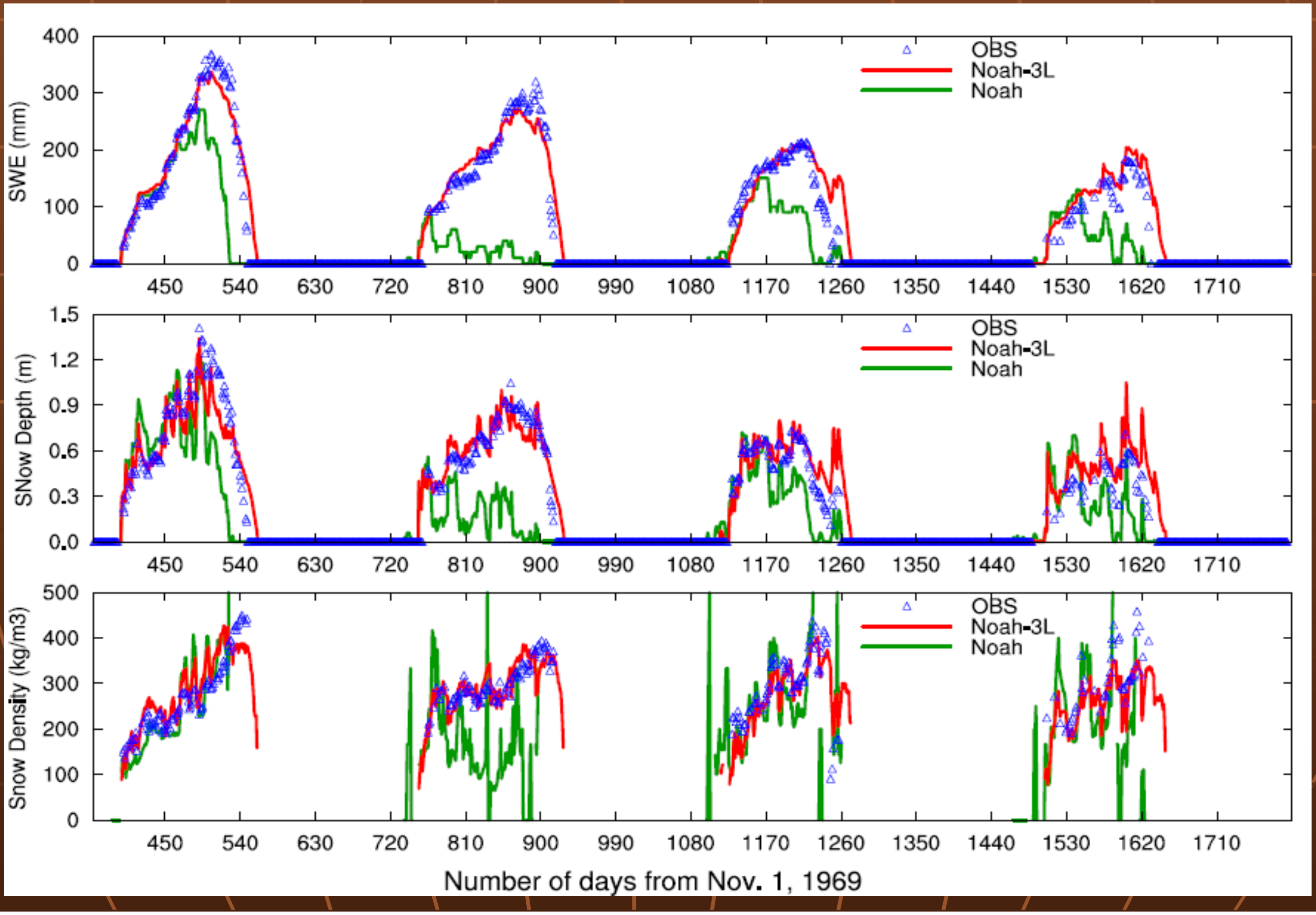
To develop high-resolution datasets of land surface state variables (e.g., soil moisture) in conjunction with NCAR’s HRLDAS.

To perform ensembles of WRF simulations illustrating the role of soil moisture, groundwater, vegetation, frozen soil, and snow in predicting precipitation at intra-seasonal to interannual timescales.

Why Augment Noah LSM?

1. Modeled snow water equivalent or snow depth is too shallow.

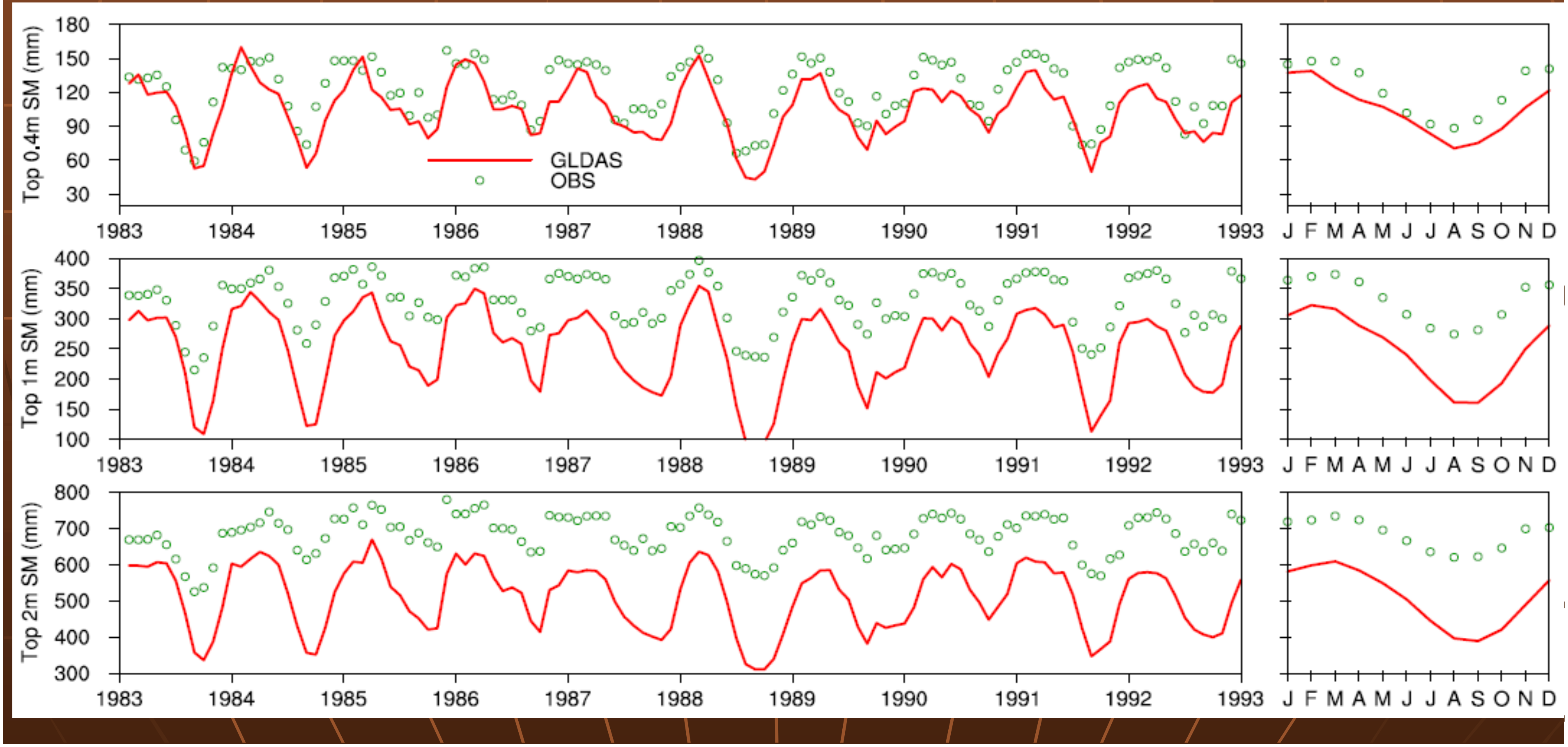
Sleepers River Watershed, Vermont



Why Augment Noah LSM?

2. Modeled soil moisture is too low, especially in deep soil layers and in the summertime.

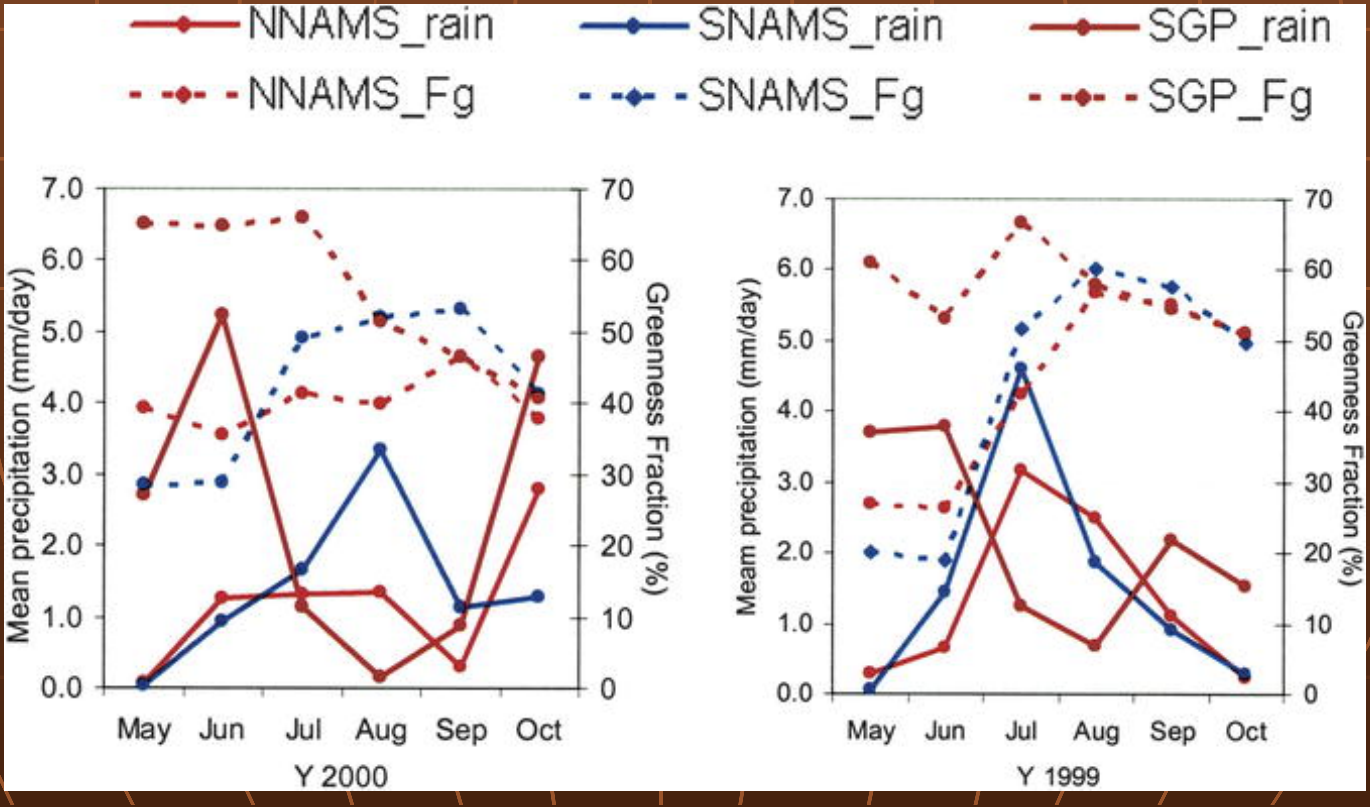
Illinois Soil Moisture



Why Augment Noah LSM?

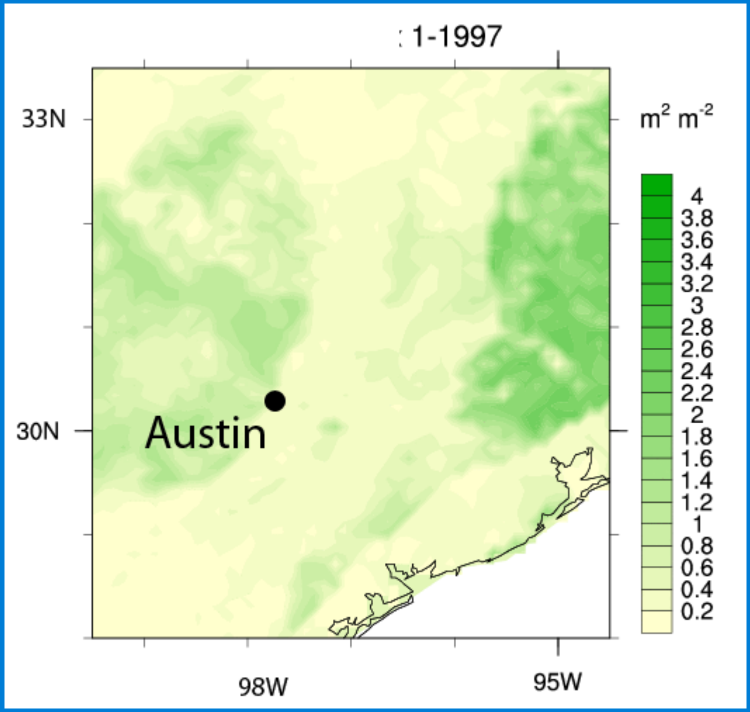
3. The present model lacks leaf area–rainfall interaction. Feedbacks between rainfall and rain-green vegetation are hypothesized to play a role in intra-seasonal to interannual climate predictions; see observations below.

Matsui et al. (2005) JCL

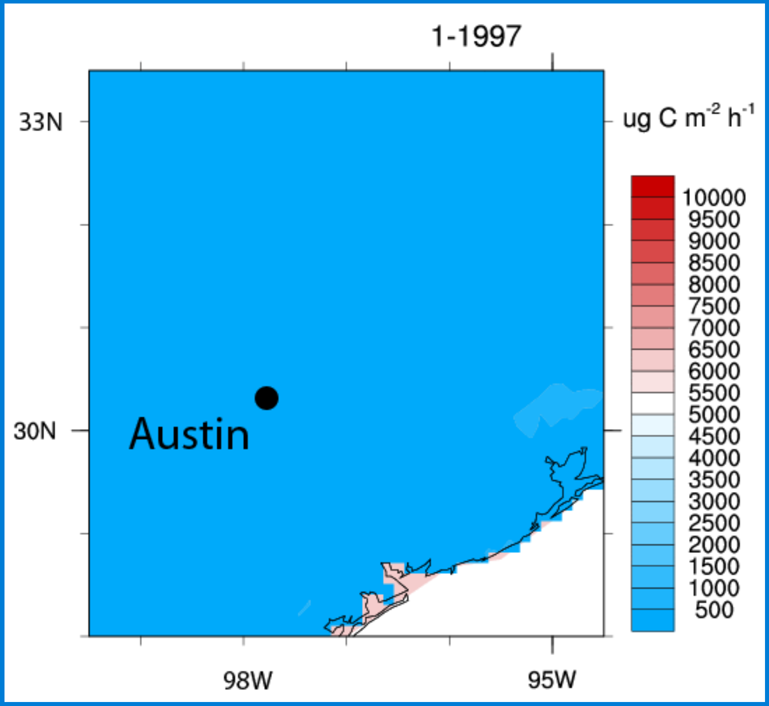


Precipitation Variability Drives Year-to-year Changes in Leaf Biomass and Biogenic Emissions (movie)

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.

Why Augment Noah LSM?

4. The present model does not distinguish vegetation canopy temperature and ground temperature, which makes it difficult to incorporate other physically-based processes.

5. Seamless predictions and ensemble forecasts demand more from the current Noah LSM.

What Have We Done?

1. Submitted a joint UT, NCAR, and NCEP proposal in July 2006.
2. Chen visited UT in October 2006.
3. Mitchell visited UT in January 2007.
4. UT, NCEP/EMC, NCEP/OHD, NCAR, and NASA had a 4-hour telecon meeting where Yang's group presented.
5. Yang/Niu visited Mitchell's group at NCEP/EMC in May 2007
6. Chen hosted the Noah development workshop at NCAR in July 2007; Mitchell, Yang, Peters-Lidard, and others attended.
7. Regular telecon meetings among UT, NCEP, NCAR, and others in the past two years.
8. Xia (of Ek's group) visited UT to transition Noah-MP in Feb. 2009.
9. Noah-MP (offline, and coupled to WRF) was ported to NCAR repository in spring 2009.
10. More testing and evaluations of Noah-MP at NCAR and UT since.

Progress to date

Peer-reviewed papers

1) Gulden, L.E. 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) Jiang, X**.**, et al., 2009, Impacts of vegetation and groundwater dynamics on warm season precipitation over the Central United States, *J. Geophys. Res.,* 114, D06109, doi:10.1029/2008JD010756.
3) Rosero, E., Z.-L. Yang, L. E. Gulden, G.-Y. Niu, and D. J. Gochis, 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
4) Rosero, E., Z.-L. Yang, T. Wagener, L. E. Gulden, S. Yatheendradas, and G.-Y. Niu, 2010: Quantifying parameter sensitivity, interaction and transferability in hydrologically enhanced versions of Noah-LSM over transition zones, J. Geophys. Res., **115**, D03106, doi:10.1029/2009JD012035
5) Niu, G.Y. et al., 2010a,b: (to be submitted)

Noah-UT with new features

1. Major components:

   1-layer canopy; 3-layer snow; 4-layer soil

2. Subgrid scheme: semi-tiled vegetation and bare soil (Niu et al., 2010a).

3. Iterative energy balance method to predict the canopy and snow/soil surface (skin) temperatures.

4. Modified two-stream radiation transfer scheme to consider the 3-D structure of the canopy (Niu and Yang, 2004).

5. More realistic snow physics: a thin surface layer, liquid water retention, and snowpack densification (Yang and Niu, 2003).

6. TOPMODEL-based runoff scheme (Niu et al., 2005).

7. Unconfined aquifer interacting with overlying soil (Niu et al., 2007).

8. More permeable frozen soil (Niu and Yang, 2006).

9. Ball-Berry stomatal resistance related to photosynthesis.

10. Dynamic (or interactive) leaf area (Dickinson et al., 1998).

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Niu et al. (2010a)

Noah-UT 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. (2010a,b)

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

Niu et al. (2010a,b)

2x2x3x2x2x2x2x3x2x4 = 4584 combinations

Recommended # of Combinations

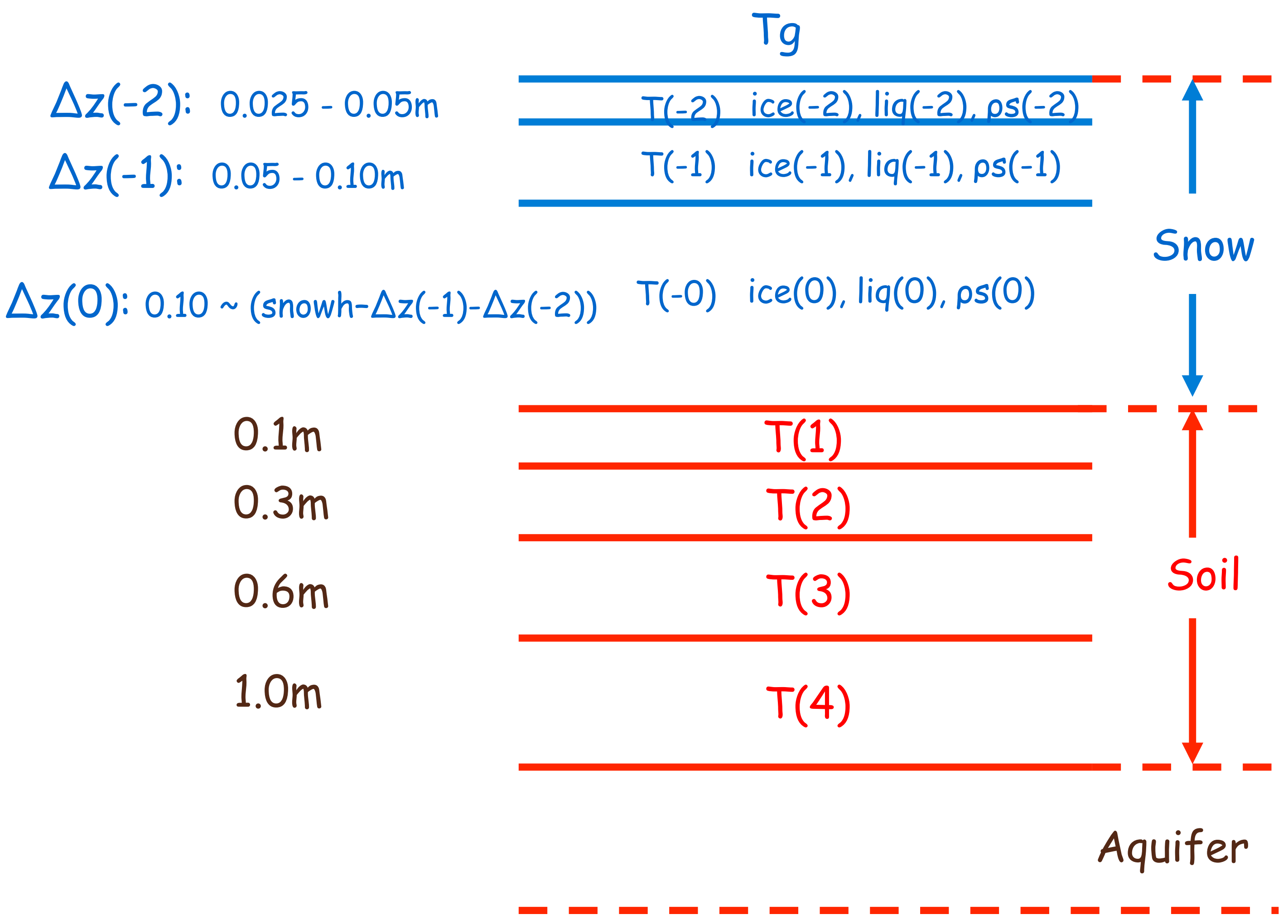
1. Leaf area index (prescribed; predicted) 1
2. Turbulent transfer (Noah; NCAR LSM) 1
3. Soil moisture stress factor for transp. (Noah; BATS; CLM) 3
4. Canopy stomatal resistance (Jarvis; Ball-Berry) 2
5. Snow surface albedo (BATS; CLASS) 1
6. Frozen soil permeability (Noah; Niu and Yang, 2006) 1
7. Supercooled liquid water (Noah; Niu and Yang, 2006) 1
8. Radiation transfer: 1
   - 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) 1
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

1x1x3x2x1x1x1x1x1x4 = 24 combinations

Niu et al. (2010a,b)

Structure of Vertical Layers

The structure of vertical soil layers remains the same as in the previous Noah version except for the 3-L snow above it and an unconfined aquifer below it.



Tg

$\Delta z(-2)$: 0.025 - 0.05m T(-2) ice(-2), liq(-2), ρs(-2)

$\Delta z(-1)$: 0.05 - 0.10m T(-1) ice(-1), liq(-1), ρs(-1)

Snow

$\Delta z(0)$: 0.10 ~ (snowh-$\Delta z(-1)$-$\Delta z(-2)$) T(-0) ice(0), liq(0), ρs(0)

0.1m T(1)

0.3m T(2)

0.6m T(3)

Soil

1.0m T(4)

Aquifer

One Matrix Solving All Temperatures

$$
\begin{pmatrix}
B(-2) & C(-2) & 0 & 0 & 0 & 0 & 0 \\
A(-1) & B(-1) & C(-1) & 0 & 0 & 0 & 0 \\
0 & A(0) & B(0) & C(0) & 0 & 0 & 0 \\
0 & 0 & A(1) & B(1) & C(1) & 0 & 0 \\
0 & 0 & 0 & A(2) & B(2) & C(2) & D(2) \\
0 & 0 & 0 & 0 & A(3) & B(3) & C(3) \\
0 & 0 & 0 & 0 & 0 & A(4) & C(4)
\end{pmatrix}
\times
\begin{pmatrix}
T(-2) \\ T(-1) \\ T(0) \\ T(1) \\ T(2) \\ T(3) \\ T(4)
\end{pmatrix}
=
\begin{pmatrix}
R(-2) \\ R(-1) \\ R(0) \\ R(1) \\ R(2) \\ R(3) \\ R(4)
\end{pmatrix}
$$

A(i), B(i), C(i), R(i) are a function of

- $\lambda(i)$ - thermal conductivity
- C(i) - heat capacity
- z(i) - layer-bottom depth from the snow/soil surface (neg.)

R(-nsn+1) is a function of G:

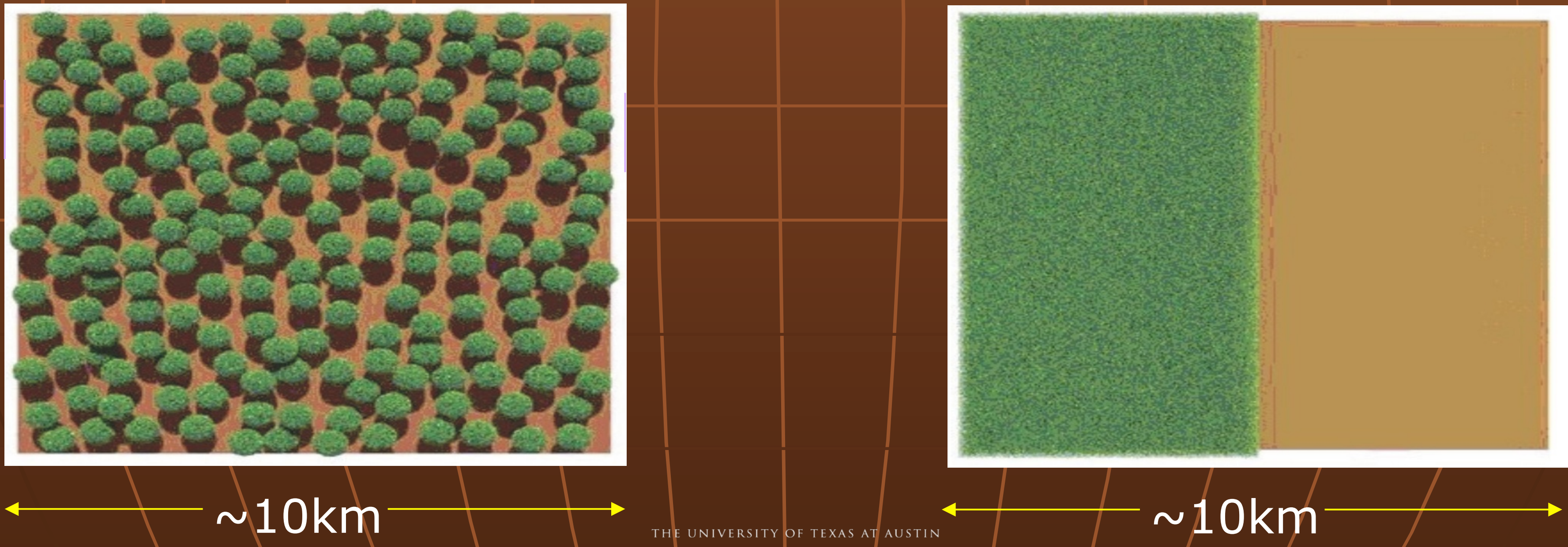
$$G = \lambda(1)\ (\ T12 - T(-nsn+1)\ )/\ (\ 0.5*dz(-nsn+1)\ )$$

T12: skin temperature

Subgrid Scheme: Mosaic, Tile or Mixture?

Given GVF (green vegetation fraction) for a land grid, how to represent radiative and turbulent processes?

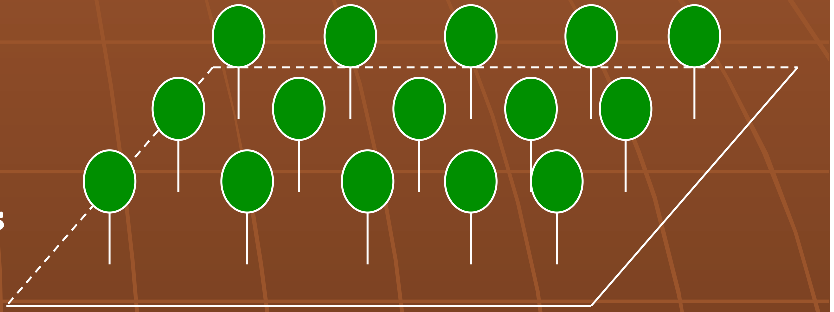
Radiative transfer needs to consider the shadow effects or the zenith angle dependence.

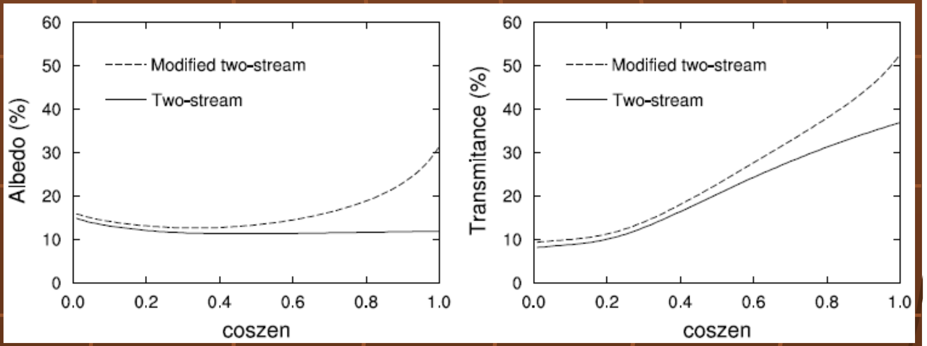


Subgrid Vegetation Scheme

Radiation: Modified Two-stream (Yang and Friedl, 2001)

1. Evenly-distributed crowns
2. Between-canopy and within canopy gaps
3. Computes over the whole grid-cell:
   - SAG – ground absorbed solar R
   - SAV – vegetation absorbed R





Turbulent transfer:

Two tiles: dominant vegetation
and bare ground

Energy balance:

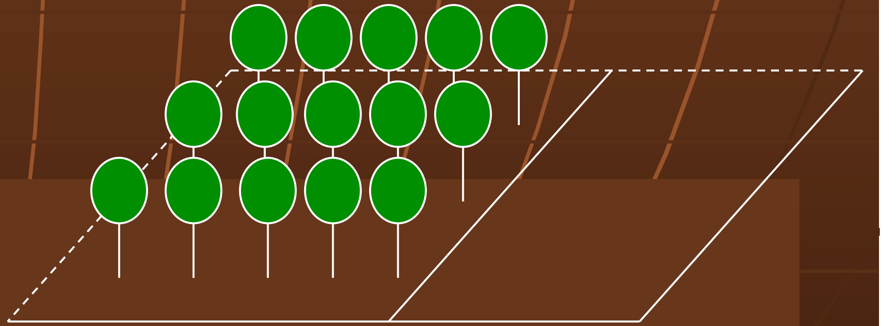
vegetation-tile:

Canopy: SAV – GVF*(IRC+SHC+EVC+TR) = 0.

Ground: SAG – (IRG+SHG+EVG+GHV) = 0.

Bare ground:

SAG – (IRB+SHB+EVB+GHB) = 0.



The grid cell SH and EV:

SH = (SHG+SHC)*GVF + SHB*(1-GVF)

EV = (EVG+TR+EVC)*GVF + EVB*(1-GVF)

Niu et al. (2008)

Multi-layer Snowpack Model

☐ The 3-L snow model has 4 major prognostic variables: layer depth (or density), temperature, ice content, and liquid water content for each layer.

☐ The 3-L snow temperatures and the 4-L soil temperatures are solved through one tri-diagonal matrix.

☐ The skin temperature, Tg, is solved through an iterative energy balance method.

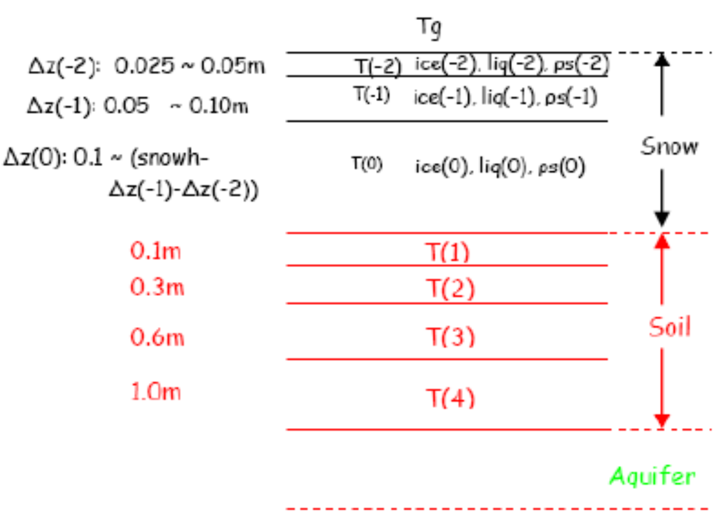
☐ Freezing/melting energy is assessed as the energy deficit or excess needed to change snow temperature to the melting/freezing point (Yang and Niu, 2003):

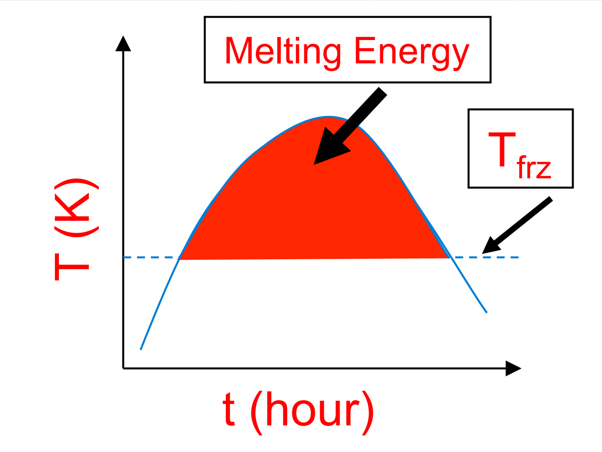
$$H_{fm}(i) = C(i) * dz(i) * (T(i) - T_{frz}) / dt \;;\quad \text{i-th layer}$$

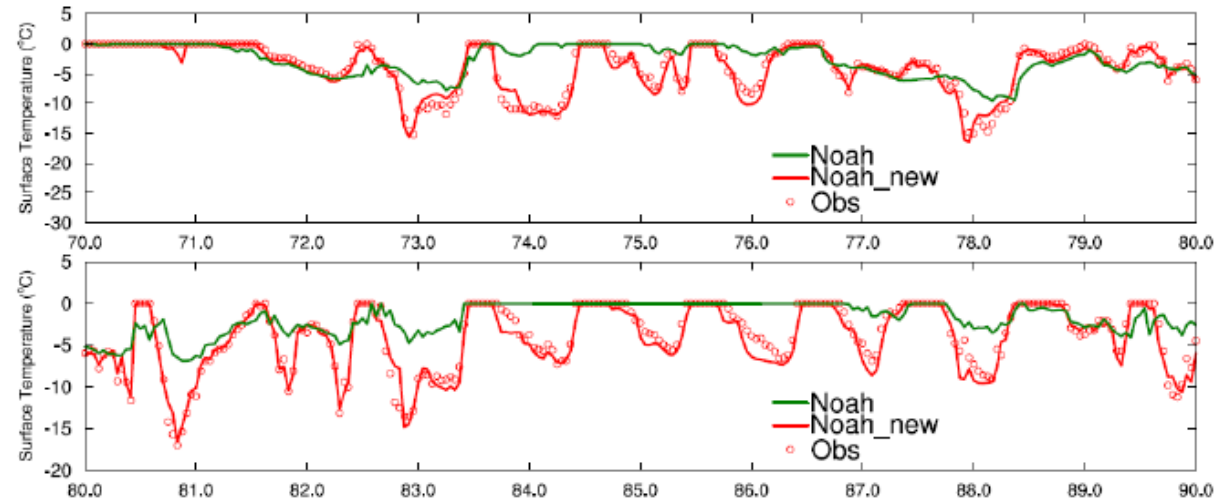
☐ Snow cover fraction (Niu and Yang, 2007):

$$f_{sno} = \tanh\left(\frac{h_{sno}}{2.5 z_{0g} (\rho_{sno}/\rho_{new})^{m}}\right)$$

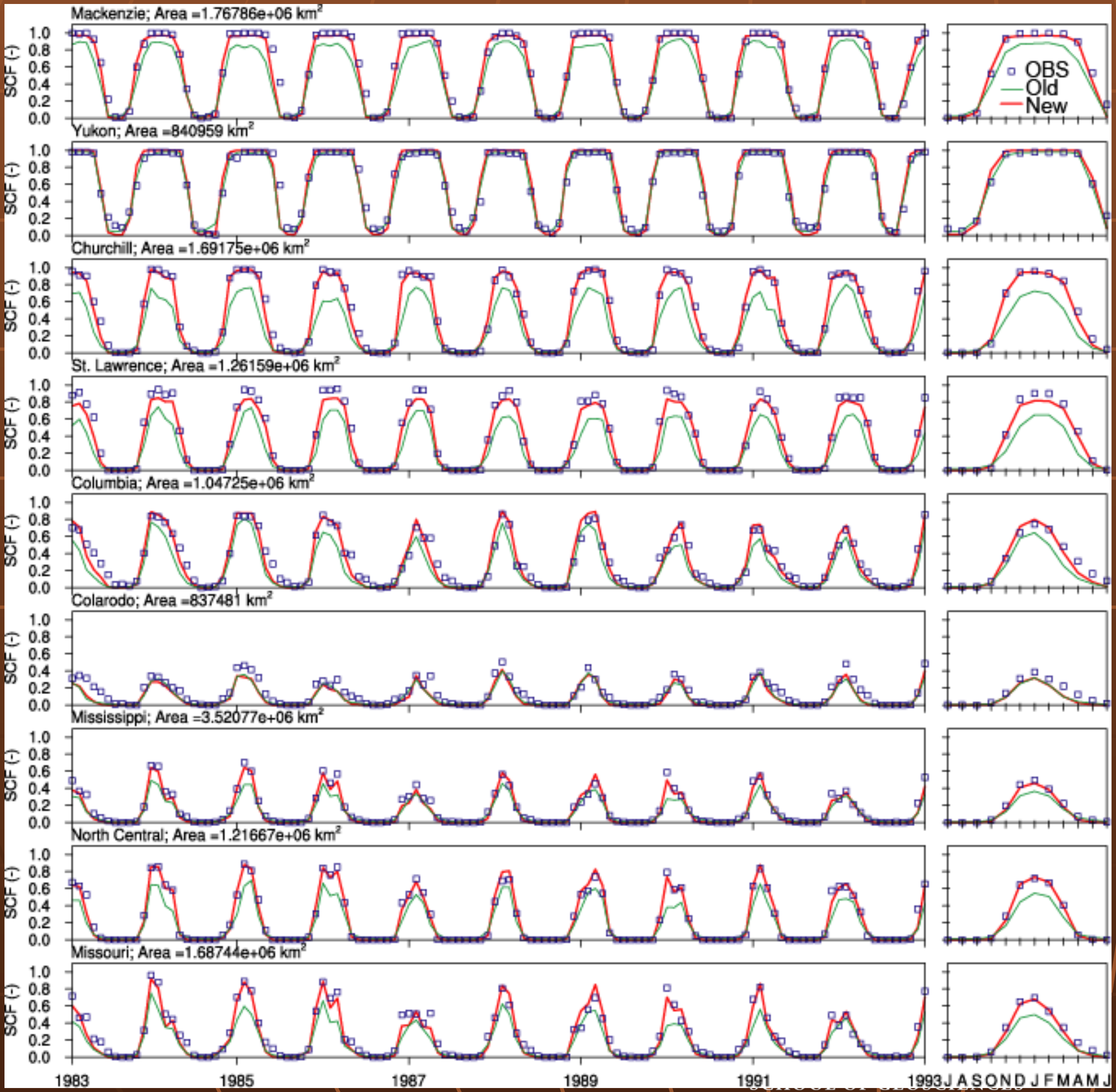
when melting factor, m = 0., it turns to Yang et al. (1997)

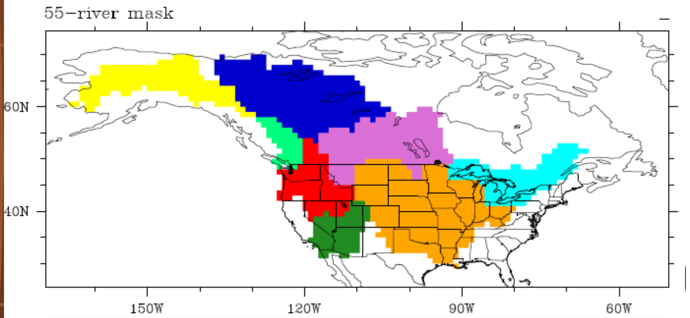






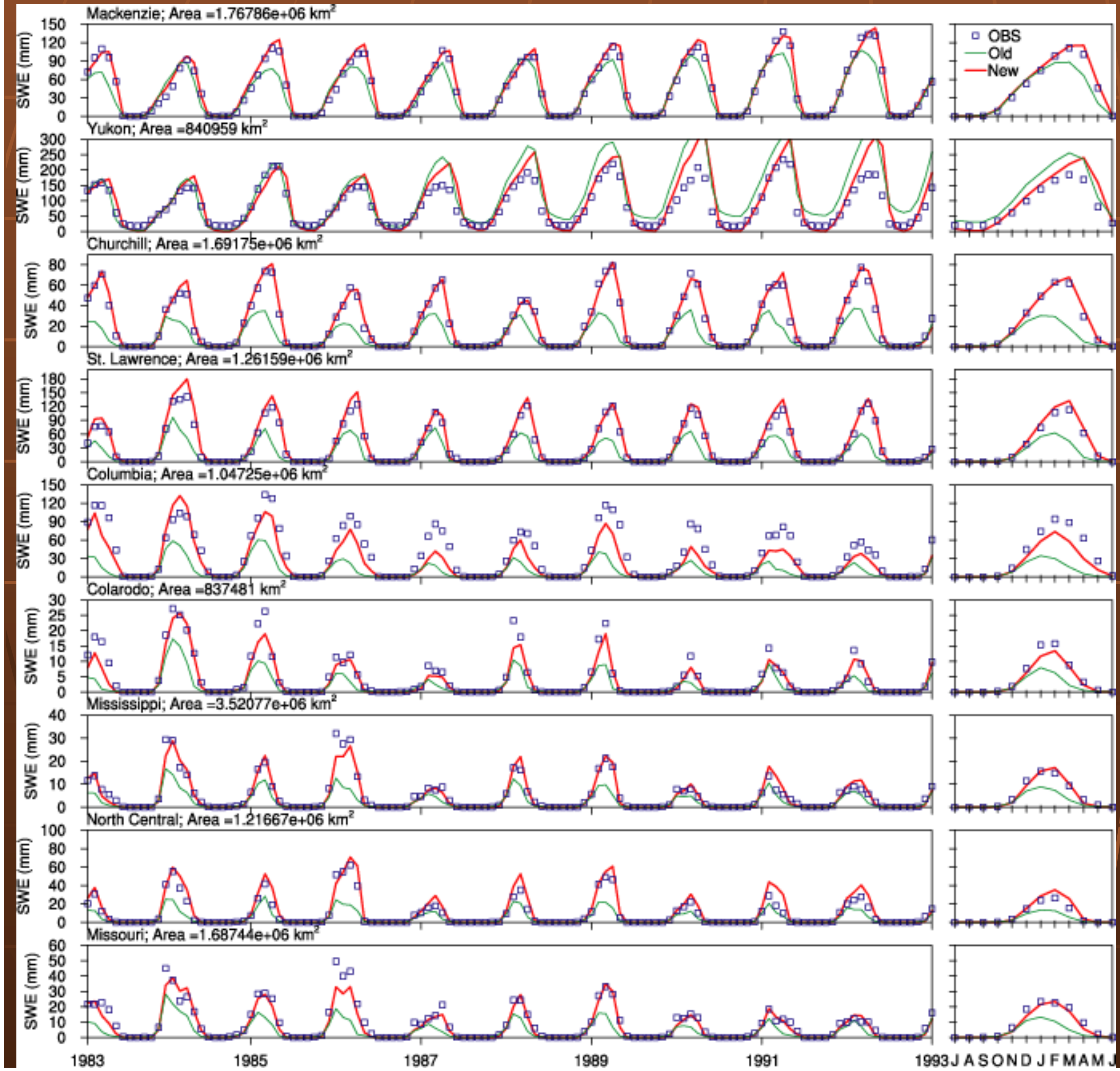
Snow Cover Fraction Over 9 River Basins

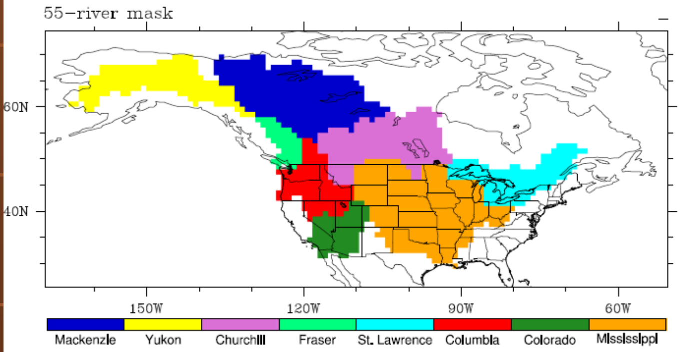




Niu et al. (2010a,b)

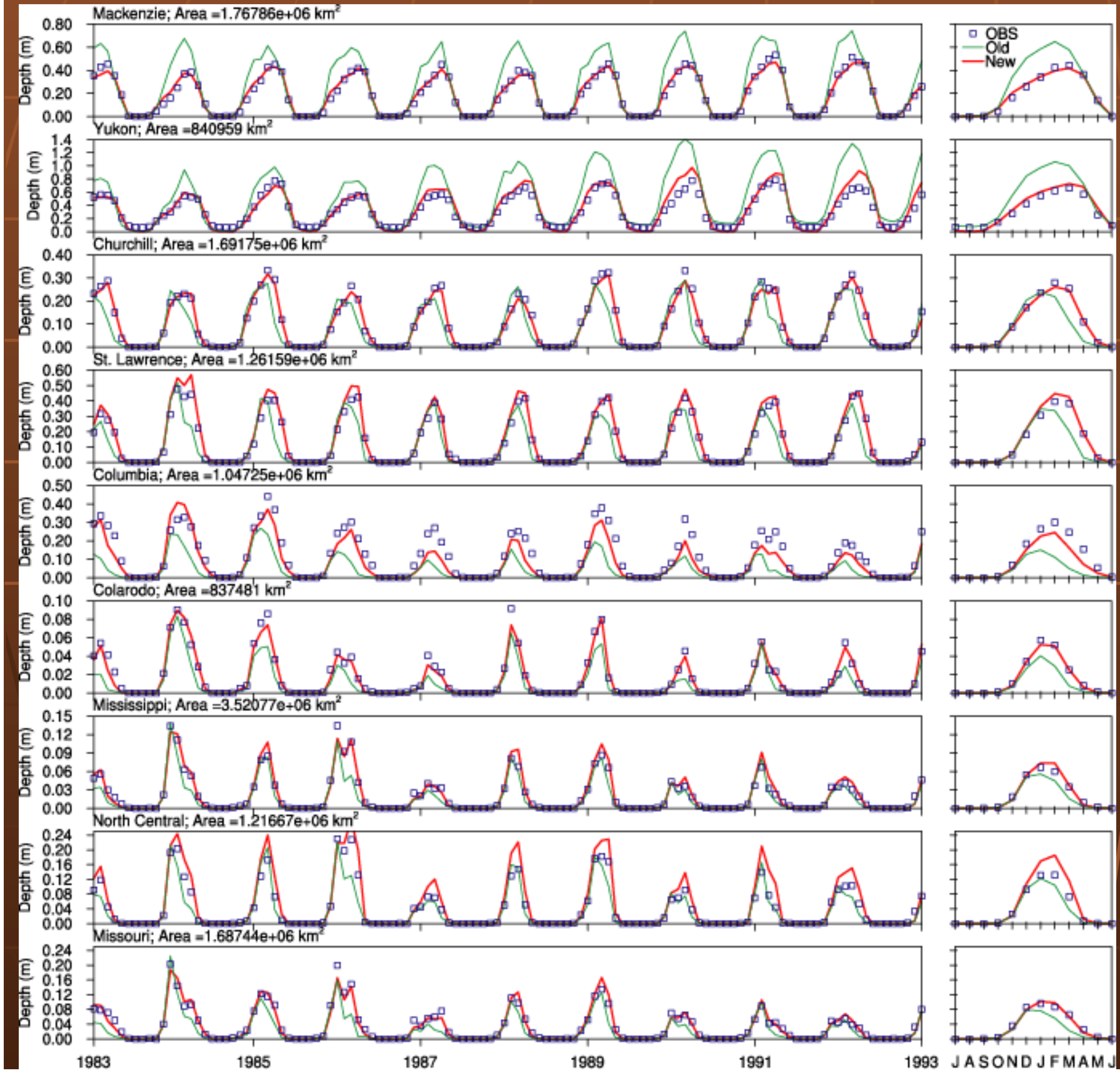
Snow Water Equivalent Over 9 River Basins

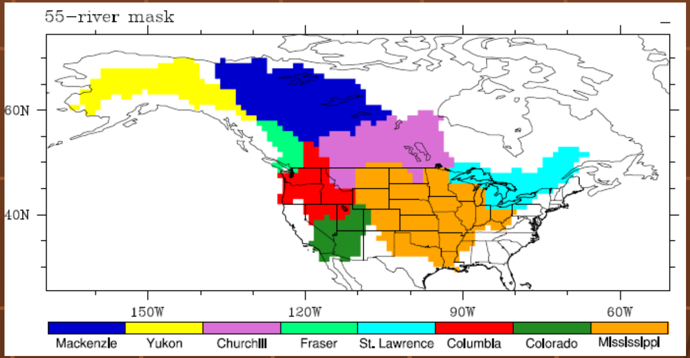




Niu et al. (2010a,b)

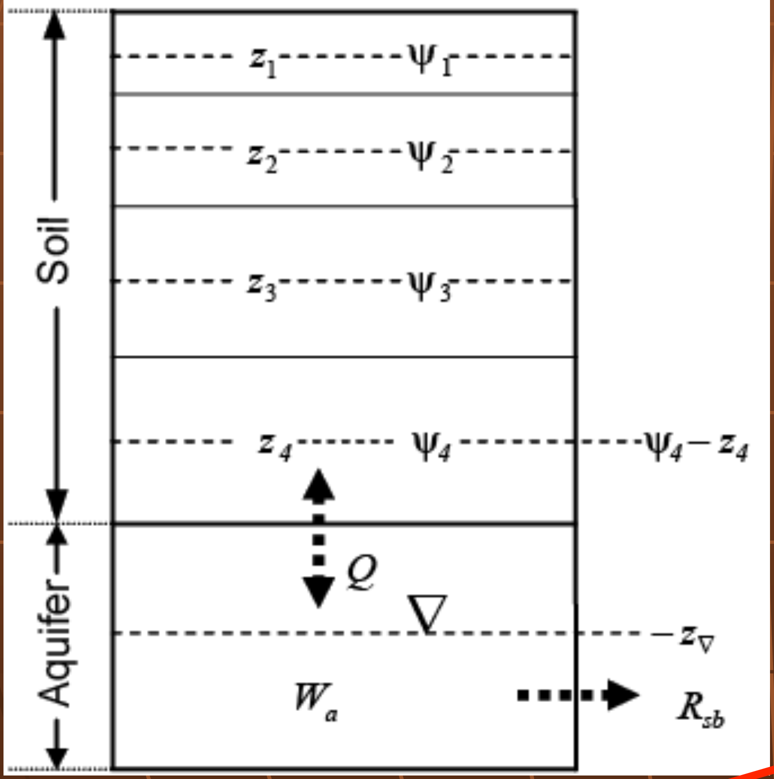
Snow Depth Over 9 River Basins





Niu et al. (2010a,b)

A Simple Groundwater Model (SIMGM)



Water storage in an unconfined aquifer:

$$\frac{dW_a}{dt} = Q - R_{sb}$$

$$z_\nabla = W_a / S_y$$

Recharge Rate:

$$Q = -K_a \frac{-z_\nabla - (\psi_{bot} - z_{bot})}{z_\nabla - z_{bot}}$$

$$= K_a \left(1 + \frac{\psi_{bot}}{z_\nabla - z_{bot}}\right)$$

Modified to consider macropore effects:

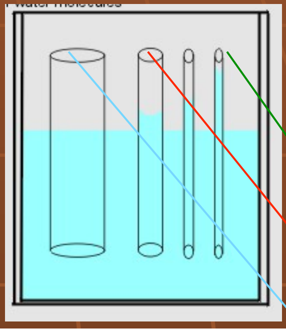
C_{mic} * ψ_{bot} ***C_{mic} → fraction of micropore content***

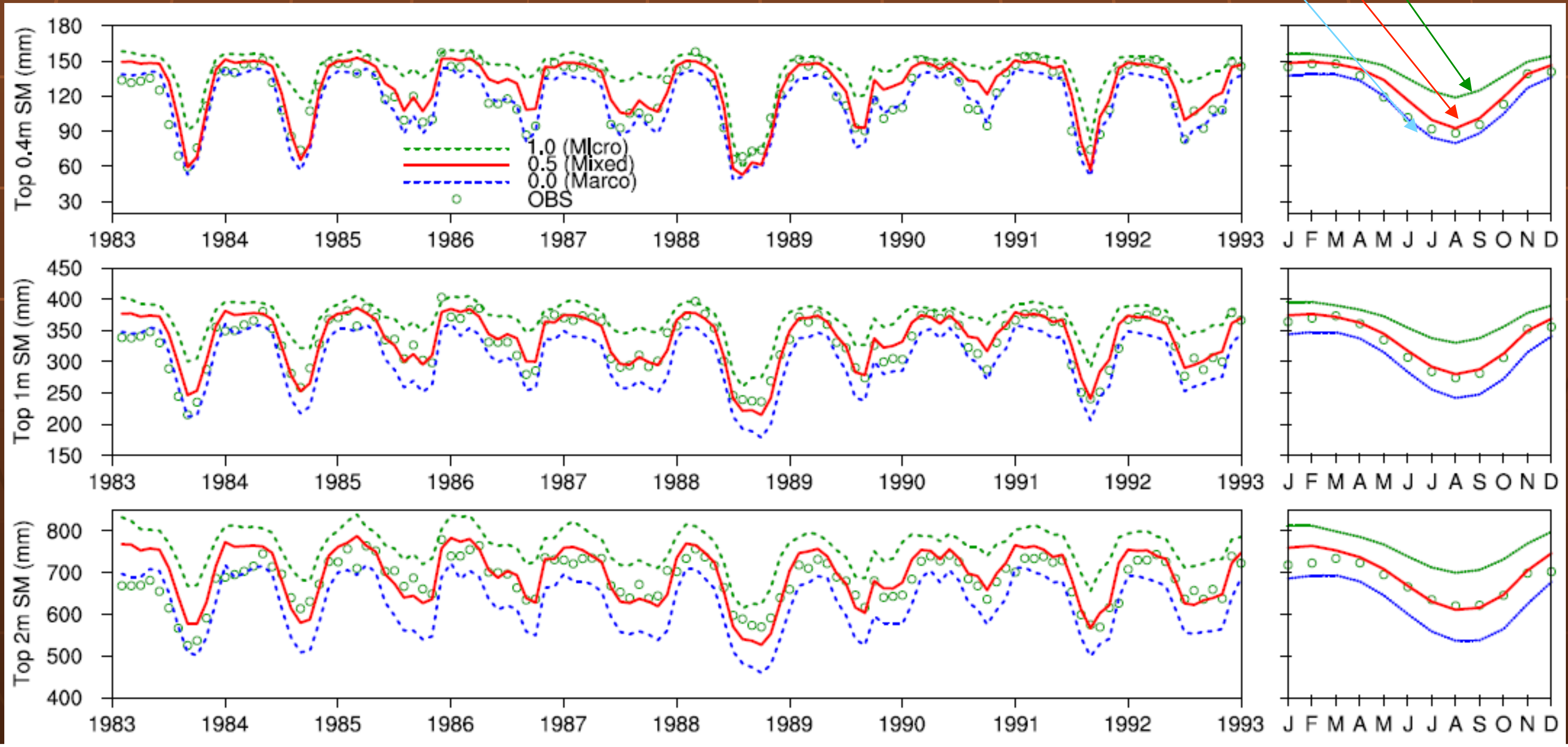
0.0 – 1.0 (0.0 ~ free drainage)

Niu et al. (2010a,b)

A Simple Groundwater Model (SIMGM)

Micropore fraction: $C_{mic} = 0.5$

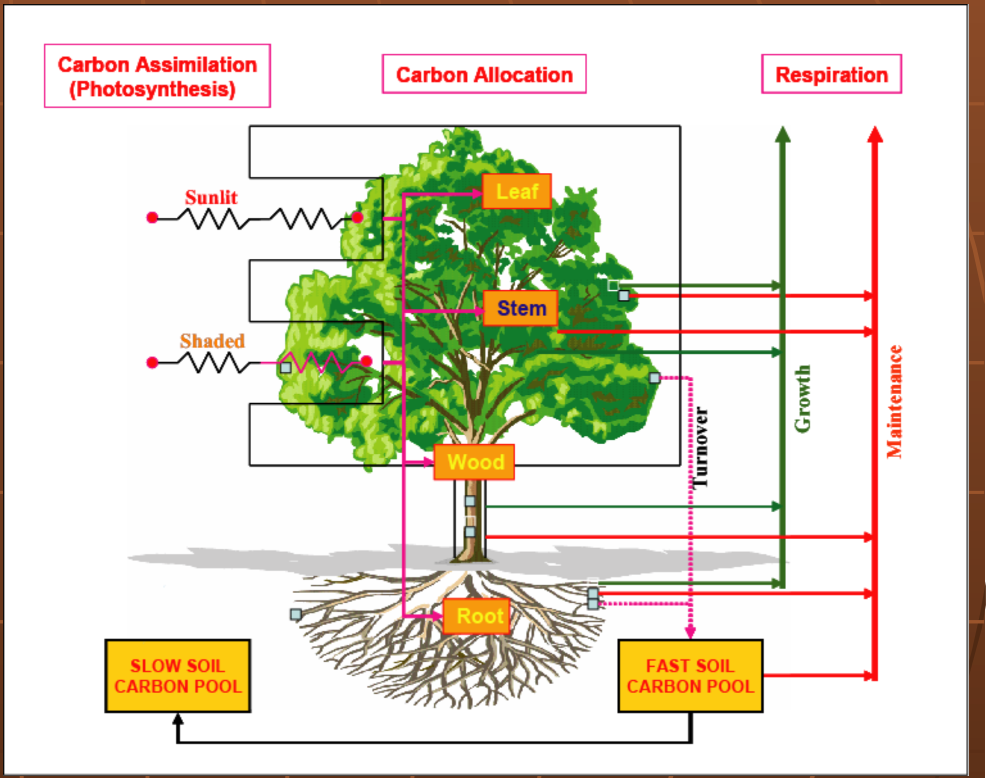




Dynamic Vegetation Canopy

DLM 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})

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

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).

Dickinson et al. (1998)

Six Transitional Experiments:

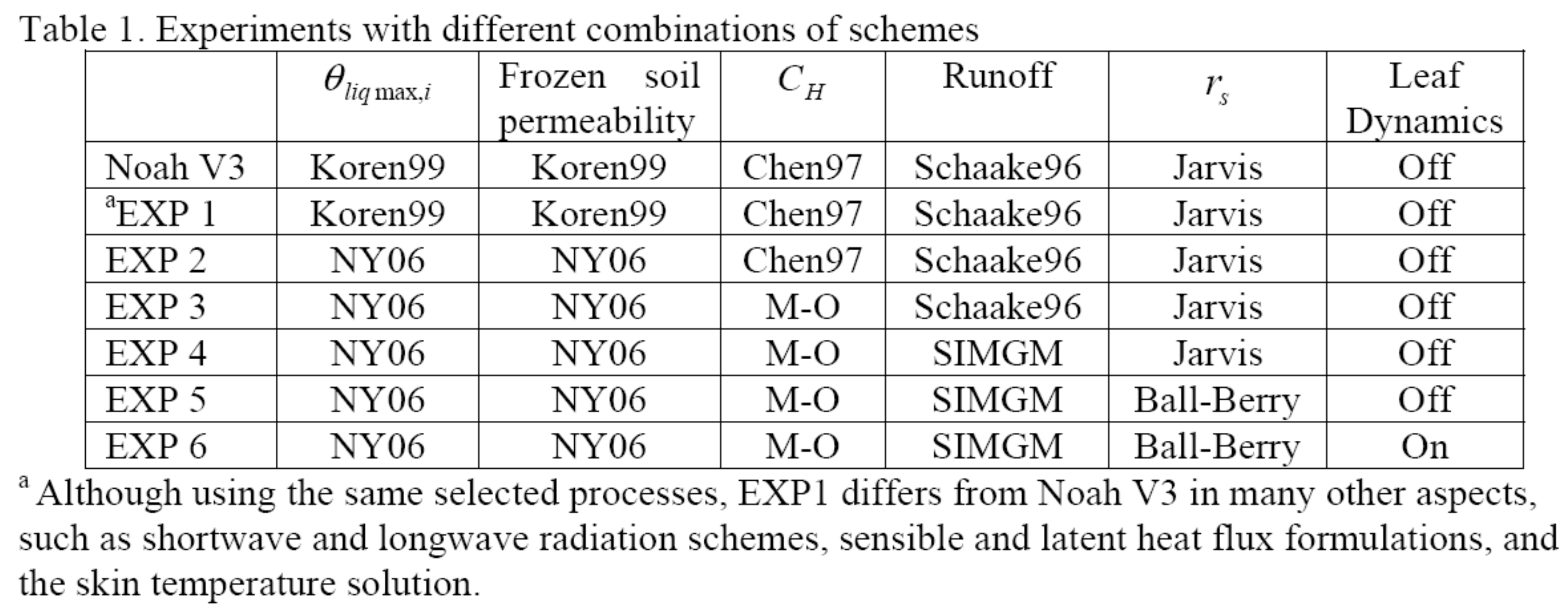


Table 1. Experiments with different combinations of schemes

	$\theta_{liq\,\max,i}$	Frozen soil permeability	C_H	Runoff	r_s	Leaf Dynamics
Noah V3	Koren99	Koren99	Chen97	Schaake96	Jarvis	Off
[a]EXP 1	Koren99	Koren99	Chen97	Schaake96	Jarvis	Off
EXP 2	NY06	NY06	Chen97	Schaake96	Jarvis	Off
EXP 3	NY06	NY06	M-O	Schaake96	Jarvis	Off
EXP 4	NY06	NY06	M-O	SIMGM	Jarvis	Off
EXP 5	NY06	NY06	M-O	SIMGM	Ball-Berry	Off
EXP 6	NY06	NY06	M-O	SIMGM	Ball-Berry	On

[a] Although using the same selected processes, EXP1 differs from Noah V3 in many other aspects, such as shortwave and longwave radiation schemes, sensible and latent heat flux formulations, and the skin temperature solution.

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Niu et al. (2010a,b)

Global Energy and Water Balances:

Table 2. Global (60S–90N) 10-year (1986–1995) area-weighted averages of land surface energy and water budgets [S_a–net solar radiation, L_a–net longwave radiation (positive upward), R_{net}–net radiation, H–sensible heat, LE–latent heat, P–precipitation, ET–evapotranspiration, R–runoff, R_s–surface runoff, and R_b–baseflow]

	S_a W/m^2	L_a W/m^2	R_{net} W/m^2	H W/m^2	LE W/m^2	P mm/a	ET mm/a	R mm/a	R_s mm/a	R_b mm/a
Noah-V3	133	65	68	37	30	769	376	388	84	305
[a]EXP1	141	65	76	38	37	769	460	308	98	211
EXP2	141	65	76	38	37	769	463	305	64	241
EXP3	140	64	77	43	33	769	416	352	69	283
EXP4	140	64	77	42	34	769	422	347	93	254
EXP5	140	64	77	42	34	769	422	347	93	254
EXP6	137	64	73	37	34	769	430	339	91	248
[b]EN36	139	64	75	41	34	769	421	347	121	226
[c]GSWP2	142	68	74	35	37	827	471	322	119	203

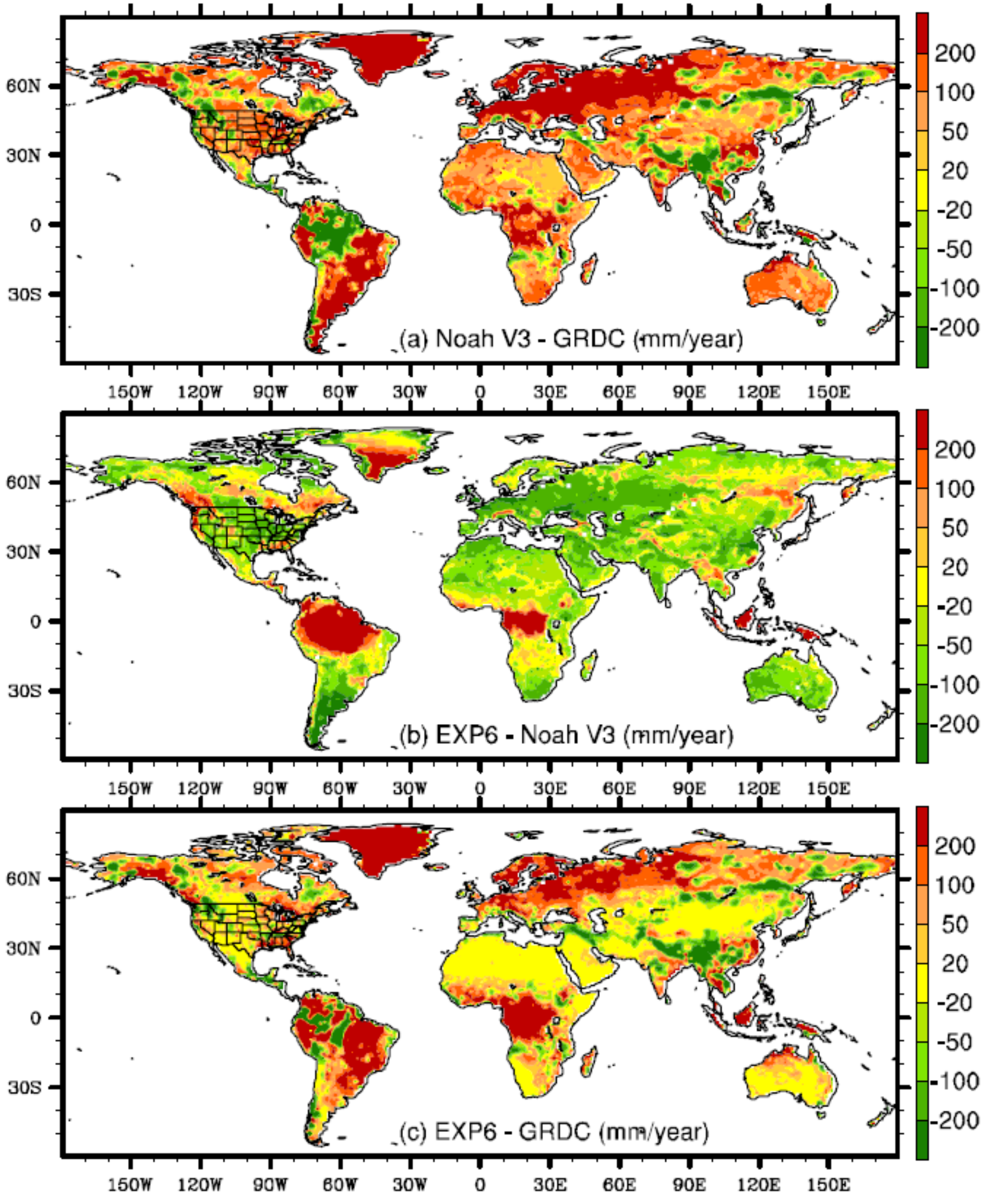
[a] Lake points are excluded in experiments from EXP1 to EXP6 (which compute lake surface temperature and ET) for comparison with Noah V3 (without lake).

GRDC: 280mm/year

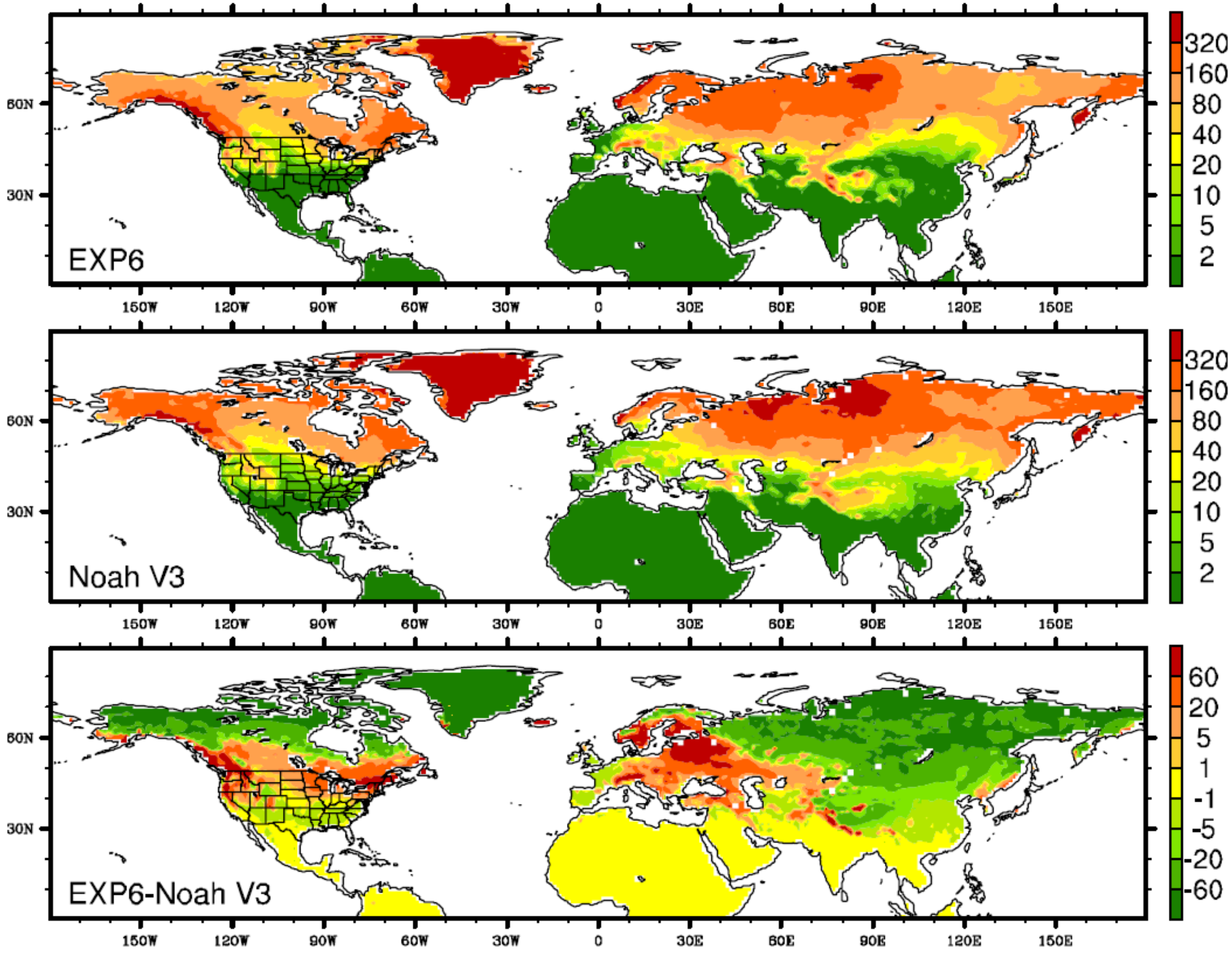
[b] Ensemble mean of the 36 experiments (see section 5.0).

[c] GSWP2: Global Soil Wetness Project phase-2 12-model mean, which is available at http://hydro.iis.u-tokyo.ac.jp/GLASS/GSWP2/ICC_Report01.html. The 12 model's results are averaged regardless of imbalance of water or energy of any model.

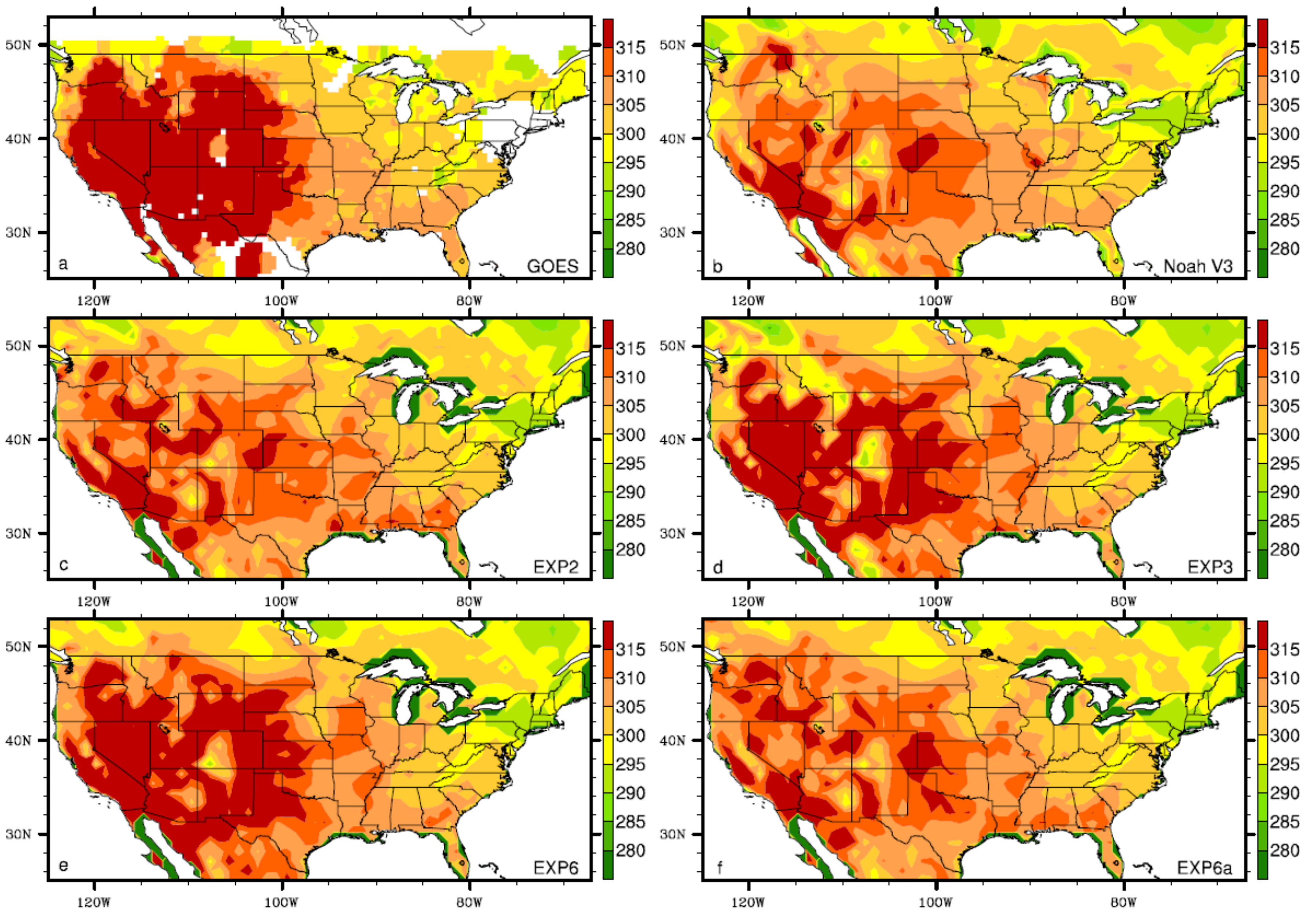
Runoff (mm/year)



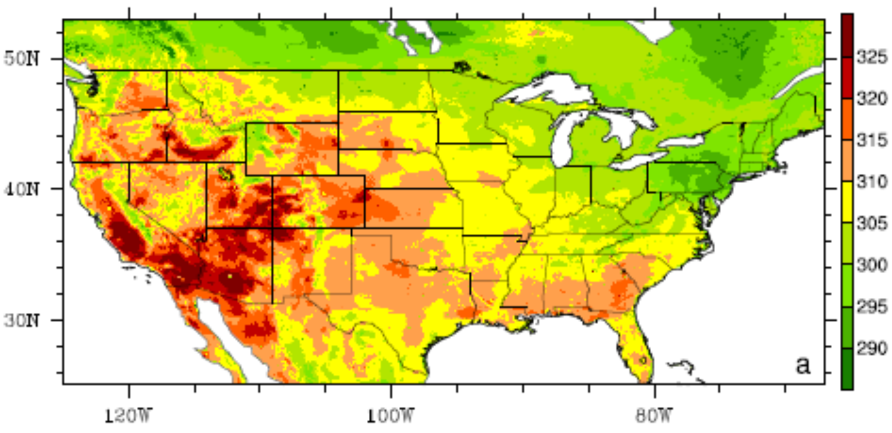
Snow Water Equivalent (Feb; in mm)



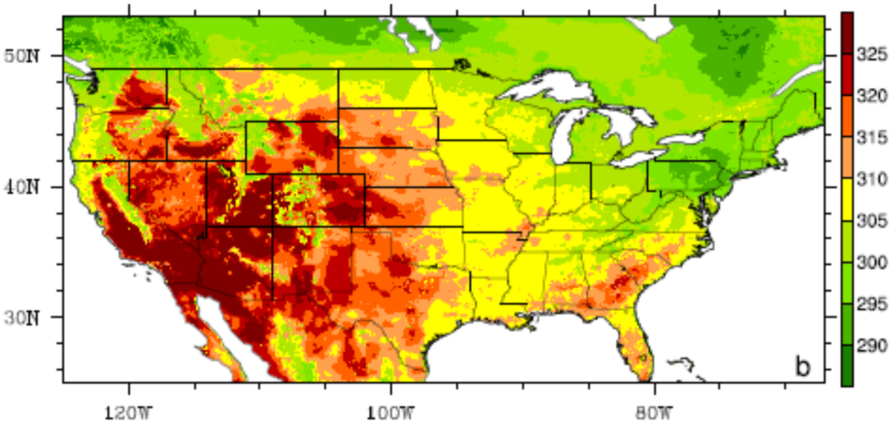
Modeled Tskin *(July 12th, 21:00 UTC, 2004)*



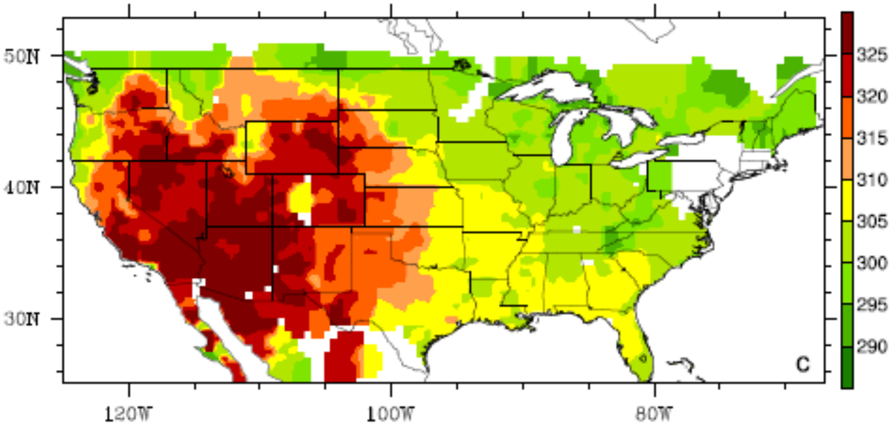
Modeled Tskin *(July 12th, 21:00 UTC, 2004)*



Noah_MP with Chen97

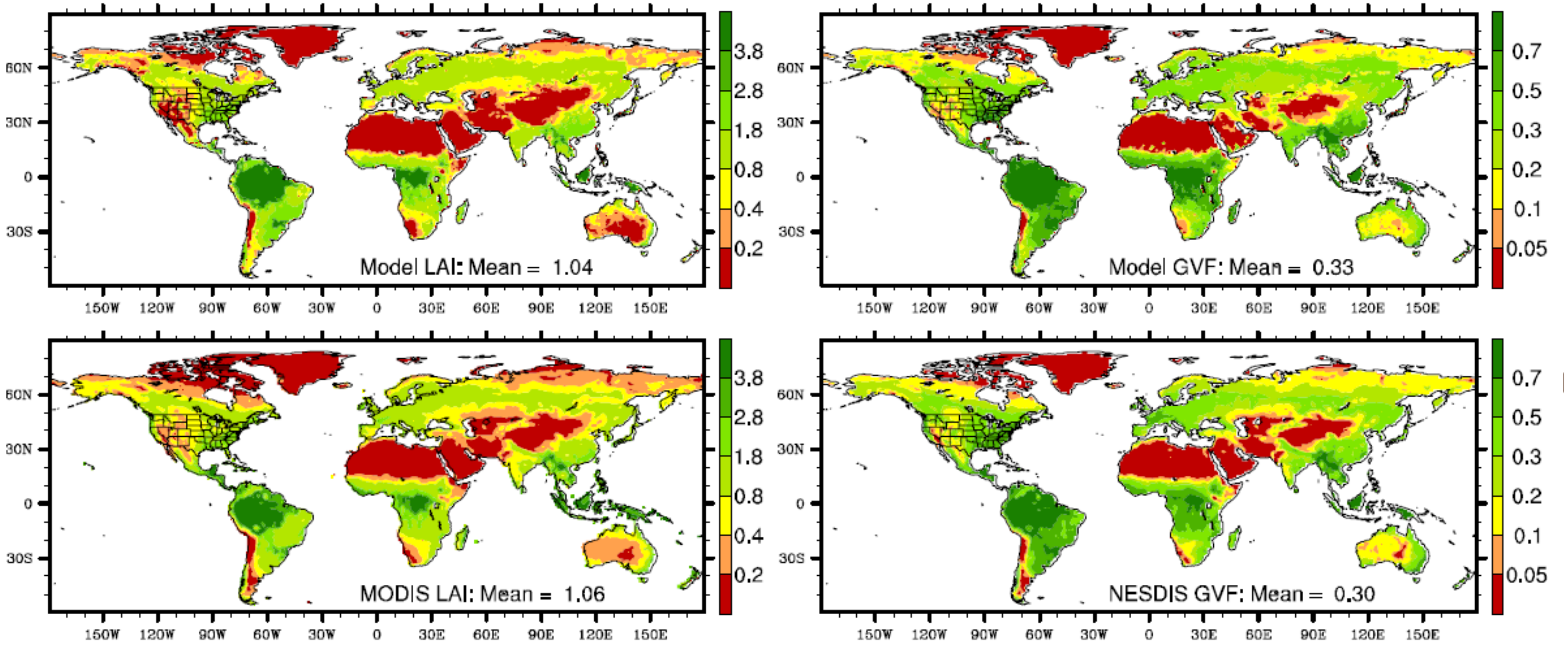


Noah_MP with M-O



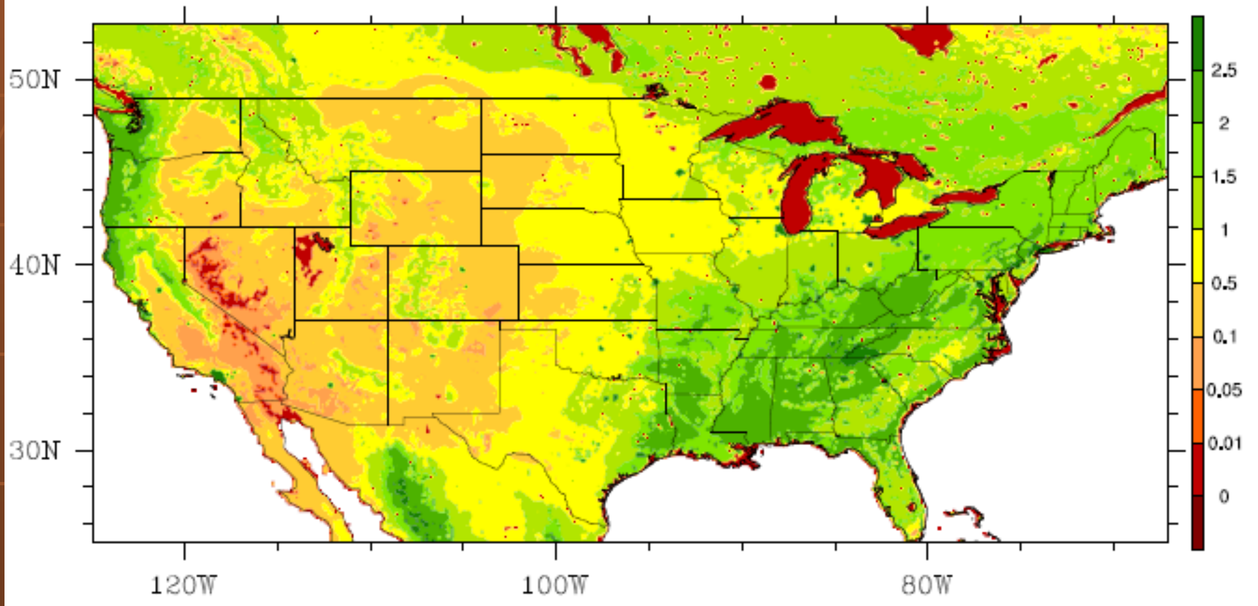
GOES

Comparison of Modeled and Satellite-estimated LAI and GVF

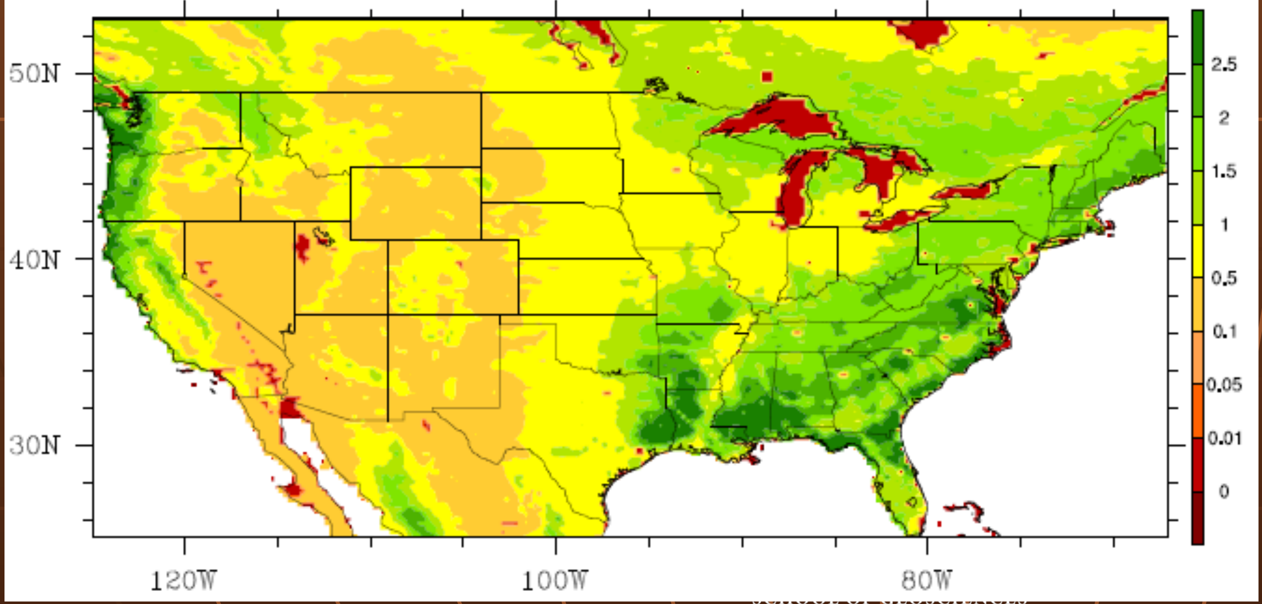


Niu et al. (2010a,b)

Modeled LAI Using NLDAS

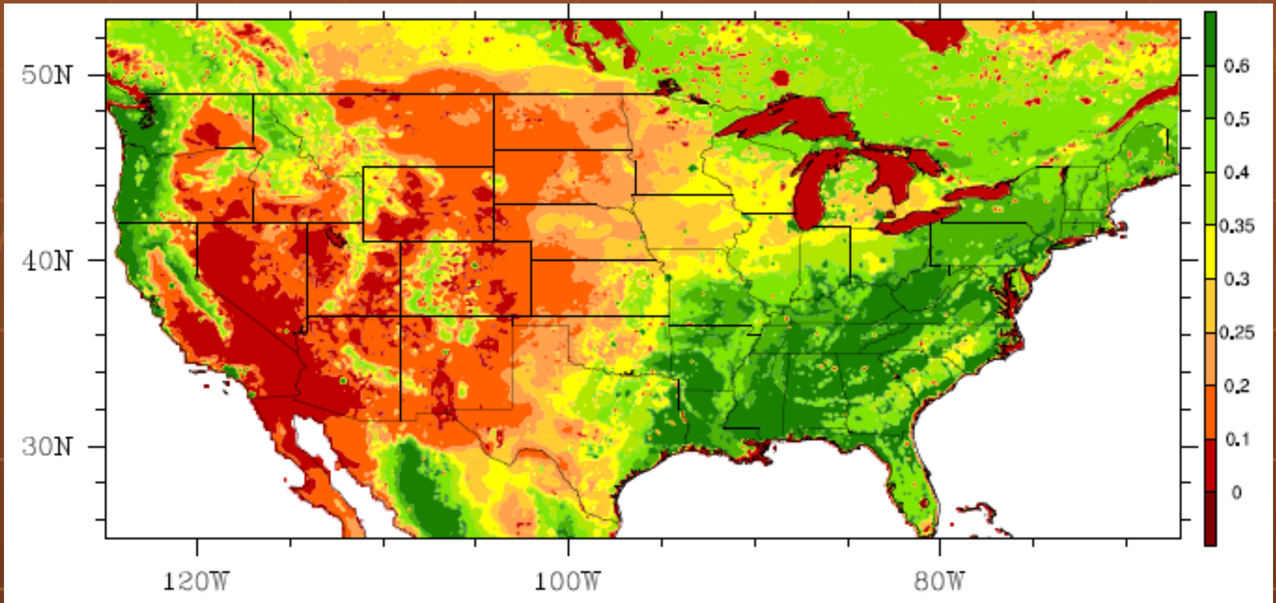


Model
(2002 – 2007)

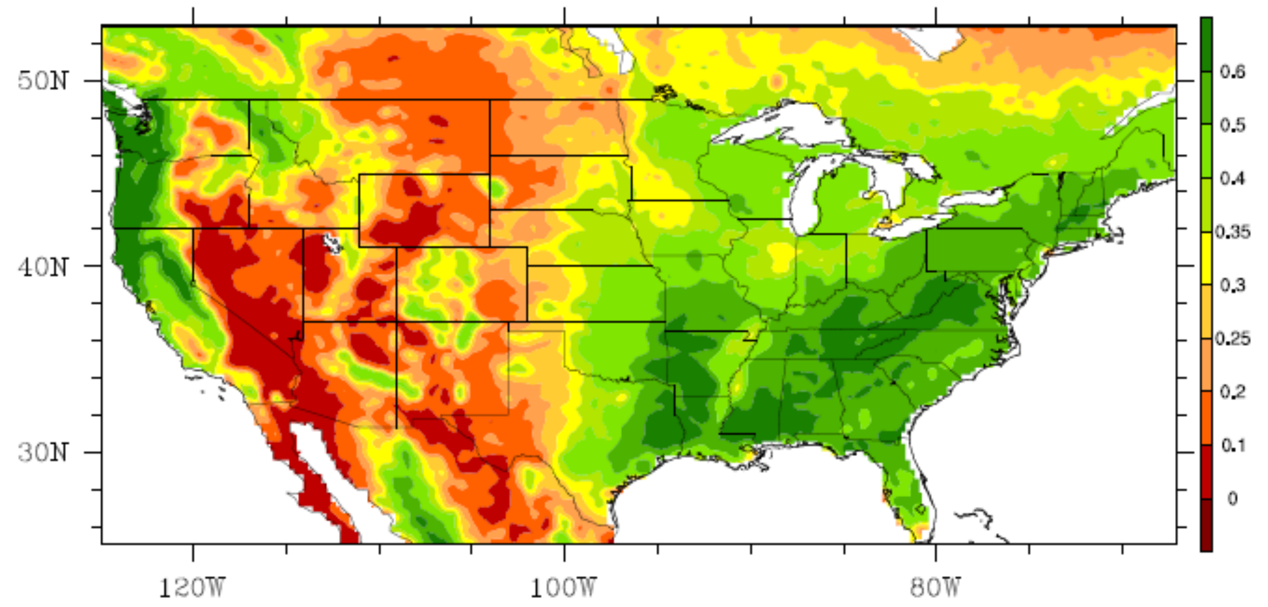


MODIS (1/4th degree)
(Mar. 2000 – Jul. 2008)

Modeled GVF Using NLDAS

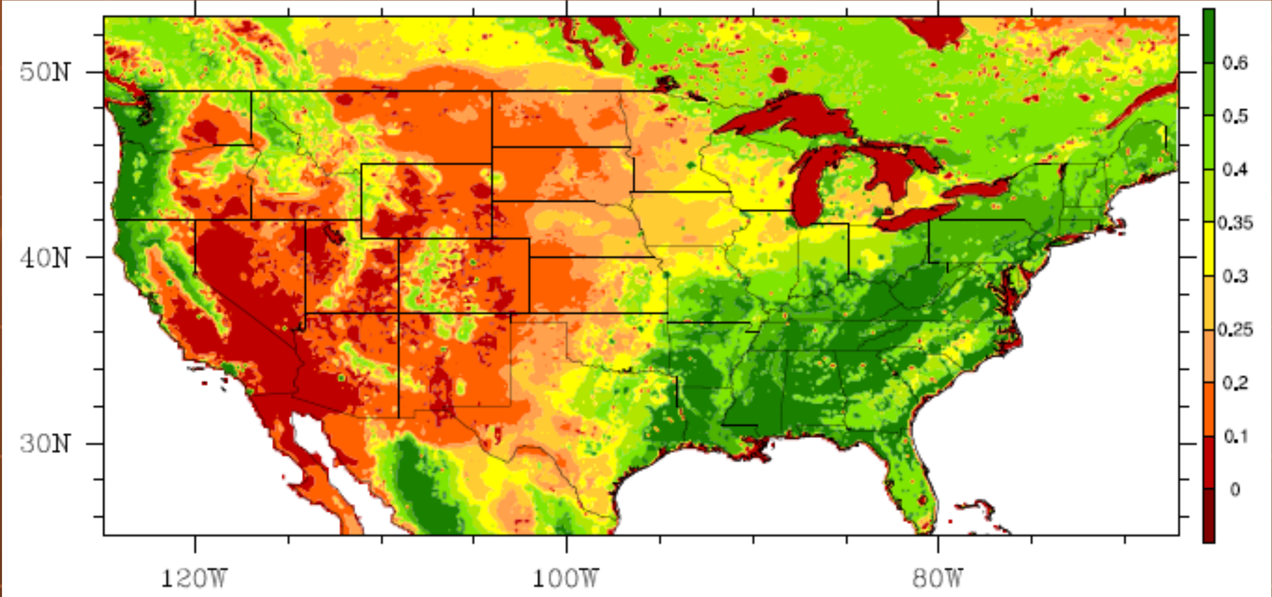


Model
(2002 – 2007)

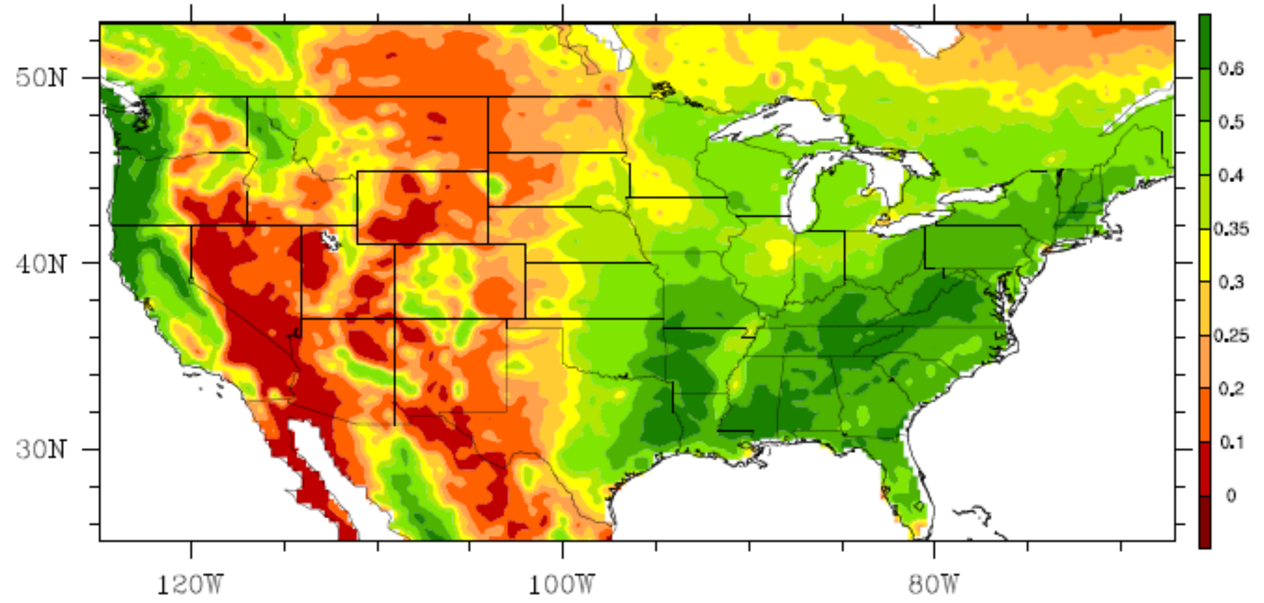


NESDIS (0.144 degree)
(Gutman & Ignatov, 1998)
(5-year mean)

Modeled GVF Using NLDAS

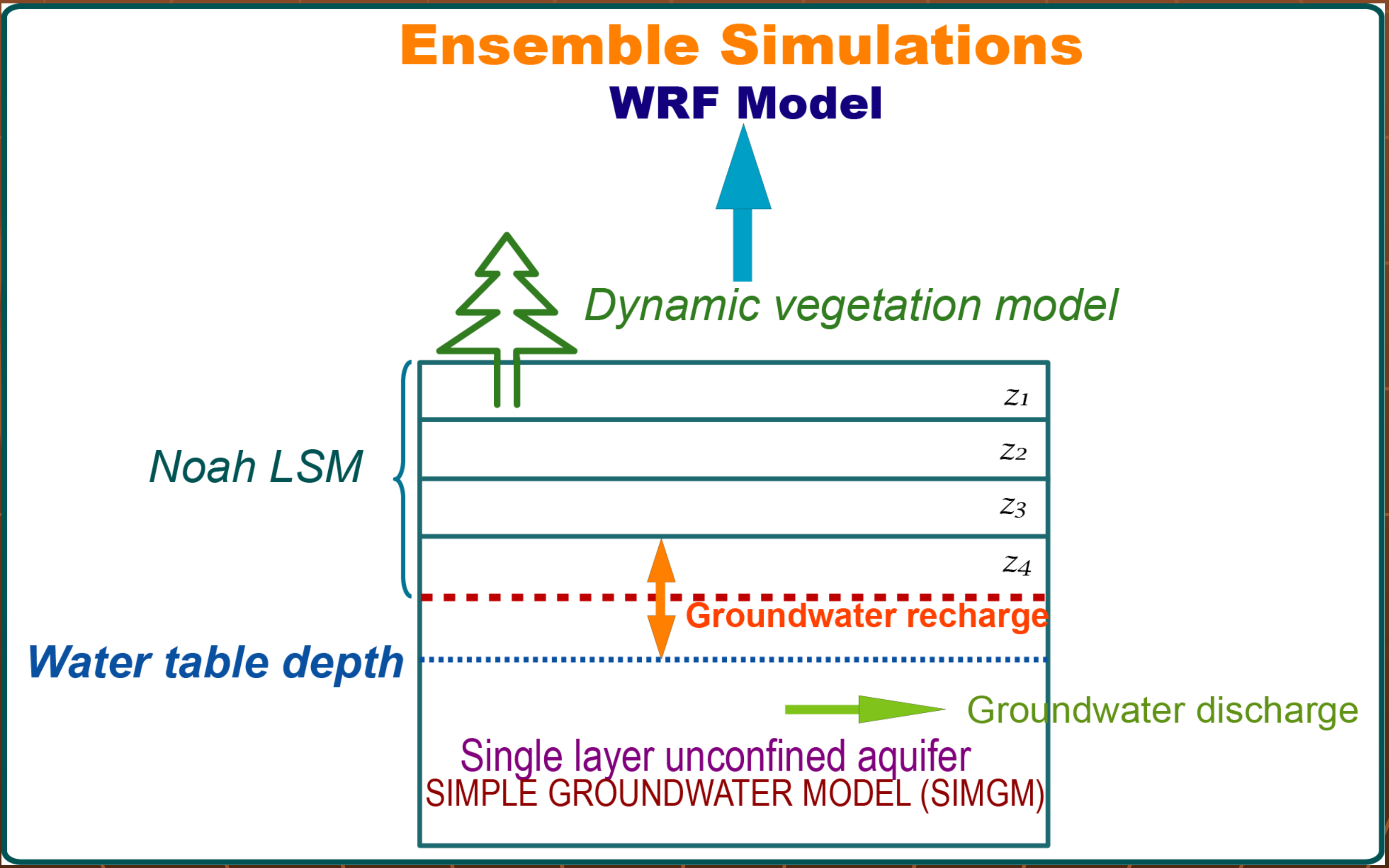


Model
(2002 – 2007)



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

Improving Seasonal Precipitation Prediction Through A Coupled Groundwater-Vegetation-Atmosphere System



Ensemble Simulations

WRF Model

Dynamic vegetation model

Noah LSM

z_1

z_2

z_3

z_4

Groundwater recharge

Water table depth

Groundwater discharge

Single layer unconfined aquifer

SIMPLE GROUNDWATER MODEL (SIMGM)

Niu, G.-Y., Z.-L. Yang, R.E. Dickinson, L.E. Gulden, and H. Su, 2007, JGR
Jiang, X.Y., G.Y. Niu, and Z.-L. Yang, 2009: JGR

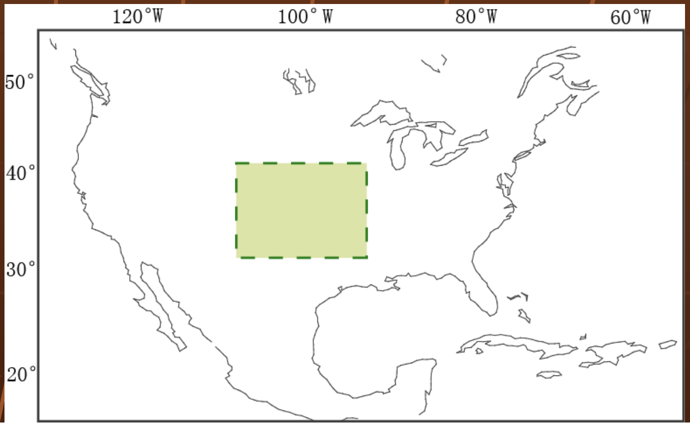
WRF/Noah Model

- The version 2.1.2 of the Weather Research and Forecasting model (WRF) with time-varying sea surface temperatures.

- WRF Physics options:
- Lin et al. microphysics scheme;
- Kain-Fritsch cumulus parameterization scheme;
- Yonsei University Planetary boundary layer;
- A simple cloud interactive radiation scheme;
- Rapid Radiative Transfer Model longwave radiation scheme

- Default Noah LSM augmented by:
  - dynamic vegetation canopy (DV) of Dickinson et al. (1998)
  - a simple groundwater model (GW) of Niu et al. (2007)

- NCEP-NCAR reanalysis data

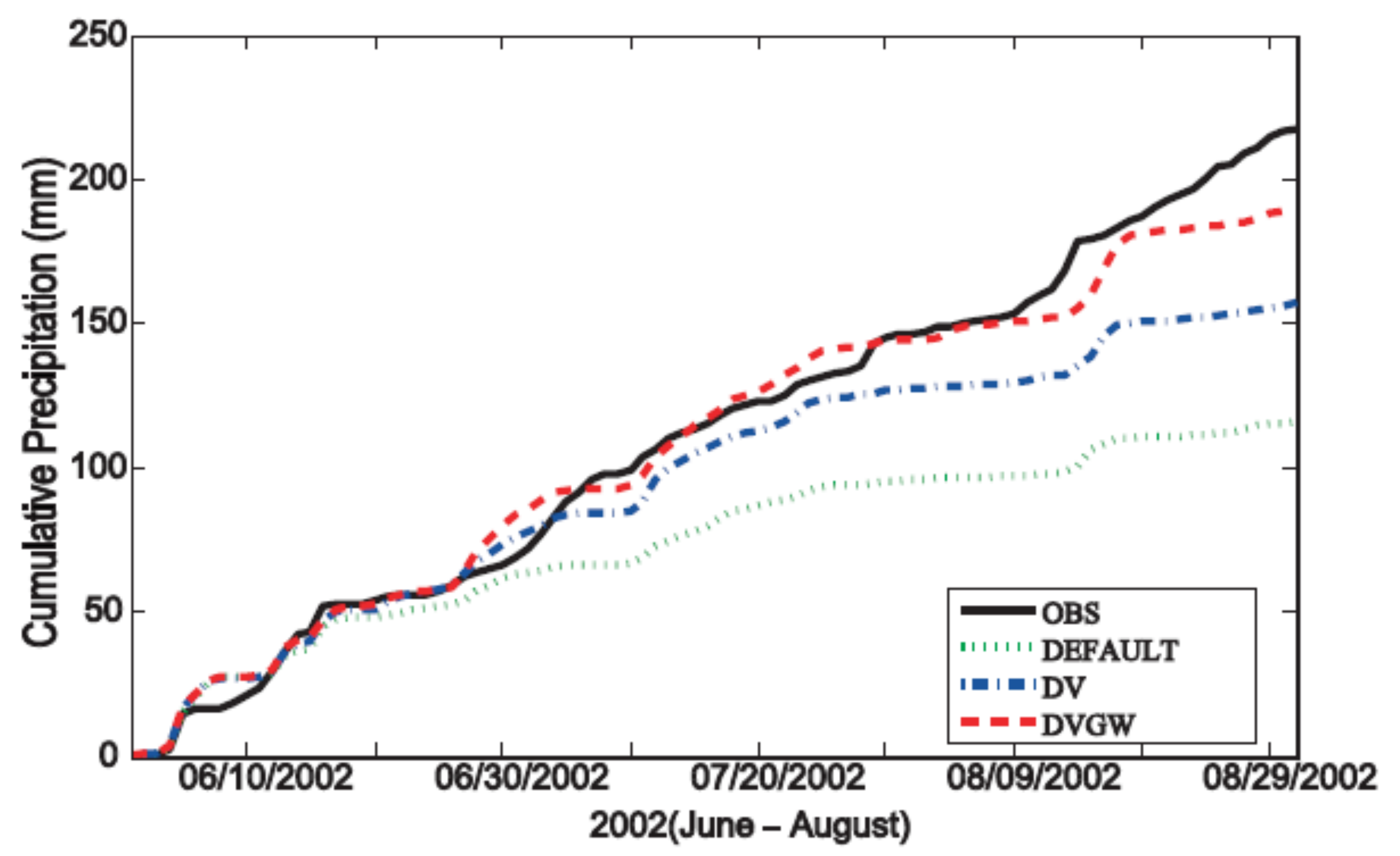


The model domain covers the whole continental U.S. and the resolution is 32 km

Ensemble experiments

Cases	Start from different dates to 8/31/2002	Experiment description
DEFAULT	05/31 00:00 05/31 06:00 05/31 12:00 05/31 18:00 06/01 00:00	Use prescribed greenness fraction in the WRF model
DV		Use dynamic Vegetation in the WRF model
DVGW		Include dynamic vegetation and groundwater in the WRF model

Observed versus simulated cumulative precipitation over the Central United States



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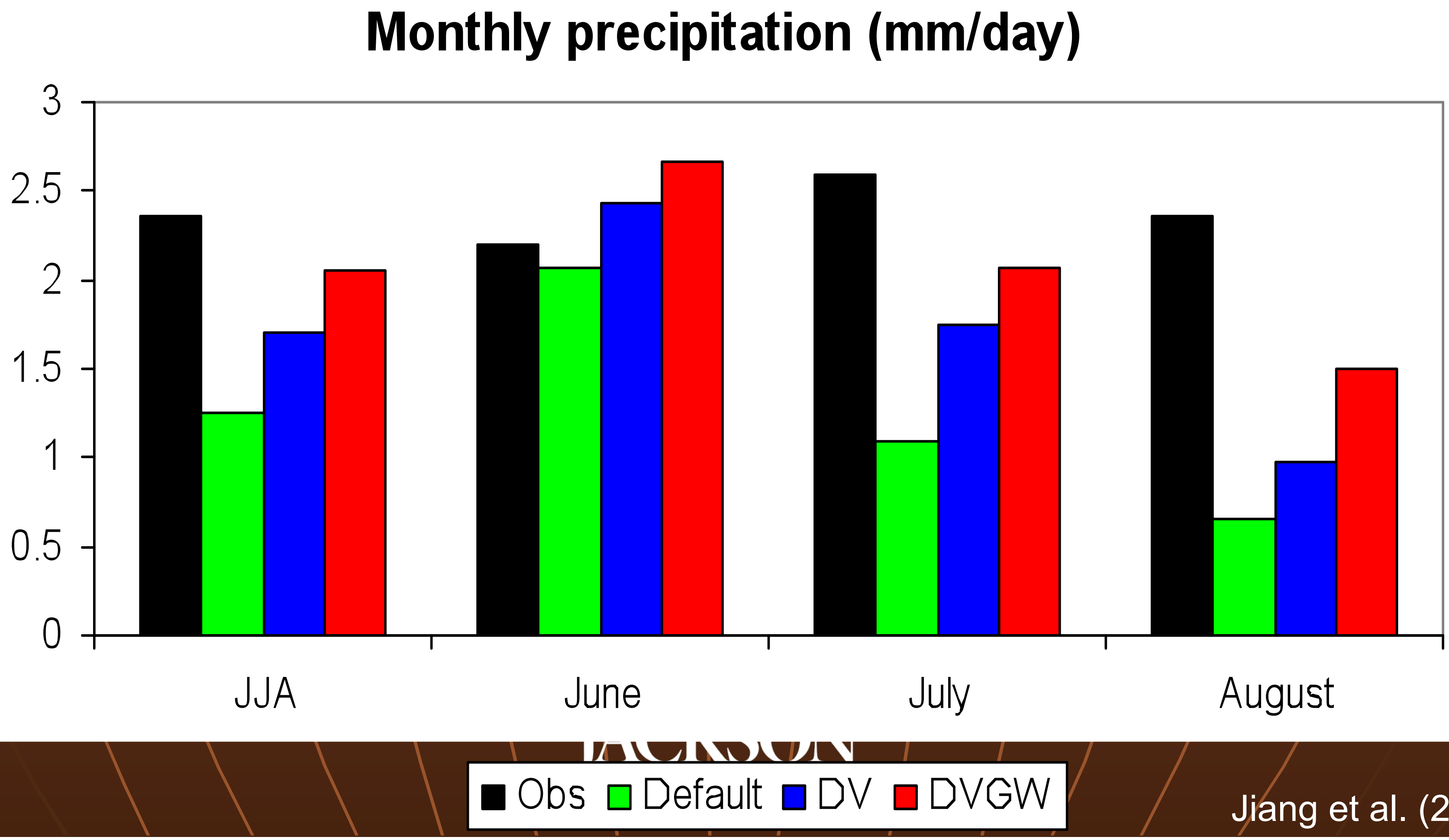
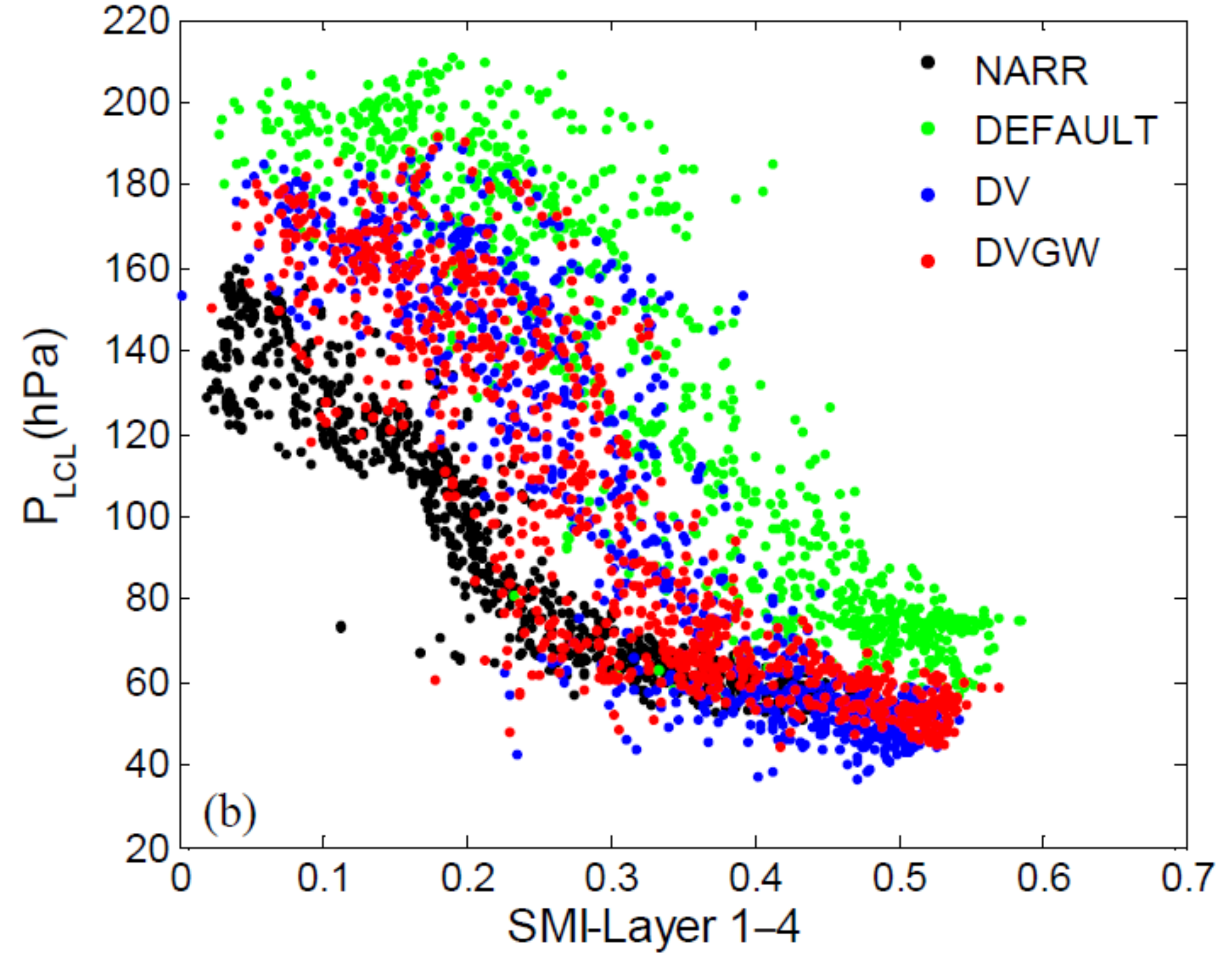
WRF Simulated & Observed Monthly and Seasonal Mean Precipitation in Central Great Plains



Jiang et al. (2009)

Lifting condensation level (LCL) versus soil moisture index (SMI) for soil layers 1–4



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Jiang et al. (2009)

Continental Water Dynamics and Petascale Computing

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

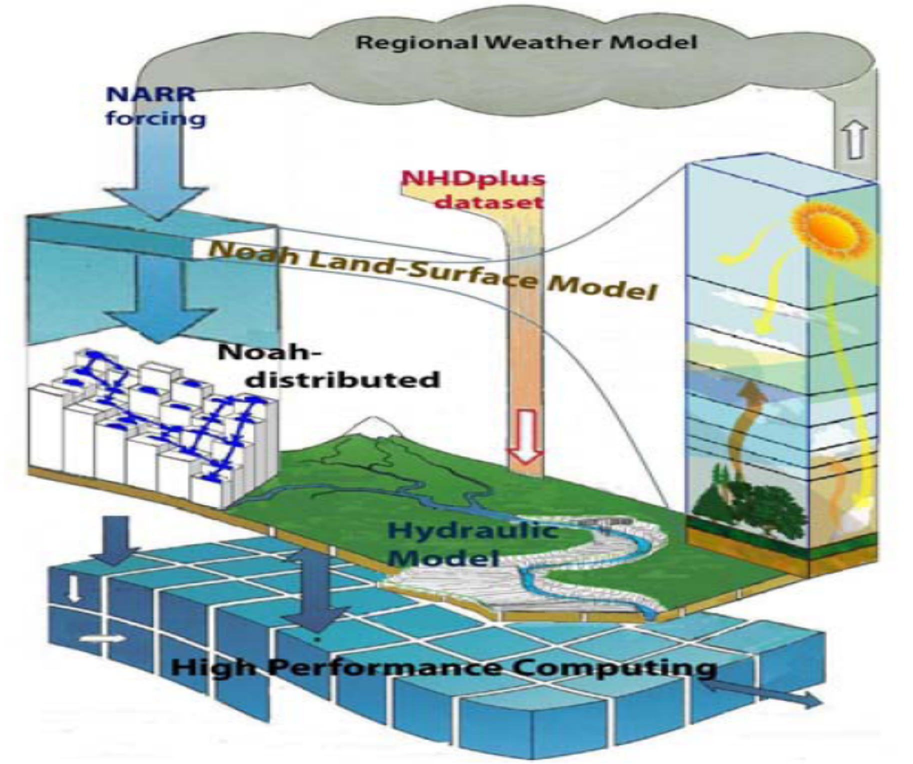

Figure 1: Schematic diagram of components in continental water dynamics

- 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.

Animation: flow map for April 2004

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Thank you to: Cedric David and Ahmad Tavakoly, University of Texas at Austin

Summary

1. We, working closely between UT, NCAR and NCEP investigators and scientists, have significantly restructured the Unified Noah LSM by including the latest developments in groundwater, dynamics vegetation, snow, and frozen soil.

2. One important feature is multi-physics options, a new framework conducive for ensemble weather and climate predictions.

3. Regional and global offline tests show promising results.

4. Coupled WRF/Noah simulations show groundwater dynamics and vegetation growth improve intra-seasonal to seasonal precipitation predictions, especially in transitional regions (i.e. the central U.S.). More tests using the Noah-MP are ongoing.

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