A Framework for Multi-Physics Representation of the Coupled Land-Atmosphere System for Predicting Extreme Weather Events

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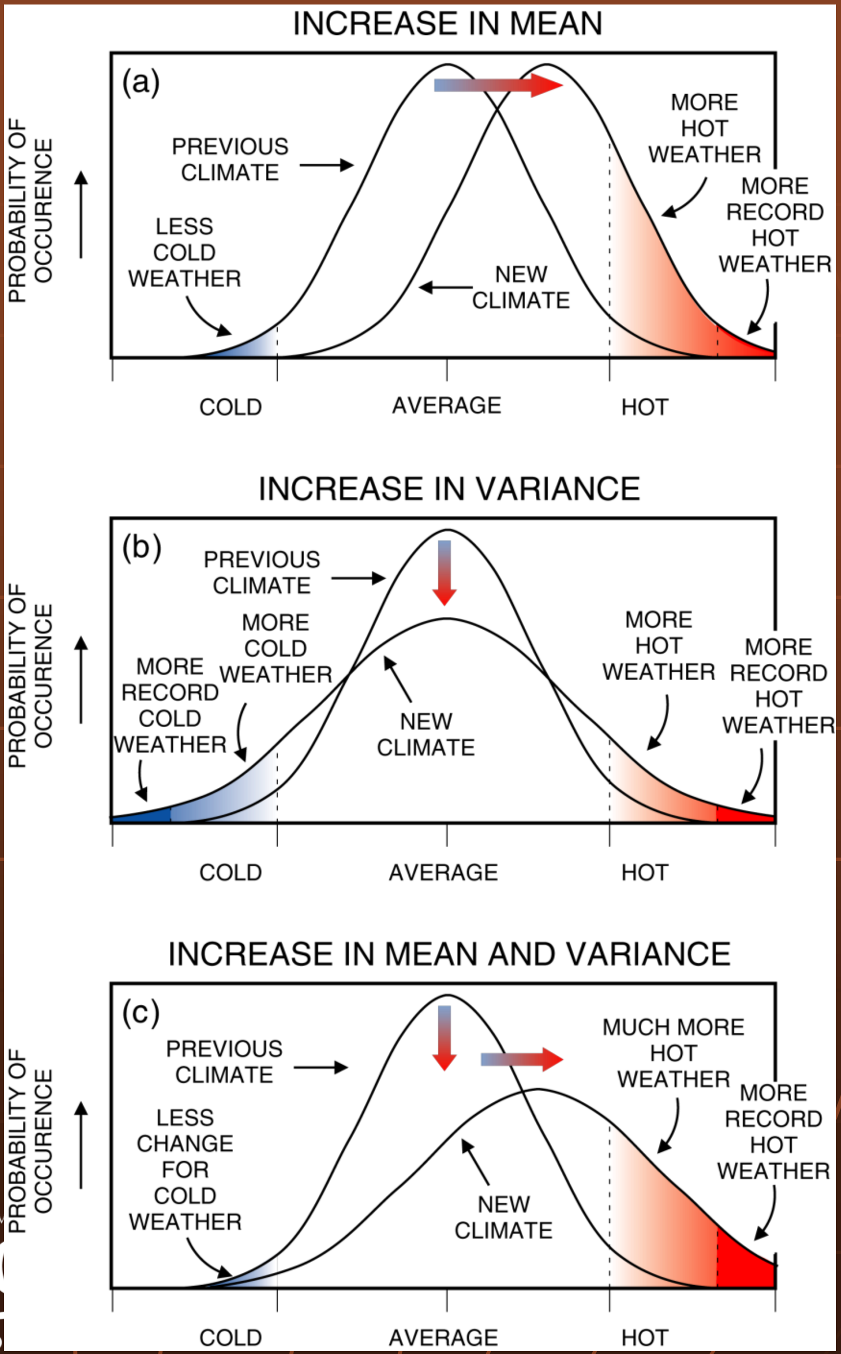
http://www.geo.utexas.edu/climate

Climate change and its manifestation in terms of weather (climate extremes)

Global warming increases the frequency and intensity of extreme weather events

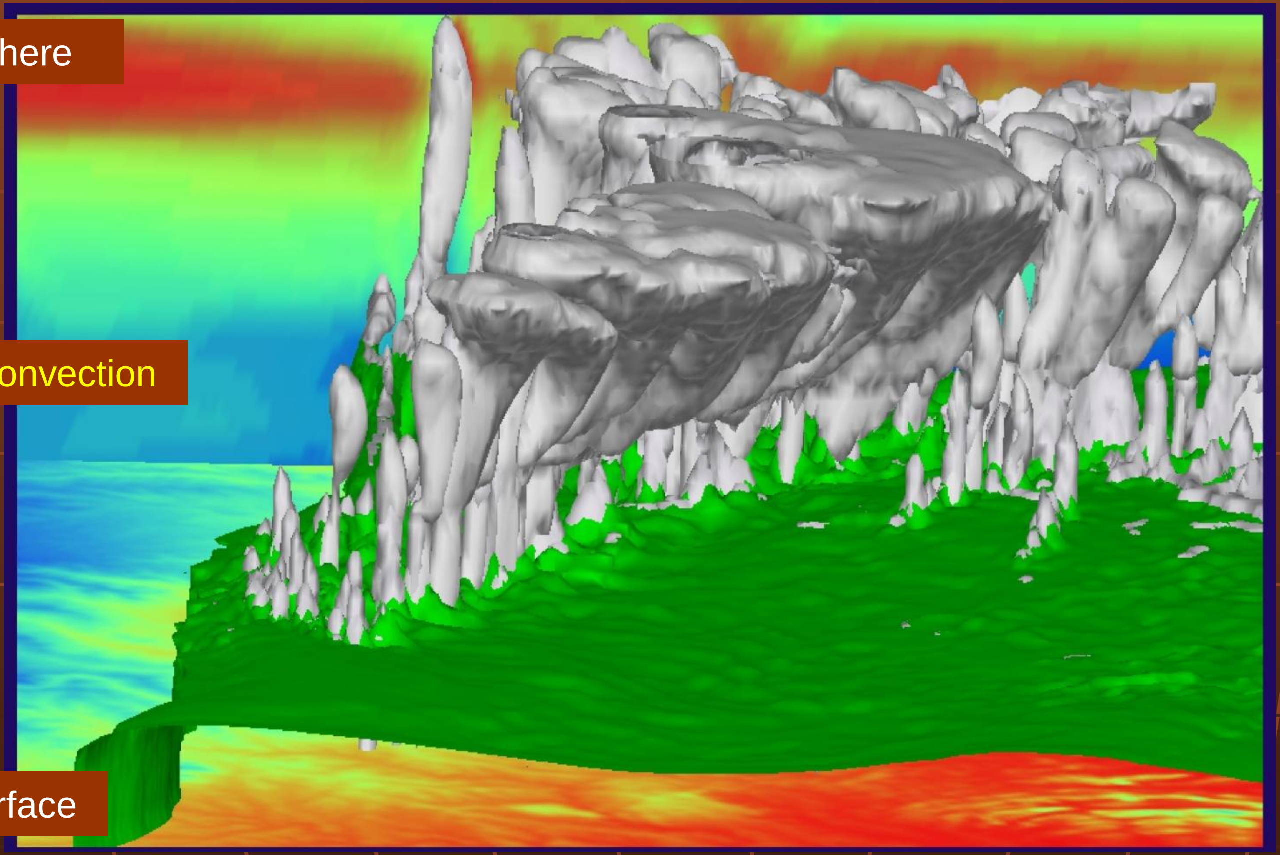


How is the land surface and the atmosphere coupled?

Atmosphere

Moist Convection

Land Surface



Probabilistic forecasts:

Initial condition ensemble

Multi-model ensemble

Parameter ensemble

One model but with multiple physics parameterizations! Both in the Atmosphere and at the Land Surface.

WRF: multi-physics options

1. Microphysics
2. Cumulus convection
3. Long- and shortwave radiation
4. Boundary layer turbulence
5. Subgrid-scale diffusion
6. Land surface parameterization
7. … …

Noah with multi-physics options

1. Leaf area index (prescribed; predicted) 2
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3. Soil moisture stress factor for transp. (Noah; BATS; CLM) 3
4. Canopy stomatal resistance (Jarvis; Ball-Berry) 2
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   - Modified two-stream: Gap = F (3D structure; solar zenith angle; ...) ≤ 1-GVF
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10. Runoff and groundwater: 4
    - TOPMODEL with groundwater
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    - BATS surface runoff and free drainage

2x2x3x2x2x2x2x3x2x4 = 4584 combinations

We also remove known weaknesses in the default Noah LSM:

1. Failure to differentiate vegetation canopy temperature and ground temperature.

2. Free drainage at the bottom of the soil column.

3. Neglect of the effects of zero-displacement height (d_0) on CH → a smaller CH over forest regions.

4. Lumped snow and soil in computing the surface energy balance.

5. Too impervious frozen soil → too strong runoff peaks in cold regions.

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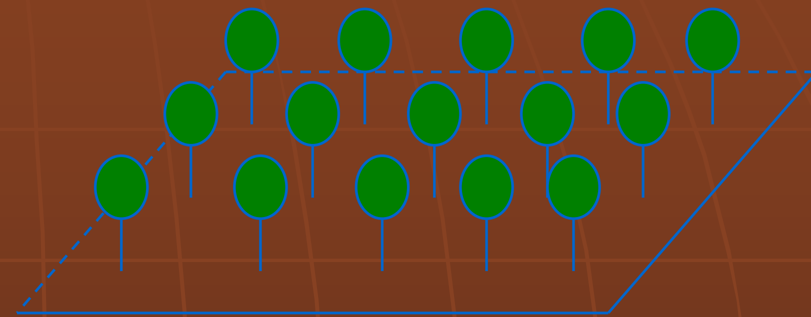
Semi-tile method:

Radiation: Modified two-stream

(Yang and Friedl, 2001; Niu and Yang, 2004)

1. Evenly-distributed crowns
2. Between- and within-canopy gaps
3. Outputs: α, Sa_g, Sa_v, PAR_{shd}, PAR_{sun}



Turbulent transfer: "Tile" scheme

Two separated tiles: vegetation and bare

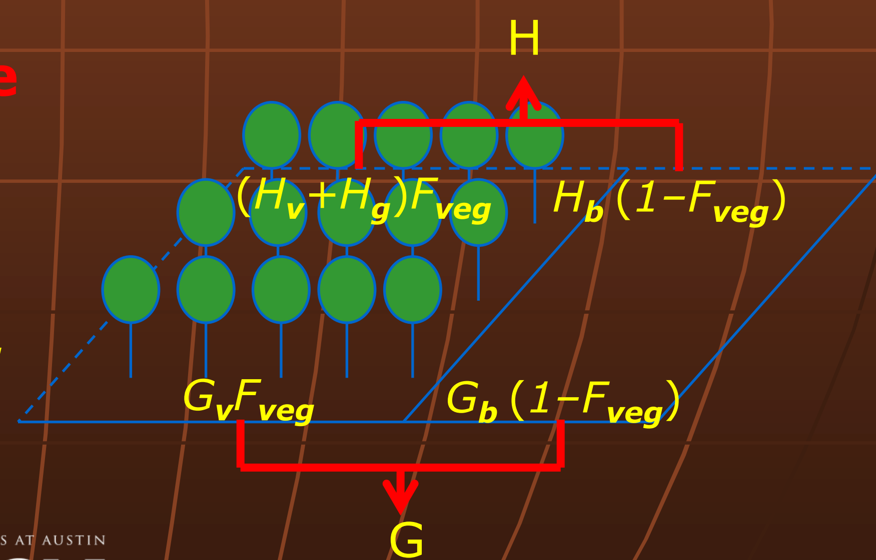
Vegetation tile:

Canopy: $Sa_v - F_{veg}(La_v+H_v+LE_v) = 0.$

Ground: $F_{veg}\, Sa_g - F_{veg}(La_g+H_g+LE_g+G_v) = 0.$

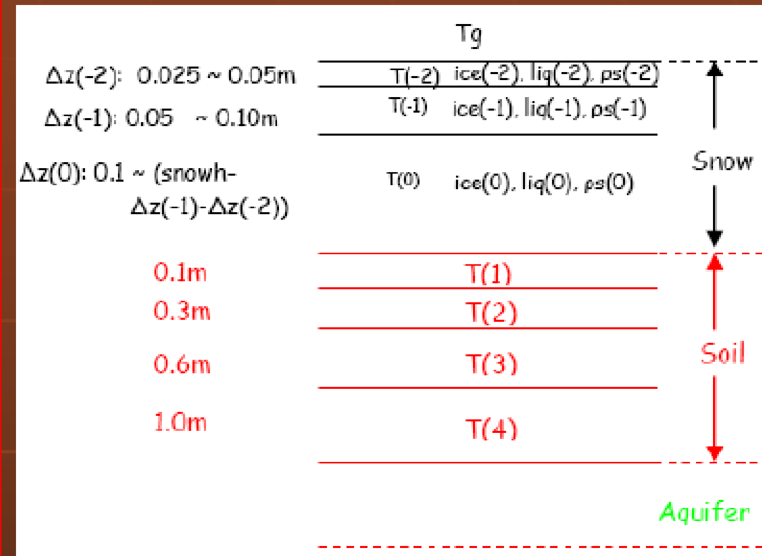
Bare-ground tile:

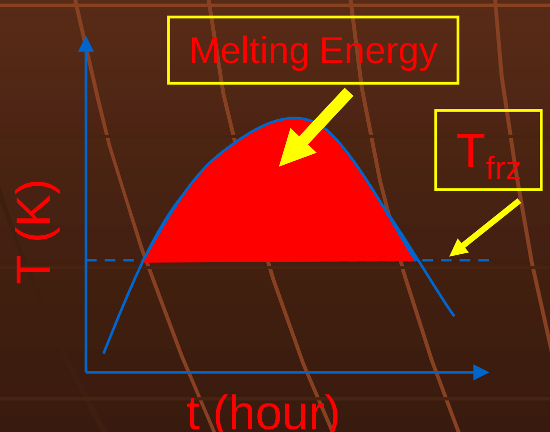
$(1-F_{veg})Sa_g - (1-F_{veg})(La_b+H_b+LE_b+G_b) = 0.$

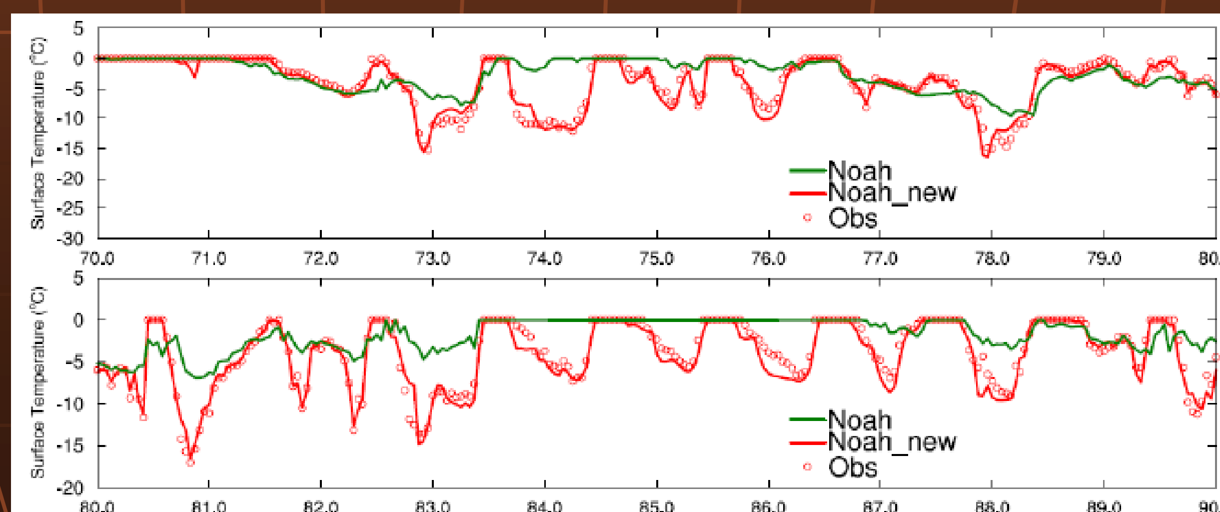


Snow submodel:

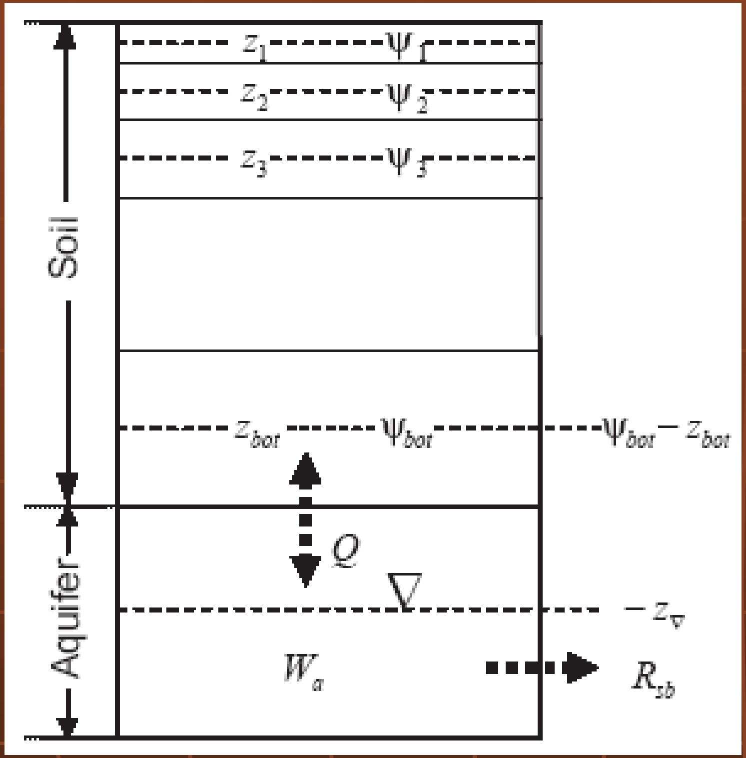
1. The 3-L snow model has 4 major prognostic variables: layer depth (or density), temperature, ice content, and liquid water content for each layer.
2. The 3-L snow temperatures and the 4-L soil temperatures are solved through one tri-diagonal matrix.
3. The skin temperature, Tg, is solved through iterative energy balance method.
4. Freezing/melting energy is assessed as the energy deficit or excess needed to change snow temperature to melting/freezing point (Yang and Niu, 2003):
   $H_{fm}(i) = C(i) * dz(i) * (T(i) - T_{frz}) / dt$;   i-th layer
5. 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)







Groundwater model:



Water storage:

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

$$z_\nabla = W_a / S_y$$

Recharge Rate:

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

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

Problems when applied to CLM: too wet soil due to

- Too small recharge rate from soil to aquifer (too small K_a);
- Too strong upward flow (too large soil suction, ψ_{bot});
- Too small groundwater discharge inducing overflow of groundwater to soil

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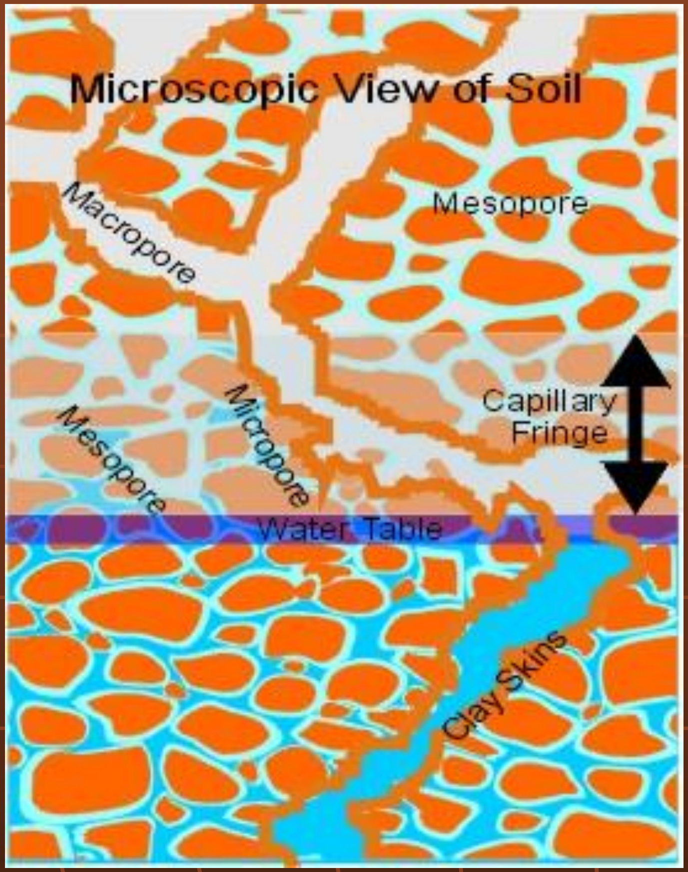
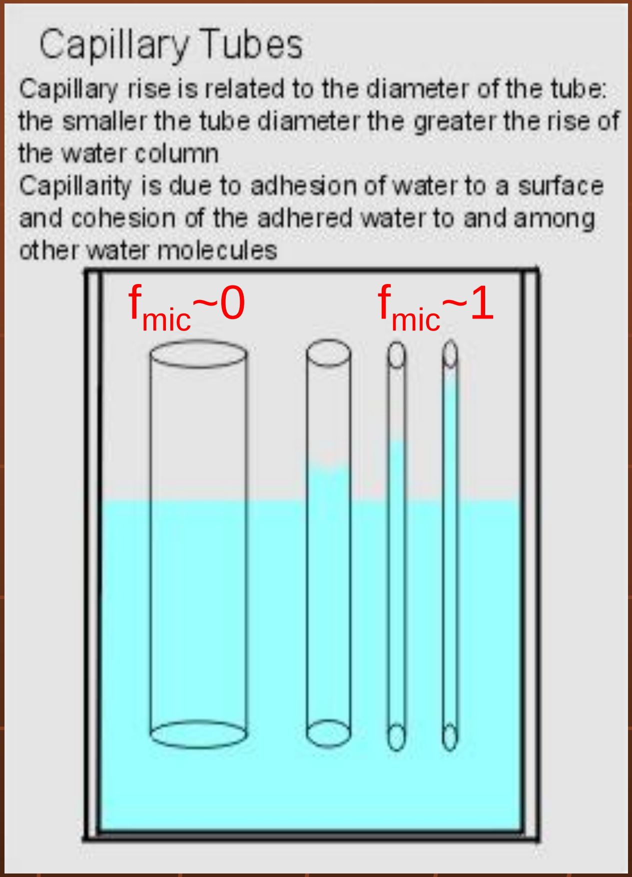
Niu et al. (2007)

Capillary Fringe and Soil Pore-Size Distribution

See http://www.earthdrx.org/poresizegwflow.html





Macropore effects:

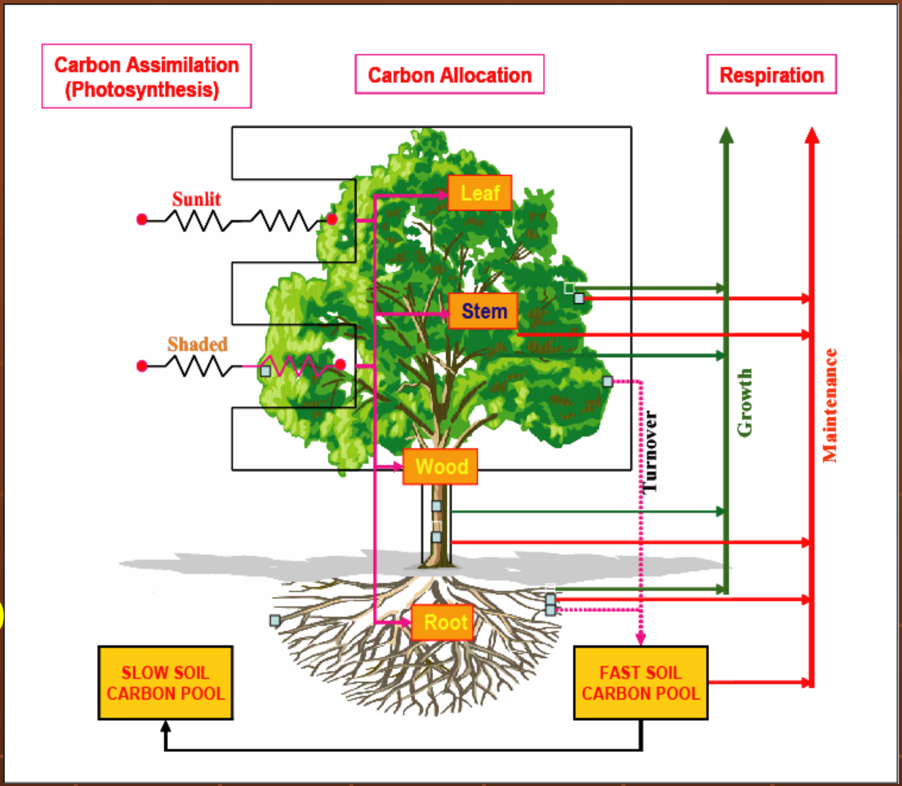
1. Larger recharge rate (through macropores)

2. Smaller upward flow (through micropores)

A Dynamic Leaf Model (Dickinson et al., 1998)

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).

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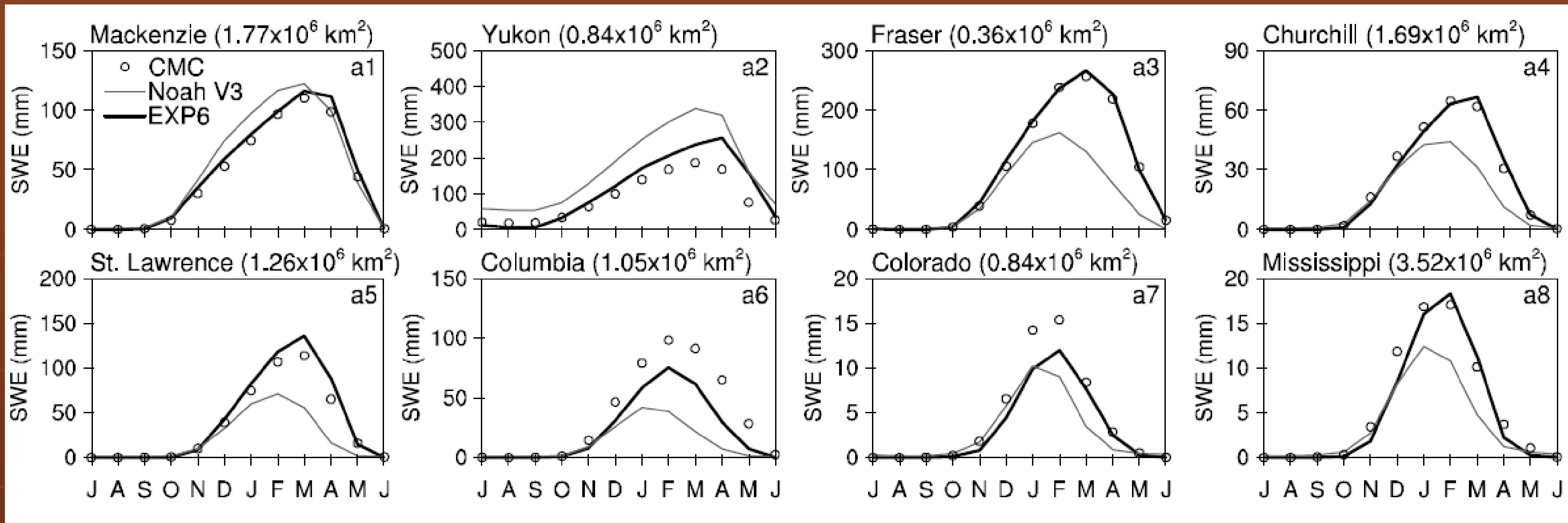
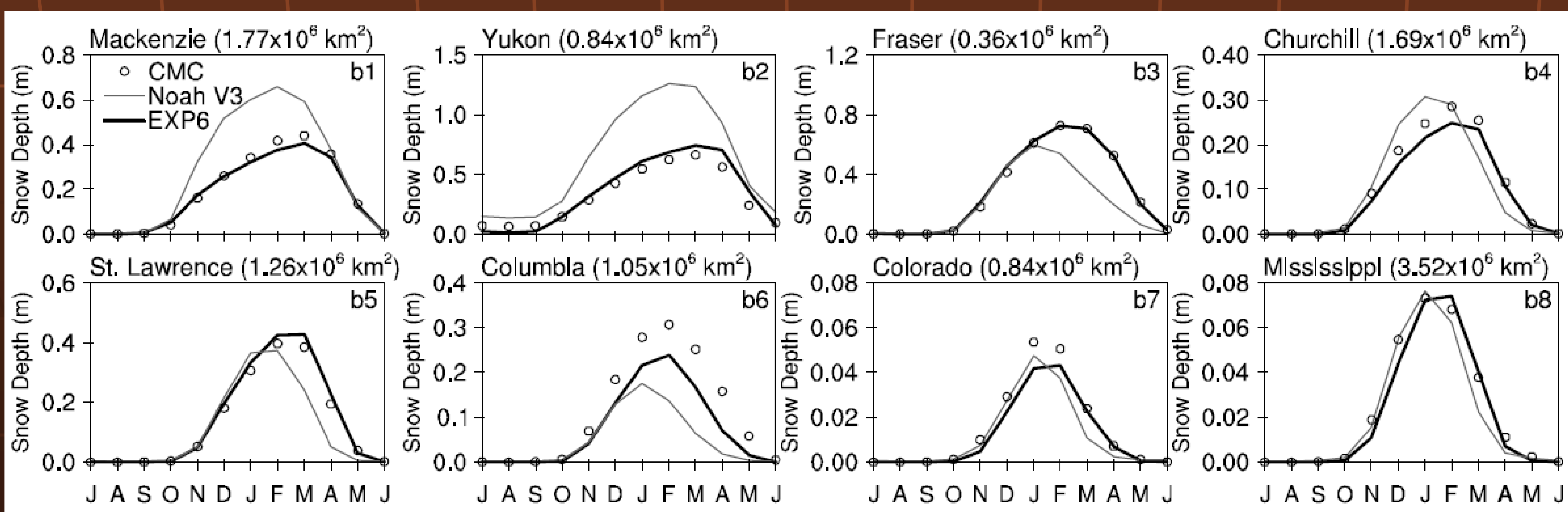
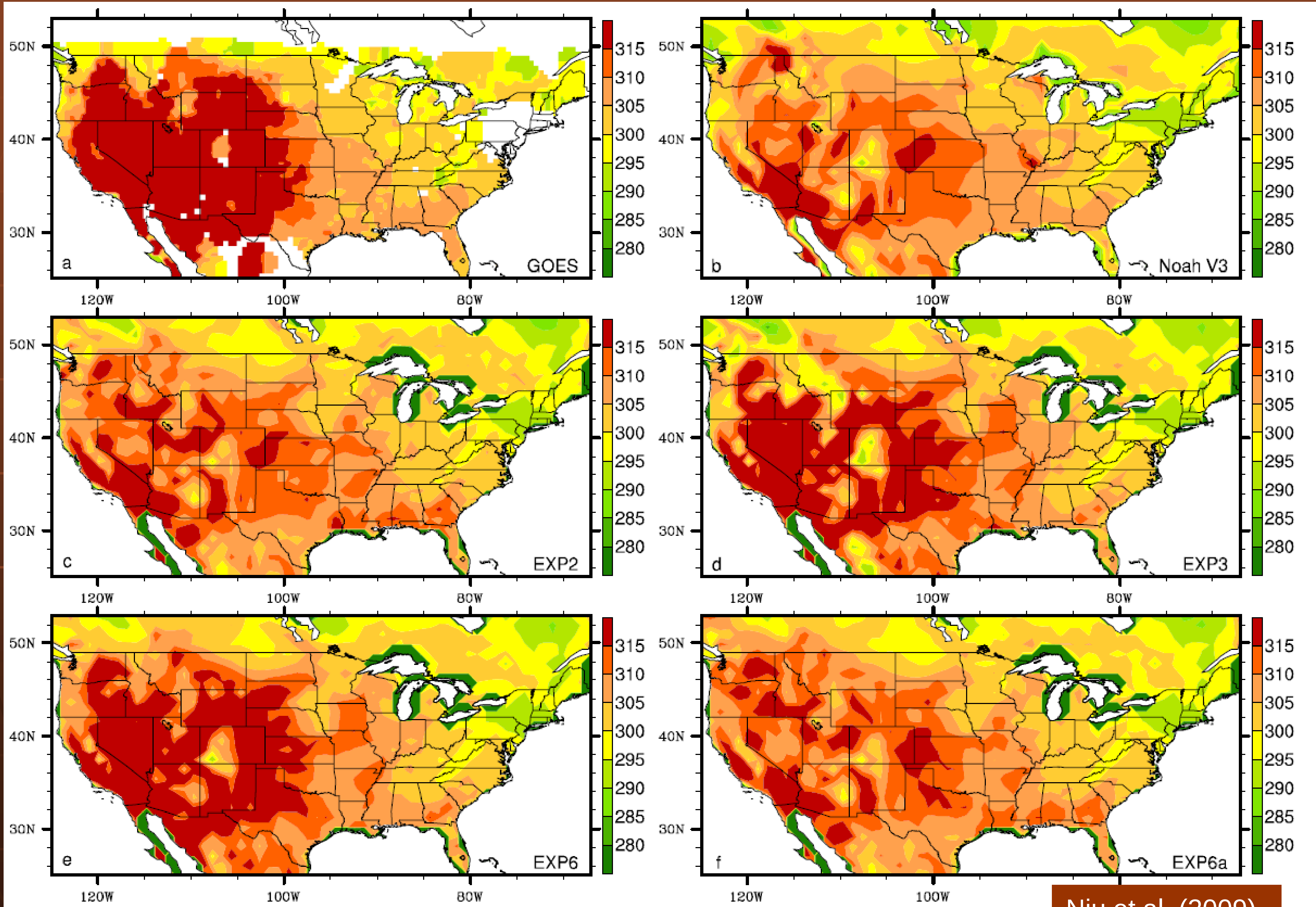
Snow Water Equivalent (in mm)



Snow Depth (in m)

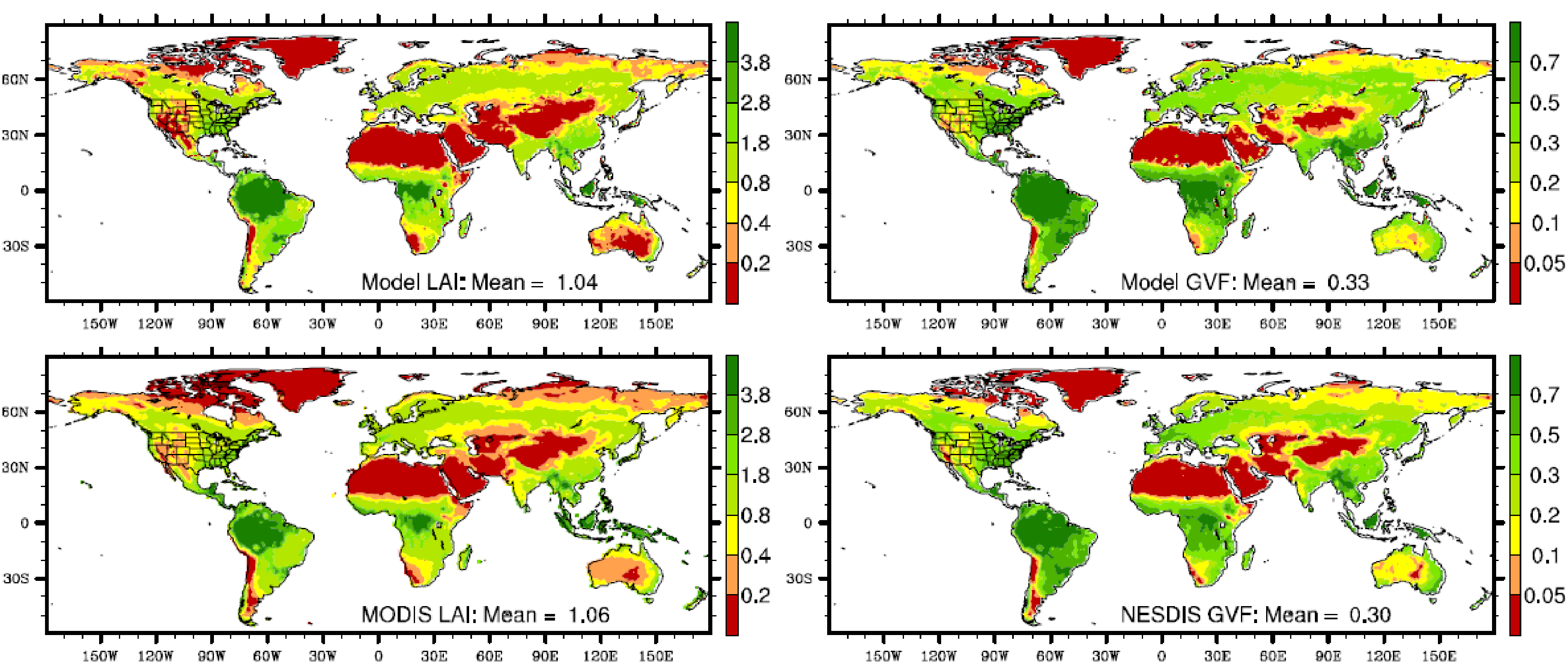


Modeled Tskin *(July 12th, 21:00 UTC, 2004)*



Niu et al. (2009)

Modeled Leaf Area Index (LAI) and Green Vegetation Fraction (GVF)



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Niu et al. (2009)

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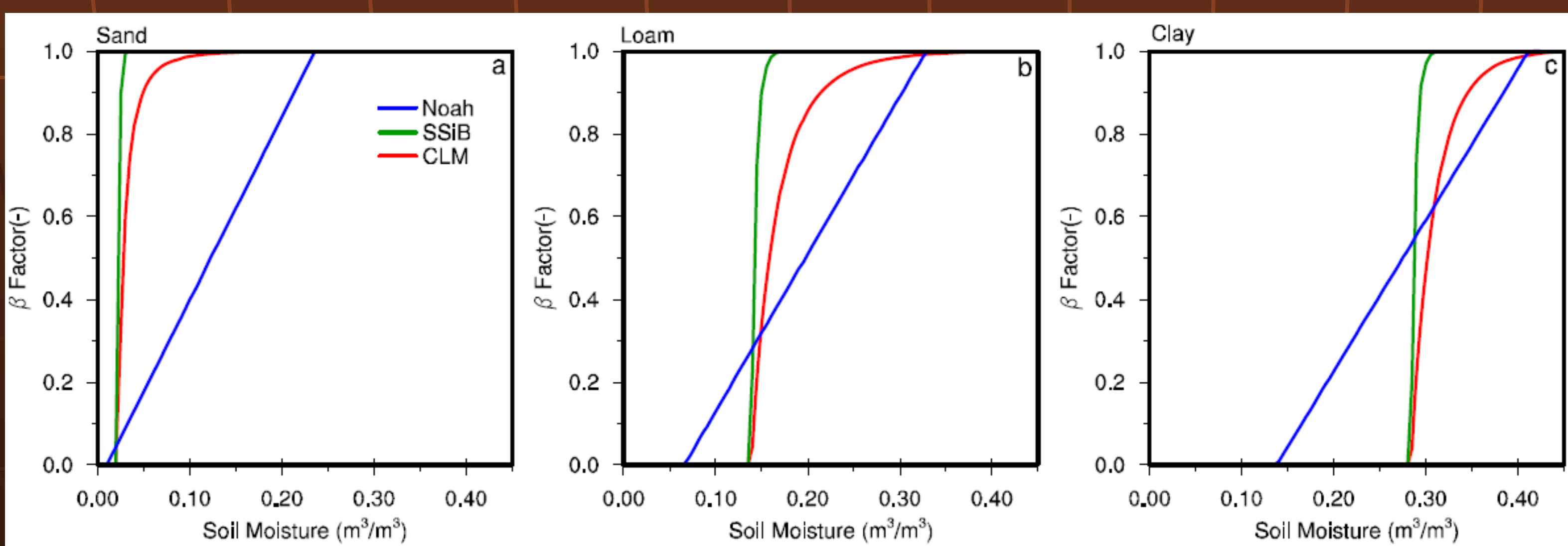
36 Offline Ensemble Experiments:

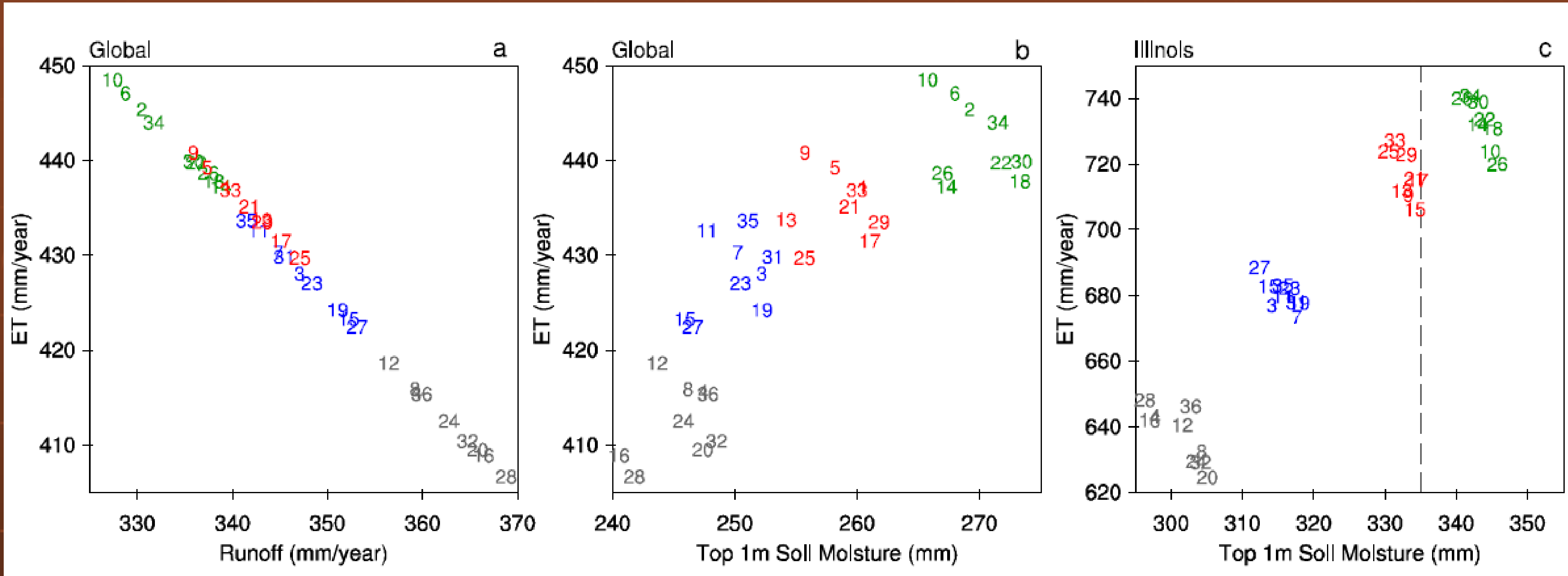
Table 3. The first group of 12 experiments and their corresponding options of schemes.

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

Huge uncertainty to represent processes



Results from 36 Offline Runs



Study Case: An Extreme Precipitation Event in Texas July 2002

- San Antonio River Basin, Central Texas
- June 30 – July 10
- Stationary upper-level trough and strong **southeasterly surface winds** cause continuous low-level **moisture flow** across the Gulf of Mexico into Central Texas
- Heavy rainfall (>100mm/day) persists over the San Antonio area for 6 days

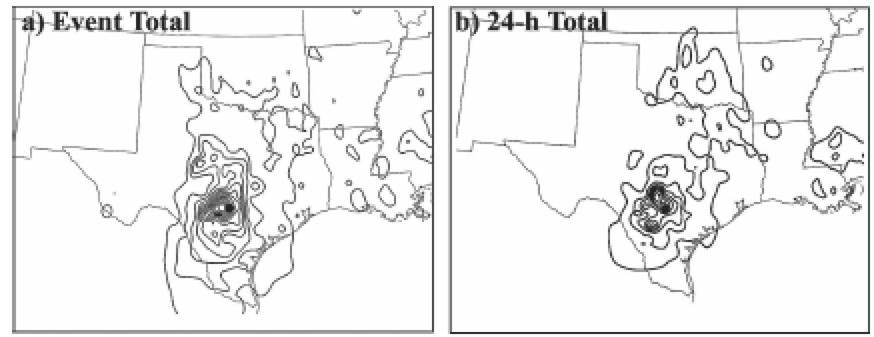
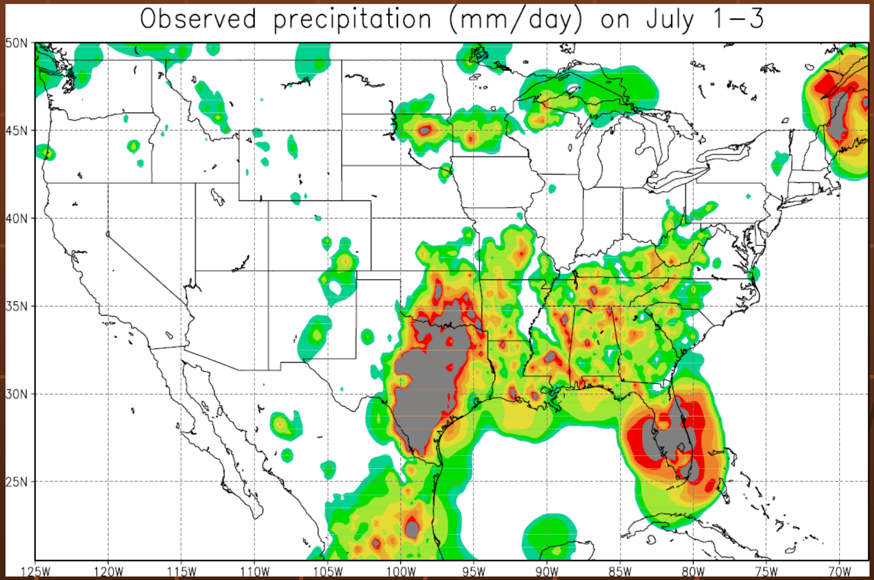


FIG. 1. The observational analysis of accumulated precipitation from gridded data acquired through NCDC. (a) The 8-day event total precipitation (every 50 mm) from 1200 UTC 28 Jun 2002 to 1200 UTC 7 Jul 2002. (b) The 24-h accumulated precipitation (every 20 mm) valid at 1200 UTC 2 Jul 2002. The location of SAT is marked with dots.

Zhang et al. (2006)

Model and Experiments

- WRF 3.0.1
- Initial/Boundary Conditions: NARR Reanalysis
- 30-km grid spacing
- July 1-3, 2002
- Experiments
  - WRF/Noah with three convection schemes (KF, BMJ, Grell)
  - WRF/Noah-MP (three runoff schemes: SIMGM, SIMTOP, Noah) and three convection schemes (KF, BMJ, Grell)



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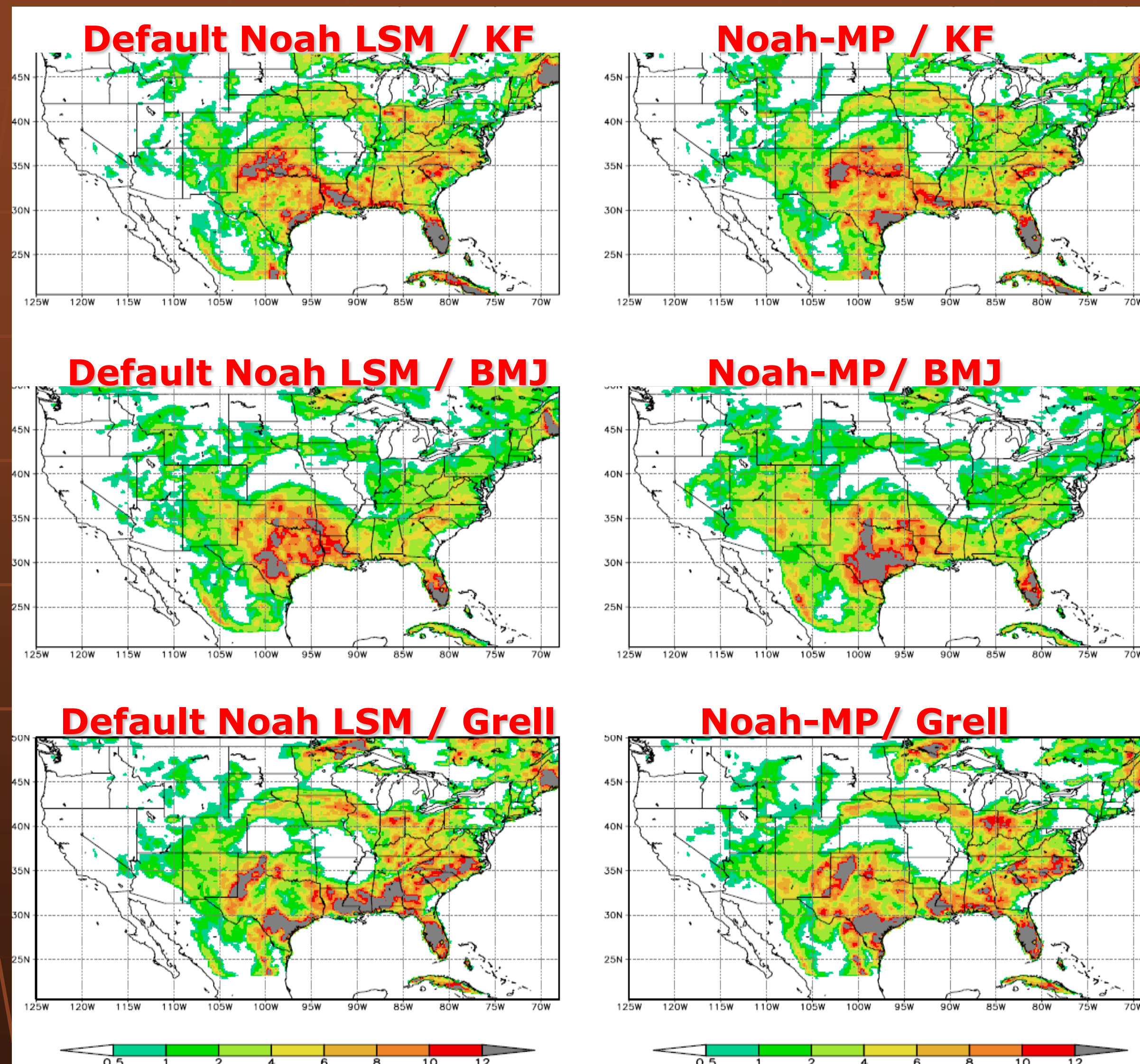
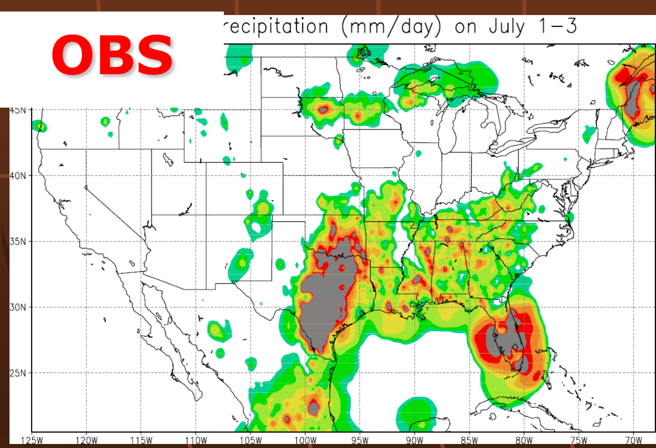
Comparison of July 1-3 Precipitation from observations and various runs





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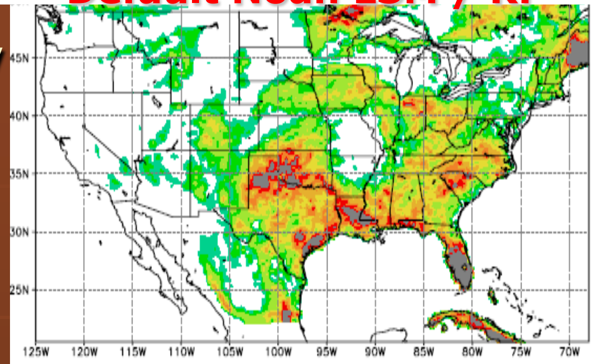
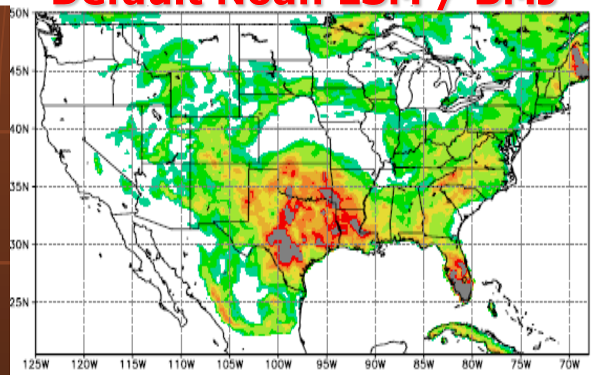
Comparison of July 1-3 Precipitation from observations and various runs

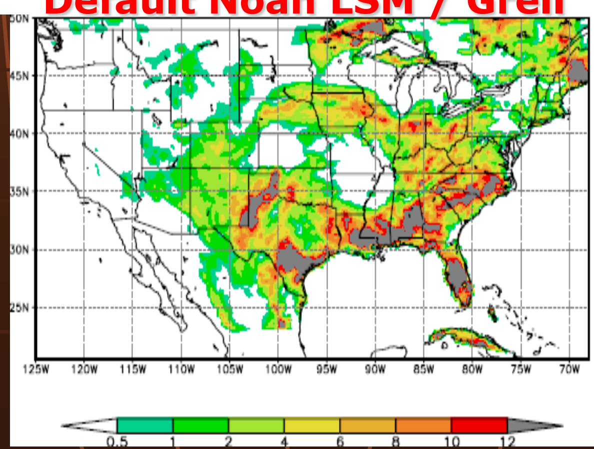
Default Noah LSM / KF



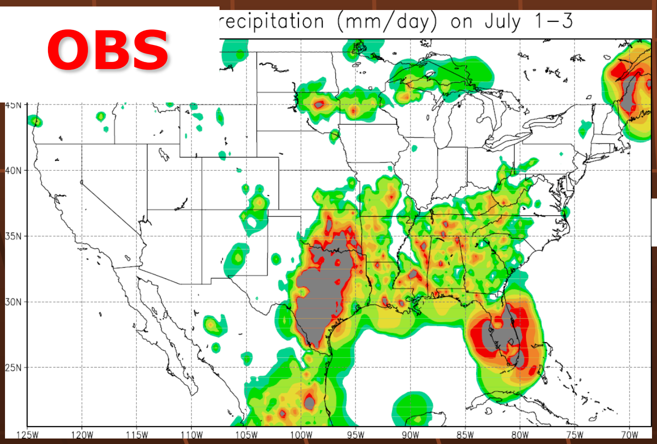
Default Noah LSM / BMJ

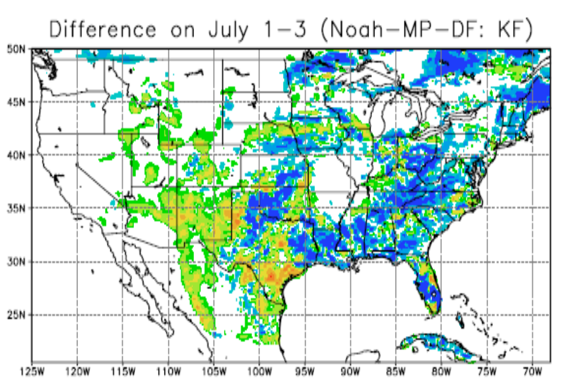


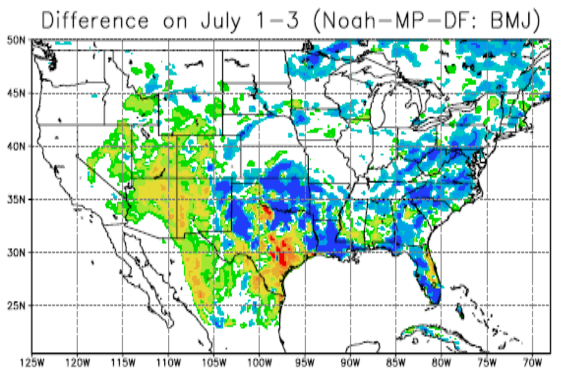
Default Noah LSM / Grell

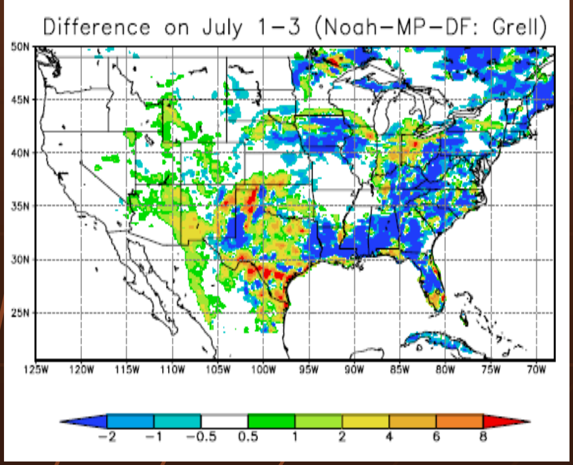


OBS

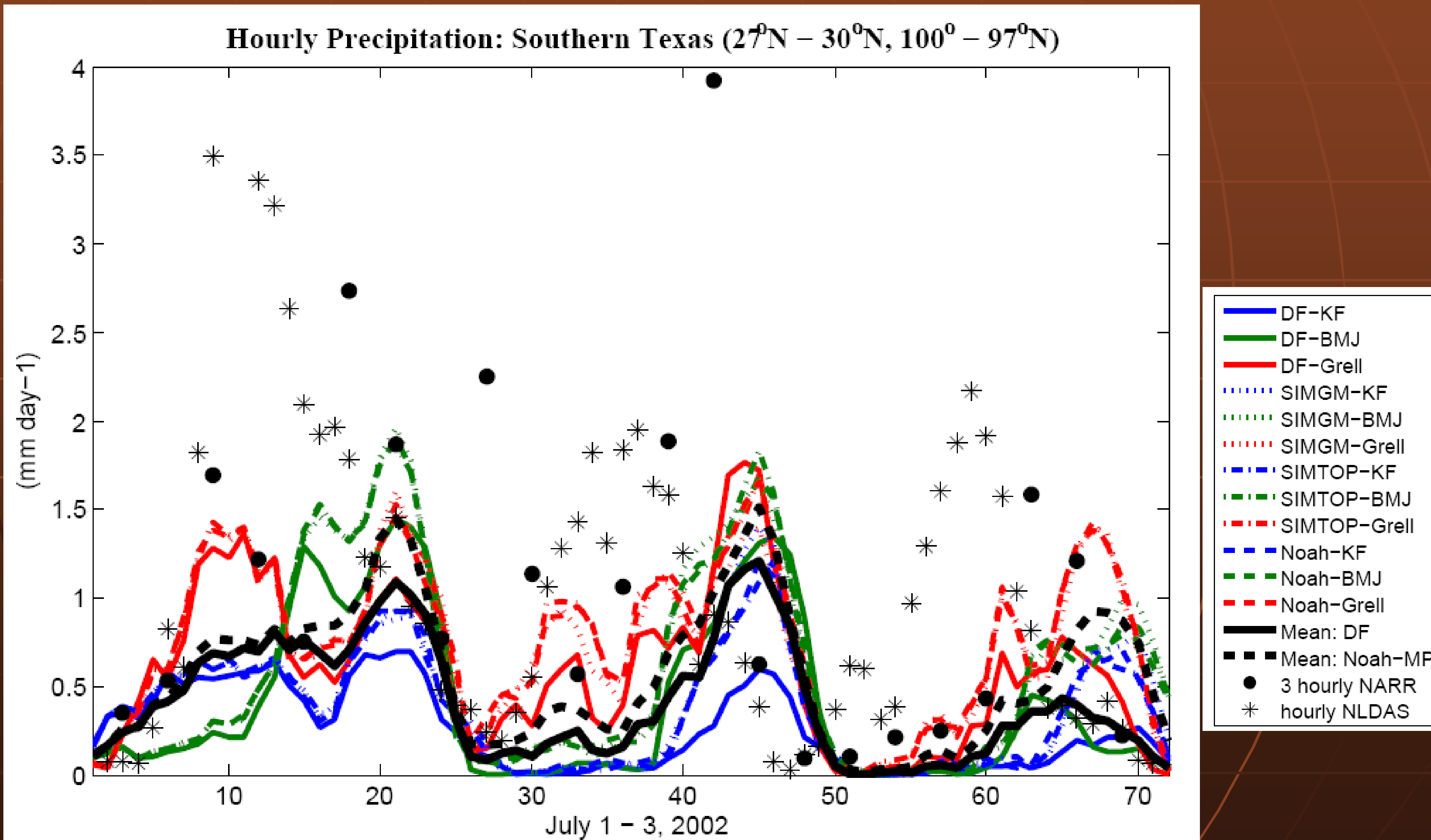








Hourly Precipitation (mm/hour) from July 1 to 3, 2002 for Various Convection & Runoff Runs



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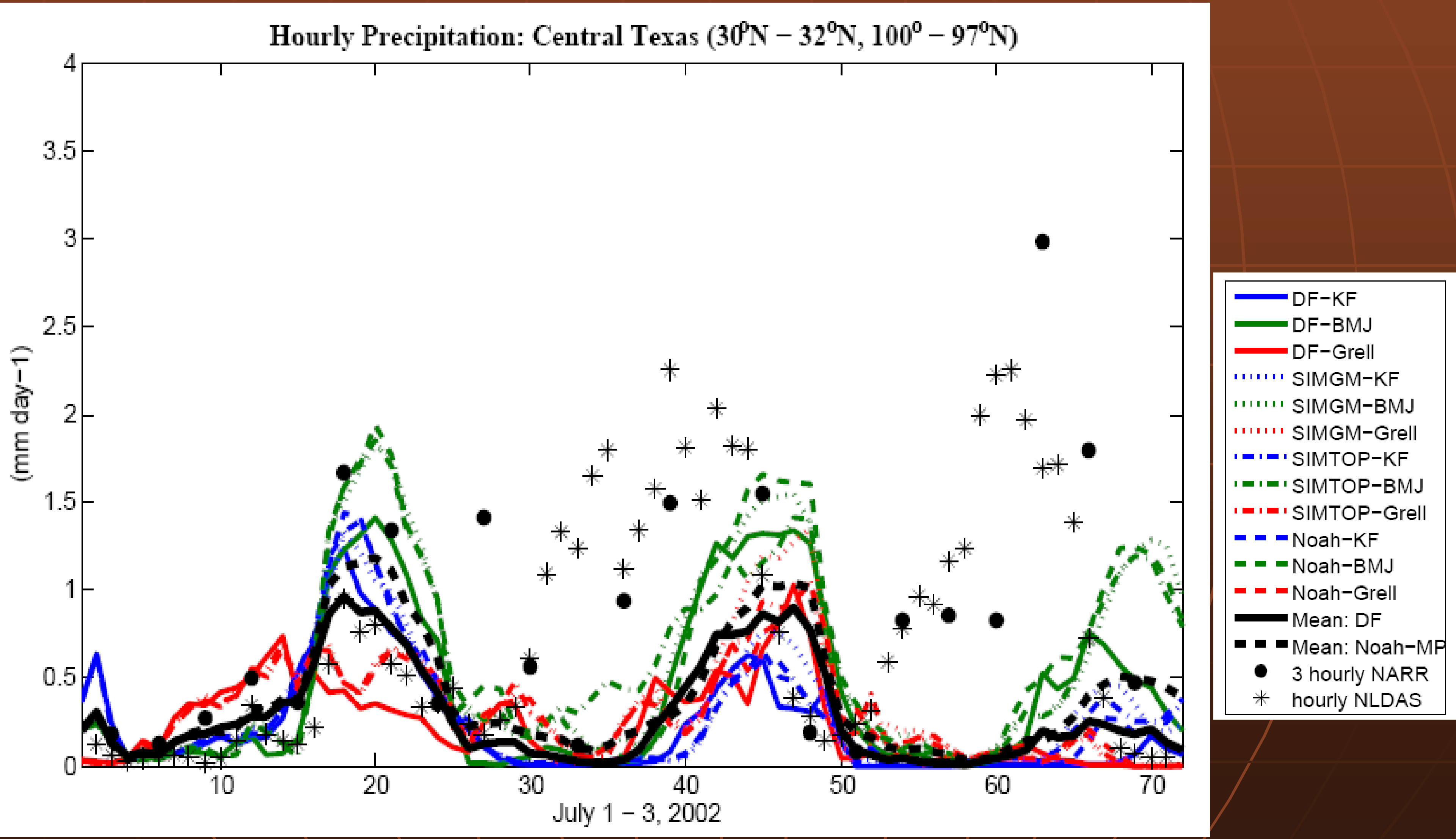

Summary

- We have developed a 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.
- Noah-MP improves over the default Noah LSM, both in offline and coupled simulations. In the coupled runs, runoff schemes have considerable effects on rainfall after day 1.
- Convection schemes dominate the simulations of extreme rainfall in the warm season!
- Special attention is required in initializing soil moisture and leaf biomass. A high-resolution land data assimilation system needs to be configured to provide required land data for initialization.

Thank you!

- Questions?

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