Exploring the role soil moisture feedbacks in the North American Monsoon region

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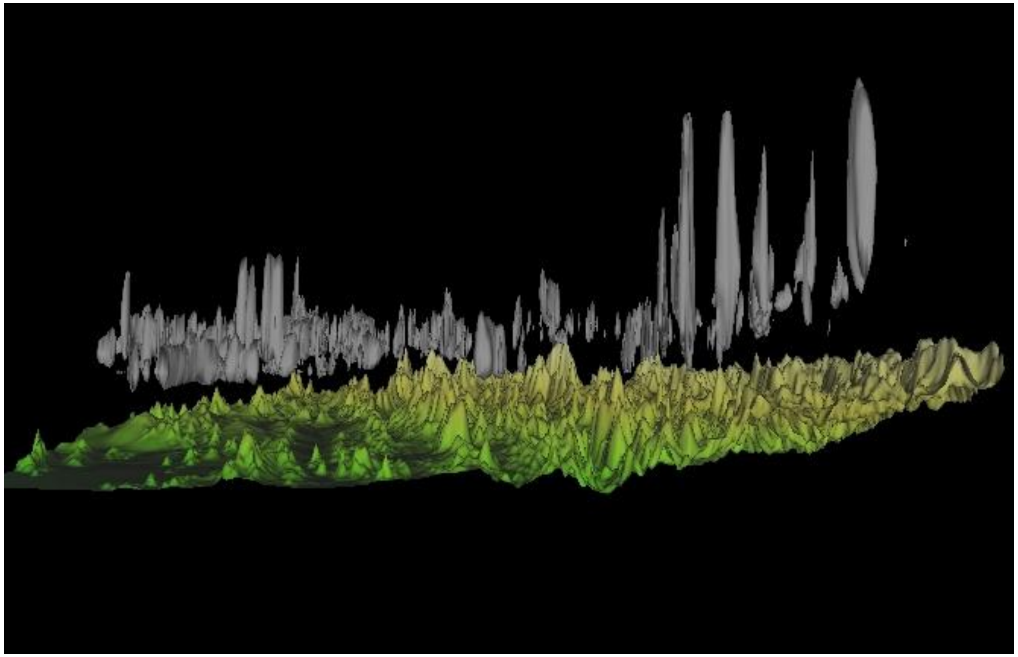

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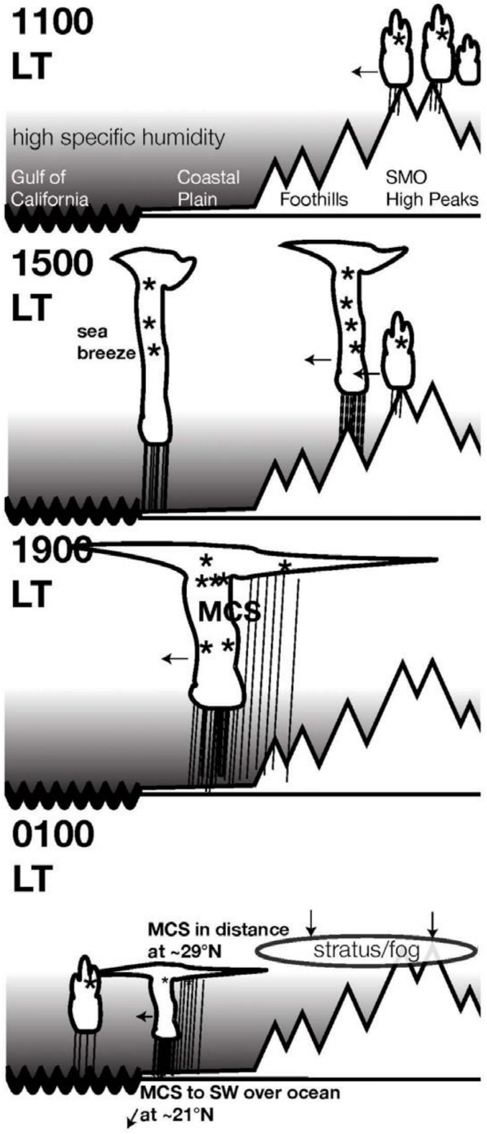
Land-Atmosphere Coupling Investigations

Monsoon
Daily Rainfall Patterns:

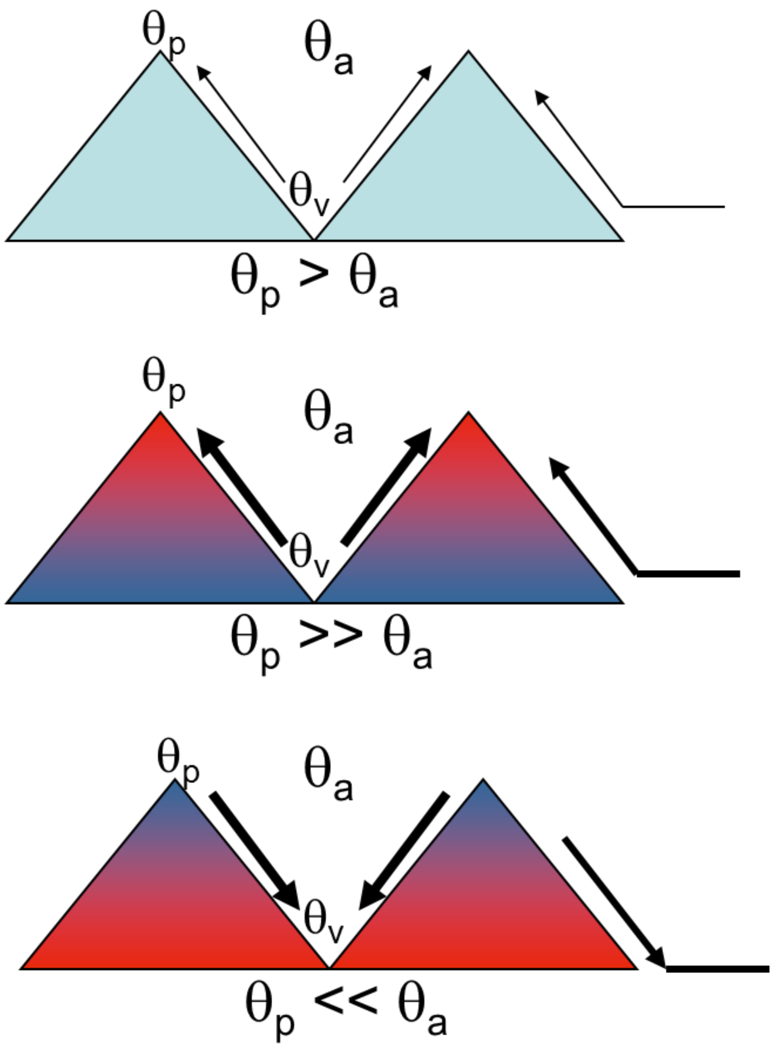
- Clouds and rainfall form earliest over high topography, rainfall is light
- Storms grow and organize later in the afternoon, growing taller and with heavier rainfall
- Large, organized thunderstorms exist in the evenings over low elevation areas
- Light, shallow rainfall occurs at night
- Growth of storms appears to be linked to moisture availability, and other dynamics



Basic Principles on Coupled Hydrometeorological Processes

<u>Foundational questions…</u>

- How do changes in soil moisture impact land-atmosphere exchange in the N. American Monsoon region?



For later…

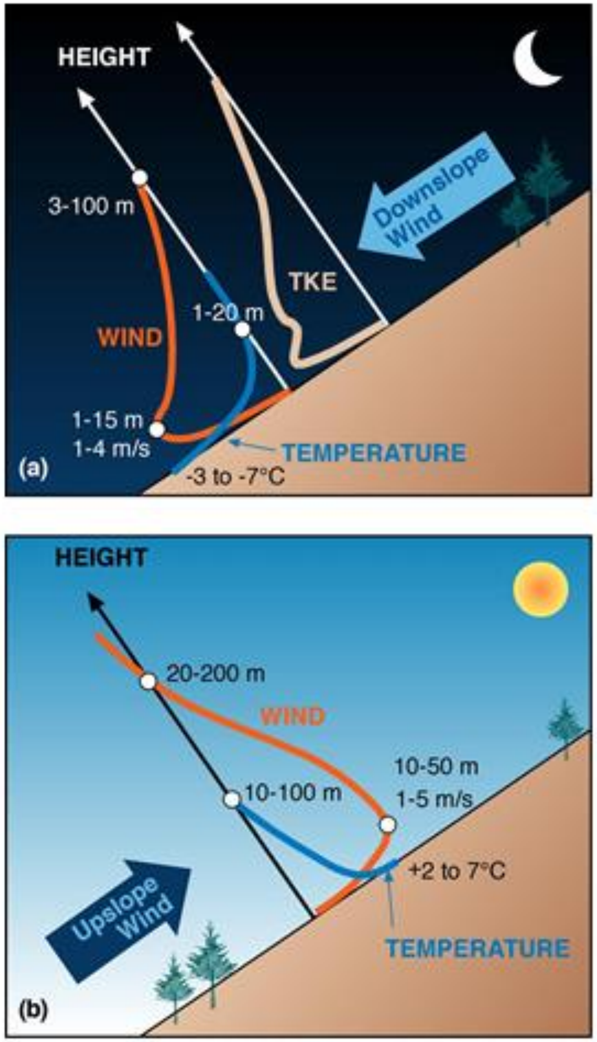
- How do routing processes in complex terrain influence these circulations?
  - Is there a detectable difference from an NWP/QPF perspective?

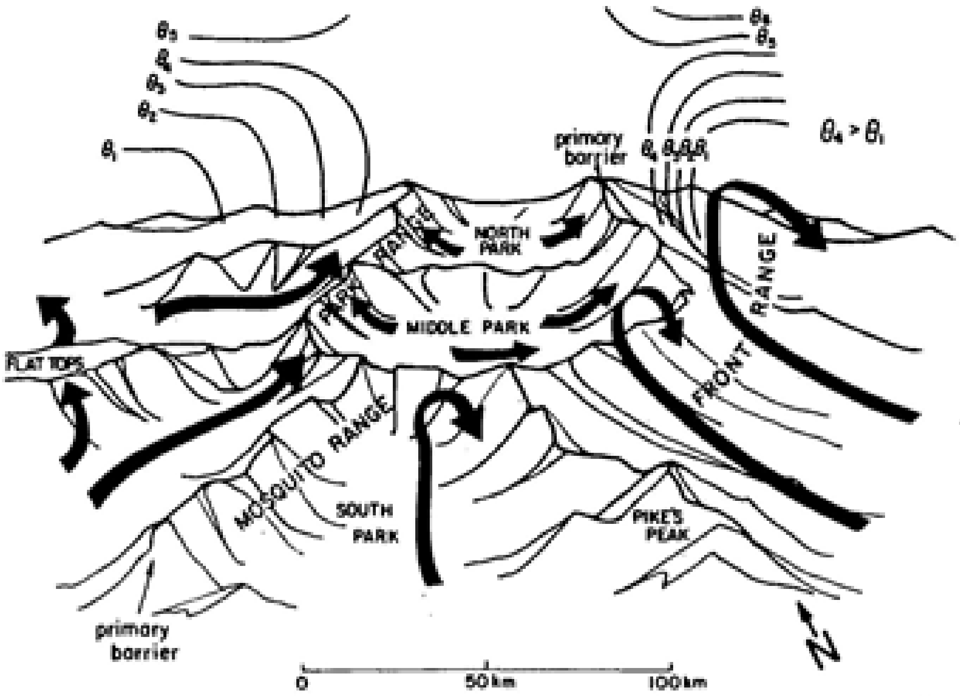
Outline

- Basic Principles on Coupled Hydrometeorological Processes and Research Question
- WRF-Hydro System Description
- Uncoupled model deployment and evaluation
- Fully-coupled land-atmosphere coupling investigations

Basic Principles on Coupled Hydrometeorological Processes

- Thermally-driven circulations….under 'light-wind' conditions…





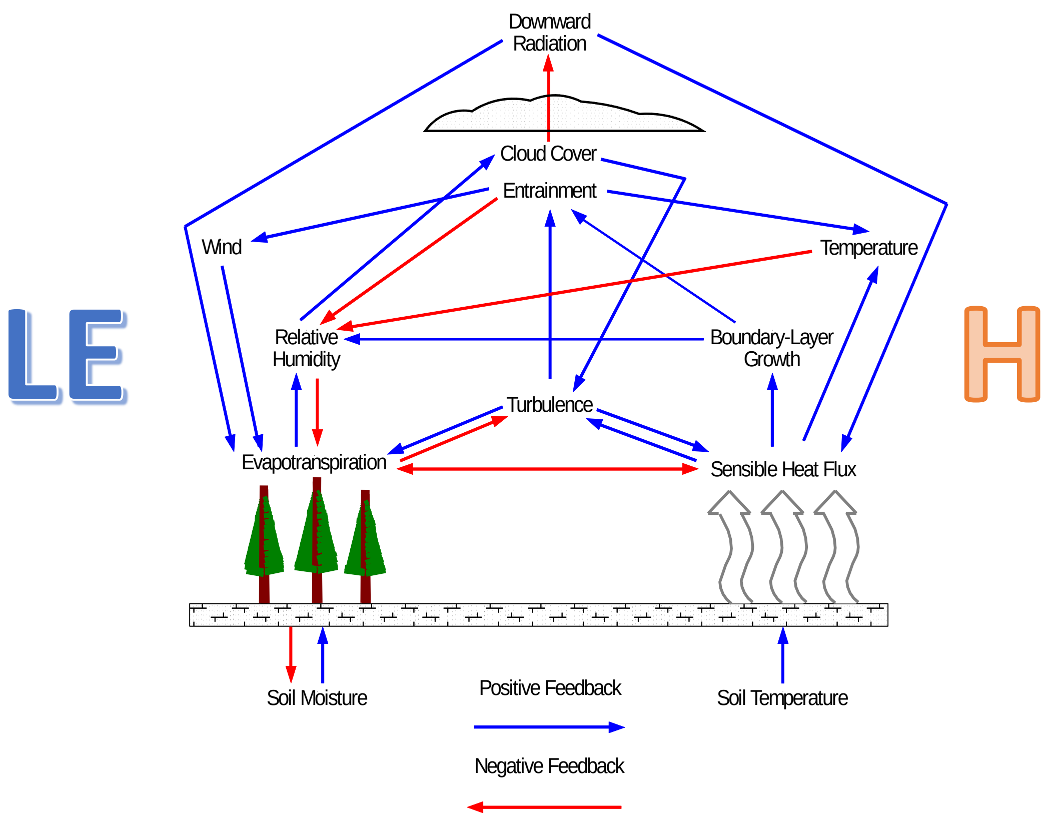
Images courtesy Zardi and Whiteman, 2012

Basic Principles on Coupled Hydrometeorological Processes

- Surface Energy Flux Partitioning…

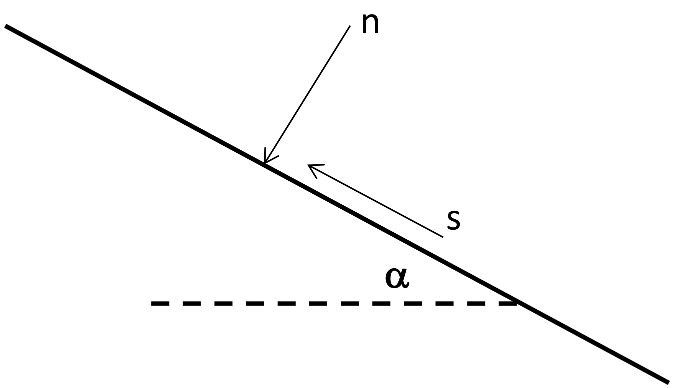
$$Rn - G - S + A = H + LE$$ (units: Watts / m^2)

Rn – Net radiation: $R_{net} = S(1-\alpha) + L_{Down} - L_{Up}$



Basic Principles on Coupled Hydrometeorological Processes

- Thermally-driven circulations….formalization



Local Press. Perturbation

Buoyancy-reduced Gravity

$$\frac{\partial u}{\partial t} + u\frac{\partial u}{\partial s} + w\frac{\partial u}{\partial n} = -\frac{1}{\rho_0}\frac{\partial (p - p_a)}{\partial s} - g\frac{d}{\theta_0}\sin\alpha - \frac{\partial \overline{u'w'}}{\partial n}$$

$$\frac{\partial w}{\partial t} + u\frac{\partial w}{\partial s} + w\frac{\partial w}{\partial n} = -\frac{1}{\rho_0}\frac{\partial (p - p_a)}{\partial n} + g\frac{d}{\theta_0}\cos\alpha$$

$$\frac{\partial \theta}{\partial t} + u\frac{\partial \theta}{\partial s} + w\frac{\partial \theta}{\partial n} = -\frac{1}{\rho_0 c_p}\frac{\partial R}{\partial n} - \boxed{\frac{\partial \overline{w'\theta'}}{\partial n}}$$

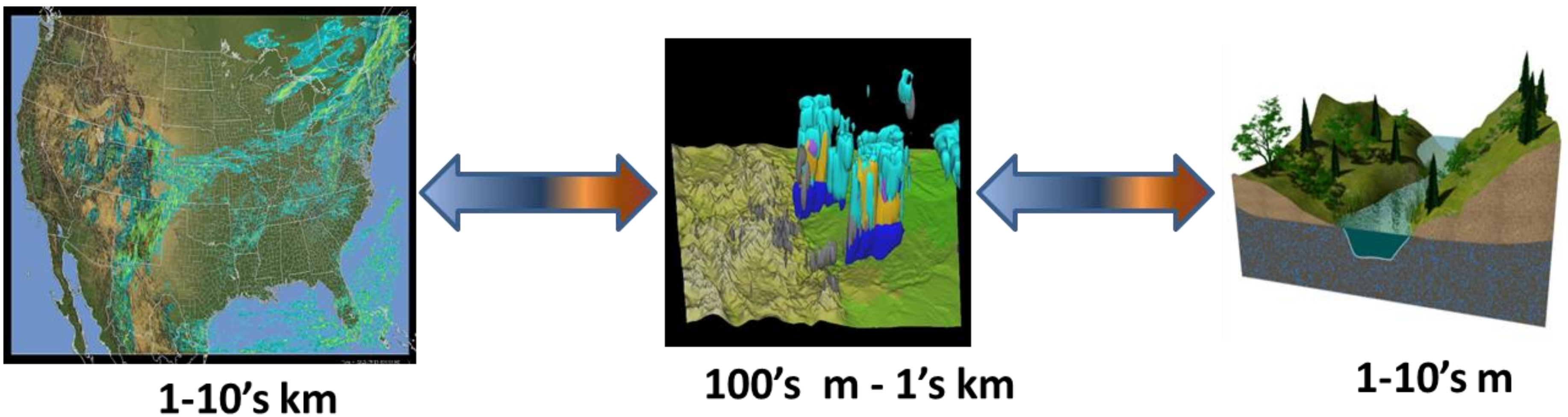
Sensible Heat Production

$$\frac{\partial u}{\partial s} + \frac{\partial w}{\partial n} = 0$$

WRF-Hydro Modeling System

A community-based, supported coupling architecture designed to provide:

1. An extensible *multi-scale & multi-physics* land-atmosphere modeling capability for conservative, coupled and uncoupled *assimilation & prediction* of major water cycle components such as precipitation, soil moisture, snowpack, groundwater, streamflow, inundation
2. ‘Accurate’ and ‘reliable’ streamflow prediction across scales (from 0-order headwater catchments to continental river basins & minutes to seasons)
3. Research modeling testbed for evaluating and improving physical process and coupling representations

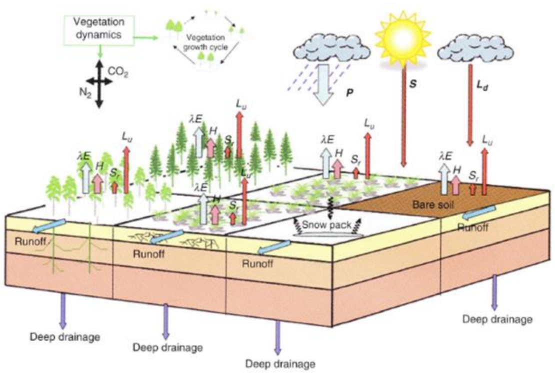


Can be run fully-coupled with WRF or in an offline mode, driven by prescribed meteorological data

[Website: https://www.ral.ucar.edu/projects/wrf_hydro](https://www.ral.ucar.edu/projects/wrf_hydro)

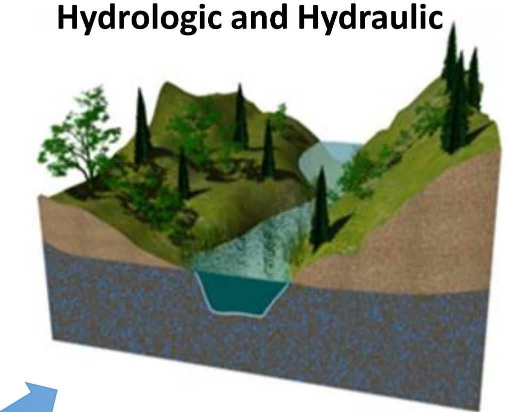
WRF-Hydro system description

Column Land Surface Models:
Noah/NoahMP/SAC-HTET*

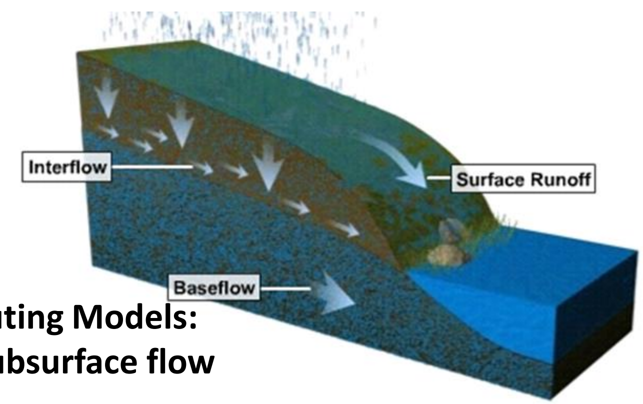


<u>Output Variables:</u>
Evapotranspiration
Soil moisture/Soil Ice
Snowpack/snowmelt
Runoff
Radiation Exchange
Energy Fluxes
Plant Water Stress

Channel & Reservoir
Routing Models:
Hydrologic and Hydraulic



2-way coupling



1-way coupling or
2-way coupling

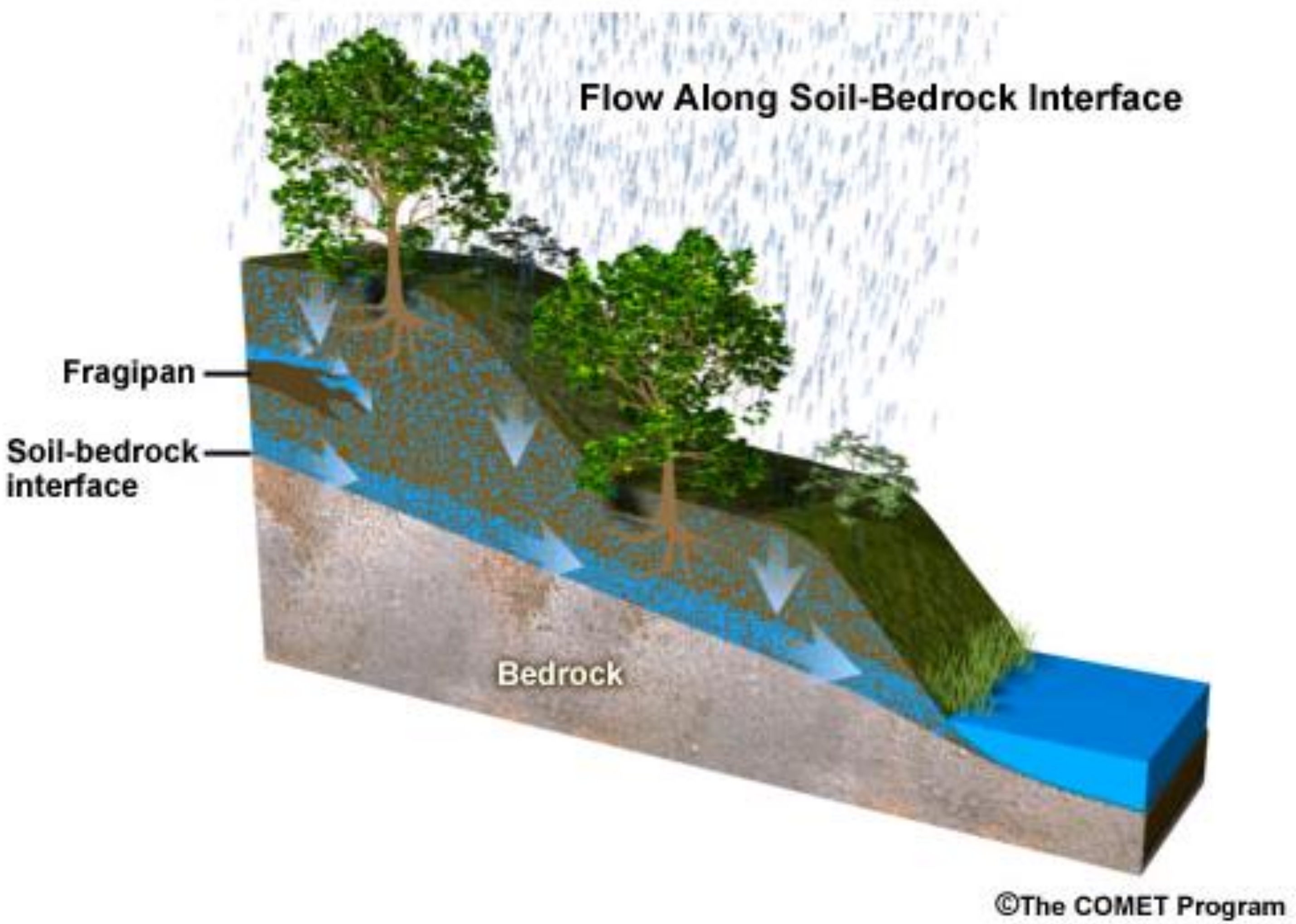
<u>Output Variables:</u>
Streamflow
River Stage
Flow Velocity
Reservoir Storage
& Discharge

Terrain Routing Models:
Overland, subsurface flow

<u>Output Variables:</u>
Stream Inflow, Surface Water Depth, Groundwater Depth, Soil Moisture

Basic Principles on Coupled Hydrometeorological Processes

- Organization of spatial variability



Basic Principles on Coupled Hydrometeorological Processes

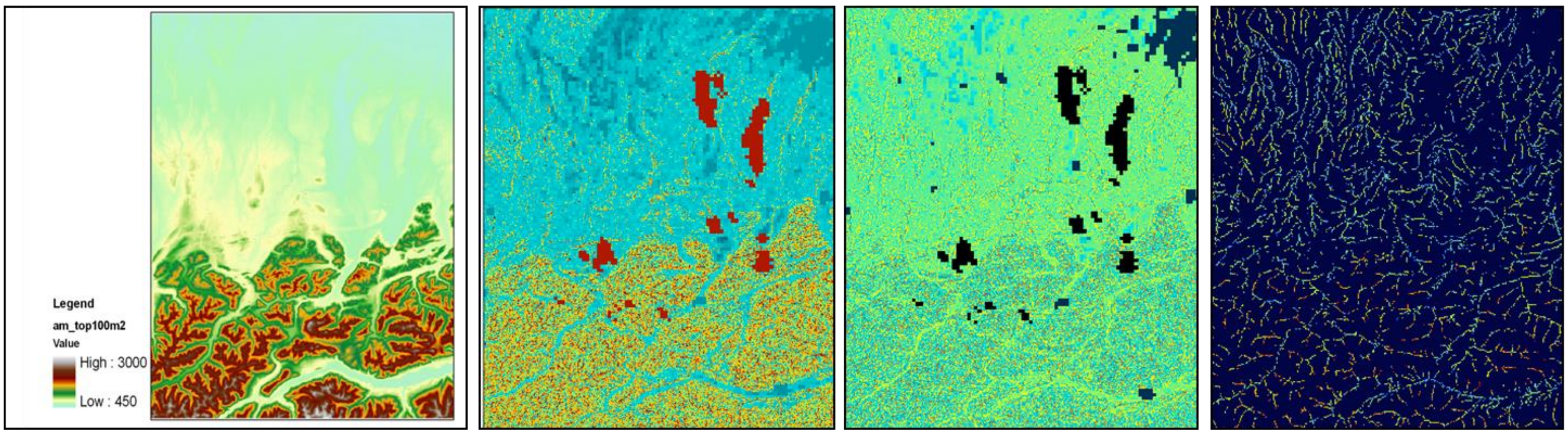
- Organization of spatial variability

DEM: 100 m

Water table depth (m)

Soil moisture

Stream channel inflows



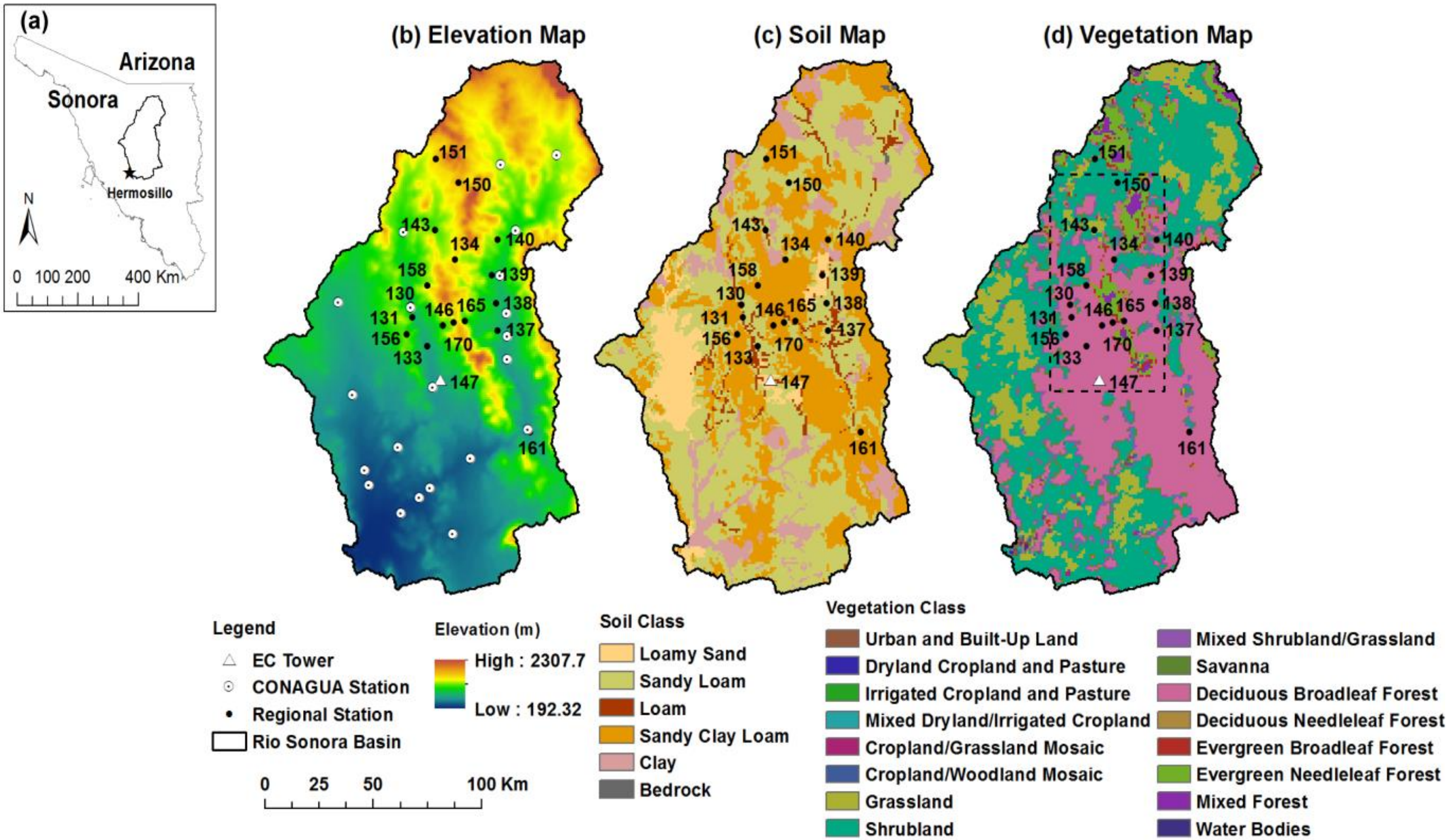
Northern Alps : Germany
Domain: ~140x220 km

Experimental Approach:

- Set up, calibrate and evaluate ‘uncoupled’ modeling components only
- Establish fidelity vs. available terrestrial hydrologic observations
  - Flux tower data
  - MODIS LST and derived ET
- Set up experimental coupled model simulations:
- Examine sensitivity of atmospheric structure to surface hydrologic initialization

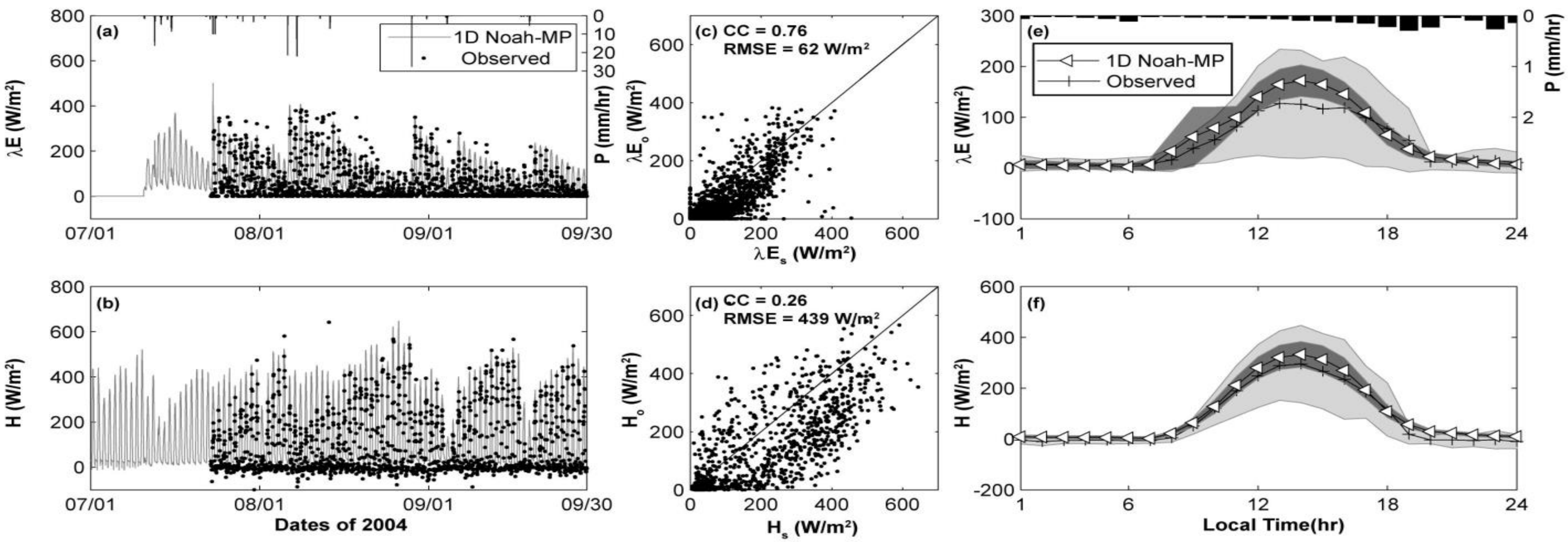
WRF-Hydro Implementation in NW Mexico:

- Initial implementation and calibration…



WRF-Hydro Implementation in NW Mexico:

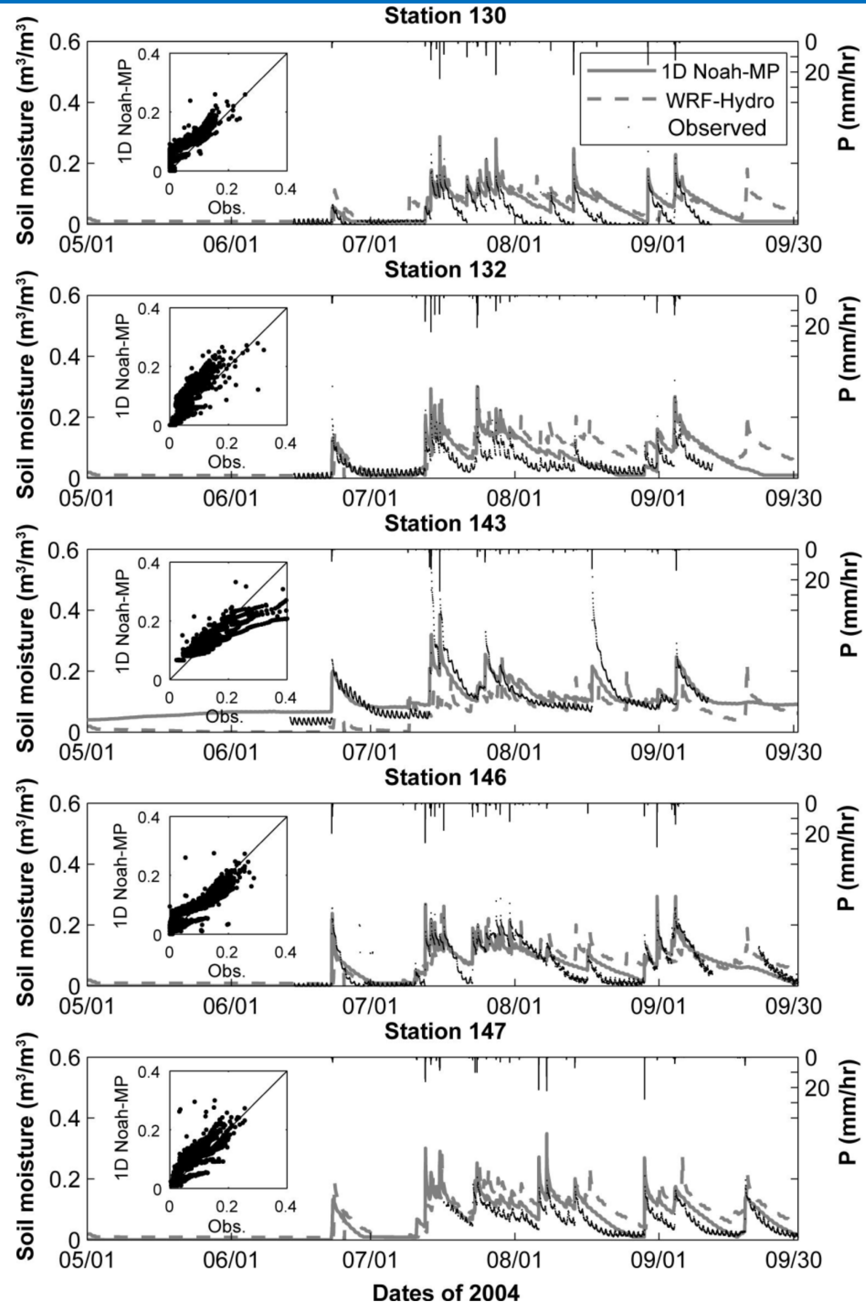
- Initial implementation and evaluation of 1D NoahMP against tower flux data…



WRF-Hydro Implementation in NW Mexico:

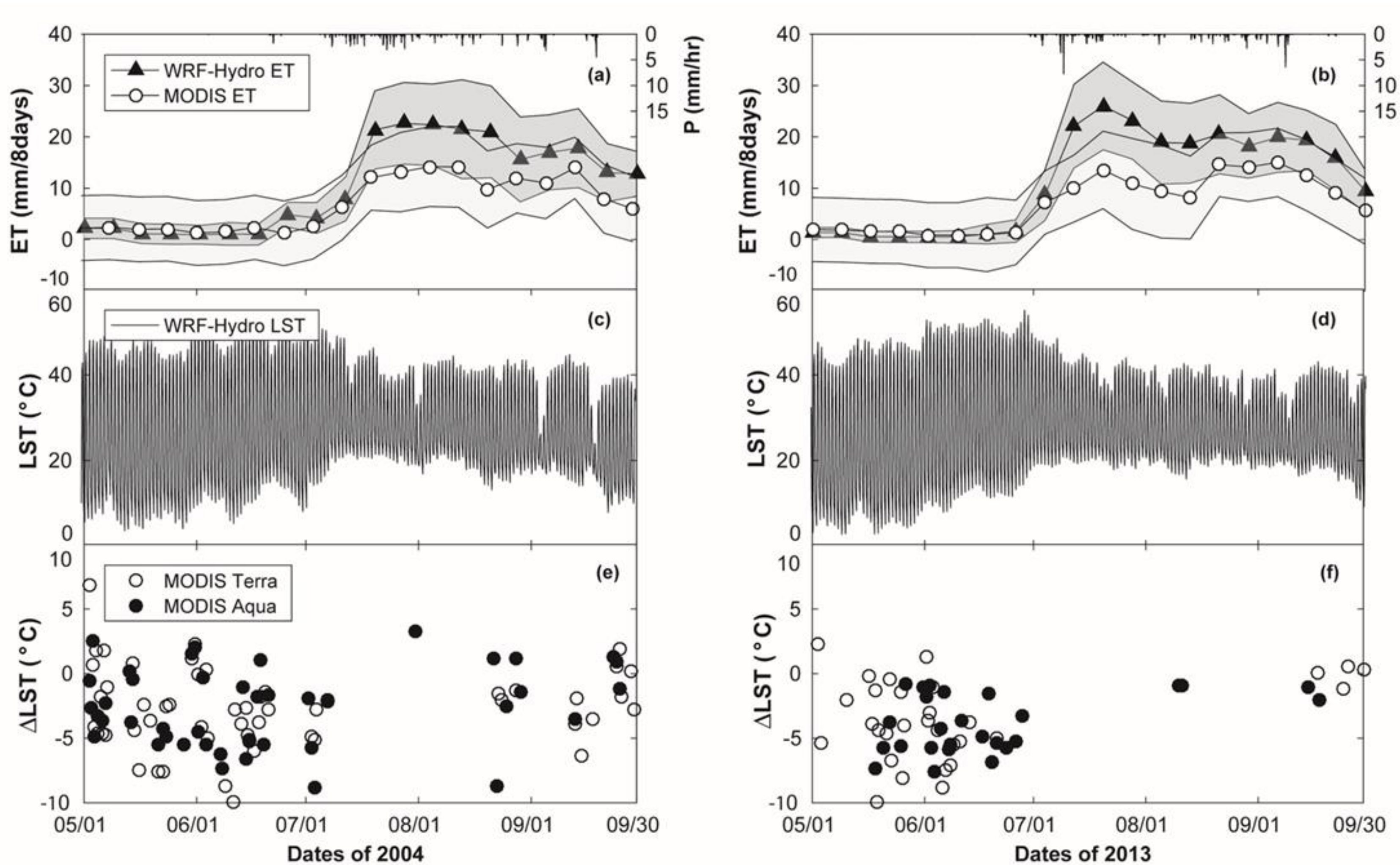
- Distributed WRF-Hydro and 1D NoahMP reasonably track observed soil moisture

- Distributed WRF-Hydro tends to be wetter than 1D NoahMP mostly due to slower dry-down at these sites



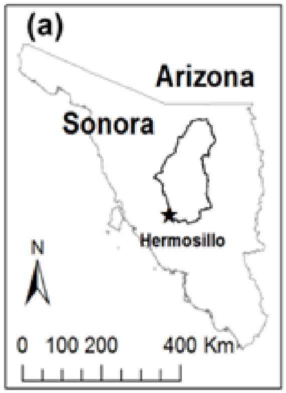
WRF-Hydro Implementation in NW Mexico:

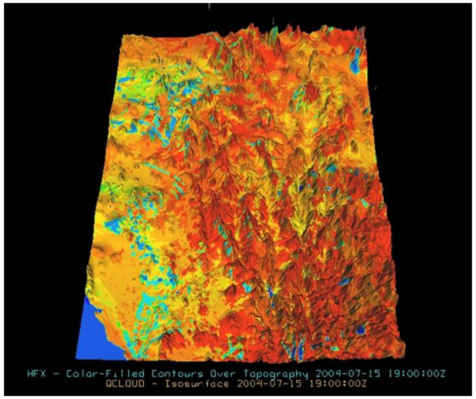
- Initial implementation and evaluation of distributed WRF-Hydro ET against MODIS ET and LST products…

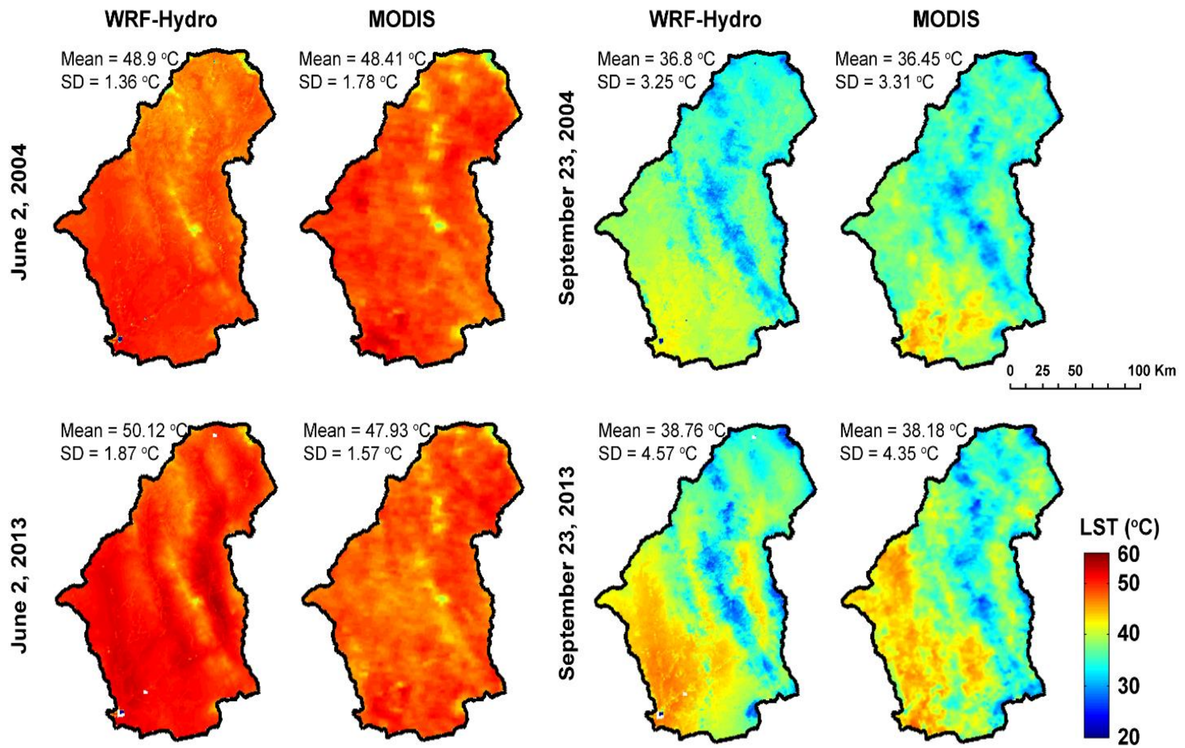


Land-Atmosphere Coupling Investigations

- Initial implementation and evaluation of distributed WRF-Hydro ET against MODIS ET and LST products…







Xiang et al., 2017, JGR

Coupled WRF/WRF-Hydro Implementation

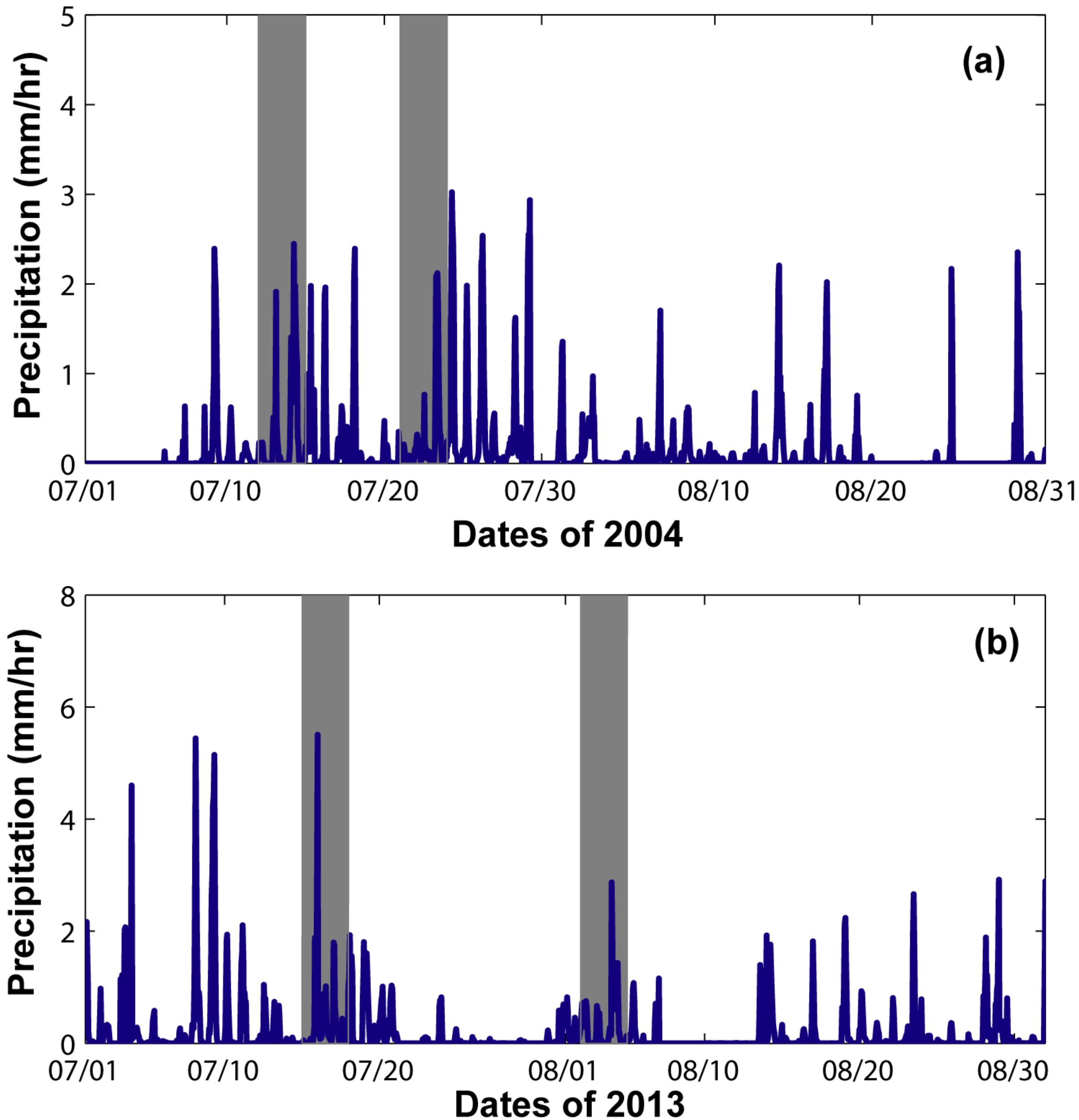
Physics Categories	Selected Option	Reference
Microphysics	Thompson	Thompson *et al.* (2008)
Longwave and Shortwave Radiation	Revised MM5 surface layer	Paulson (1970); Zhang and Anthes (1982); Beljaars (1994)
Land Surface Model	Noah-MP	Niu *et al.* (2011); Yang *et al.* (2011)
Planetary Boundary Layer	Yonsei University Scheme	Hong *et al.* (2006)
Cumulus Parameterization	Kain-Fritsch	Kain (2004)

- WRF Model Setup:
  - 44 vertical levels (telescoping)
  - Model top at 100 hPa
  - 3-nest domain (12, 4, 1 km)
  - Lateral boundaries specified by NARR (32km)
  - 4, 72 hr precipitation event periods:
    - 2004 (July 12-15 and July 23-24) and 2013 (July 15-18 and August 2-5)
  - WRF-Hydro NoahMP Setup:
    - 1km NoahMP
    - 100m terrain routing
    - Daily specification of green vegetation fraction and LAI from MODIS

Xiang et al., 2017, Atmosfera

Coupled WRF/WRF-Hydro Implementation

Experimental rainy periods for coupled model implementation

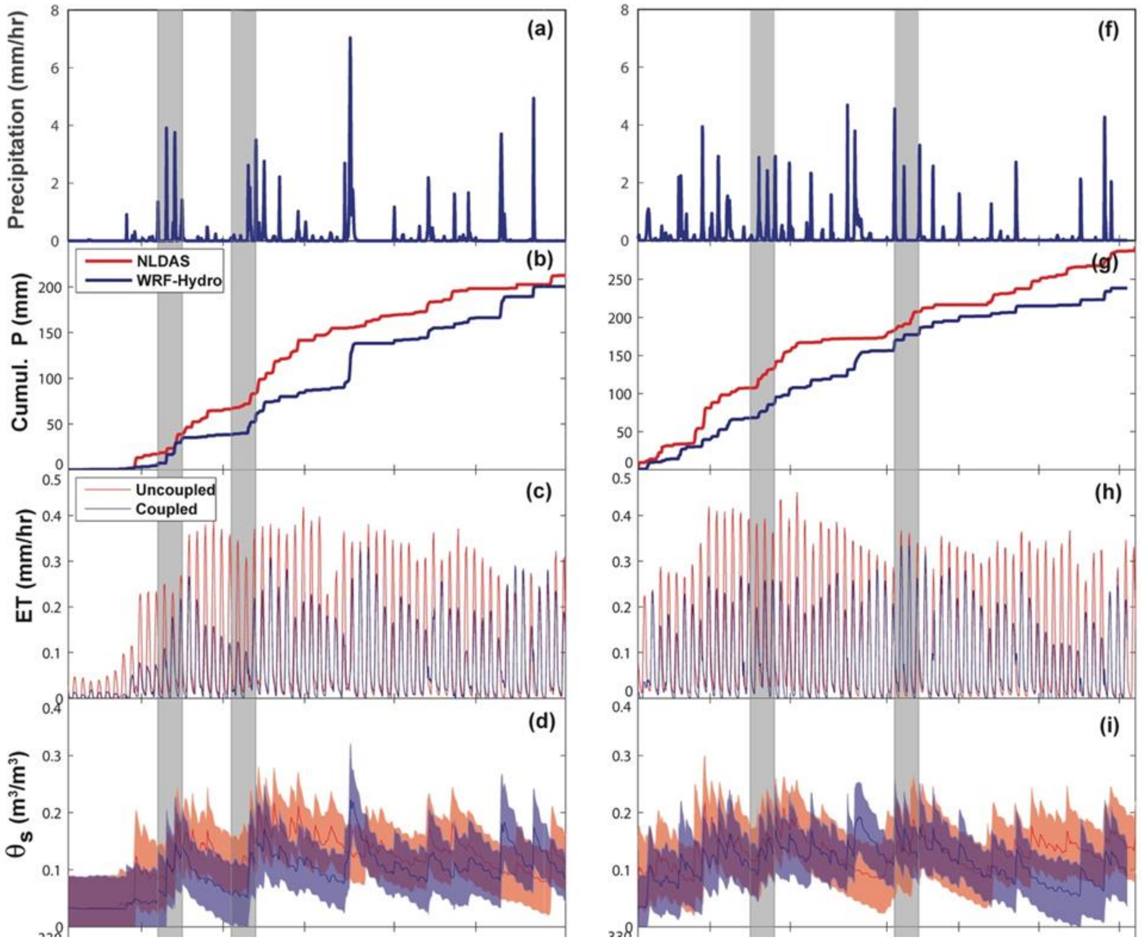


Xiang et al., 2017, Atmosfera

Coupled WRF/WRF-Hydro Implementation

Coupled WRF/WRF-Hydro modeled precipitation is more episodic with stronger pulses than NLDAS…

Results in lower overall ET and higher soil moisture variability



Xiang et al., 2017, Atmosfera

Coupled WRF/WRF-Hydro Implementation

Four initialization experiments were conducted for each storm period by perturbing the initial soil moisture and vegetation conditions. *Only soil moisture perturbation experiments discussed here.*

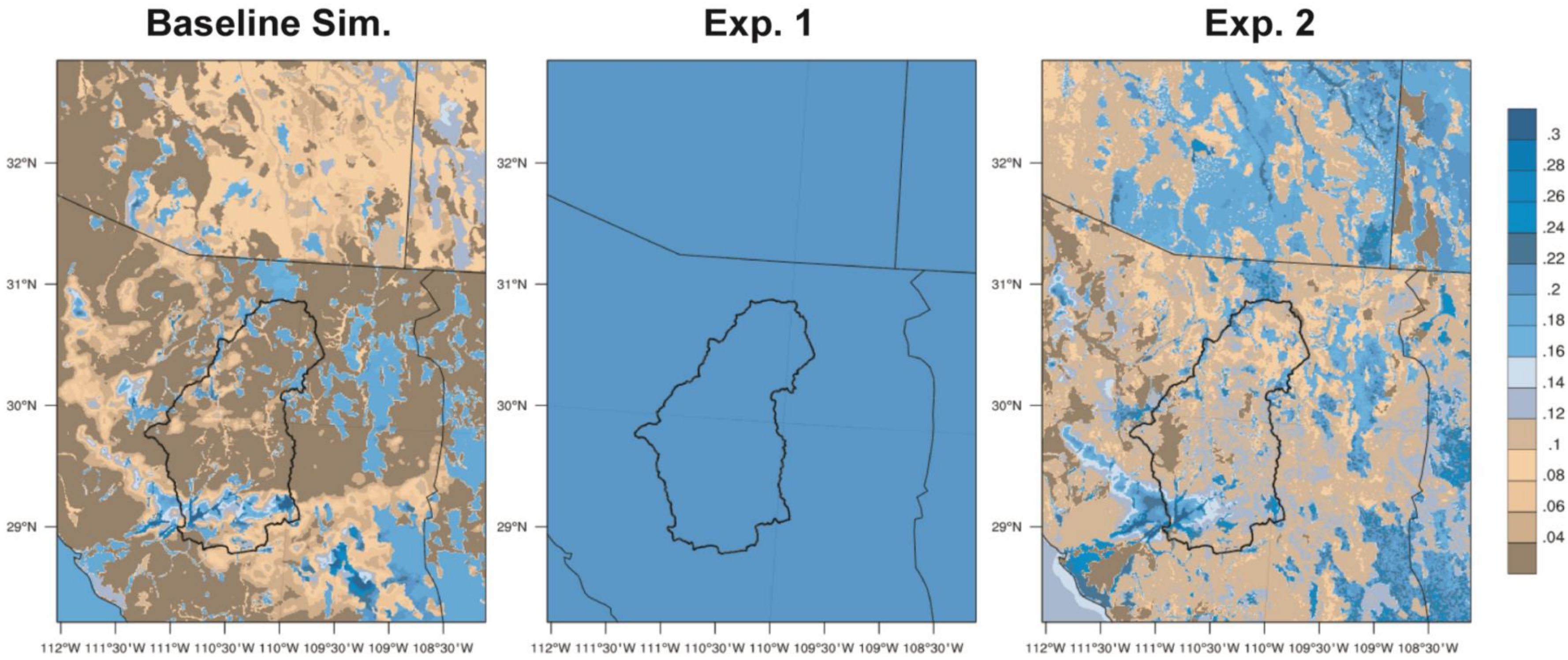


Fig. Initial soil moisture (m^3/m^3) distributions at 00 UTC July 12, 2004 for the baseline simulation and for experiments 1 (Uniform soil moisture, 0.2 m^3/m^3) and 2 (Spatially variable soil moisture).

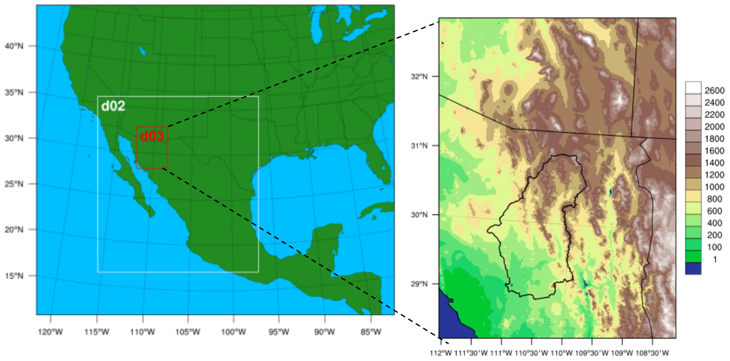
Xiang et al., 2017, Atmosfera

Coupled WRF/WRF-Hydro Implementation

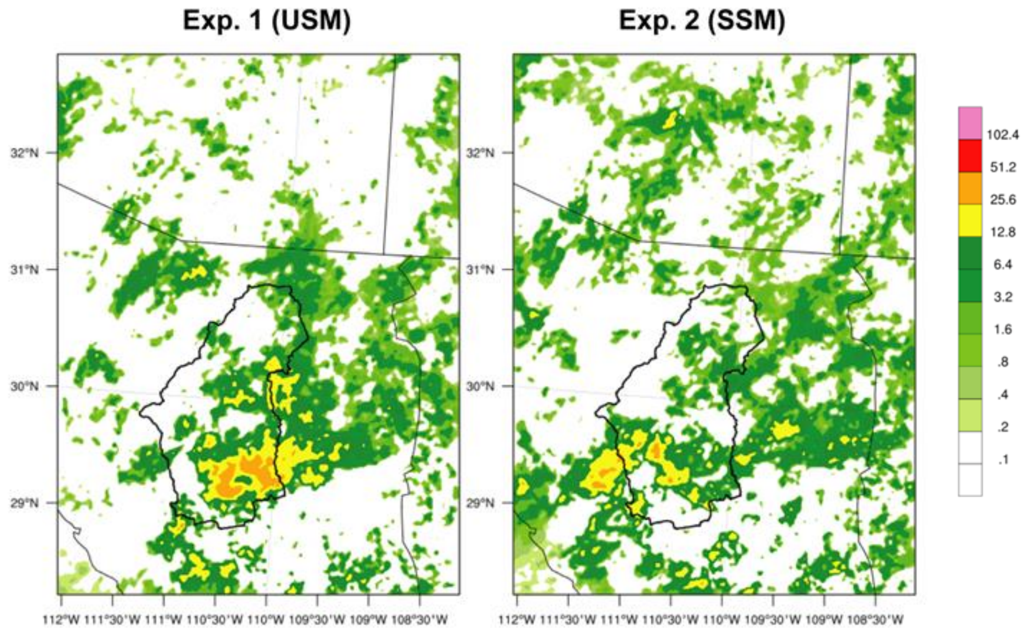
- **Analysis metrics:**
- surface energy balance,
- relationship between net radiation at the surface and boundary layer conditions
- linkage among boundary layer states and precipitation generation through linear regression parameters (and coefficients of determination, R^2) and correlation coefficients (CC)
- basin-averaged surface soil moisture (ϑ_s)
- surface albedo (a)
- surface temperature (T_s)
- evaporative fraction (EF)
- net radiation (R_n)
- atmospheric conditions are inspected using:
  - basin-averaged planetary boundary layer depth ($PBLH$)
  - wet bulb temperature (T_{wb})
  - lifting condensation level (LCL)
  - convective available potential energy ($CAPE$)

Xiang et al., 2017, Atmosfera

Land-Atmosphere Coupling Investigations



- Feedback to precipitation is complicated but appreciable between experiments where terrain-induced flux variability drives differences in modeled monsoon rainfall



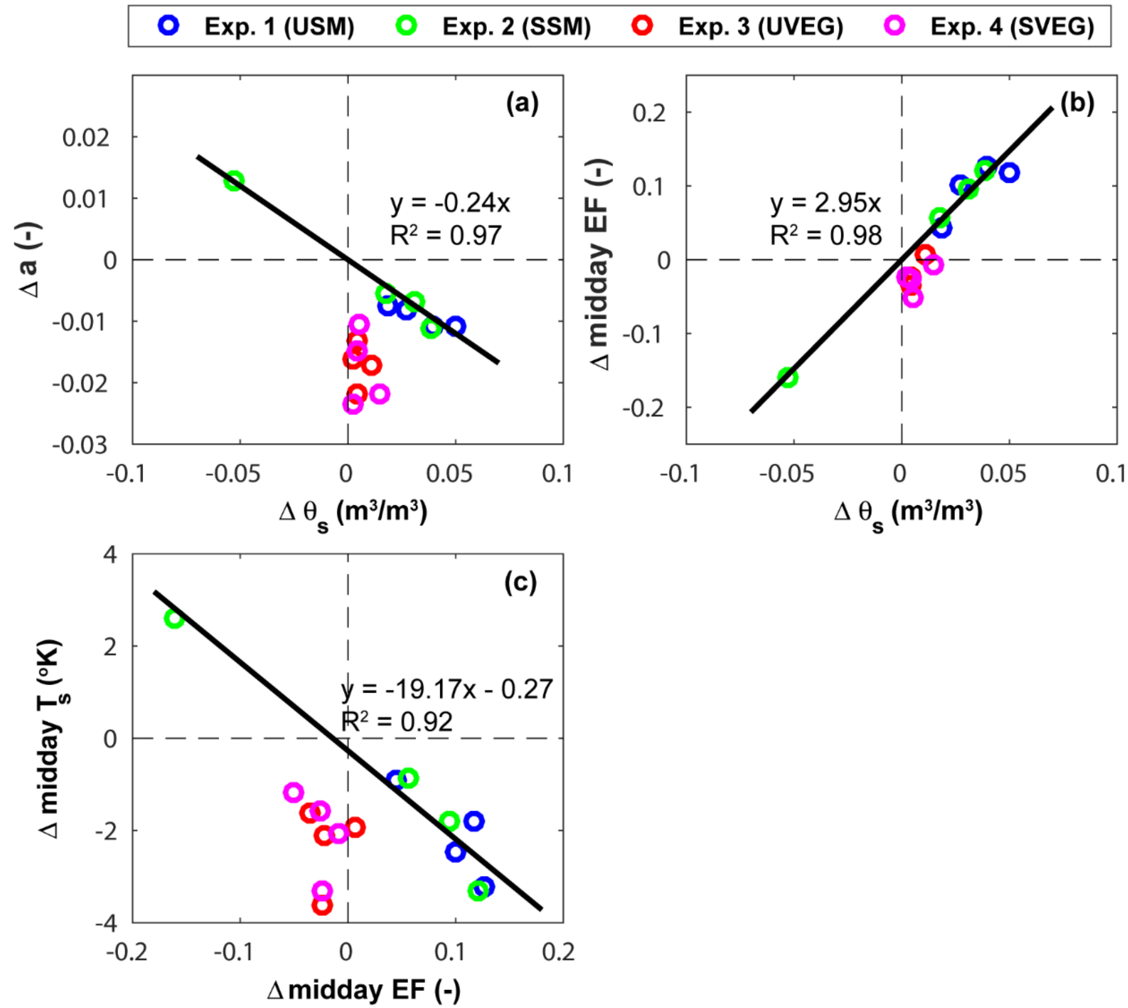
uniform (USM) and spatial varying initial soil moisture condition (SSM)

- However…deciding which one is 'right' can be tricky….

Xiang et al., 2017, Atmosfera

Land-Atmosphere Coupling Investigations

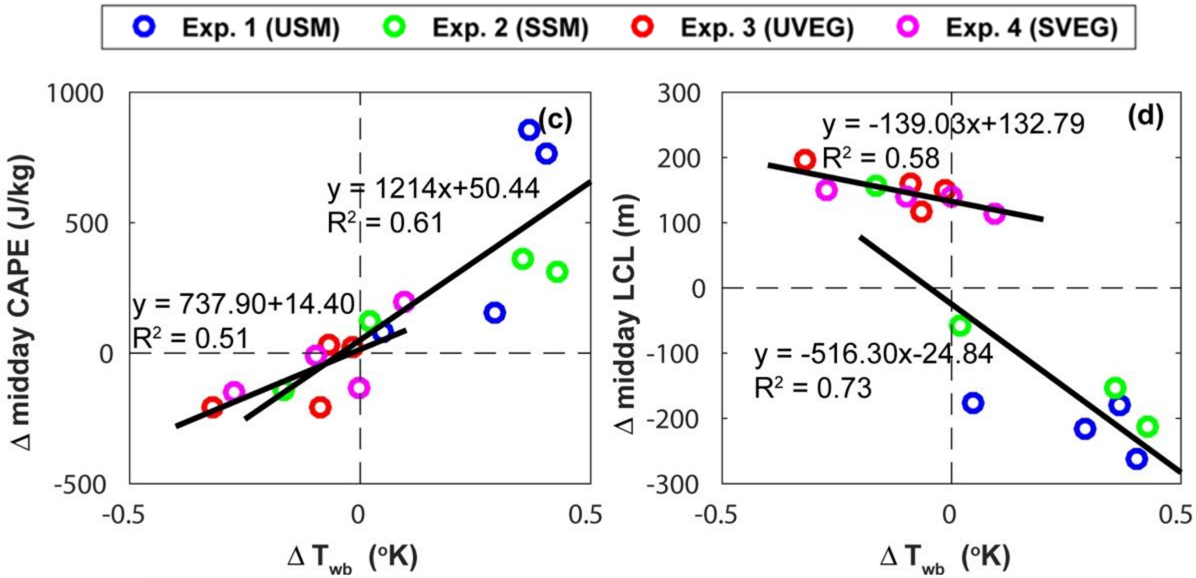
- Soil moisture correlates more strongly with albedo and evaporative fraction than does vegetation suggesting fundamental control in coupling here is moisture availability
- Greater soil moisture thus increases available energy

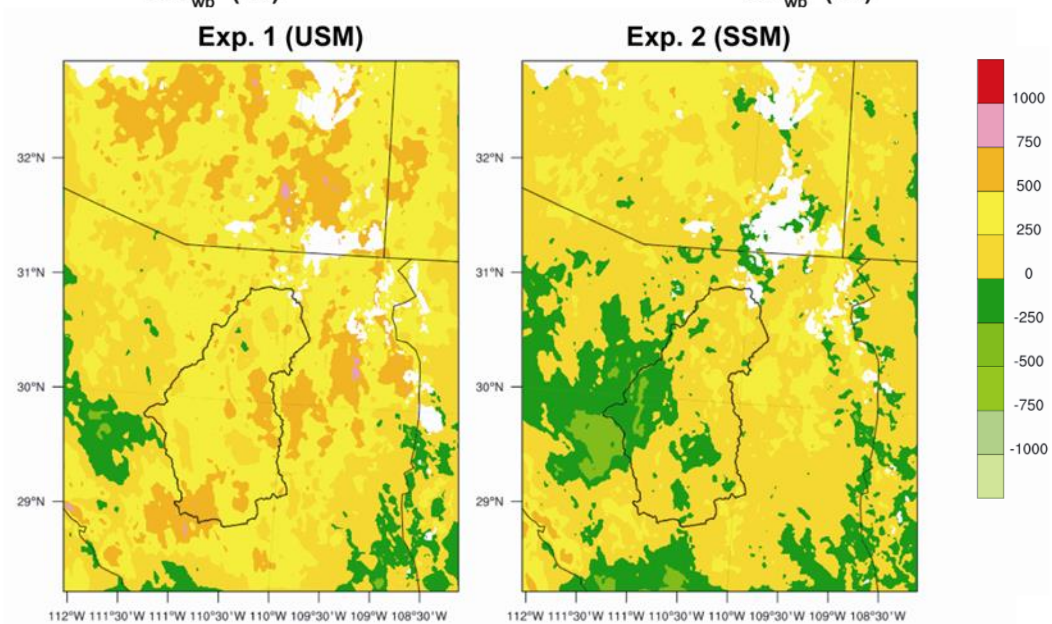


Xiang et al., 2017, Atmosfera

Land-Atmosphere Coupling Investigations

- Increases in wet bulb temperature associated with wetter soils are positively correlated with more CAPE and lower LCLs
- Maps of differences in CAPE between experiments and baseline show increases in CAPE using the updated (wetter) soil moisture initializations
- Combined Factors imply a more energetic boundary layer when soils are wet following rains in the NAM regions



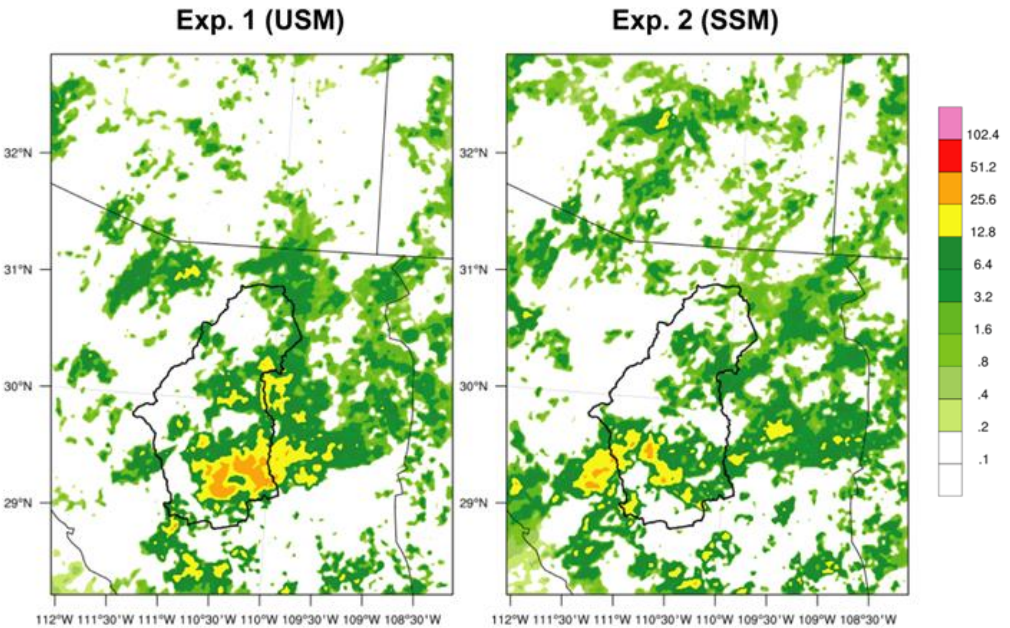


Xiang et al., 2017, Atmosfera

Land-Atmosphere Coupling Investigations

- Overall, soil moisture initialization experiments point to a positive feedback between soil moisture and precipitation in the NWM region…

- Implications:
  - Sufficient energy to drive convective dynamics
  - System is more 'moisture limited' than 'energy limited'



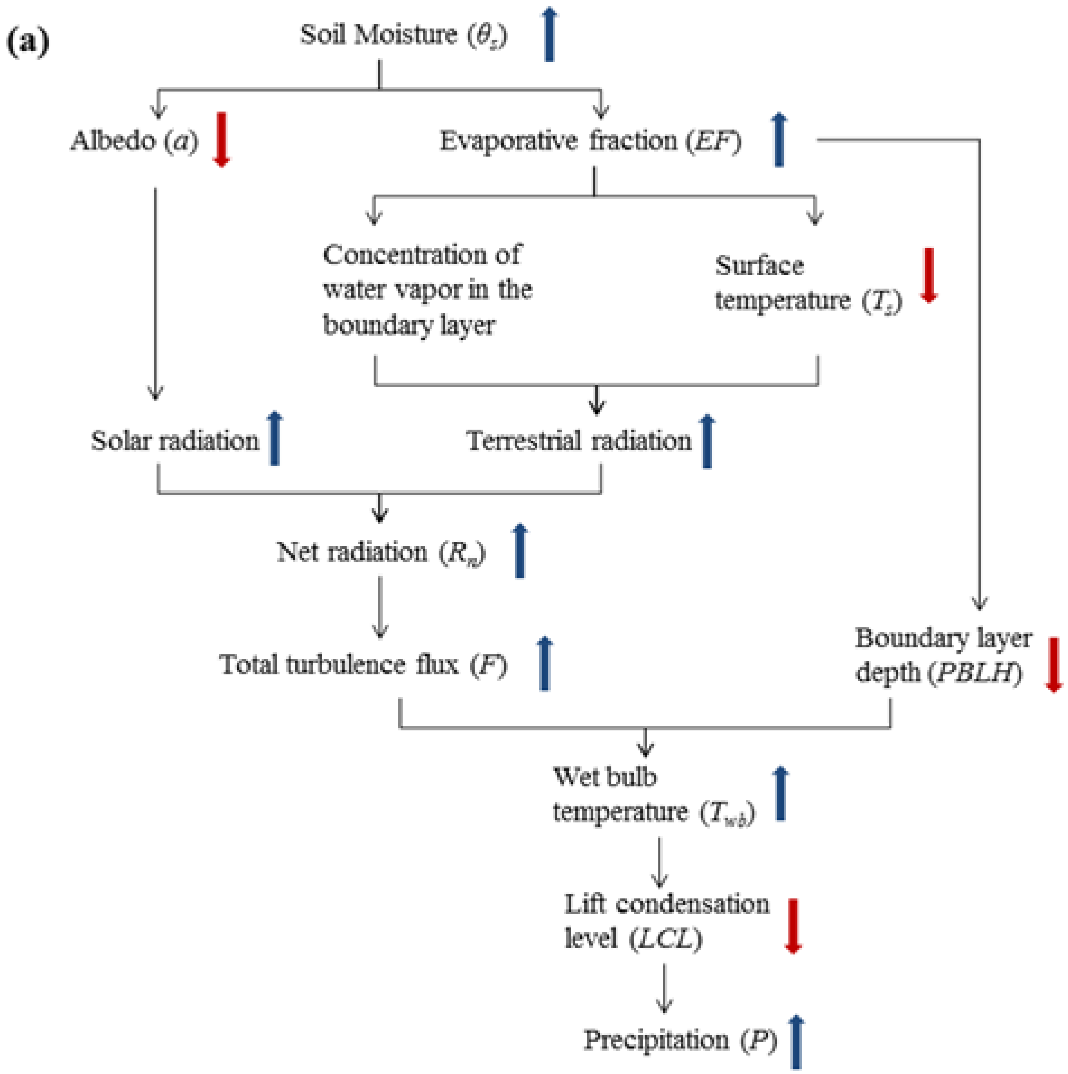
Change in precipitation compared with baseline model run: uniform (USM) and spatial varying initial soil moisture condition (SSM)

Xiang et al., 2017, Atmosfera

Land-Atmosphere Coupling: Conclusions

- Eltahir (1998) framework suggest great soil moisture provides both a small local source for moisture but also a mechanism that partitions incoming radiation into terms that allow for more energetic PBL:
  - Decrease in albedo/increase in net radiation
  - Increase in wet bulb temp
  - Increases in CAPE
  - Lowering of LCL/PBL hgt

  - Greater precipitation



Xiang et al., 2017, Atmosfera

Next Steps:

- Increased soil moisture in N. American Monsoon region is associated with greater surface available energy, a more ‘energetic PBL’ and greater precipitation

- Next steps: Isolate the role, if any, of terrain routing processes in land-atmosphere exchange and N. American Monsoon precipitation

Thanks!

NWM:

http://water.noaa.gov/about/nwm

WRF-Hydro:

https://www.ral.ucar.edu/projects/wrf_hydro

Rwrfhydro Evaluation Tools:

https://github.com/mccreigh/rwrfhydro

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