An Incremental and Interactive Process for Watershed Characterization and Modeling: A Case Study in Southwestern North America

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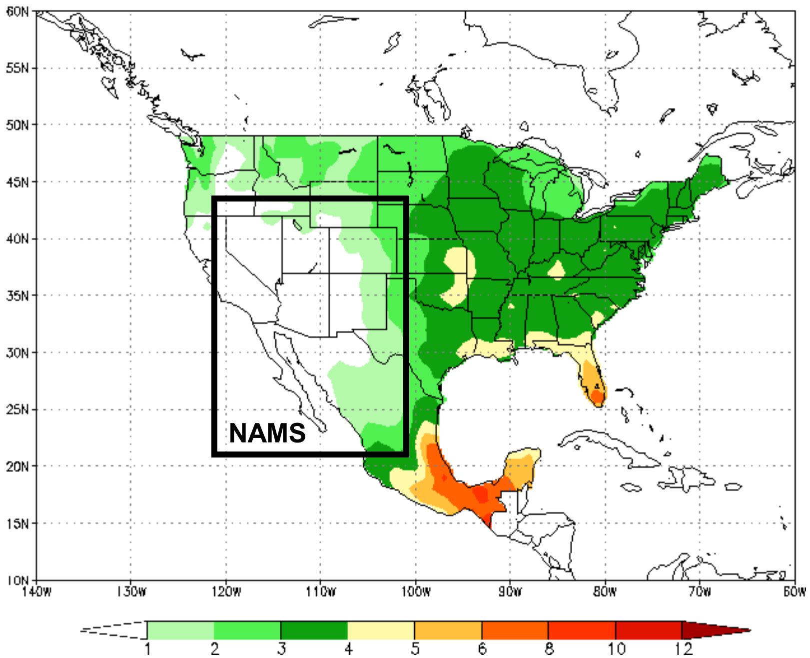
Motivation

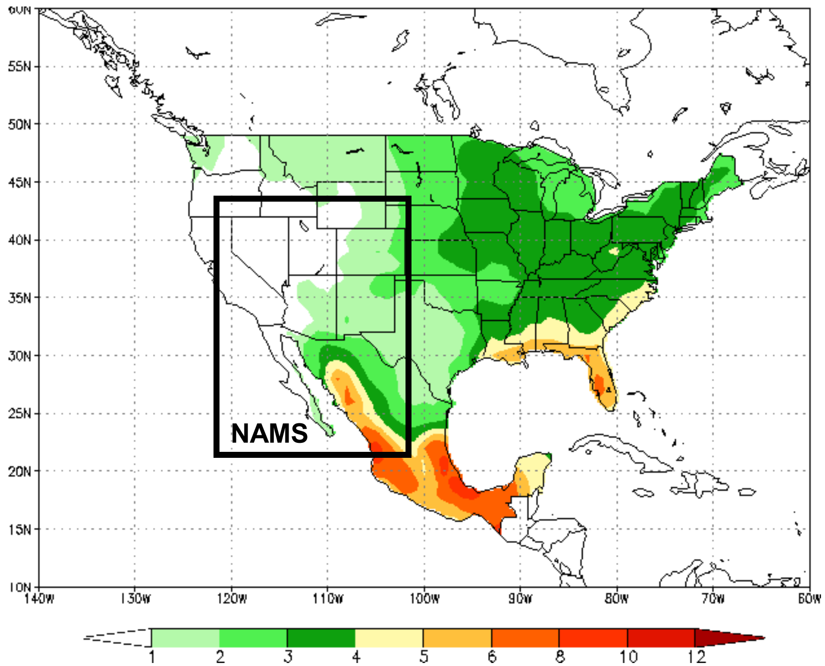
North American Monsoon System (NAMS) leads to a seasonal increase in summer precipitation (July, August, September) in the arid and semiarid mountainous basins of southwestern North America.

June Climatology



Rainfall (mm/day)

July Climatology



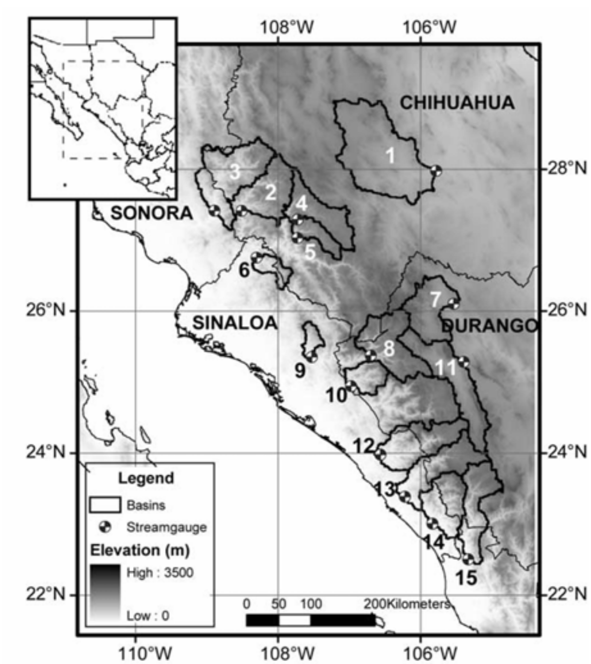
Rainfall (mm/day)

CPC Daily Gridded Precipitation Analysis for US and Mexico
1 degree by 1 degree, Monthly Climatology, 1970-1999

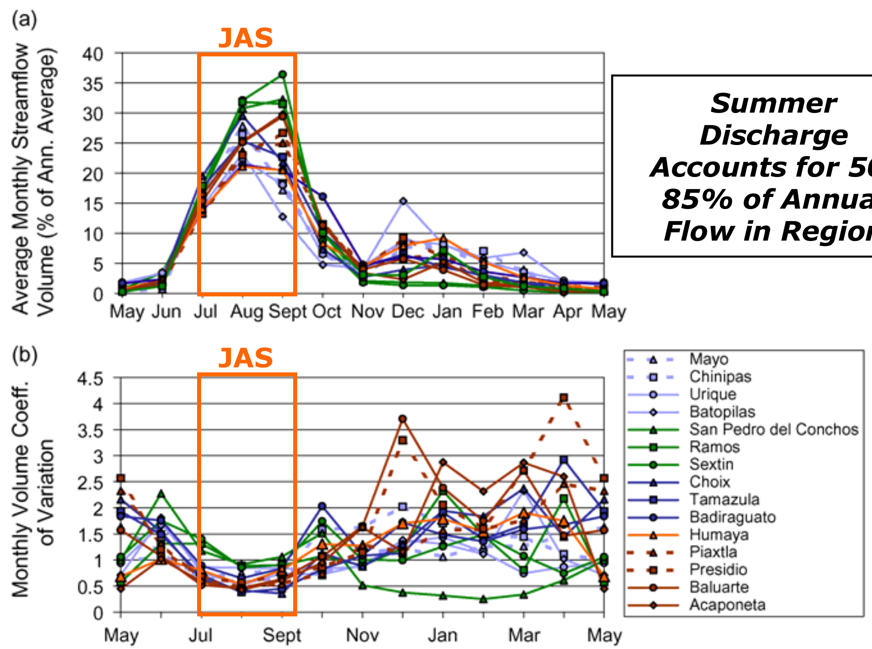
Motivation

Precipitation during NAMS leads to a latitudinal gradient and temporal variations in the streamflow response in the region as observed in a set of large, gauged mountainous basins.

Gauged Basins in NAMS Region



Long-term Averaged Streamflow Response

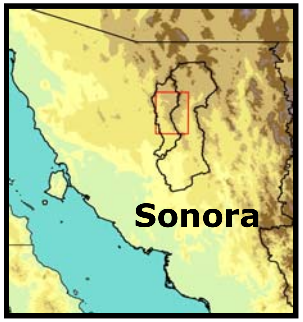


Summer Discharge Accounts for 50-85% of Annual Flow in Region

Reduced Interannual Variations in JAS

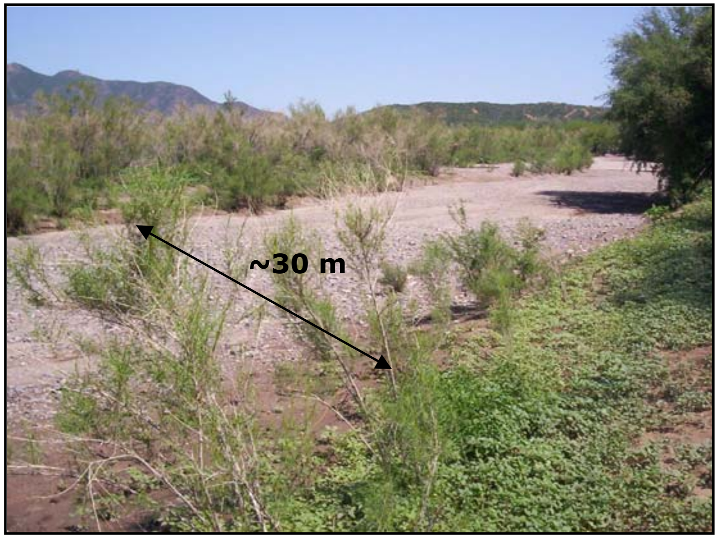
Streamflow and Precipitation Analyses for NAMS Basins by *Gochis et al.* (2006), Journal of Hydrology

Motivation



Seasonality in precipitation and basin conditions (vegetation greening) significantly impacts runoff production, flood propagation and aquifer recharge.

Ephemeral systems with frequent flood pulses (lasting 1-2 days) which recharge underlying alluvial aquifer in response to NAMS convection.



Pre-Event Conditions

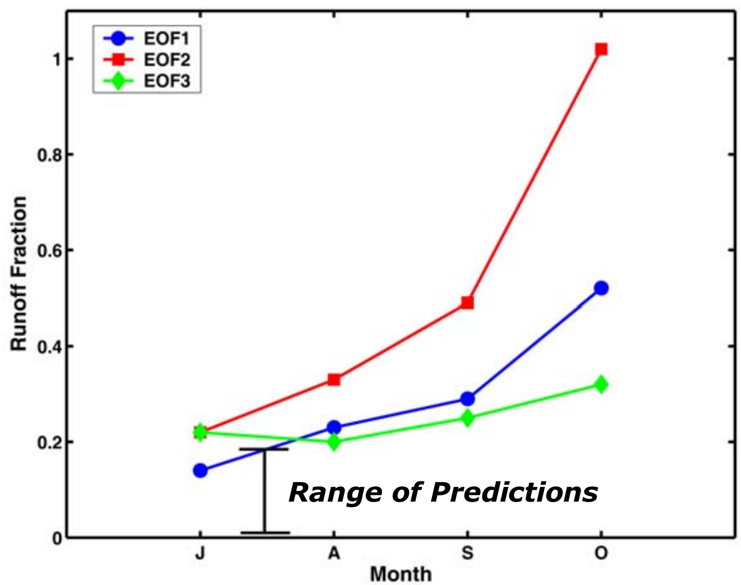
Post-Event Conditions

Photographs from Main Channel in Rio San Miguel basin (~3500 km^2) in Northern Sonora, Mexico – Summer Season 2006

Motivation

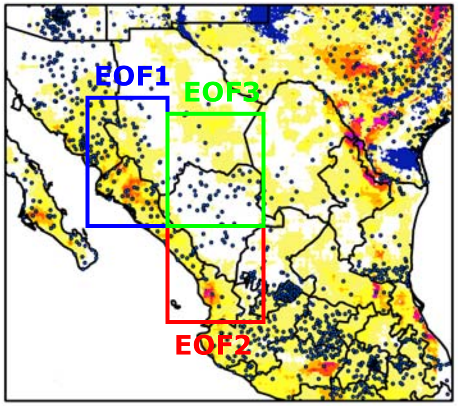
Streamflow characterization in NAMS basins through models remains elusive due to coarse observations and models that limit assessments of rainfall-runoff mechanisms.

Observed Runoff Fractions

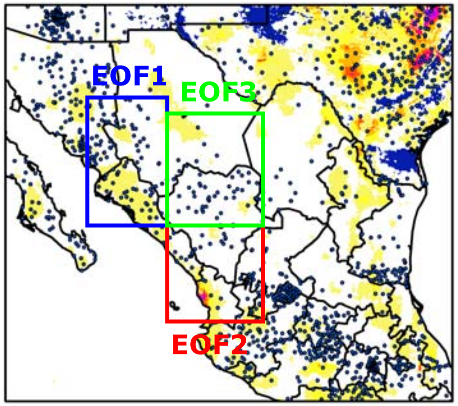


In general, numerical models of NAMS hydrology are not capable of capturing seasonal rainfall-runoff dynamics.

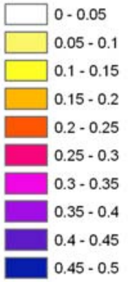
TRMM-NOAH Model



RMORPH-NOAH Model



July-Aug Runoff Fraction



Runoff Fraction Analyses for NAMS Basins by *Gochis et al.* (2006) and Preliminary NOAH Simulations with TRMM and RMORPH Forcing (*Gochis et al*. 2007)

Outline

Watershed Characterization and Modeling in Southwestern North America (NAMS Region):

1. **Incremental and Interactive Process (IIP):**

   General Description, Study Site, Numerical Model.

2. **IIP Stage A: Observations and Simulations:**

   Preliminary Studies under Poorly-gauged Conditions.

3. **IIP Stage B: Observations and Simulations:**

   Current Studies based on Improved Data Sets.

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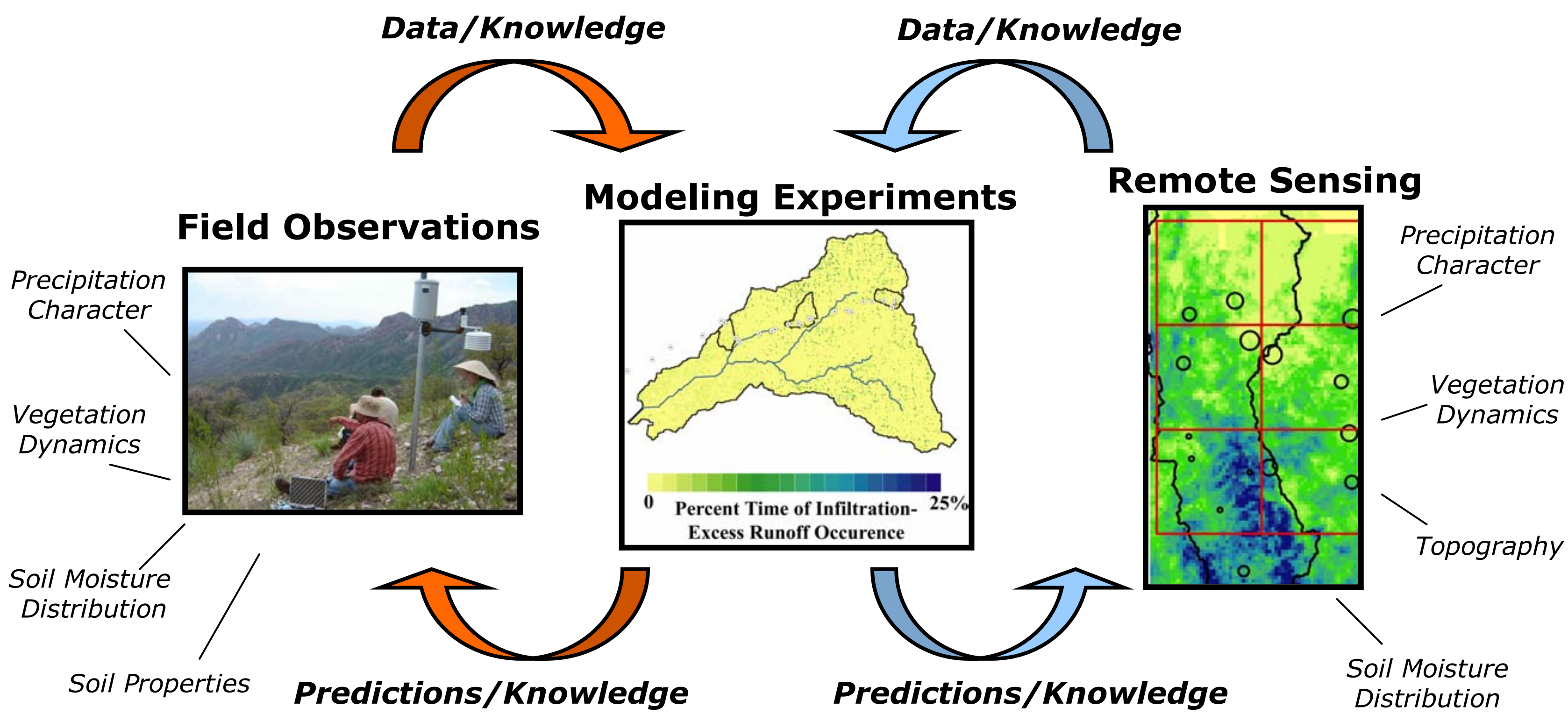
Incremental Interactive Process

To characterize streamflow generation in NAMS basins, we have developed a process for incremental and interactive hydrological studies based on field experiments, remote-sensing and modeling.



Multiple Stage Process carried out over a number of Field Campaigns and Numerical Modeling/Data Analysis Periods

Incremental Interactive Process

As an example of the IIP for watershed characterization, we selected an ungauged, mid-size basin (~100 km^2) in Sonora, Mexico which is representative for conditions in the NAMS region.

2003

Preliminary Site Visits and Analysis

- *GIS Data Collection*
- *Site Visits and Selection*

→

2004

Stage A: Initial Data Collection

- *SMEX 2004 Field Campaign*
- *Two Continuous Stations*
- *Distributed Soil Moisture Data*
- *Eddy Covariance Tower*

→

2004-2006

Stage A: Initial Model Experiments

- *tRIBS Model Experiments*
- *Distributed Testing with 2004 Data*
- *Limited Soil and Land cover Data*

↓

2006-2007

Stage B: Expanded Data Collection

- *IRES 2006 -2007 Field Campaigns*
- *23 Rain Gauge Stations*
- *Soil Profile Characterization*
- *Eddy Covariance Tower Experiments*
- *Remote Sensing Data Collection*

←

2007-2008

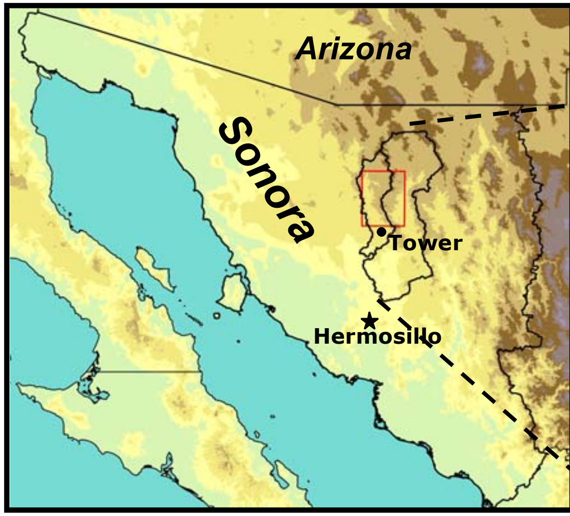
Stage B: Revised Model Experiments

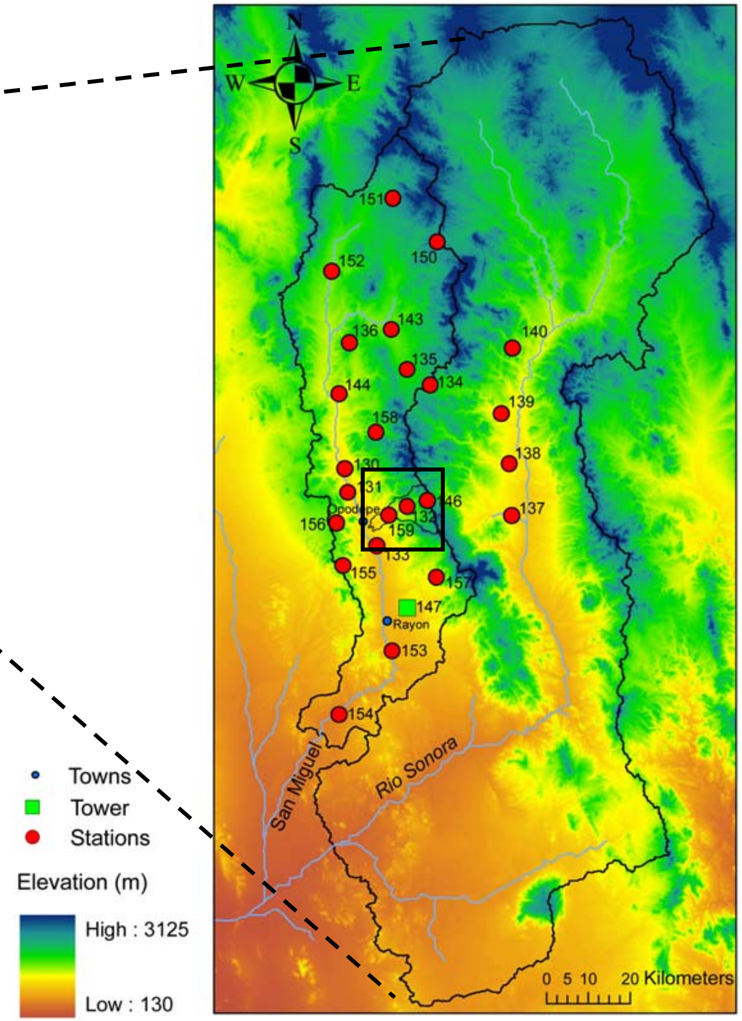
- *tRIBS Model Experiments*
- *Impact of Improved Soils Data*
- *Impact of Improved Rainfall Data*
- *Impact of Improved Topography*

←

New Stages in Watershed Characterization and Modeling

Study Region





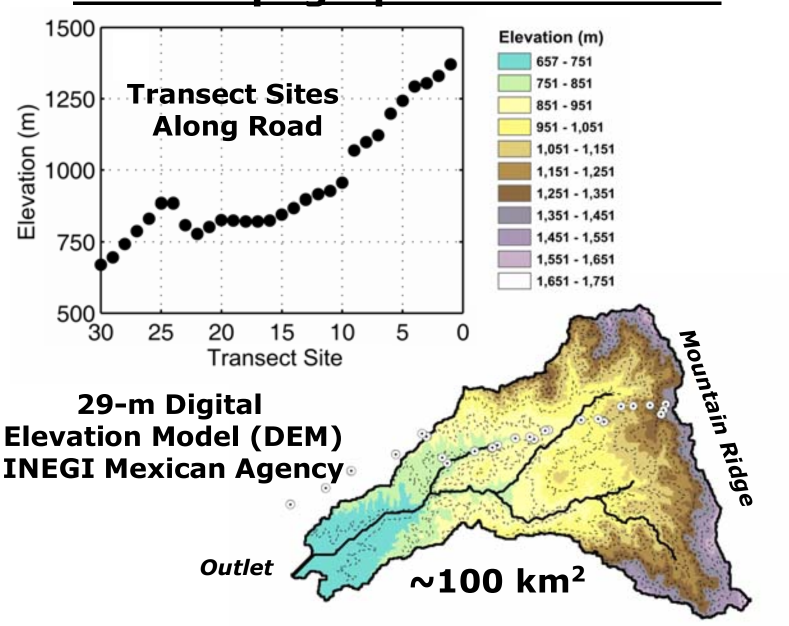
Rio Sonora Study Basins

- A large-scale intensive study site has been established in the mountainous Rio Sonora basin (~15,500 km^2)
- Region characterized by north-to-south mountain ranges and two major rivers: **Rio San Miguel, Rio Sonora**.
- Complex topography with semiarid monsoon climate, seasonally-green vegetation and ephemeral streams.

SMEX 2004: Soil Moisture Field Campaign
NAME 2004: Eddy Covariance Tower Network
Sonora IRES: Expanded Hydromet Network
(2006-2008) Eddy Covariance Experiments

Study Region

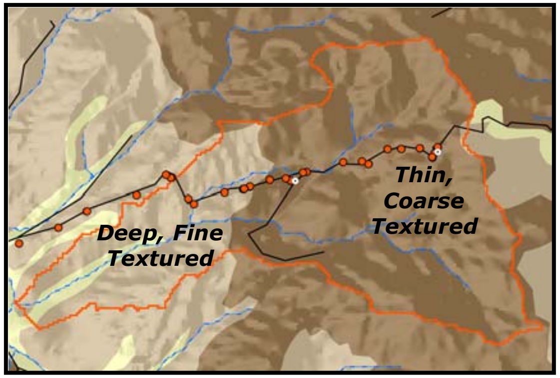
Basin Topographic Distribution

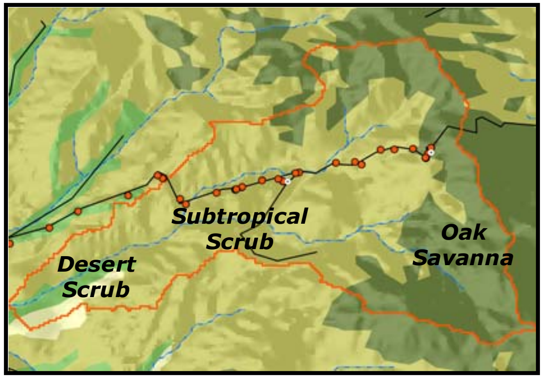


Sierra Los Locos Study Basin

- From 2004-present, <u>we have conducted studies in the ungauged Sierra Los Locos</u> (~100 km^2) in Rio San Miguel.
- Basin elevations vary from 657 m to 1681 m over the domain, with a range of slopes from 0 to 64 degrees.
- <u>Preliminary data suggest a strong topographic control</u> on the distribution of soils and vegetation:
  - Deeper, finer soils at lower elevations
  - Woody species at higher elevations

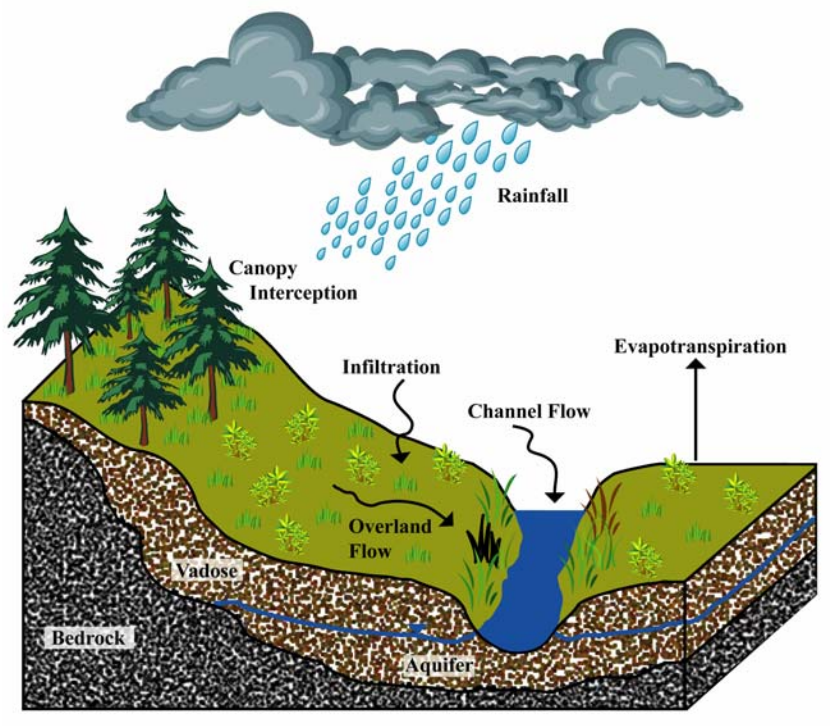
Coarse Soil and Vegetation Distributions





Hydrological Modeling

We are utilizing the TIN-based Real-time Integrated Basin Simulator (tRIBS) (Ivanov et al. 2004) for distributed modeling of hydrologic processes in complex mountainous basins in the NAMS region.



Surface-subsurface hydrologic processes over complex terrain

Additional Details in Ivanov et al. (2004a,b), Water Resources Research, Journal of Hydrology

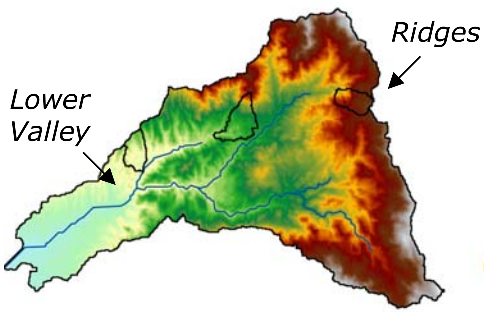
Distributed Hydrologic Modeling

- Coupled vadose and saturated zones with dynamic water table.
- Soil moisture infiltration waves.
- Lateral soil moisture redistribution.
- Topography-driven lateral fluxes in vadose and groundwater.
- Radiation and energy balance.
- Interception and evapotranspiration.
- Hydrologic and hydraulic routing.

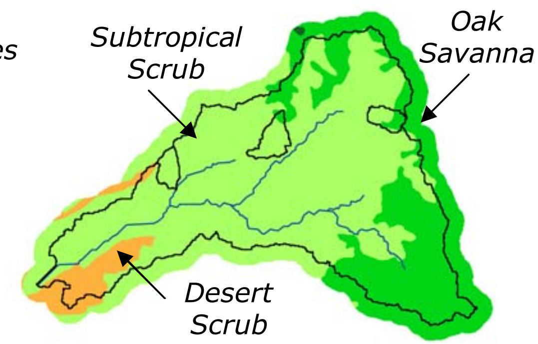
Hydrological Modeling

Distributed model parameterization is based on <u>'best-available' land surface characteristics for ungauged basin</u>. DEM and land surface data used to populate properties of a Voronoi polygon network (VPN).

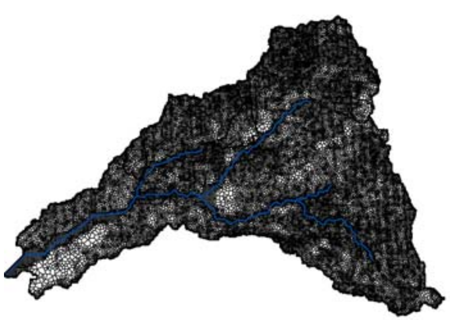
Digital Elevation Model (29-m)



Coarse Land Cover Distribution

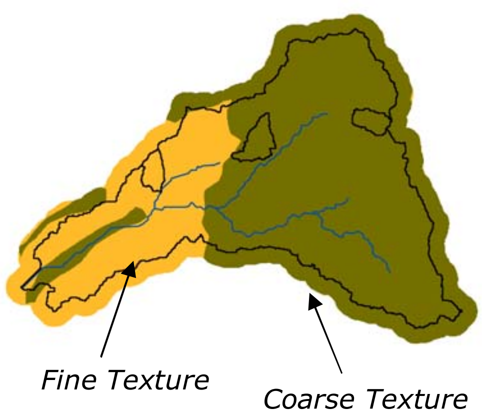


Voronoi Polygon Model Domain



Voronoi Polygons derived from Triangulated Irregular Network

Coarse Soil Cover Distribution



<u>Distributed Model Representations</u>

- DEM used to derive Triangulated Irregular Network (TIN) and Voronoi Polygon Network (VPN).
- TINs preserve stream network and basin boundary features.
- Multiple resolutions achieved using a slope preservation method.
- Nested (inner) basins can be represented in larger domains.
- Soil and land cover properties assigned unique values to Voronoi polygons (finite volume elements).

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IIP Stage A

Stage A: Goals and Objectives

I. *Initial installation of continuous stations* for rainfall and soil moisture in two ecosystems in Sierra Los Locos basin.

II. *Distributed soil moisture and temperature sampling* along a topographic transect spanning the basin elevations.

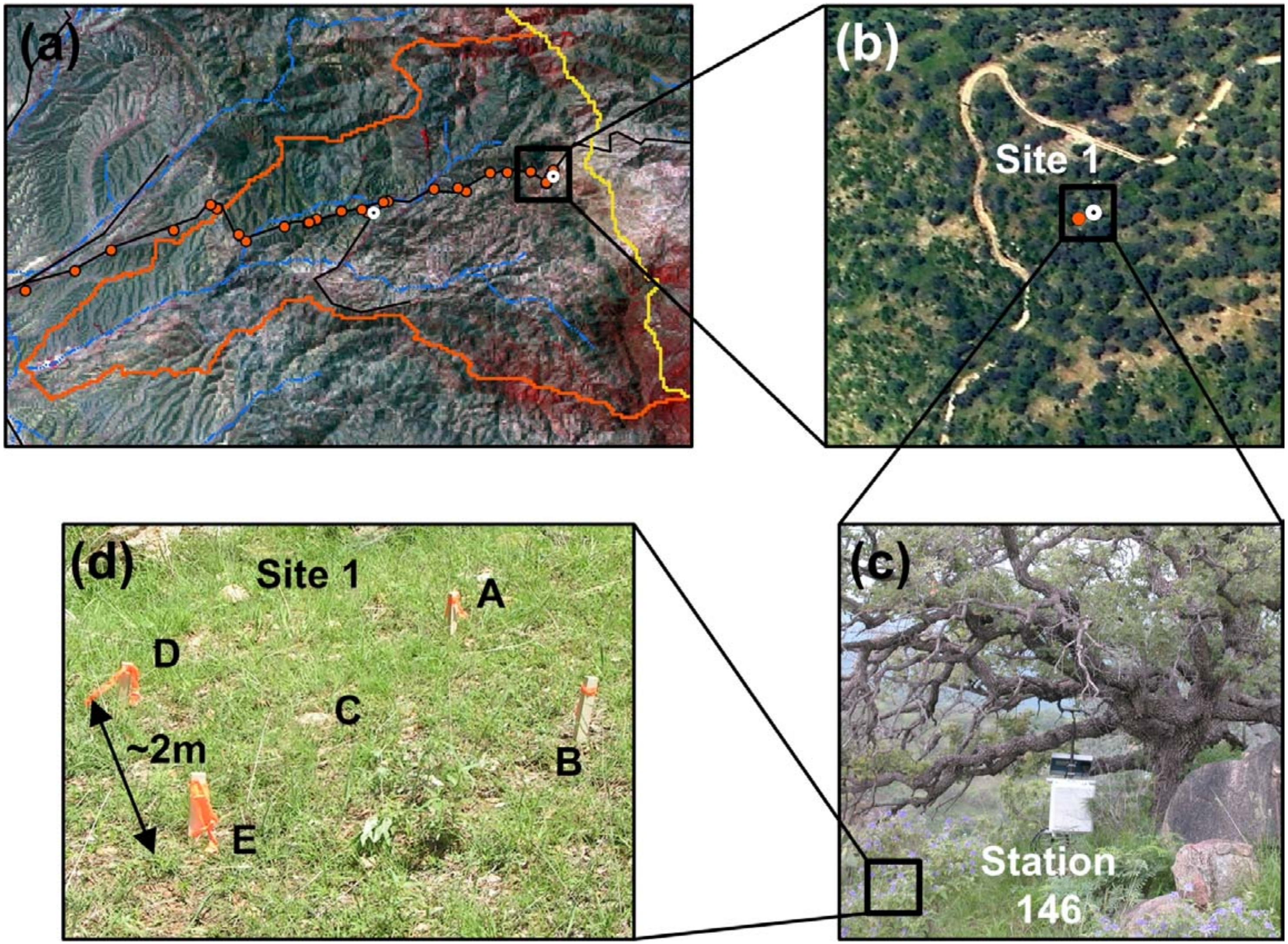
III. *Intercomparisons with aircraft-based soil moisture* estimates from PSR/CX sensor flown over summer conditions in basin.

IV. *Preliminary testing of soil moisture simulations* using best-available data with field and remote sensing observations.

V. Focus on summer 2004 period in Sierra Los Locos.

IIP Stage A: Observations

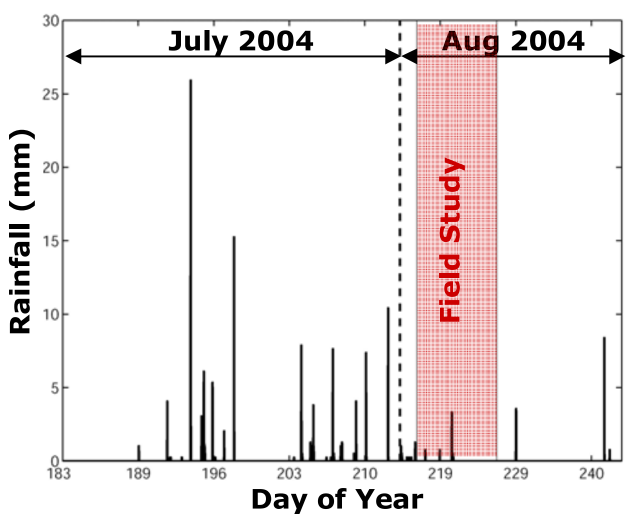
Satellite Remote Sensing **Aircraft Remote Sensing**



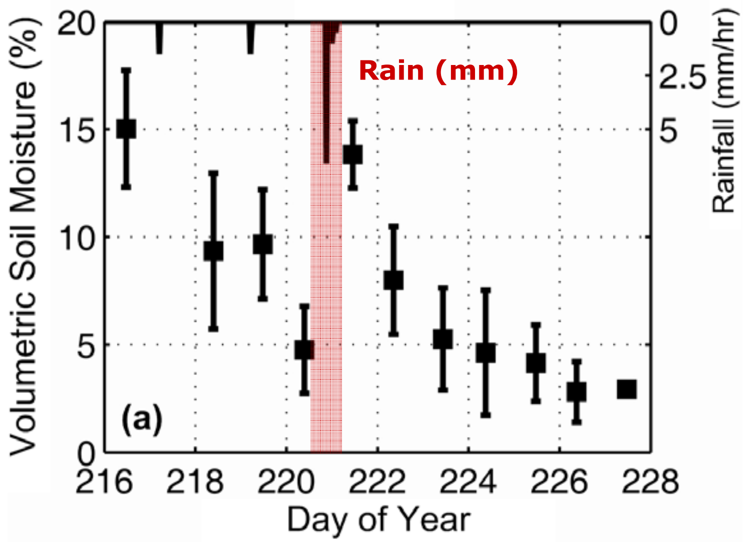
Plot-Scale Measurements **Regional Stations**

IIP Stage A: Observations

Oak Savanna Precipitation



Oak Savanna Soil Moisture



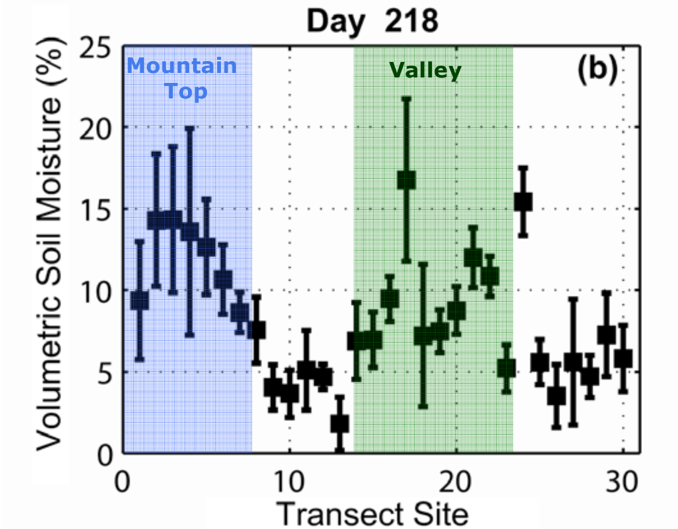
Basin Precipitation and Soil Moisture Observations

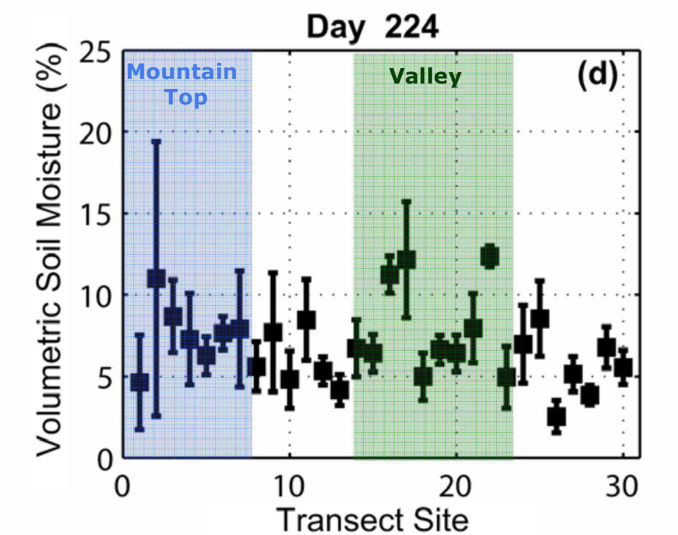
- We investigated the temporal and spatial variability of precipitation using 2 rain gauges in the Sierra Los Locos.
- We investigated the spatial and temporal variation of soil moisture in the basin based on 30 transect sampling sites.
- Precipitation and soil moisture data for 2004 monsoon season revealed:
  - Differences in precipitation character with topographic position in the basin.
  - Intense soil moisture response to localized rainfall events within the basin.
  - Varying soil moisture dynamics in each ecosystem due to variations in ET and leakage.
  - Large plot-scale variability comparable to variation between plots for several ecosystems.

Vivoni et al. (2007), Journal of Climate
Gebremichael et al. (2007), Journal of Climate

IIP Stage A: Observations

Transect Soil Moisture Profiles in Sierra Los Locos

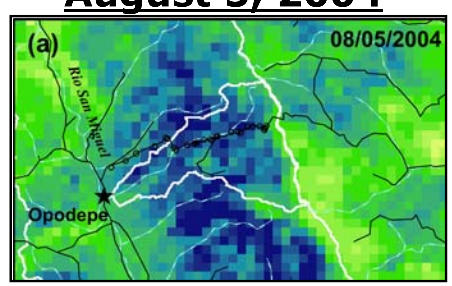




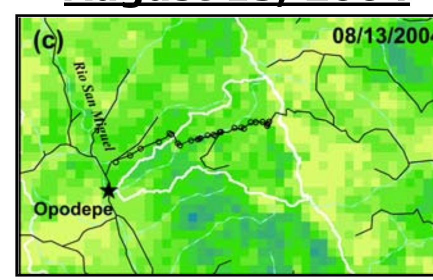
Basin Soil Moisture Drydown during Sampling Period

- A land surface drydown observed due to low precipitation with a strong terrain control:
    - Distinct behavior in soil moisture time series for different elevations in basin.
    - Homogeneization of the landscape across all elevations as the drying trend proceeded.
    - Terrain slope and curvature exhibit controls on soil moisture organization.
- Similar drydown observed in aircraft-based PSR/CX soil moisture estimates over basin.

August 5, 2004



August 13, 2004

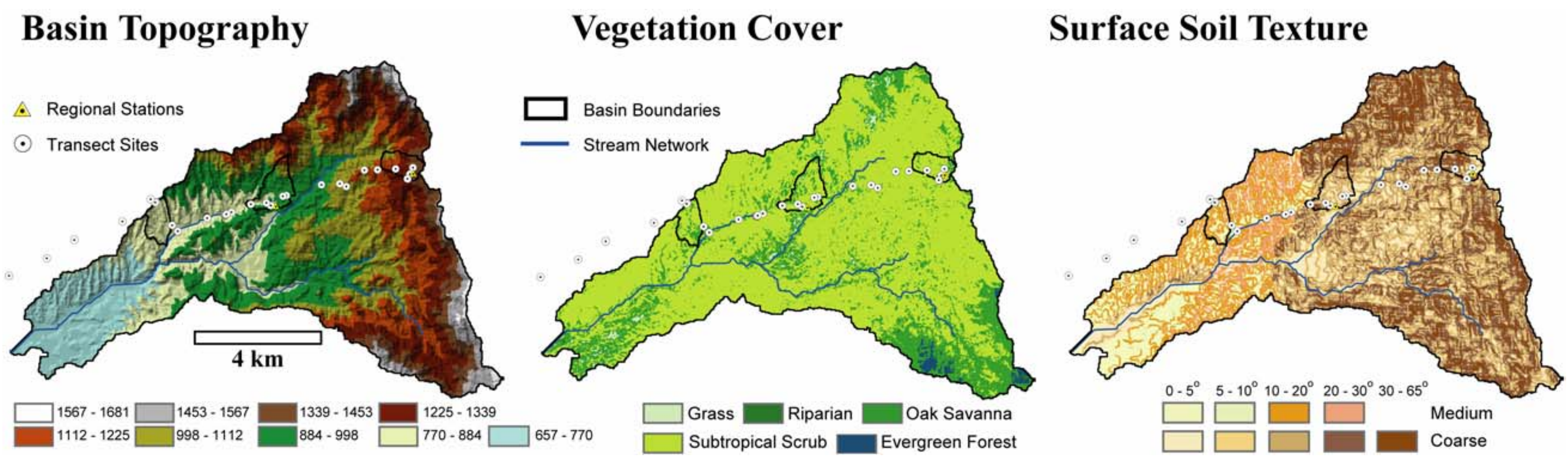


Volumetric Soil Moisture (%) in 800-m by 800-m pixels

Vivoni et al. (2007), Journal of Climate
Vivoni et. Al (2008), Remote Sensing of Environment

IIP Stage A: Simulations

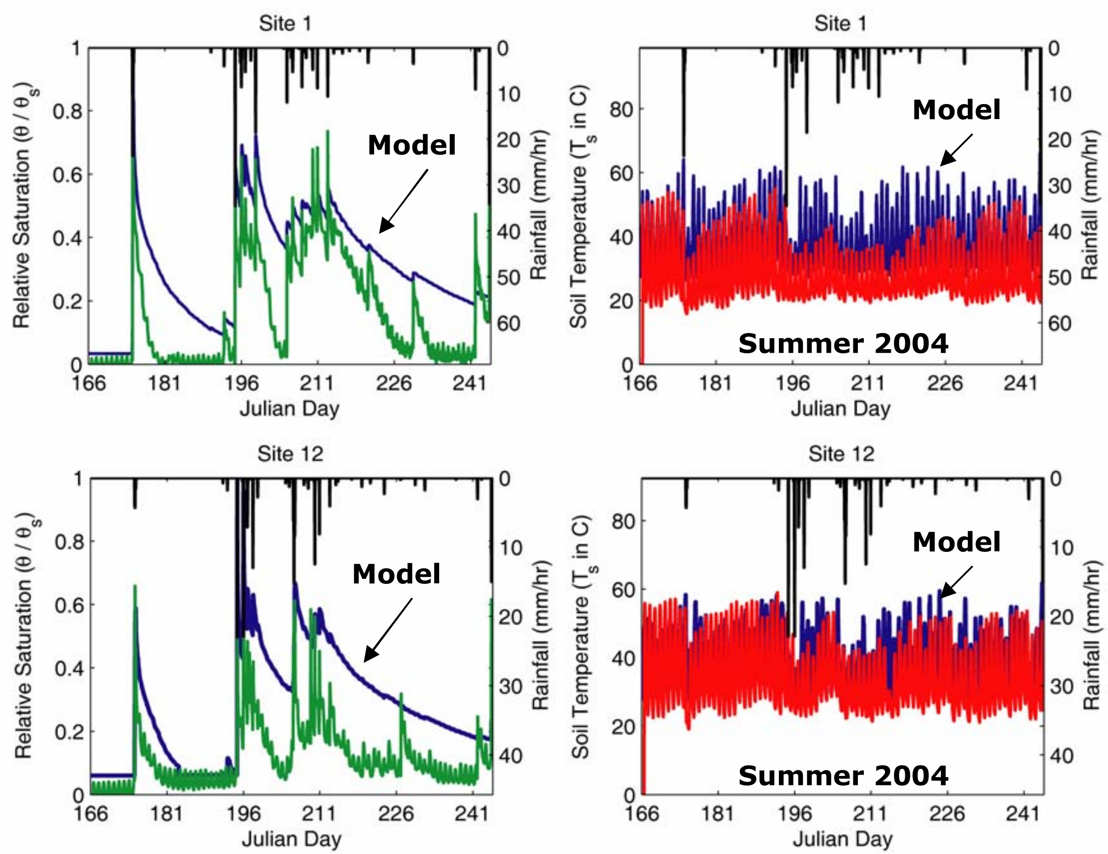
Preliminary simulations of the 2004 summer (SMEX04) to capture soil moisture conditions suggested need for improved representations of land cover, soil texture and depth to bedrock in Sierra Los Locos basin.



- A 29-m DEM used to derive an high-resolution TIN (d = 0.31).
  - Higher resolution floodplain area represented in TIN.
  - Voronoi polygon network (VPN) includes 33,300 nodes.
- Terrain variability captured using methods in Vivoni et al. (2004).
  - Three nested subdomains.
- Land-cover classification performed using several Landsat TM scenes (Hunt et al. 2008).
  - Large regions of subtropical scrubland
  - High elevation oak and evergreen forests.
- Soil texture derived using FAO classifcations (coarse, medium) and terrain slope.
  - High-slope impermeable soils.
  - Low-elevation finer soils.

IIP Stage A: Simulations

Comparisons of simulations at two stations in the basin show good performance in terms of surface moisture and temperature.



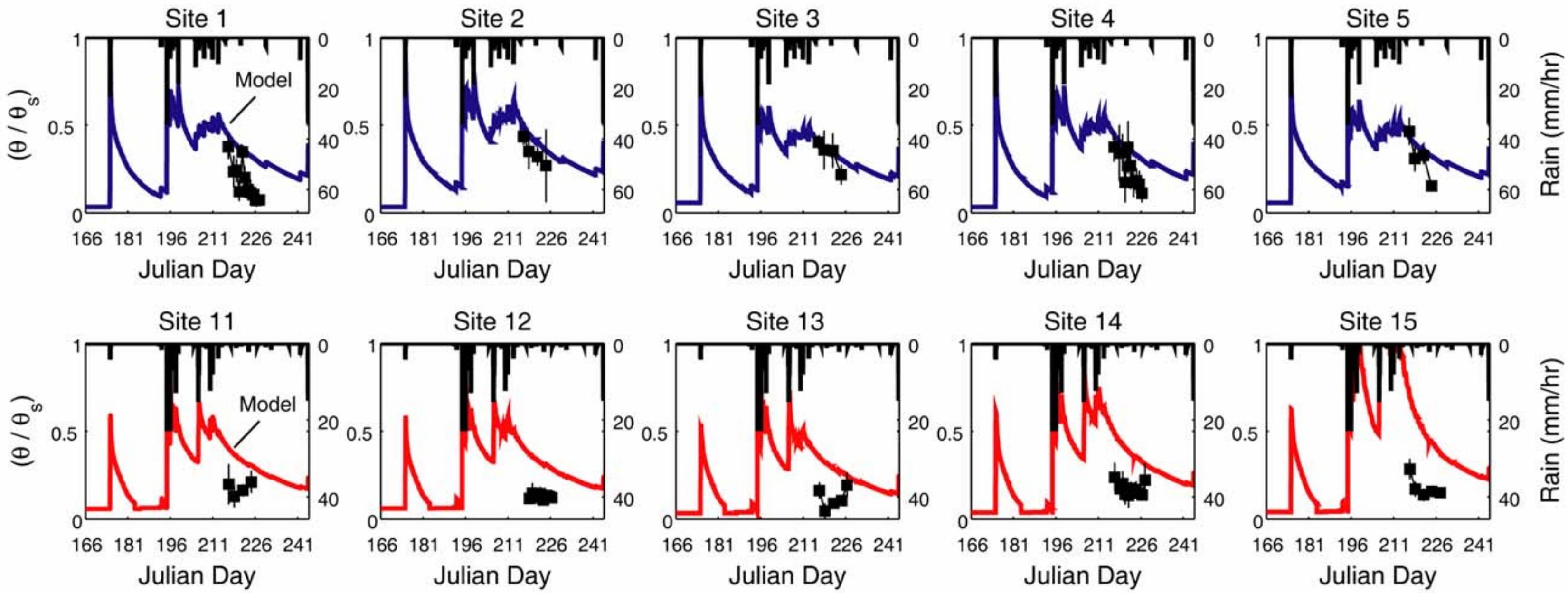
Site 1: Oak Savanna

Site 12: Subtropical Scrub

- Distributed model in Stage A does not yield soil moisture depletions that are sufficiently rapid and surface temperatures (at high elevation) which are too high.
- Exercise suggests improvements in Stage B can be made in the temperature lapse rate and in improved constraints on the soil and vegetation parameters.

IIP Stage A: Simulations

Distributed model simulations of <u>surface soil moisture at a network of locations</u> compared to daily field sampling during SMEX04 (2004).



- Stage A simulations overestimates soil moisture at the lower valley sites (in some cases significantly), while performance is adequate in upper basin locations.
- Suggest improvements are needed in Stage B for the soil texture parameterizations and in the lateral transport of moisture (soil and topographic conditions) to the valley sites.
- <u>Results are encouraging as the distributed comparison among observations and model simulations has not been previously attempted in this dynamic system</u>.

IIP Stage A

<u>Stage A: Lessons Learned</u>

I. *<u>Distributed soil moisture and temperature sampling</u>* and remote sensing indicate topographic controls during drydown periods.

II. *<u>Distributed numerical model performs reasonably well</u>* in soil moisture estimation at distributed locations.

III. *<u>Improvements are necessary in the following areas:</u>*

   a. Characterization of soil properties.
   b. Distributed rainfall measurements.
   c. Air temperature lapse rates.
   d. Improved topographic representation in model.

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IIP Stage B

Stage B: Goals and Objectives

I. *Expanded network of continuous stations* for rainfall, soil moisture, atmospheric conditions in Sierra Los Locos basin.

II. *Distributed soil characterization* based soil profiles and surface samples to train remotely-sensed classification.

III. *Enhanced topographic representation* through remotely-sensed products and improvements to model domain discretization.

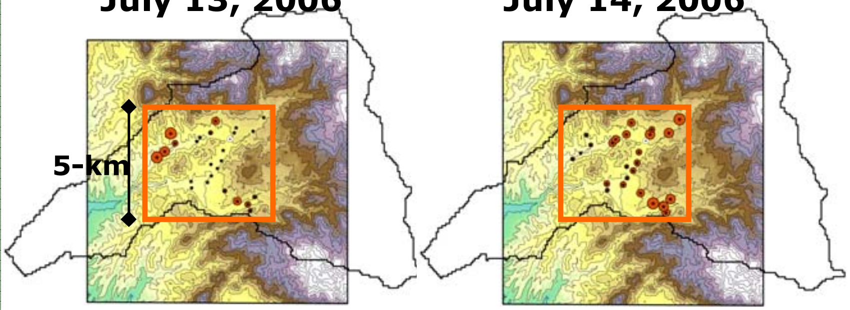
IV. *Improvements in distributed soil moisture simulations* using new data sets and accounting for parameter uncertainty.

V. Expand focus to summers 2004-2007 in Sierra Los Locos.

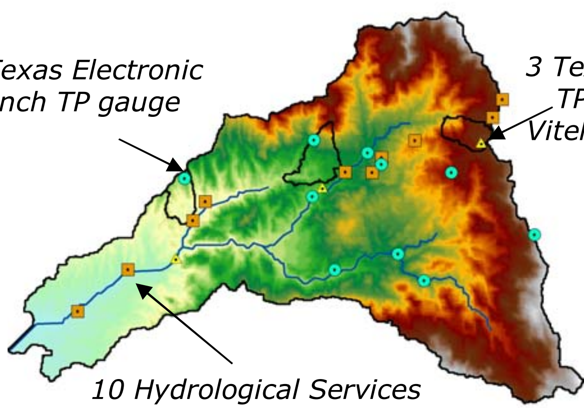
IIP Stage B: Observations

Event Rain Gauge Deployment

July 13, 2006 **July 14, 2006**



Continuous Rain Gauge Network

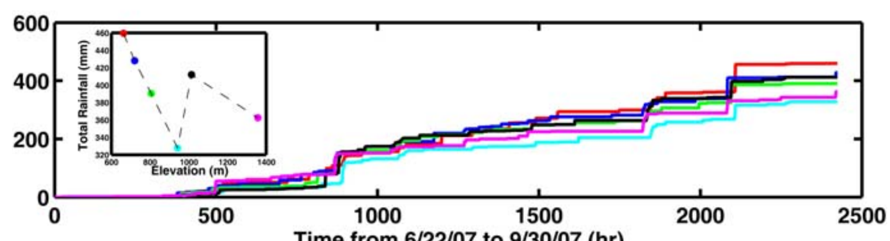


Field Deployment for 2007 included Rainfall Sampling along Elevation Gradient and Spatial Coverage in the Basin.

High-Density Precipitation Observations and Analysis

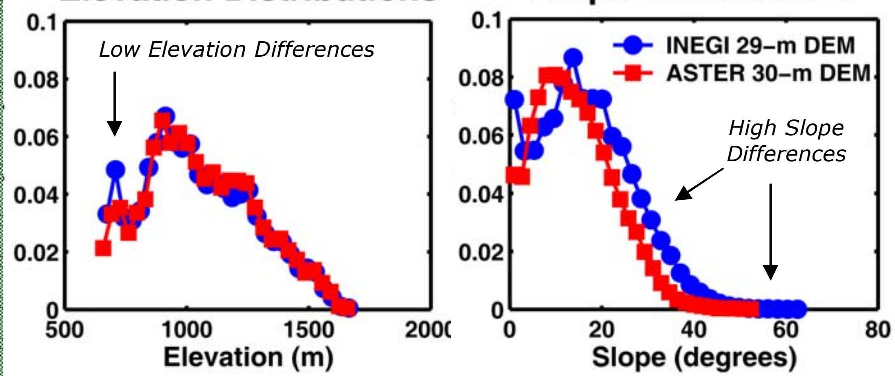
- Based on Stage A, we investigated the spatiotemporal variability of preciptation in the Sierra Los Locos using:
  - Temporary event gauges in 2006.
  - Continuous rain gauges in 2007.
- Precipitation data for 2006 and 2007 monsoon seasons revealed:
  - Strong differences in precipitation character along elevation gradient.
  - Individual storm accumulations can have significant spatial differences.
  - Large observed subgrid spatial variability within 5-km TRMM pixels.

Elevation Gradient of Cumulative Rainfall

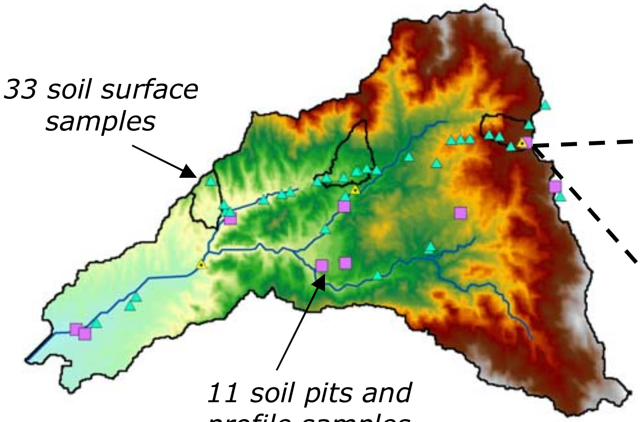


IIP Stage B: Observations

Comparison of DEM Products



Distributed Soil Sampling

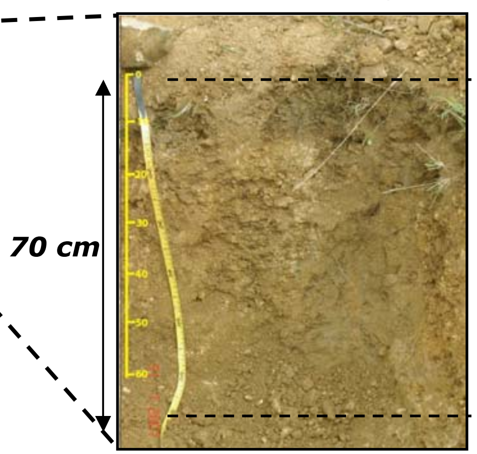


Soil Sampling across Landscape Regions (Alluvial valleys, Mountain ridges) for Analysis of Soil Hydraulic Properties

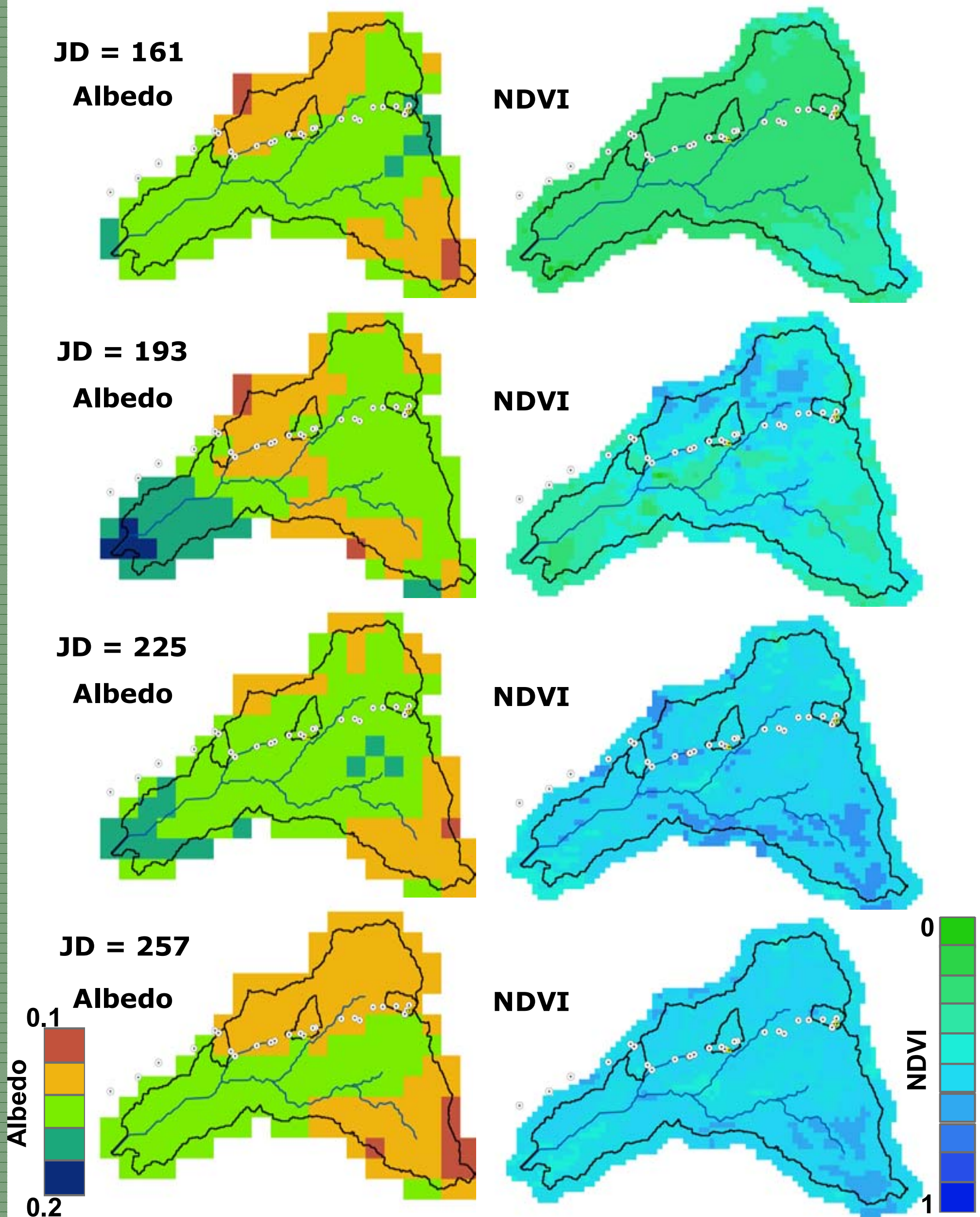
Improved Topographic and Soil Characterization

- Based on Stage A, we obtained a higher vertical accuracy satellite DEM product from ASTER (30-m).
  - Improved elevation and slope fields.
  - ASTER product has less number of high slopes and higher number of low slopes.
- Distributed soil profile sampling conducted in 2007 field campaign.
  - Provide soil texture and hydraulic properties in major landforms.
  - Improve model parameterizations.
  - Useful for remotely-sensed soil mapping.

Oak Savanna Soil Pit



IIP Stage B: Observations

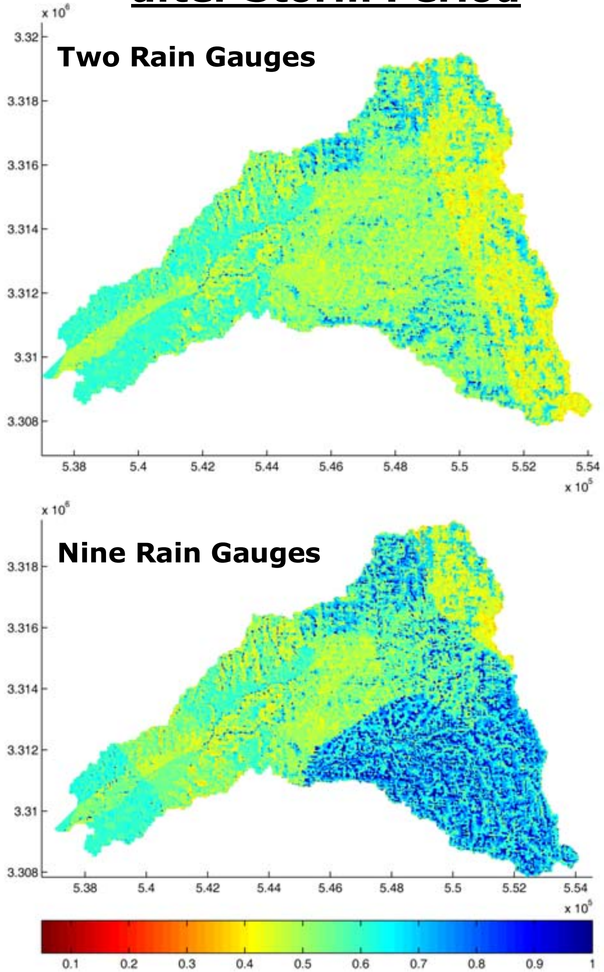


Dynamic Land Surface Conditions in Basin

- We investigated the spatial and temporal changes in land surface conditions using MODIS sensor.
- MODIS composites (16-day) used to determine:
  - A decrease in surface albedo and increase in NDVI with greening.
  - Maximum values observed for julian day 225 (August), 2004.
  - Spatially coherent changes in remotely-sensed parameters.
- Spatial resolution of albedo (1-km) and NDVI (250-m) allow for changes in model parameters in Stage B simulations.

IIP Stage B: Simulations

Soil Moisture Distribution after Storm Period



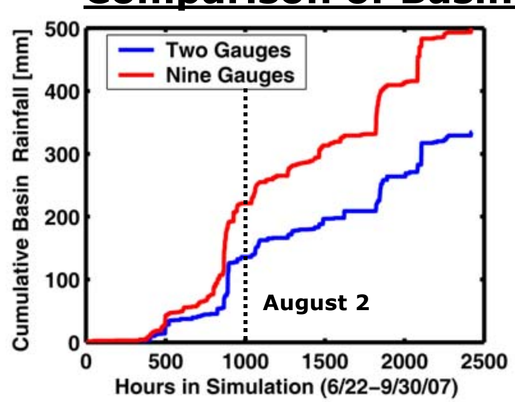
Relative Soil Moisture

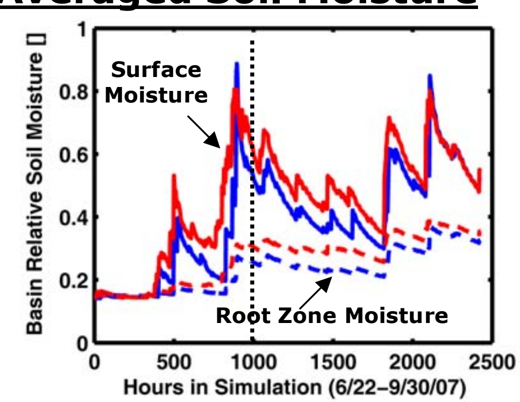
Instantaneous Soil Moisture at August 2, 2007

Distributed Rain Gauge Forcing

- Preliminary simulations for summer 2007 suggest that the high density gauge network improves spatial rainfall forcing.
  - Simulations with two (2) existing locations.
  - Simulations with nine (9) stations (out of 23 possible).
- Simulations in Stage B utilizing the rainfall distributions for summer 2007 revealed:
  - Larger basin accumulation for higher rain gauge density, indicating small-scale, high-intensity events.
  - Differences in the basin-averaged and distributed soil moisture dynamics with higher rainfall resolution.
  - Soil moisture biases introduced by sparse network depend on storm event.

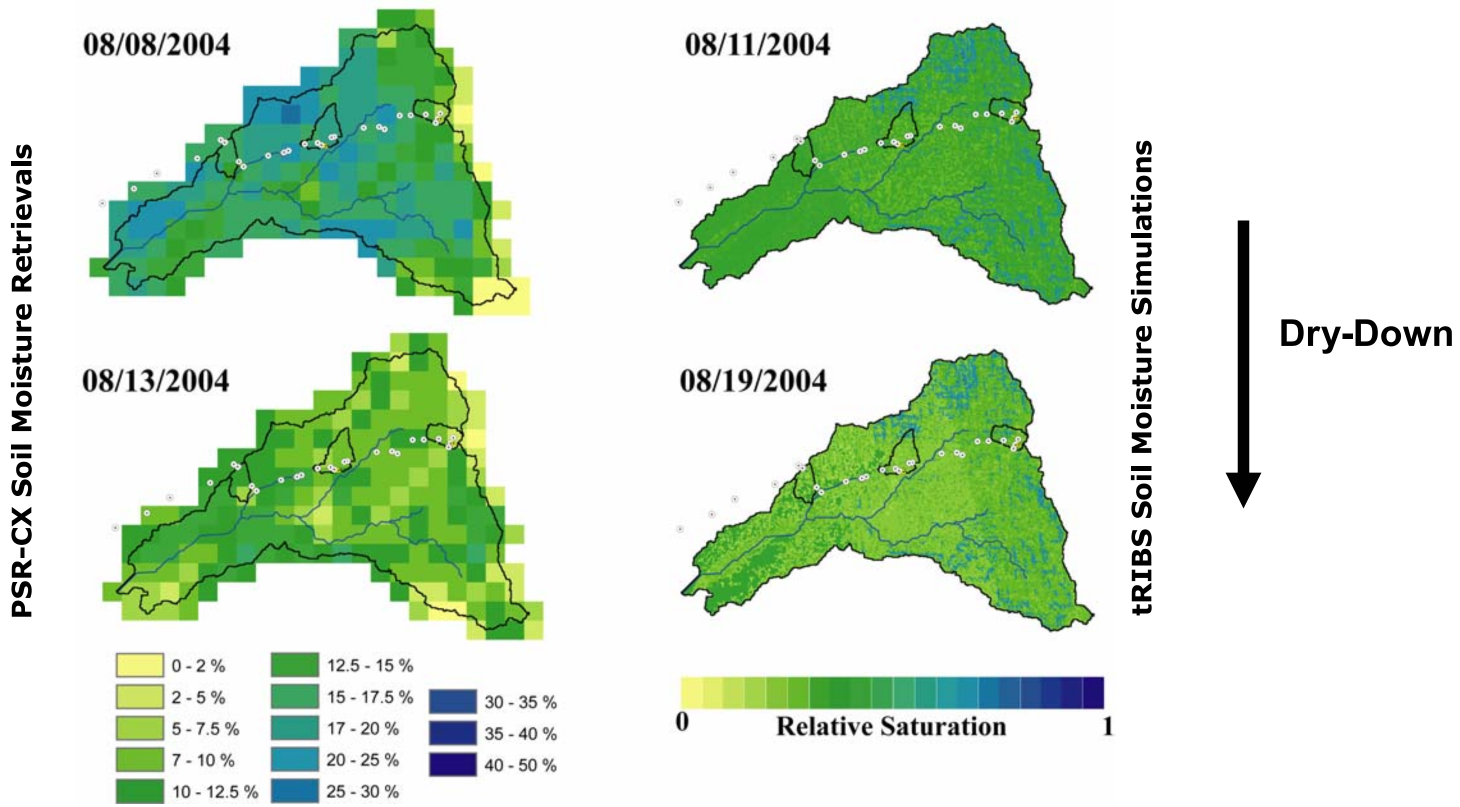
Comparison of Basin-Averaged Soil Moisture





IIP Stage B: Simulations

Distributed model simulations of <u>surface soil moisture in basin capture dry down as compared to remotely-sensed PSR/CX retrievals.</u>



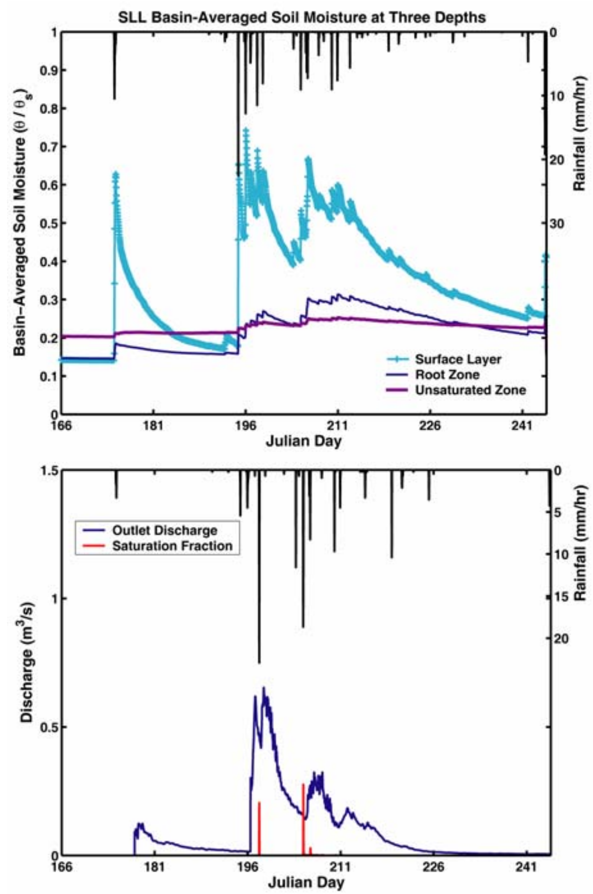
- In Stage B simulations, <u>initial comparisons of the spatial variability in soil moisture</u> during a basin dry-down period are encouraging.
- Comparison of spatial patterns and point-to-point values is required to assess the distributed simulations in more detail.

IIP Stage B: Simulations

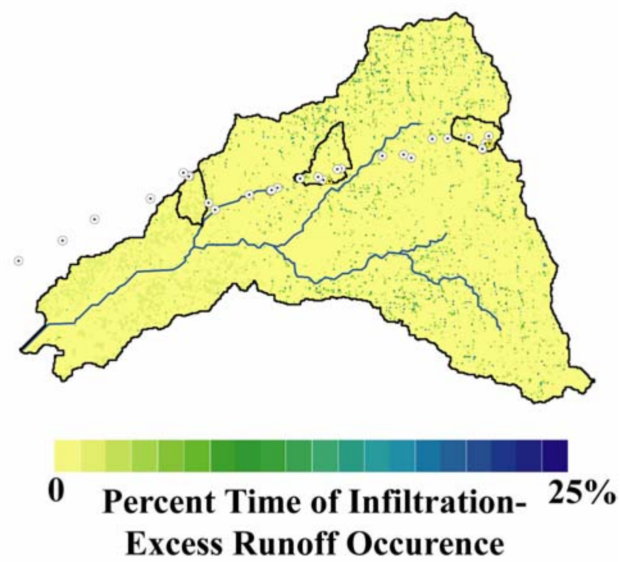
Basin runoff response obtained from simulations will be tested in Stage C through use of new stream gauge network to be installed 2008.

Basin –Averaged Soil Moisture

Basin Discharge and Saturated Area



Distributed Runoff Production



- Observations and numerical experiments of rainfall-runoff processes will allow us to conduct process-based studies on the impact of antecedent moisture on the runoff ratio.

IIP Stage B

Stage B: Lessons Learned

I. *Spatial rainfall variability* *can be captured through dense rain gauge network and used to enhance model simulations.*

II. *Improved characterization of basin topography and soil profile properties* *lead to simulation enhancements (not shown).*

III. *Further work needed in the following areas:*

a. Quantification of spatiotemporal soil moisture results.
b. Incorporation of dynamic land surface properties.
c. Installation of stream gauging sites.
d. Analysis of seasonal controls on basin runoff ratio.

Conclusions and Remarks

1. *NAMS is characterized by strong hydrologic seasonality observed by field data and remote sensing which needs to be captured in process-based, distributed models.*

2. *Distributed hydrological modeling in complex river basins experiencing monsoonal climates can be constrained by:*
    a. *Field campaign observations.*
    b. *Continuous sensing networks.*
    c. *Aircraft and satellite remote sensing.*

3. *An incremental and interactive process for watershed characterization and modeling results in:*
    a. *Step-wise improvements in hydrologic understanding.*
    b. *Direct dialogue between experimentalist and modeler.*
    c. *Simultaneously building a real and virtual observatory in an ungauged basin.*

FIN