Ecohydrology of Seasonally-Green Desert Landscapes

Acknowledgements

Field Data Collection: Luis Mendez-Barroso, Jesus Gomez, Hugo Gutierrez-Jurado, Carlos Aragon, Robert Wyckoff, Alex Rinehart, Venkat Lakshmi, Tom Jackson, Christopher Watts, Jaime Garatuza, Juan Saiz, Enrico Yepez, Soni Yatheendradas, Julio Rodriguez, and more than 20 other SMEX04 and IRES student participants from Sonora, Mexico.

Data Analysis and Modeling: Mekonnen Gebremichael, David Gochis, Luis Mendez-Barroso, Rajat Bindlish, Christopher Watts, Soni Yatheendradas, Francina Dominguez.

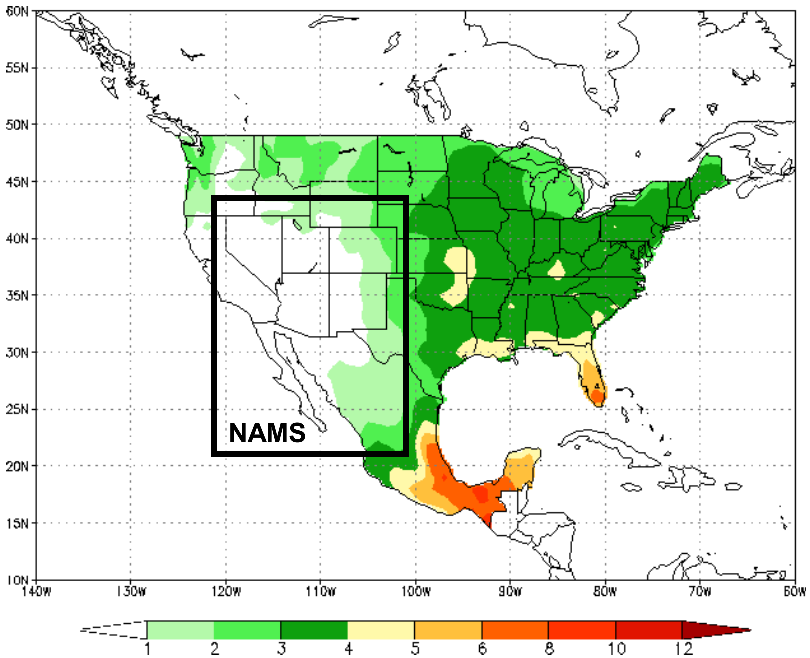
Funding Support: USDA, NSF Office of International Programs, NOAA Climate Program Office, CONACYT.

- North American Monsoon Experiment (NAME)
- Soil Moisture Experiment 2004 (SMEX04)
- Sonora IRES Campaigns 2006-2008

Motivation

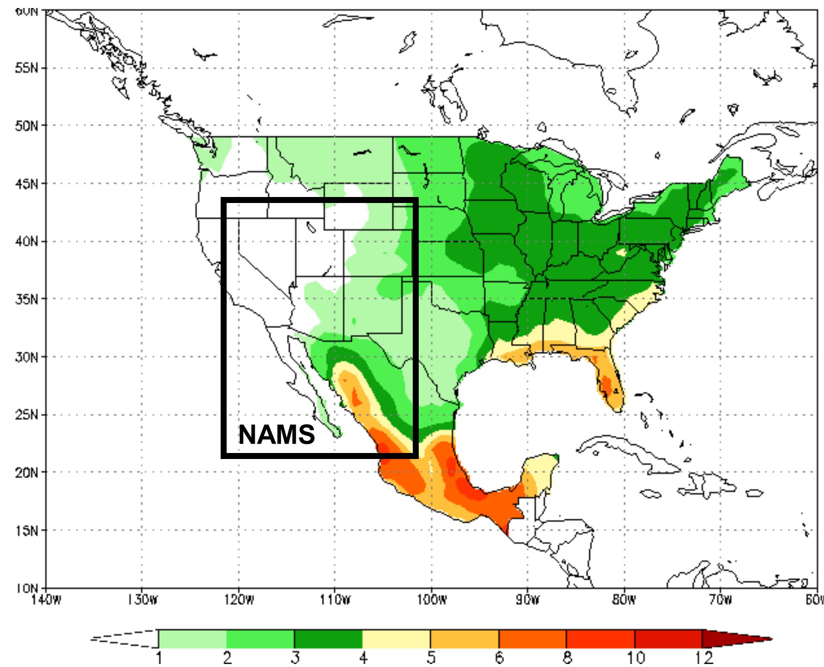
The North American Monsoon System (NAMS) is a seasonal change in atmospheric circulation leading to increased summer precipitation (July, August, September) in the southwestern US and northwestern Mexico.

June Climatology



Rainfall (mm/day)

July Climatology

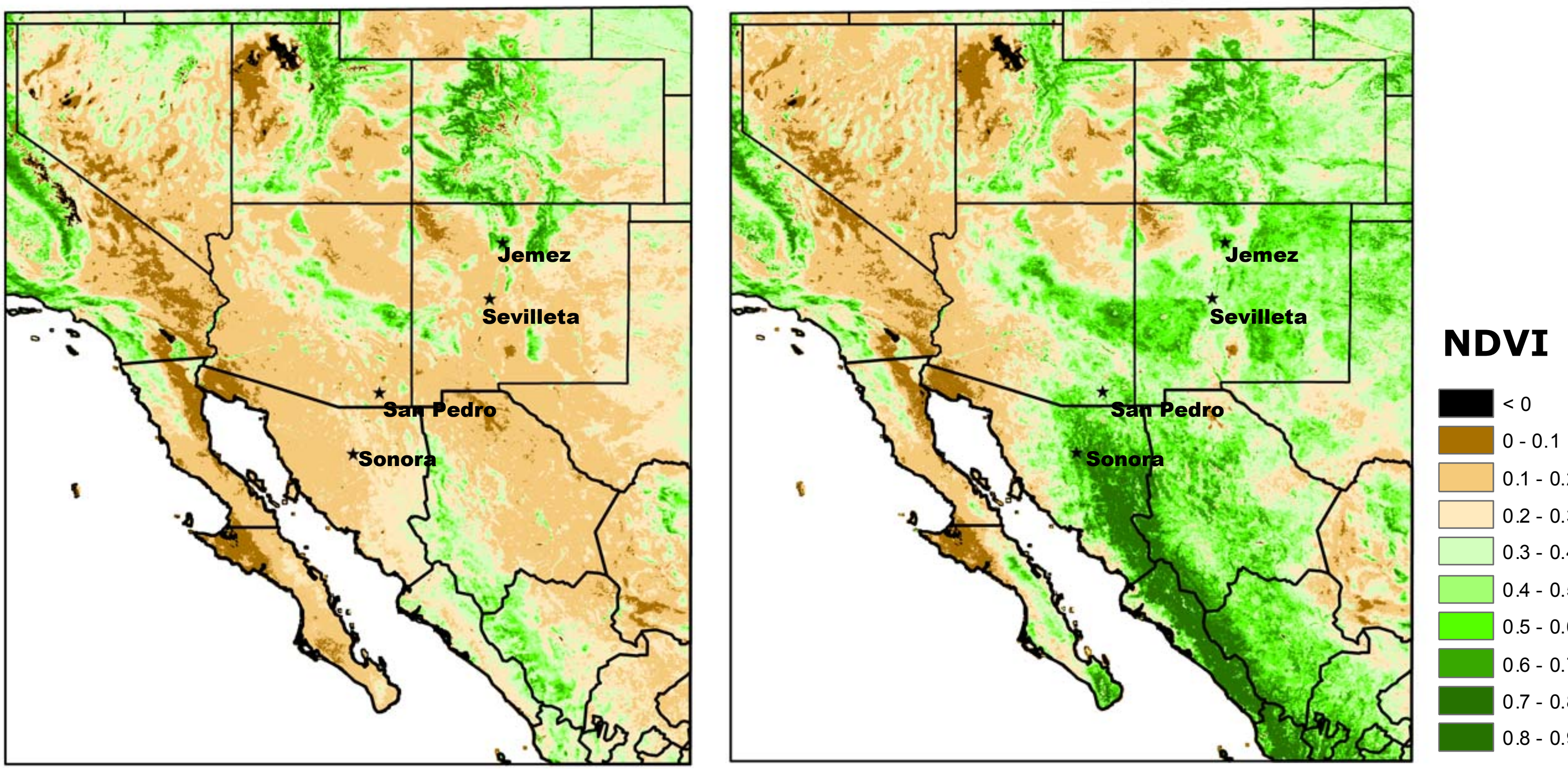


Rainfall (mm/day)

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

Motivation

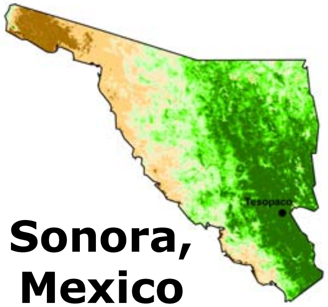
Precipitation during the NAMS leads to a strong vegetation response consisting of leaf-on of subtropical deciduous species over the complex topography in western Mexico.



June 1, 2006 **September 1, 2006**

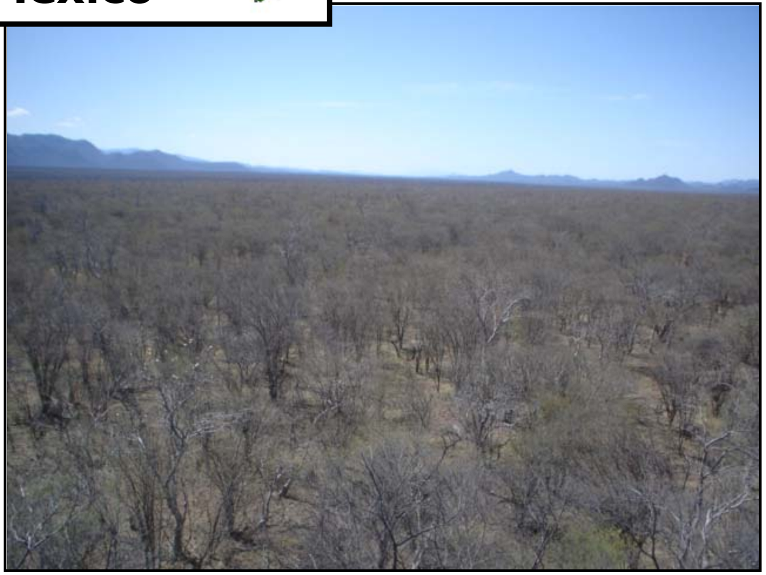
SPOT VEGETATION 2 Product, 1-km resolution
10-day composite, Normalized Difference Vegetation Index

Motivation



Sonora, Mexico

Seasonality in precipitation and vegetation has potential impacts on land-atmosphere interactions, runoff production and groundwater recharge.



Winter Conditions

Summer Monsoon Conditions

Photographs from 15-m Eddy Covariance Tower in Deciduous Subtropical Forest in Tesopaco, Sonora, Mexico

Motivating Questions

Research Questions:

- *What are the spatiotemporal ecohydrological patterns and how are these interrelated on seasonal and interannual scales?*
- *How does topography influence ecohydrological conditions in monsoon-dominated, semiarid climates?*
- *What is the role played by seasonal vegetation cover on the dynamics of the monsoon and hydrological basin responses?*

Notes:

- *We will discuss a range of hydrological analysis varying in scale from point to large river basin.*
- *Remote sensing, field instrumentation and numerical modeling approaches integrated in the assessment.*
- *Interesting "new" questions arising from the current research will be highlighted and discussed in the seminar.*

Outline

Ecohydrology of Seasonally-Green Deserts:

1. **Land Surface Hydrology in NAMS:**

   Spatiotemporal variability of ecohydrological processes.

2. **Topographic Controls on Ecohydrology in NAMS:**

   Process organization along semiarid mountain fronts.

3. **Land-atmosphere Interactions in NAMS:**

   Concurrent effects of vegetation on precipitation recycling.

4. **Numerical Modeling of NAMS Hydrology:**

   Spatiotemporal variability of simulated soil moisture.

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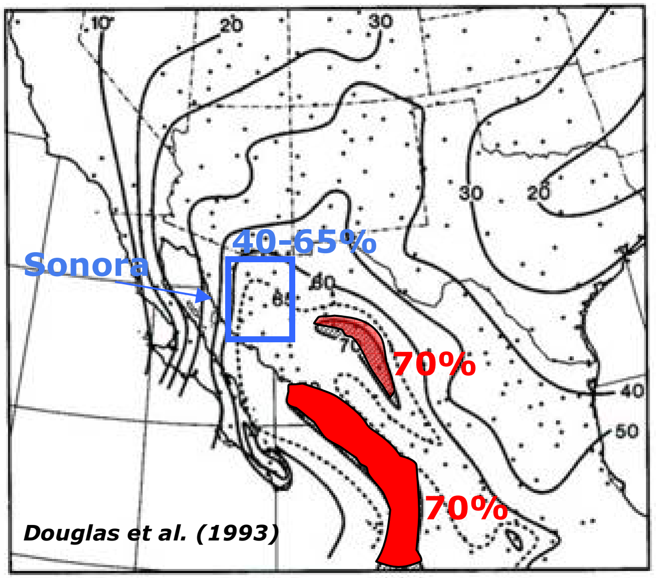
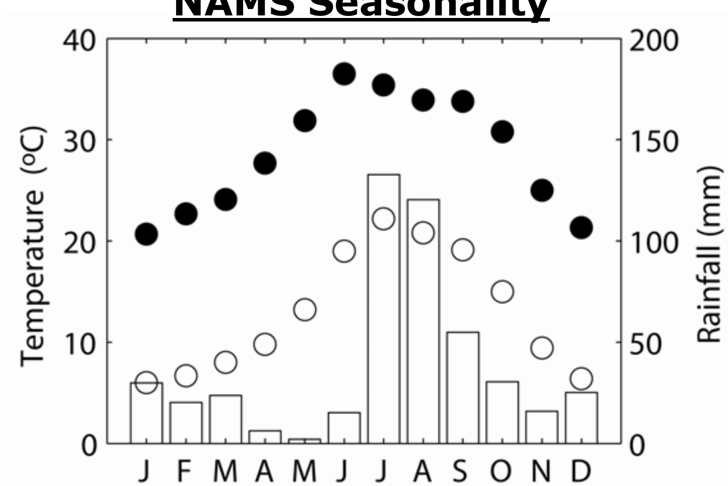
Regional Context

Annual Rainfall in NAMS



NAMS Seasonality



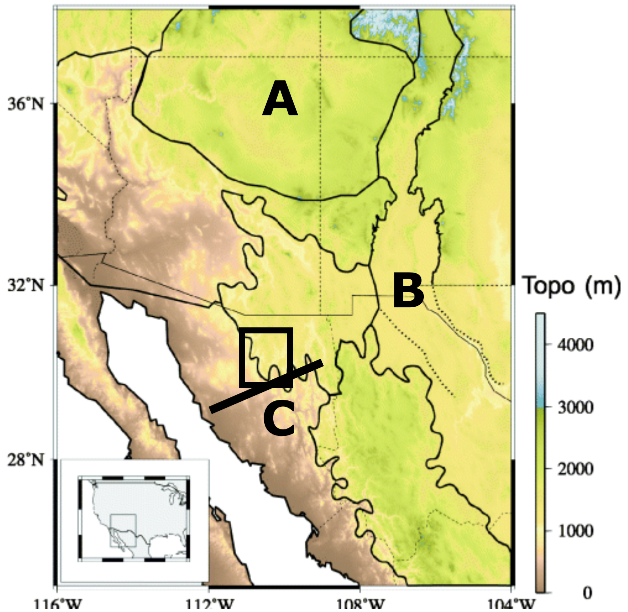
Vivoni et al. (2007)

NAMS Hydroclimatology

- NAMS is regional atmospheric circulation bringing southerly moist tropical air into southwestern North America.
- Changes in synoptic scale patterns lead to monsoon onset in late June-early July:
  - Thermal heating over desert SW leads to low pressure center.
  - Formation of low-level jet in Gulf of California and Gulf of Mexico.
  - Moisture inflow and convective instability along orographic features.
- NAMS leads to strong seasonality in the temperature, precipitation and lower atmosphere conditions during the months of July-August-September (JAS).
- Strong interannual variability exists in the NAMS hydroclimatology, including its onset, duration and rainfall accumulation.

Regional Context

Physiographic Regions



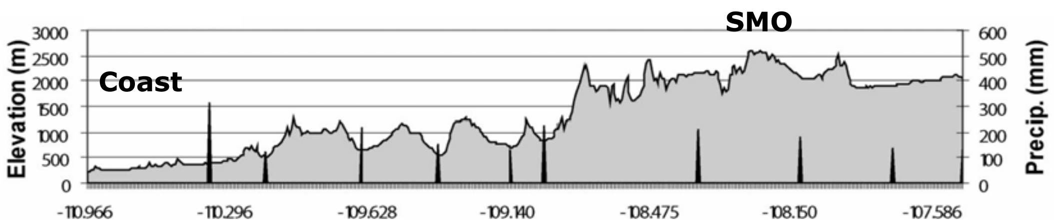
Coblentz and Riitters (2004)

A: Colorado Plateau
B: Rio Grande Rift
C: Sierra Madre Occidental

NAMS Regional Topography

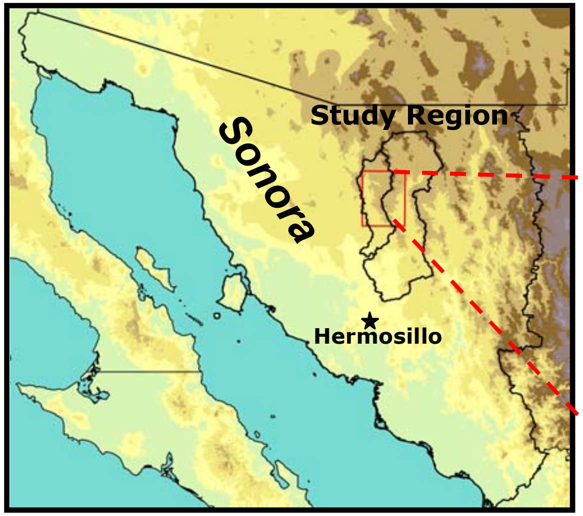
- Southwestern North America is a region of <u>complex topography</u> organized into several physiographic regions.
- Along the Sierra Madre Occidental (SMO), <u>elevation increases sharply away from the coast</u> creating a topographic barrier.
- Topographic complexity leads to strong <u>gradients in precipitation and ecosystem</u> distribution in the SMO region:
  - Orography plays a role in both winter and summer season precipitation distribution.
  - A high level of biodiversity is observed along topographic gradients in Sonoran desert.

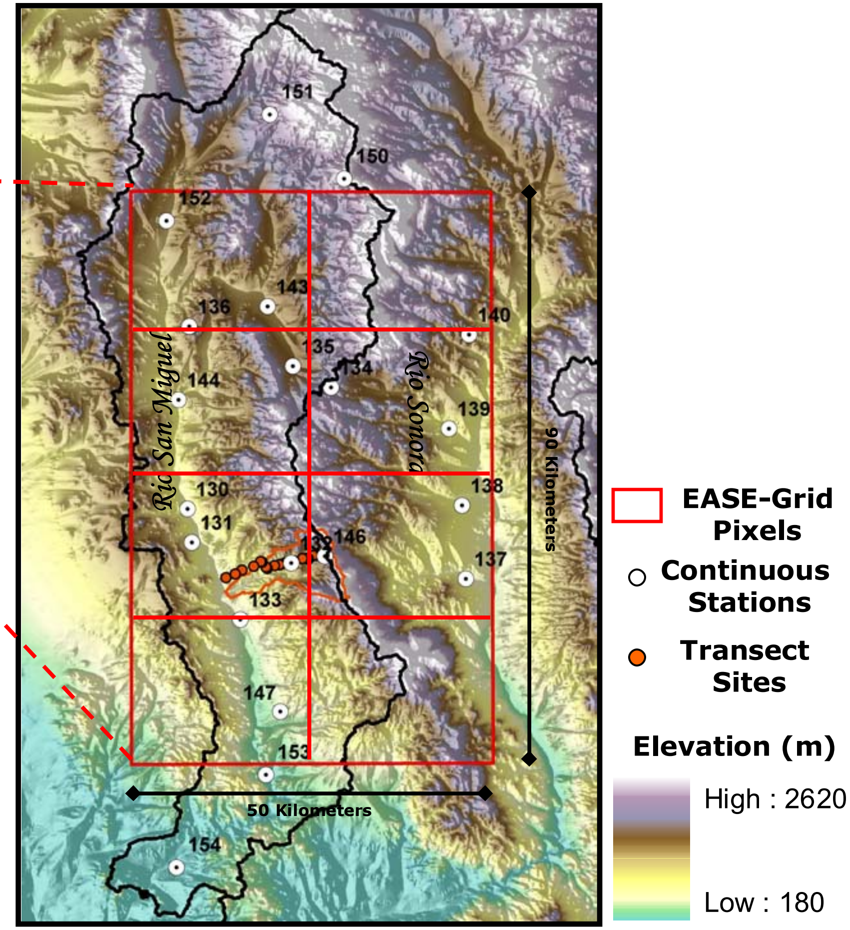
NERN Rain Gauge Transect in SMO



Gochis et al. (2004)

Intensive Study Basins





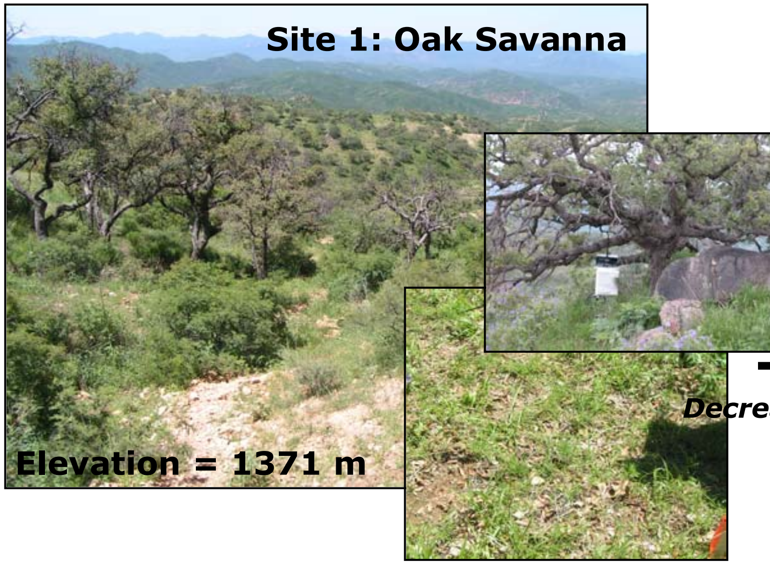
Rio Sonora Study Basins

- 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 ridges and two major rivers: **Rio San Miguel, Rio Sonora**.
- Complex topography with semiarid monsoon climate, seasonally-green vegetation and ephemeral streams.

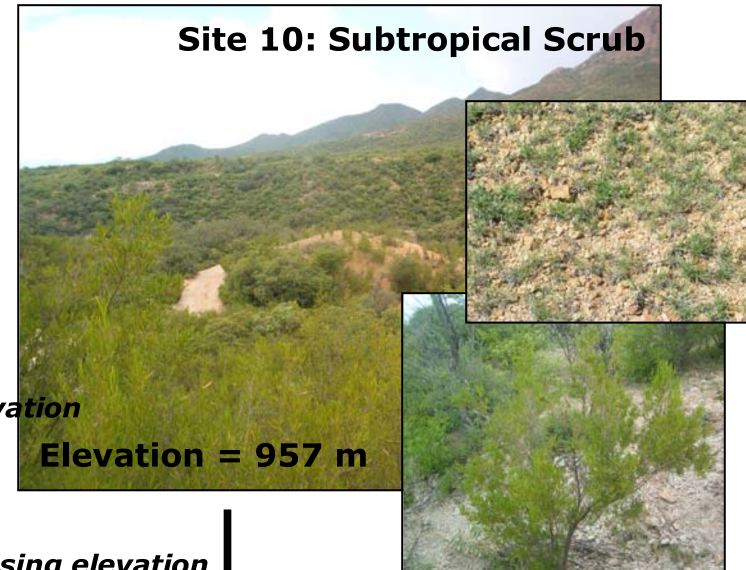
SMEX 2004: Soil Moisture Field Campaign
NAME 2004: Eddy Covariance Tower Network
Sonora IRES: (2006-2008) Rainfall Experiments
Eddy Covariance Experiments
Expanded Hydromet Network

Intensive Study Basins

Ecosystems Along Topographic Transects

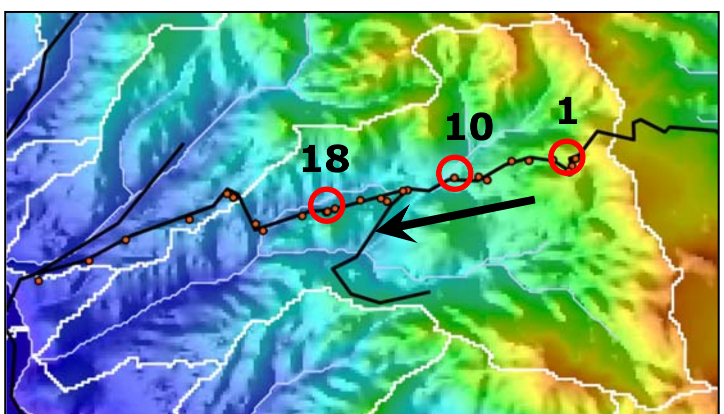


Decreasing elevation

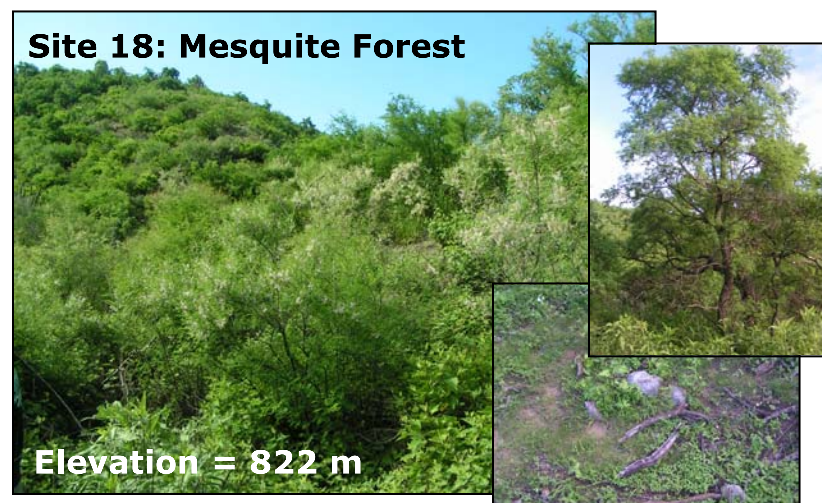


Decreasing elevation

<u>**Transect Site Locations**</u>

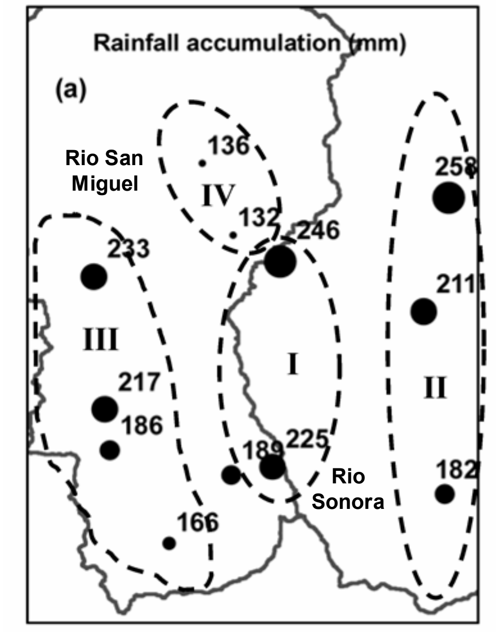


East-Flowing Transect Watershed

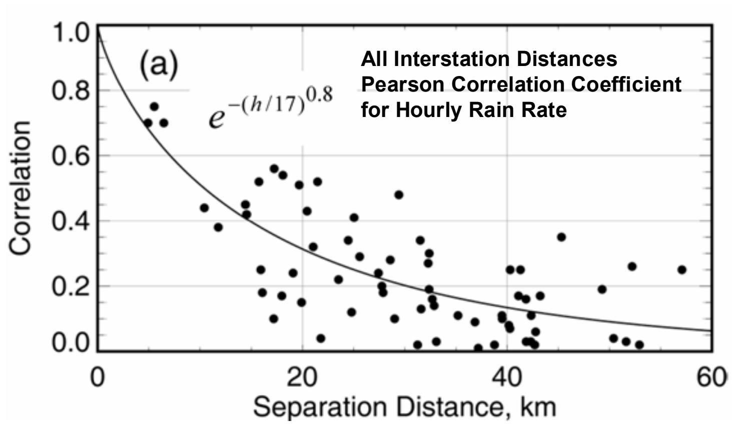


Rainfall Analysis

Spatial Precipitation Coherency



Spatial Correlation Analysis



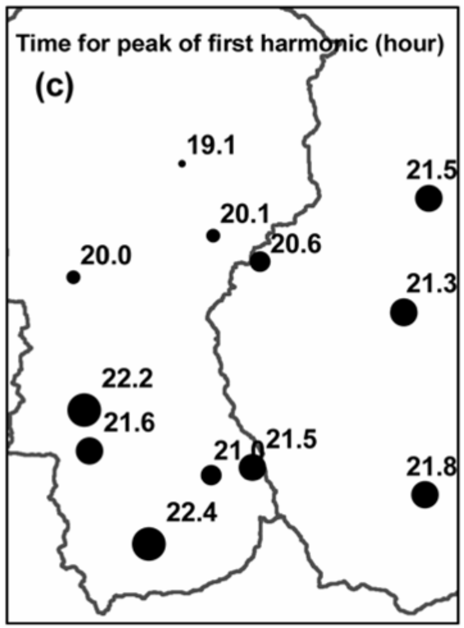
Regional Precipitation Observations and Analysis

- We investigated the spatiotemporal precipitation variability using the Rio Sonora rain gauge network (12 sites).
- Hourly precipitation data for 2004 monsoon season (JA) revealed:
  - Four subregions (I to IV) organized along valleys and mountain ranges had similar spatiotemporal variability in the domain.
  - Strong north-to-south variations in rain statistics (total rainfall, maximum intensity, rain occurrence, coefficient of variation).
  - Precipitation varies strongly with elevation. High-intensity, infrequent storms in valleys. Low-intensity, frequent events in mountains.
  - Spatial correlation distances of hourly rainfall rates was 17 km. Rain occurence revealed storm radii <5 km in the region.

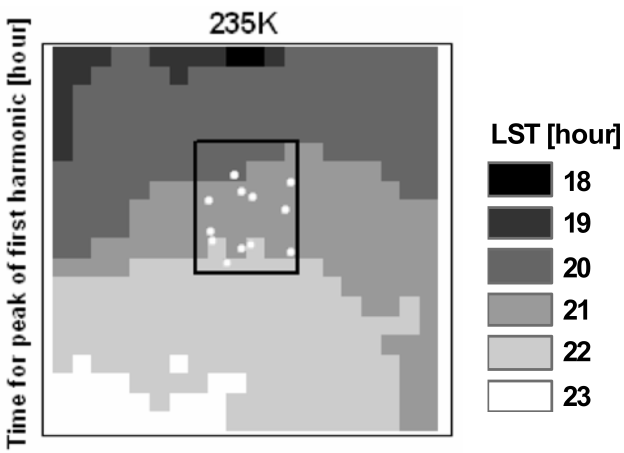
Additional Details in Gebremichael, Vivoni et al. (2007), Journal of Climate

Rainfall Analysis

Diurnal Rainfall Frequency Peak



GOES Time of Peak Cloud Cover



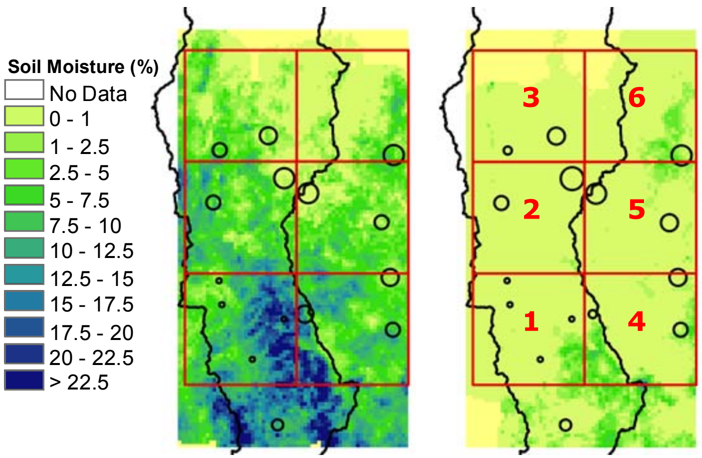
Diurnal Cycle of Cloud Cover and Precipitation

- A strong diurnal rainfall cycle was found with peak rain intensity and occurence occuring in the early evening and night.
- Strength of the diurnal cycle increases from north to south, with later evening peaks further south in the domain.
- Rain gauge analysis was complemented with GOES IR Cloud Top temperature:
  - Strong diurnal cloud cover for temperature thresholds for low, middle, high clouds.
  - Strong north-to-south variation in time of peak cloud cover and diurnal strength.

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

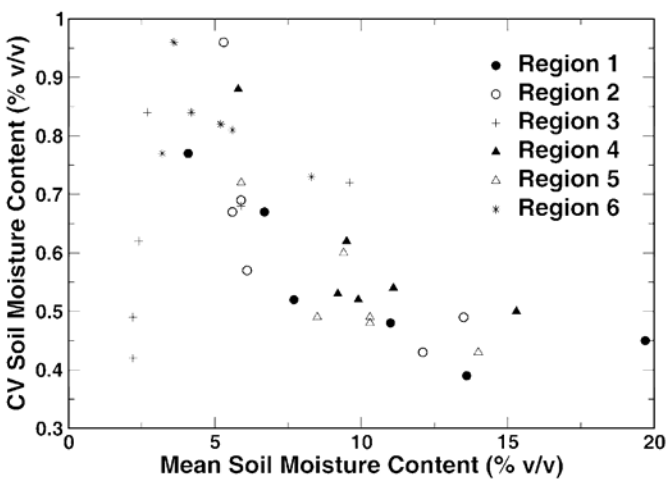
Soil Moisture Analysis

Spatial Soil Moisture Variability from Ground and Aircraft Sensors



Aug 5, 2004 **Aug 25, 2004**

PSR/CX Statistical Properties



Regional Soil Moisture Observations and Analysis

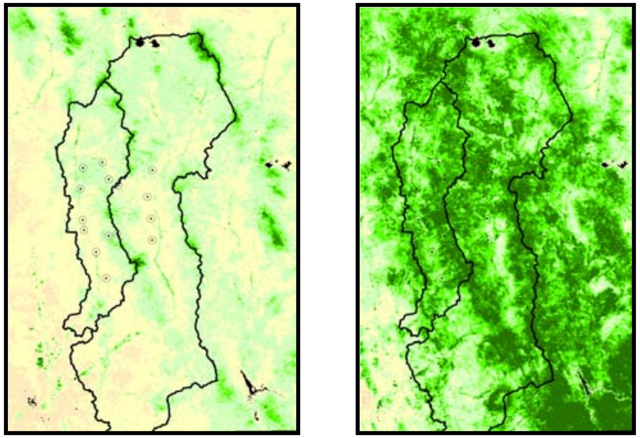
- We investigated the spatiotemporal soil moisture variability using the Rio Sonora network (14 sites).
- Comparisons made between ground and aircraft-based (PSR/CX 800-m) estimates within 6 AMSR-E (25.6-km) pixels.
- Strong spatial variability in soil moisture from PSR/CX aircraft estimates:
  - Higher soil moisture in the southern part of the domain along specific elevation bands.
  - Spatial correlation distances ranging from 2 to 14-km depending on day and region.
  - Decreasing spatial variability with increasing wetness for most regions.

Additional Details in Bindlish et al. (2008), Gebremichael and Vivoni (2008) and Vivoni et al. (2008), Remote Sensing of Environment

Vegetation Analysis

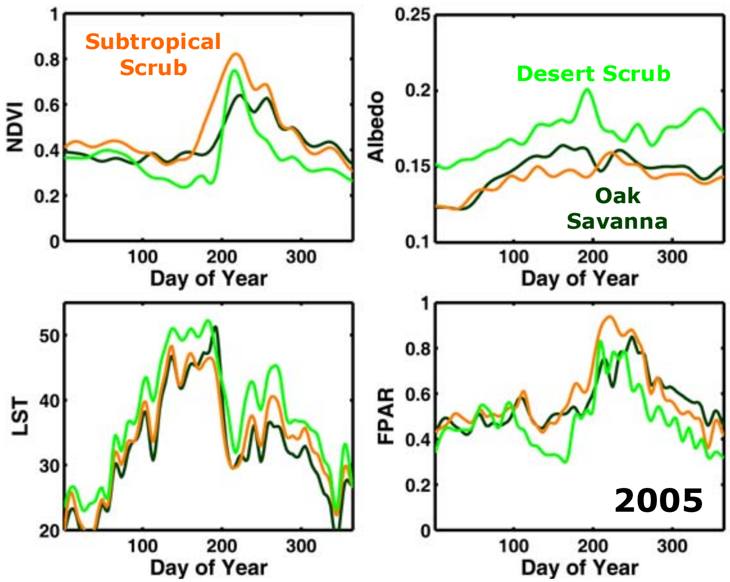
Satellite Vegetation Estimates

NDVI, 250-m, 16-day



May 25, 2005 **Aug 29, 2005**

Annual Cycle of Surface Conditions



Regional Vegetation Observations and Analysis

- We investigated the spatiotemporal variability in land surface conditions using remotely-sensed MODIS products.
- Multiday composites from MODIS AQUA for three years (2004-2006) revealed:
  - High seasonal and interannual variability in albedo, surface temperature, vegetation indices (NDVI, EVI, LAI) and fraction of photosynthetically active radiation.
  - Discernable differences among ecosystems to the monsoon and winter precipitaiton.
  - Variations in NDVI, albedo and LST follow anticipated trends during NAMS season and suggest potential for atmospheric feedback.

How is the vegetation response linked to the site precipitation and soil moisture conditions?

> On-going work on vegetation-hydrology relations

Additional Details in Mendez-Barroso, Vivoni et al (2008), Journal of Hydrology (in review)

Outline

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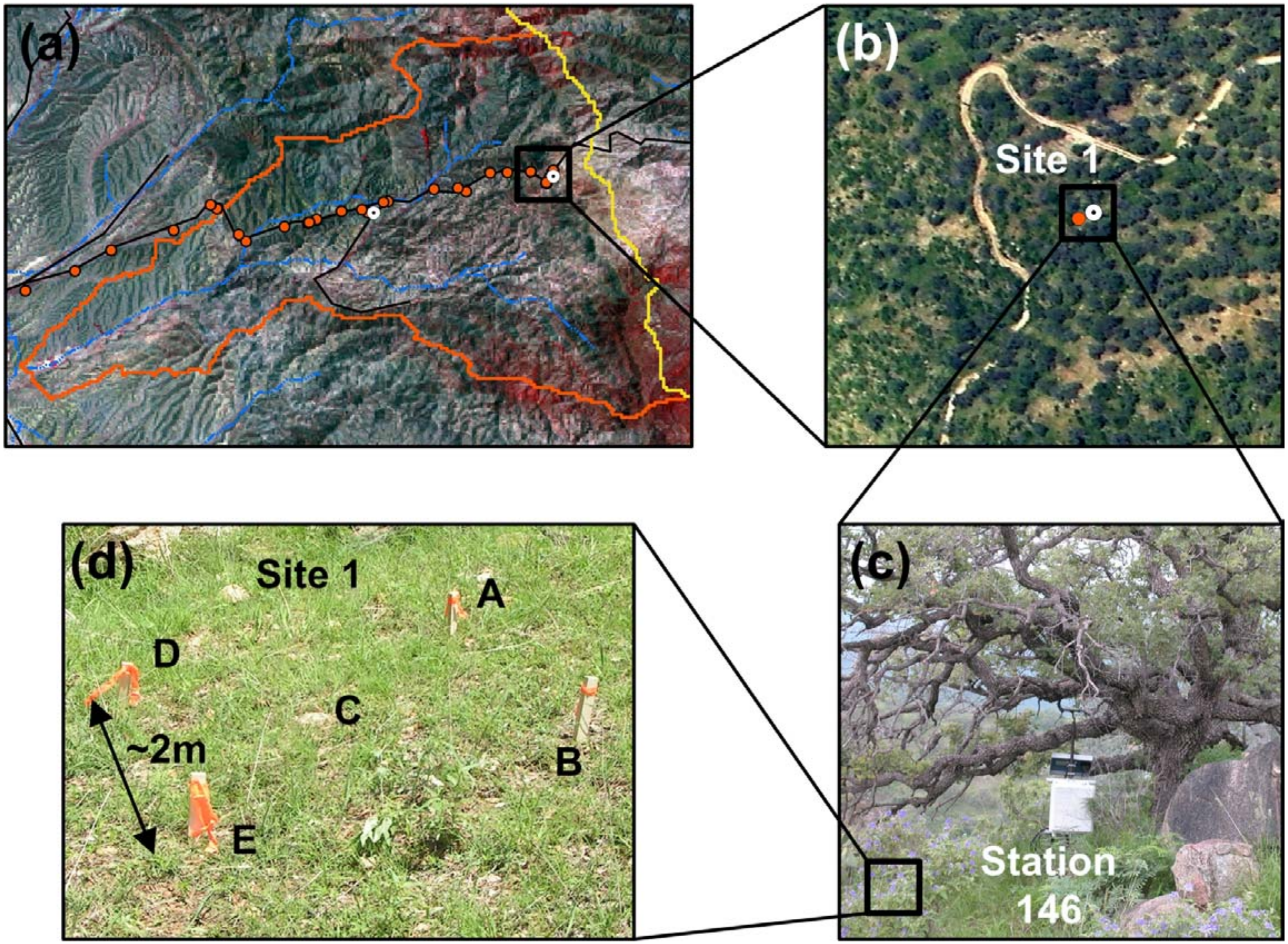
Intensive Study Transect

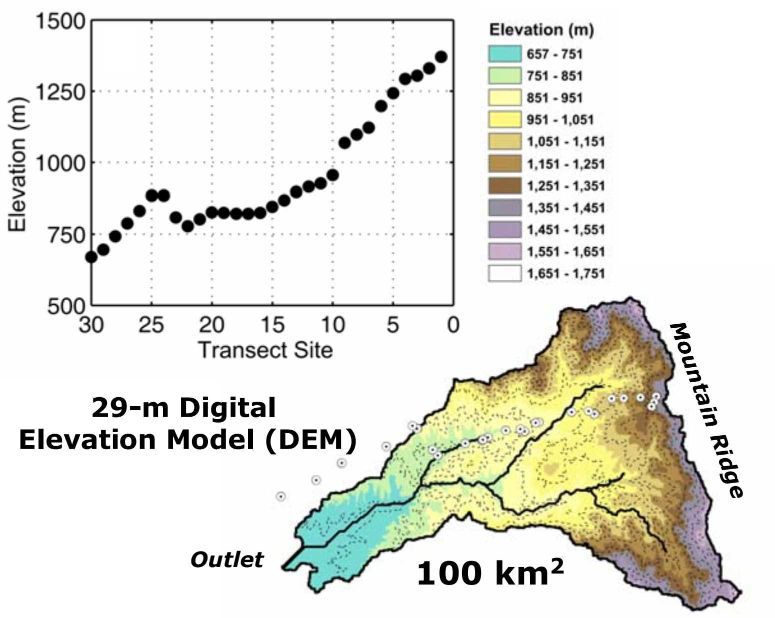
Satellite Remote Sensing **Aircraft Remote Sensing**



Plot-Scale Measurements **Regional Stations**

Intensive Study Transect

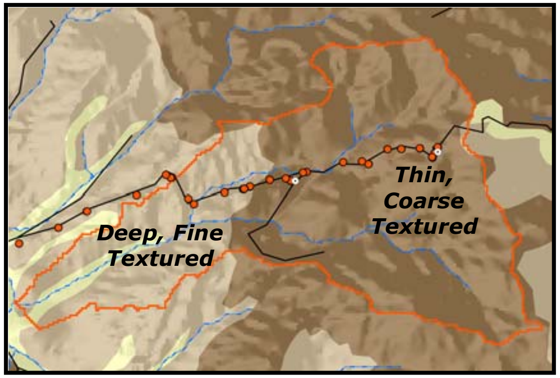
Transect Terrain Distribution

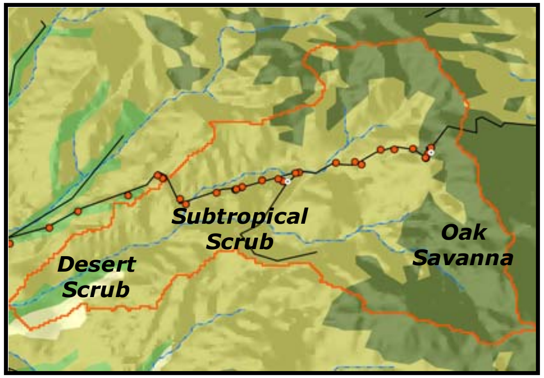


Topographic Transect

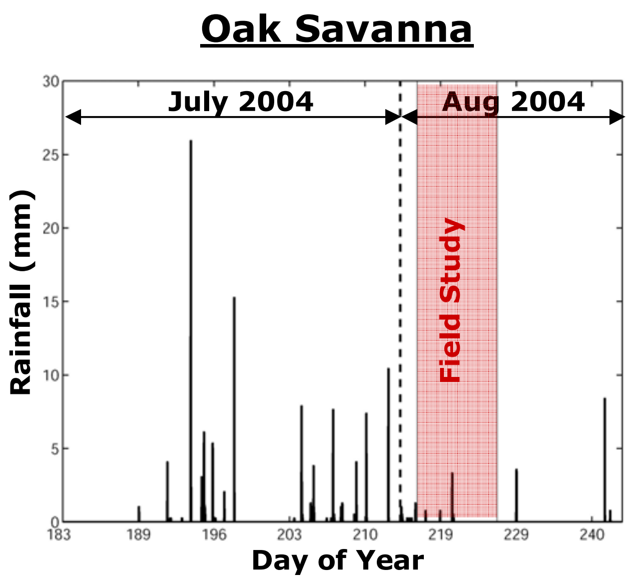
- We sampled a 22-km topographic transect along a rural mountain road in the Rio Sonora study region.
- The transect elevations vary from 668 m to 1371 m over the domain, leading to 0.032 m/m average slope.
- Strong topographic control on the distribution of soils and vegetation:
  - Deeper, finer soils at lower elevations
  - Woody species at higher elevations

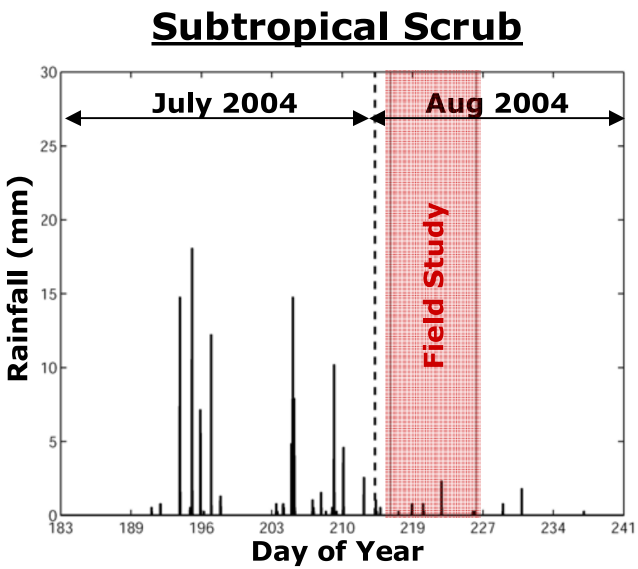
Transect Soil and Vegetation Distributions





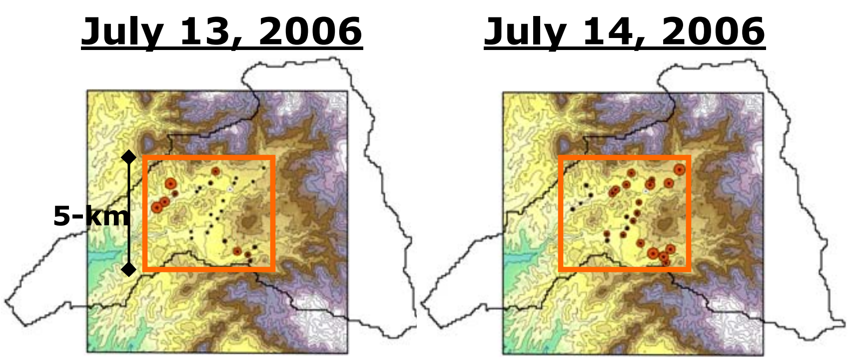
Rainfall Analysis





Transect Precipitation Observations and Analysis

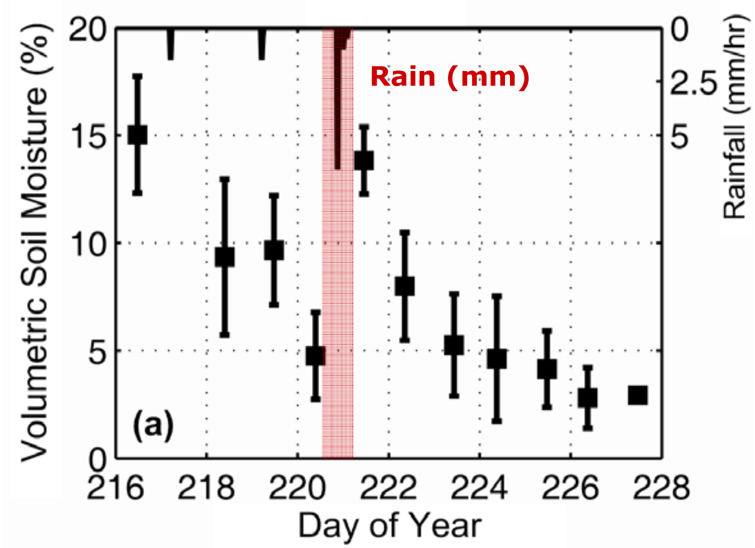
- We investigated the effect of elevation on precipitation using two continuous rain gauges and temporary event gauges.
- Precipitation data for 2004 and 2006 monsoon seasons revealed:
  - Differences in precipitation character along the topographic transect.
  - Individual storm accumulations can have significant spatial differences.
  - Large observed subgrid spatial variability within 5-km TRMM pixels.



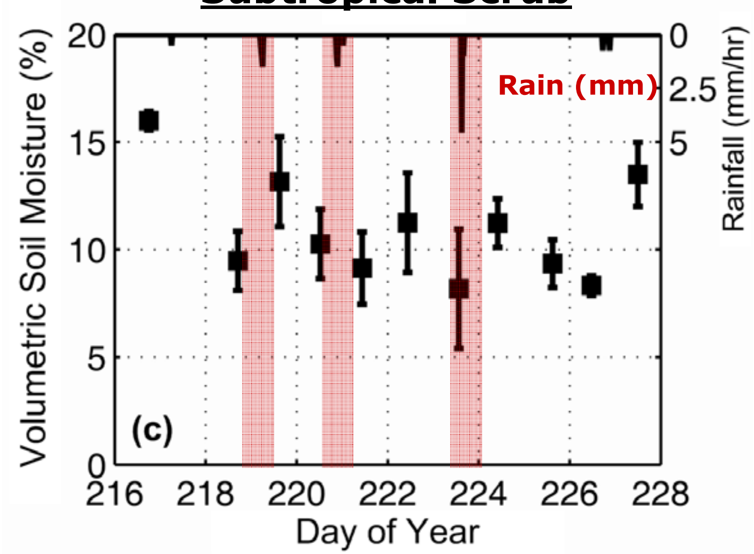
Additional Details in Vivoni et al. (2007), Journal of Climate and Vivoni et al. (in preparation)

Soil Moisture Analysis

Oak Savanna



Subtropical Scrub



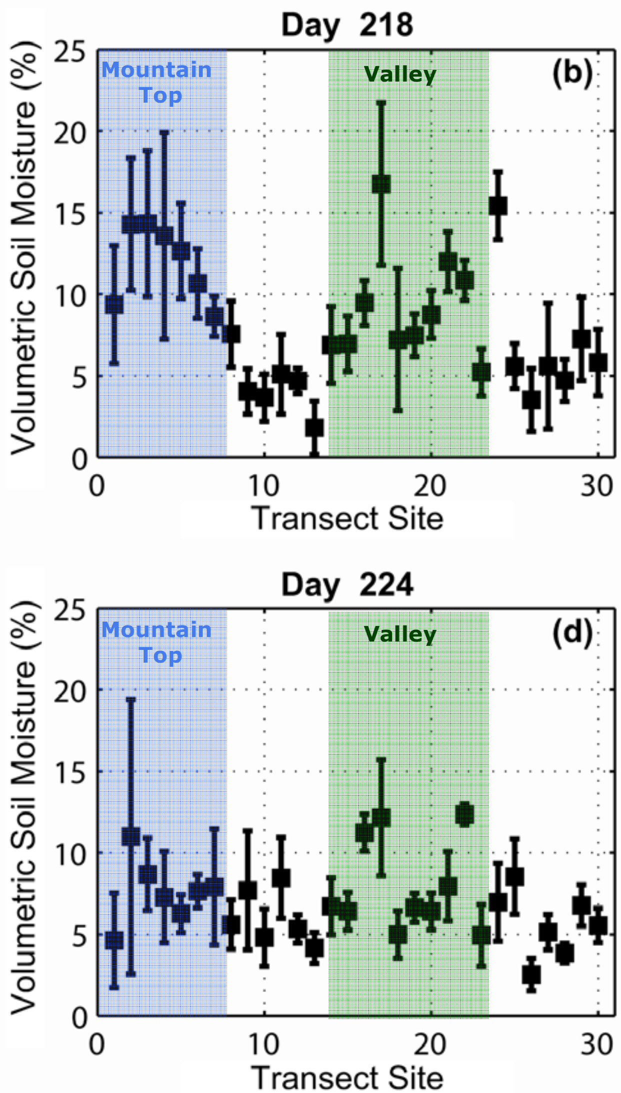
Transect Soil Moisture Observations and Analysis

- We investigated the spatiotemporal variation of soil moisture along the transect based on 30 sampling sites.
- Good agreement between soil moisture sampling, continuous sensor data and gravimetric analysis.
- Soil moisture data from the SMEX04 Field Campaign (Aug 3 - 14, 2004) revealed:
  - Intense soil moisture response to localized rainfall events along transect.
  - 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.

Additional Details in Vivoni et al. (2007), Journal of Climate

Soil Moisture Analysis

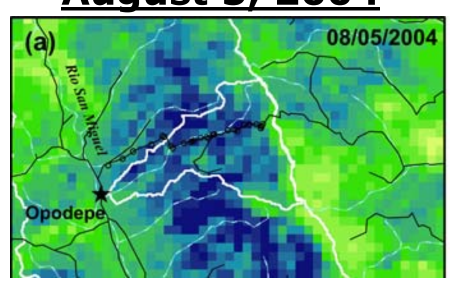
Transect Profiles



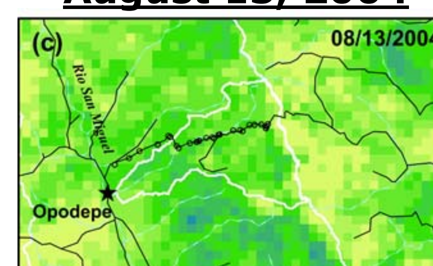
Soil Moisture Drydown along Topographic Transect

- A land surface drydown observed due to the monsoon break with a strong terrain control:
  - Distinct behavior in soil moisture time series for different elevation regions.
  - 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 from PSR/CX soil moisture estimates over transect basin.

August 5, 2004



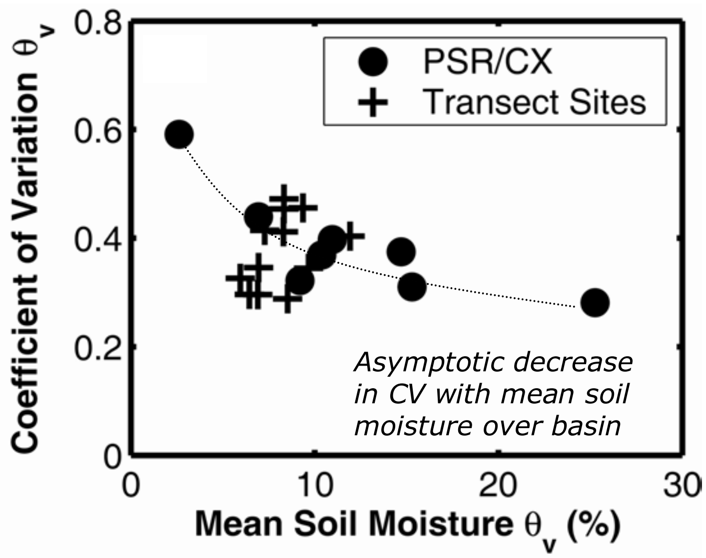
August 13, 2004



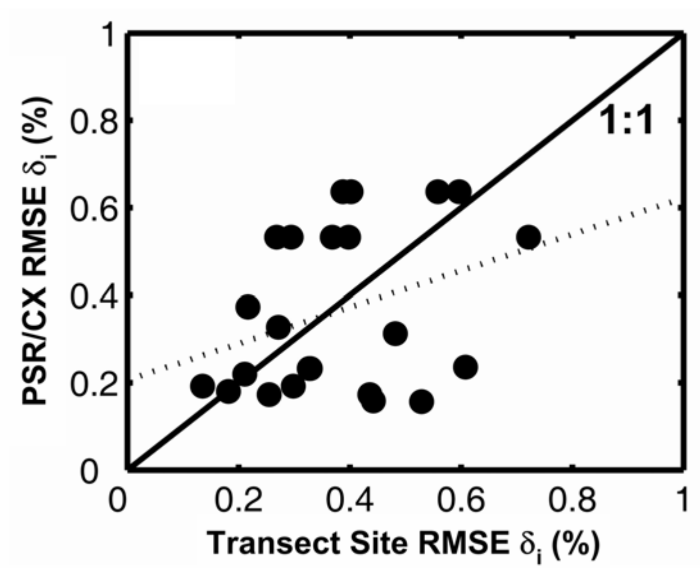
Additional Details in Vivoni et al. (2007), Journal of Climate

Soil Moisture Analysis

Statistical Properties



Time Stability Comparison



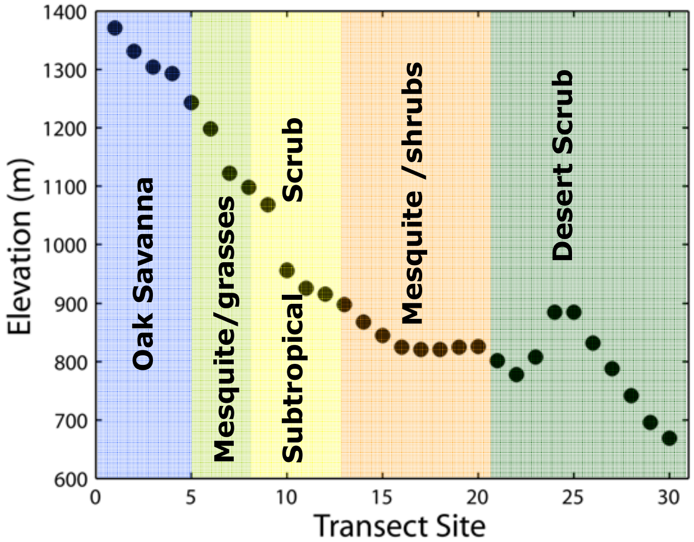
Statistical Comparison of Soil Moisture Observations

- We studied the statistical properties of the soil moisture data from ground and aircraft remote sensing (PSR/CX):
  - Statistical characterization
  - Time stability analysis
  - Joint frequency analysis with terrain attributes.
- Analysis revealed discrepancies in absolute magnitudes, but similar statistical and time stability behavior:
  - Increasing standard deviation and decreasing CV for higher soil moisture conditions.
  - PSR/CX has a wider range of absolute soil moisture conditions in basin.
  - Co-located PSR/CX and Transect sites exhibit similar time-stability patterns.

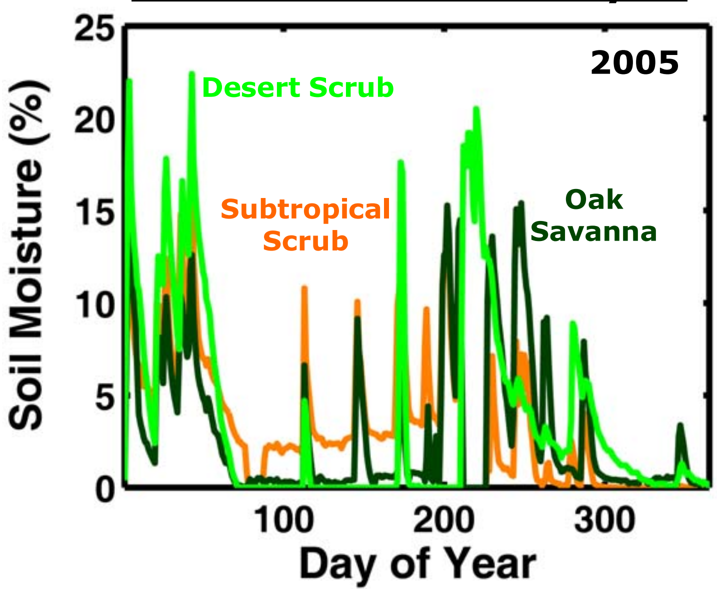
Additional Details in Vivoni et al. (2007), Remote Sensing of Environment

Vegetation Analysis

Topographic Distribution



Annual Soil Moisture Cycle



Soil Moisture Variation in Transect Ecosystems

- Transect observations indicate that the ecosystems are characterized by different soil moisture regimes:
  - Seasonal pattern of soil moisture dynamics varies between ecosystems.
  - Vegetation exerts control on moisture availability via transpiration which varies with season (evergreen vs deciduous).
  - Rates of soil moisture depletion are tied to the vegetation phenology and ecophysiological constraints.

How do hydrologic regimes lead to species organization with topography?

> On-going work on ecohydrological simulations

Oak Savanna

Subtropical Scrub

Desert Scrub

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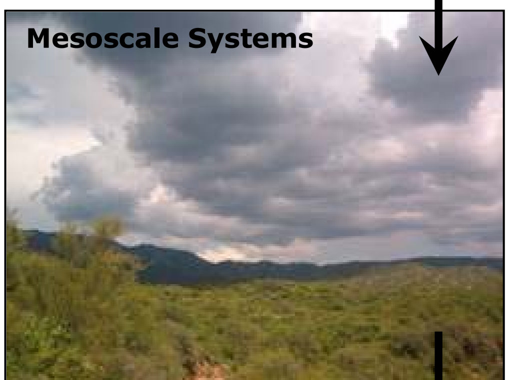
Land-Atmosphere Analysis

Early Afternoon

Storm Growth

Late Afternoon - Night



Rainfall-Runoff

Night - Next Day

Diurnal Precipitation Cycle and Land-Surface Fluxes

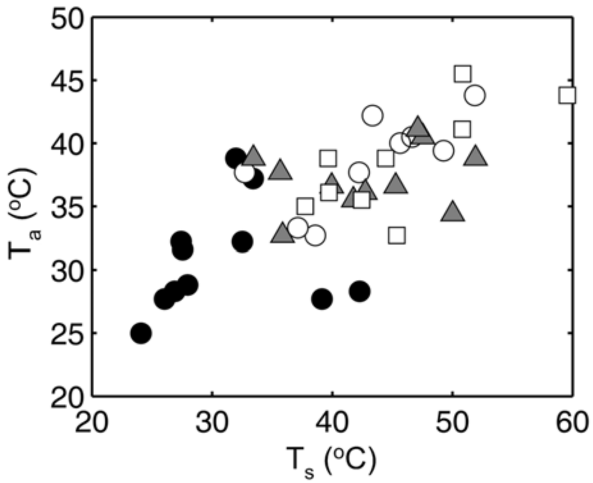
- Convection over mountain terrain leads to single and multiple cell storms which move downslope toward valleys or coastal plains.

- The ecosystems arranged along mountain slopes should play an important role in the precipitation diurnal cycle.

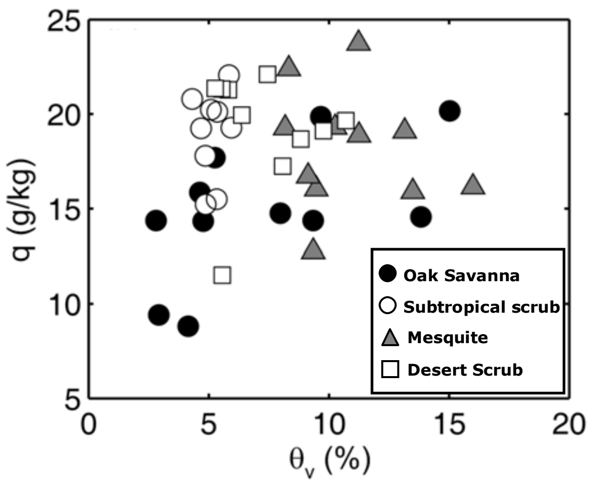
- Regional observations of storm-interstorm dynamics suggests:
  - Rainfall from thunderstorms of short-duration, yet high-intensity.
  - Soil profiles absorb water and excess runoff is transported through ephemeral channels.
  - During widespread rainfall, river flooding and aquifer recharge are produced.
  - Vegetation responds to rainfall, immediately increasing its transpiration rates.

Land-Atmosphere Analysis

Surface and Air Temperature Relationship



Specific Humidity and Soil Moisture Relationship



Observations and Analysis of Land-Atmosphere Coupling

- We conducted simultaneous measurements of land-surface and atmospheric conditions along the topographic transect.
  - Surface temperature and soil moisture
  - Air temperature and specific humidity
  - Other meteorological variables

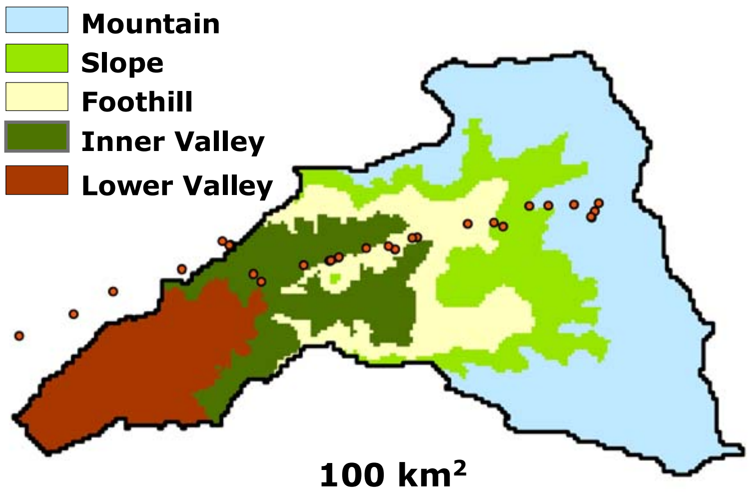
- Analysis revealed a strong relation between land and atmospheric variables:
  - Site-specific relations for each ecosystem for specific humidity and soil moisture conditions.
  - High contribution of specific humidity for low soil moisture in the subtropical scrub.
  - Coupling of land surface-atmosphere variables suggest potential for atmospheric feedback.

What are the ecosystem-specific contributions to the recycling of moisture to the atmosphere?

> On-going investigation of ET-soil moisture relations

Additional Details in Vivoni et al. (2007), Journal of Climate

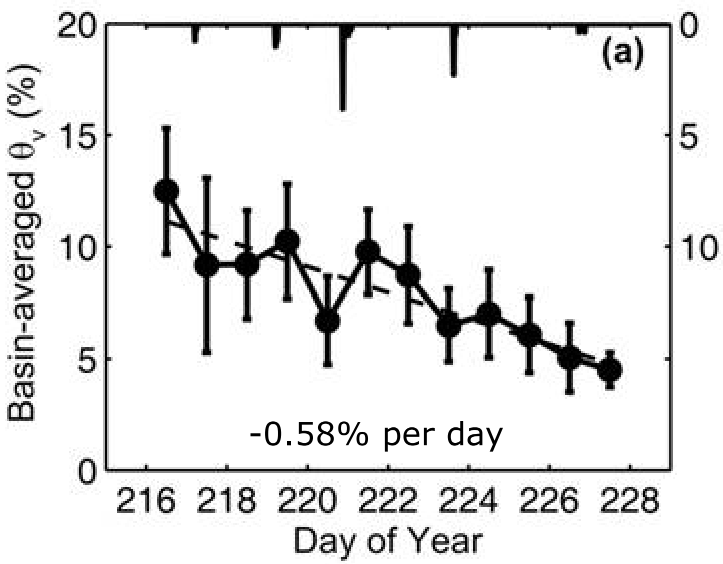
Land-Atmosphere Analysis



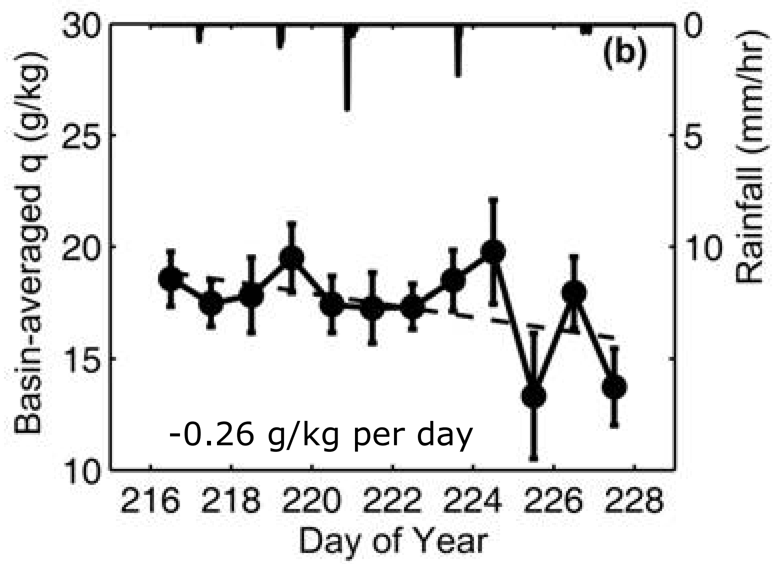
Land-Atmosphere Interactions Averaged over Basin

- We averaged soil moisture and specific humidity using the basin hypsometry.
- Analysis revealed that surface drying lowered atmospheric humidity.
- Suggests that land-surface is important for sustaining convective activity.

Mean Soil Moisture Evolution

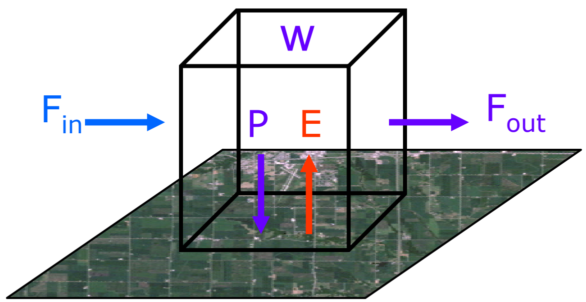


Mean Specific Humidity Evolution



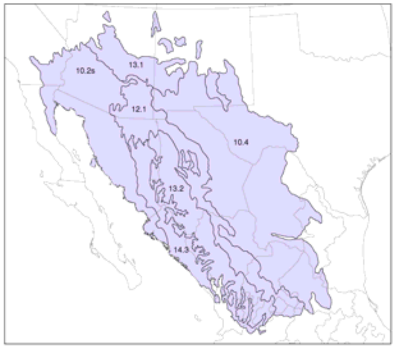
Precipitation Recycling

Dynamic Precipitation Recycling Model

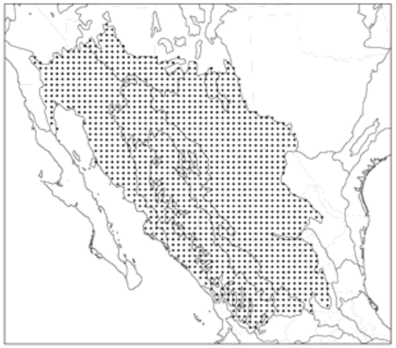


Dominguez and Kumar (2008), Journal of Climate

Application to NAMS Ecoregions



Level II Ecoregions



NARR Grid Points (32-km)

Additional Details in Dominguez , Kumar and Vivoni (2008), Journal of Climate

NAMS Precipitation Recycling

- We investigated the effect of the land surface on regional precipitation using a dynamic recycling model:
  - Accounts for transient water vapor storage in addition to advection.

$$\frac{\partial w}{\partial t} + \frac{\partial (wu)}{\partial x} + \frac{\partial (wv)}{\partial y} = E - P$$

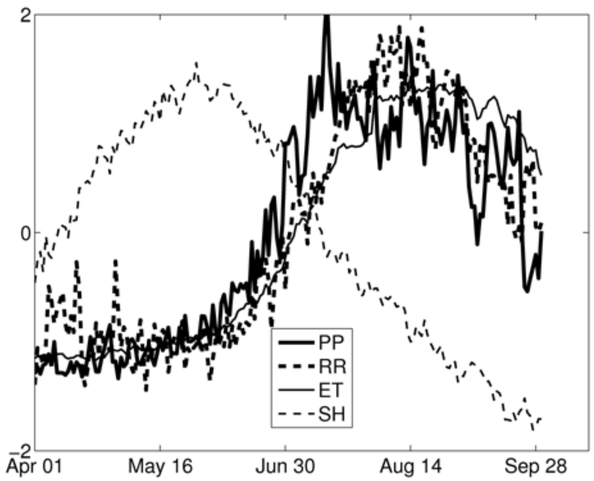
  - Tracks local recycling ratio (R) along advection pathway.

$$R = 1 - \exp\left[- \int_0^{\tau} \frac{E}{w} d\tau' \right]$$

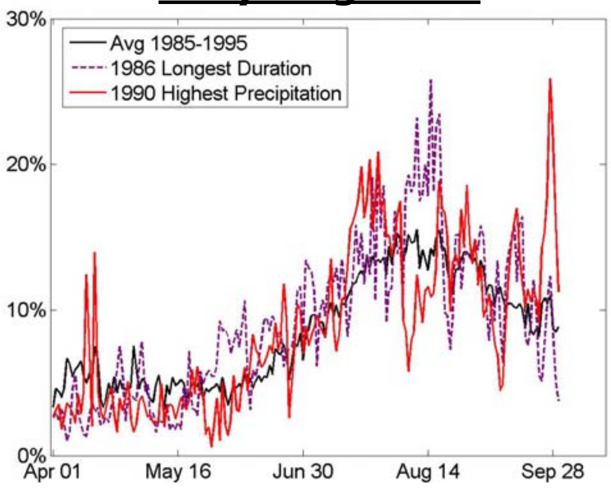
- Utilized North American Regional Reanalysis (NARR) dataset:
  - Atmospheric and surface parameters.
  - 32-km, three-hourly data set.
  - 1985-1995 period spanning intense and weak monsoons.
  - Selected NAMS ecoregions (Level II) in Sonoran and Chihuahuan deserts.

Precipitation Recycling

Warm Season Normalized Climate Variables



Seasonal Variation of Daily Recycling Ratio



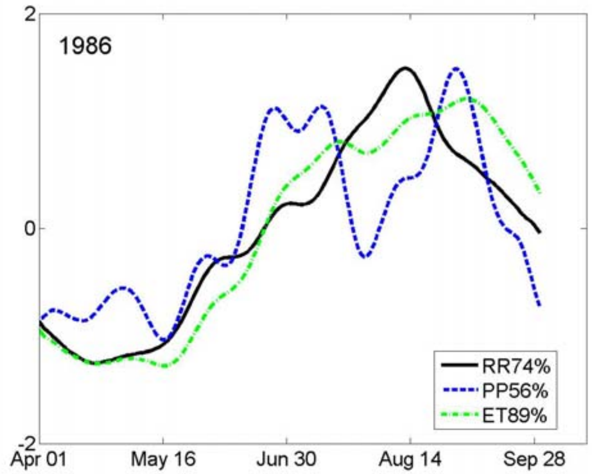
Climatological Analysis of NAMS Regional Recycling

- Using Multivariate Singular Spectrum Analysis (M-SSA), we found the dominant regional modes of monsoon climate variation:
  - Abrupt increase in monsoon rainfall leads to increase in ET, R and decrease in SH.
  - On average, the recycling ratio is 15%, although some days it reaches 25%.
  - Climatological analysis of NAMS reveals a positive recycling feedback mechanism.
- Analyzed annual climatology with respect to the season duration and total rainfall:
  - Long monsoons (1986, 1991, 1993) had two precipitation peaks separated by a large break.
  - Short monsoons (1989, 1992) exhibited a single precipitation peak.

Additional Details in Dominguez , Kumar and Vivoni (2008), Journal of Climate

Precipitation Recycling

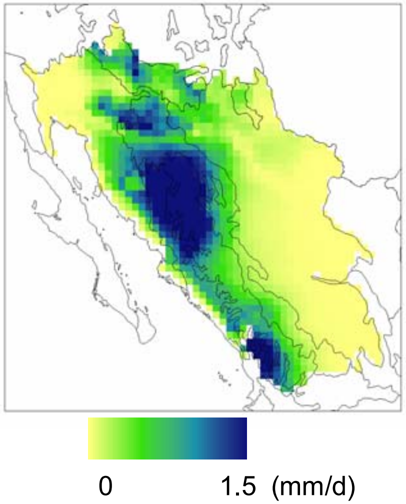
Dual Rainfall Peak during Long Monsoon Season



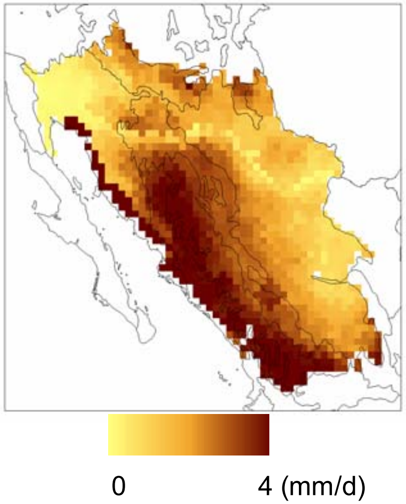
Evapotranspiration and Precipitation Recycling

- During long monsoons (with dual rainfall peak), we found that the intermediate period is sustained by surface ET:
  - Precipitation recycling peaks during the intermediate dry period.
  - ET is transported north and east where it falls as precipitation of recycled origin.
  - NDVI is sustained during dry conditions suggesting plants continue to transpire.

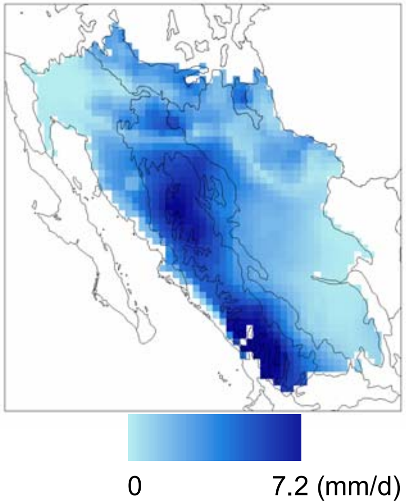
Recycled Precipitation



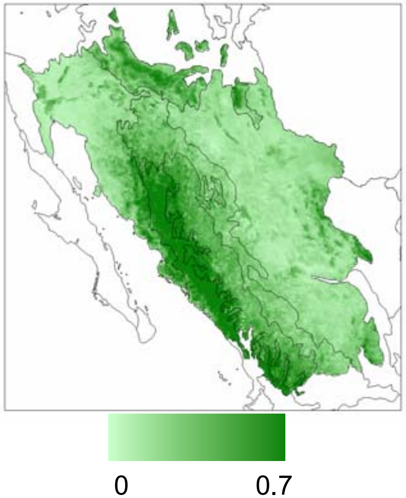
Evapotranspiration



Precipitation



NDVI



Outline

Ecohydrology of Seasonally-Green Deserts:

1. **Land Surface Hydrology in NAMS:**

   Spatiotemporal variability of ecohydrological processes.

2. **Topographic Controls on Ecohydrology in NAMS:**

   Process organization along semiarid mountain fronts.

3. **Land-atmosphere Interactions in NAMS:**

   Concurrent effects of vegetation on precipitation recycling.

4. **Numerical Modeling of NAMS Hydrology:**

   Spatiotemporal variability of simulated soil moisture.

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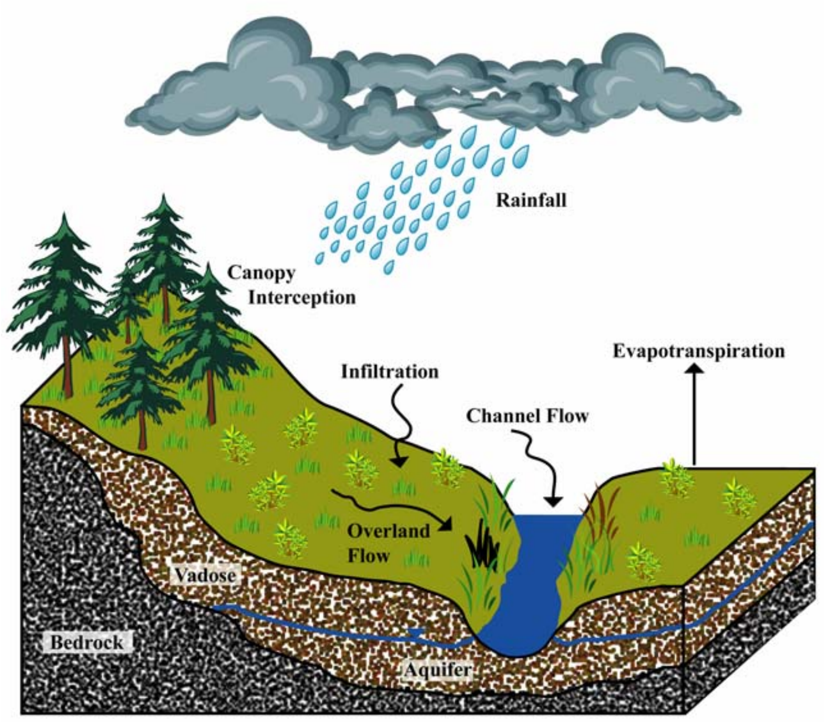
Hydrological Modeling

We utilize the TIN-based Real-time Integrated Basin Simulator (tRIBS) for distributed modeling of coupled hydrologic processes in complex basins.



Surface-subsurface hydrologic processes over complex terrain.

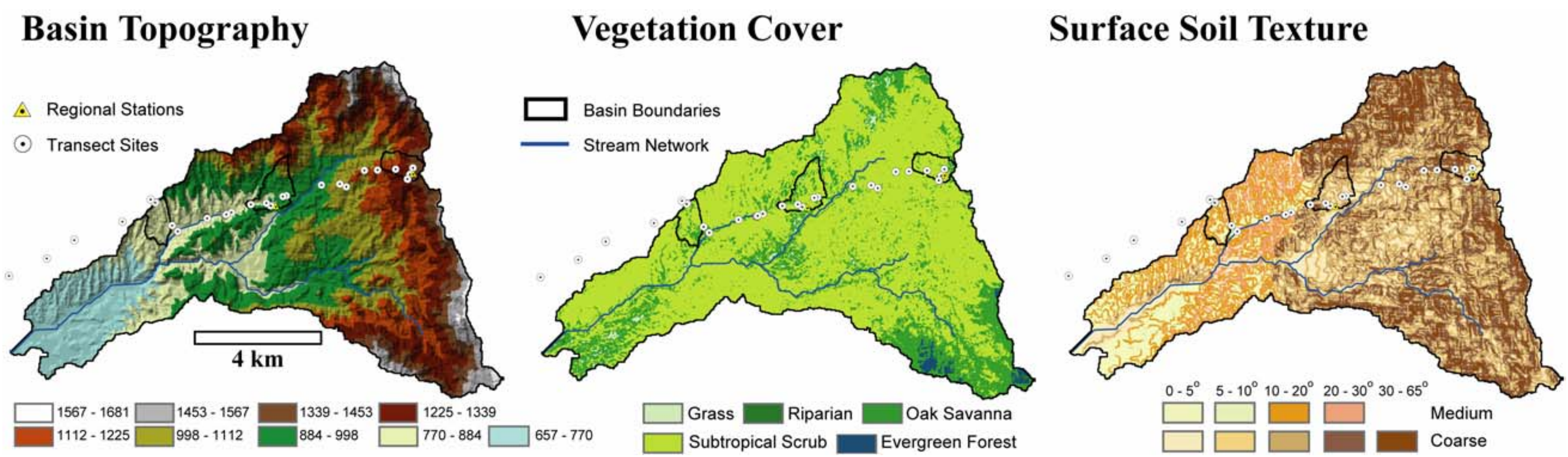
<u>Distributed Hydrologic Modeling</u>

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

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

Hydrological Modeling

Model setup included the topographic domain, vegetation classification and surface soil texture properties in the transect basin (~100 km^2).

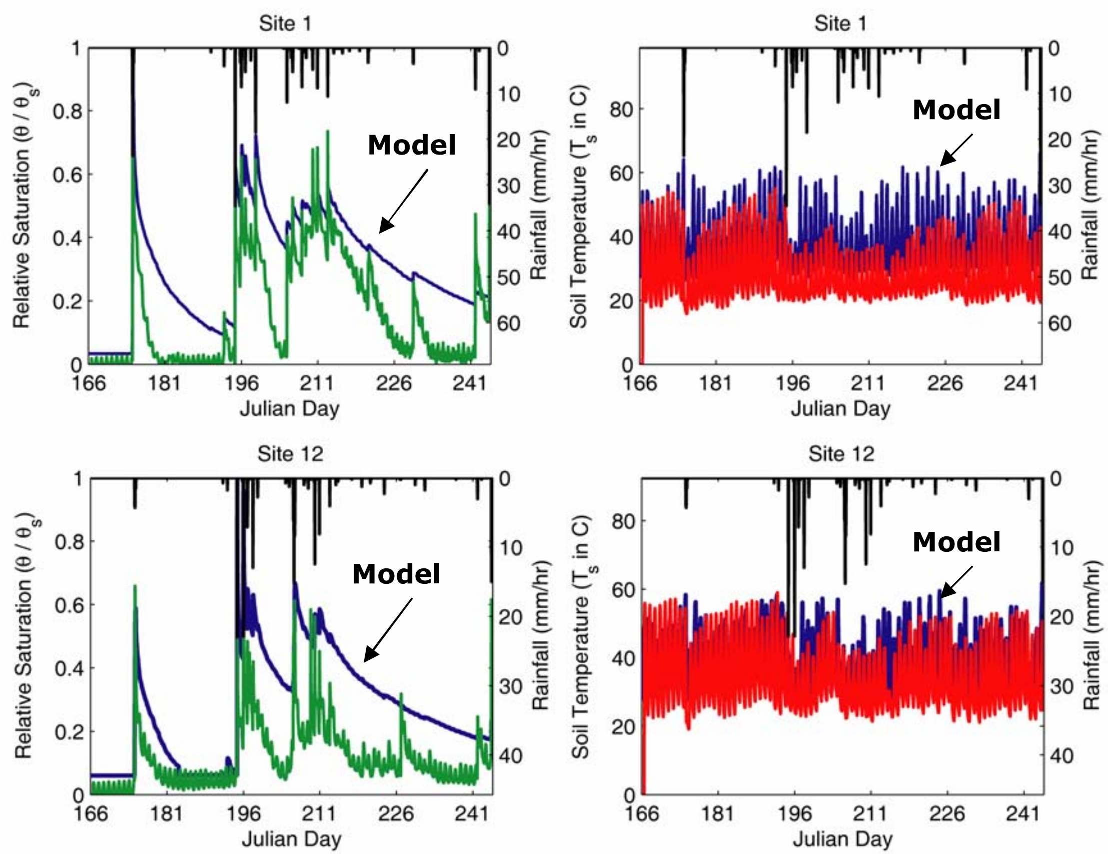


- A 29-m DEM used to derive an high-resolution TIN (d = 0.31).
  - Higher resolution floodplain area represented in TIN.
  - Voronoi polygon network (VPN) includes 33,300 nodes.
- Terrain variability captured using methods in Vivoni et al. (2004).

- 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.

Hydrological Modeling

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



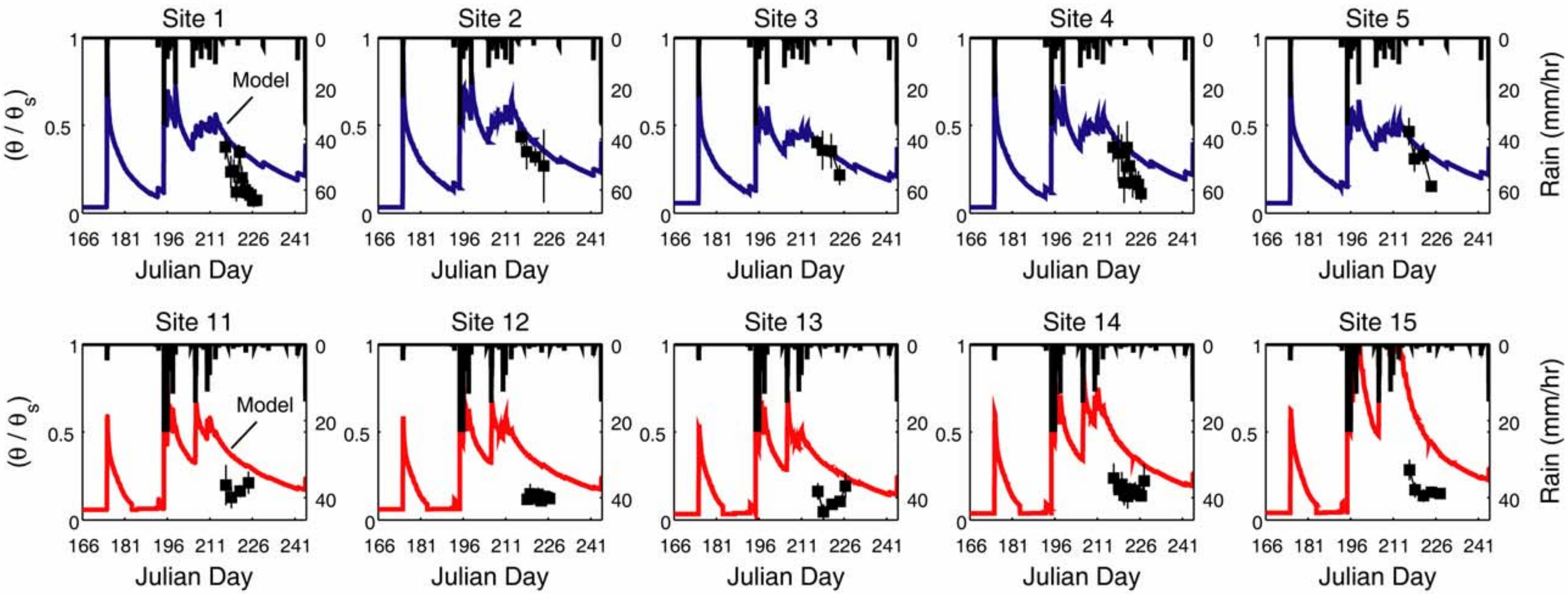
Site 1: Oak Savanna

Site 12: Subtropical Scrub

- Distributed model is not yielding soil moisture depletions that are sufficiently rapid and surface temperatures (at high elevation) which are too high.
- Improvements will be made in the evapotranspiration rate and a temperature lapse rate.

Hydrological Modeling

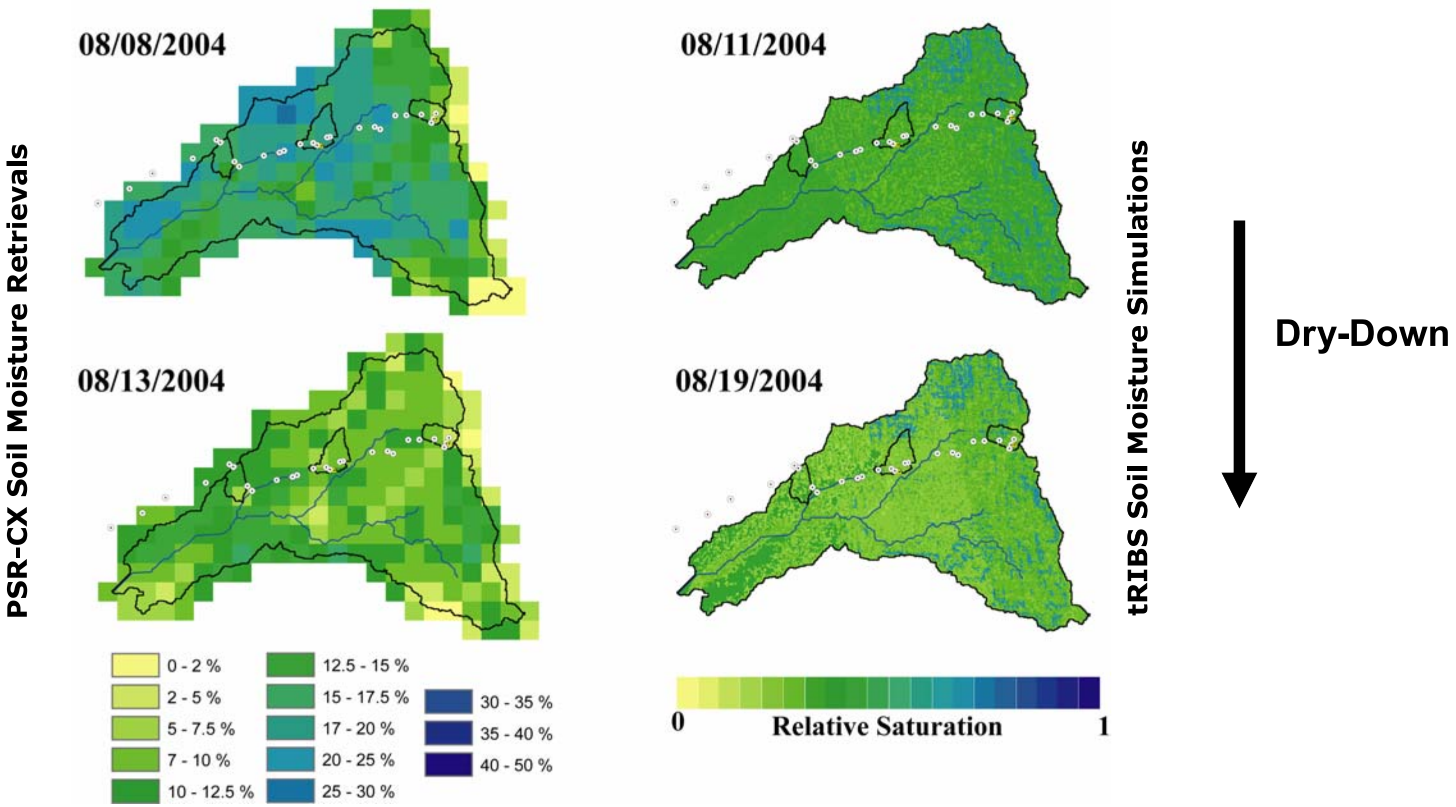
Model simulations at distributed locations along the transect indicate good performance at upper sites and poor performance at lower valley sites.



- Distributed model overestimates soil moisture at the lower valley sites (in some cases significantly), while performance is adequate in upper basin locations.
- Improvements are needed in surface soil texture parameterizations and in the lateral transport of moisture to the valley sites.
- Results are encouraging as the distributed comparison among observations and model simulations has not been previously attempted in this dynamic system.

Hydrological Modeling

Comparison of soil moisture simulations and remotely-sensed PSR/CX retrievals indicate that both methods capture the basin dry-down period.

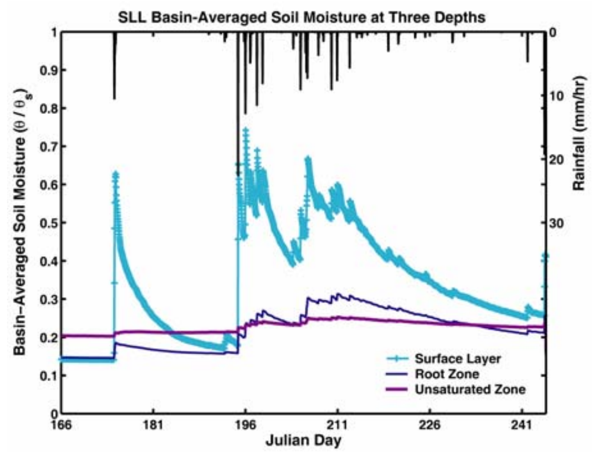


- Generally, the spatial variability in soil moisture increases during the dry-down in both the simulations and soil moisture retrievals.
- Comparison of spatial patterns and point-to-point values is required to assess the distributed simulations in more detail.

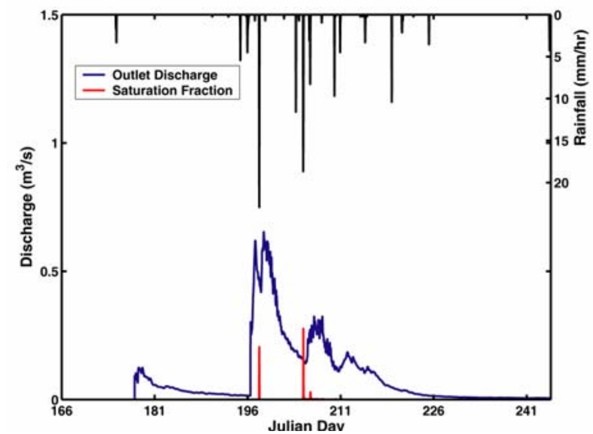
Hydrological Modeling

Basin-averaged response obtained from the simulations can be tested with stream gauging and compared to satellite remote sensing retrievals.

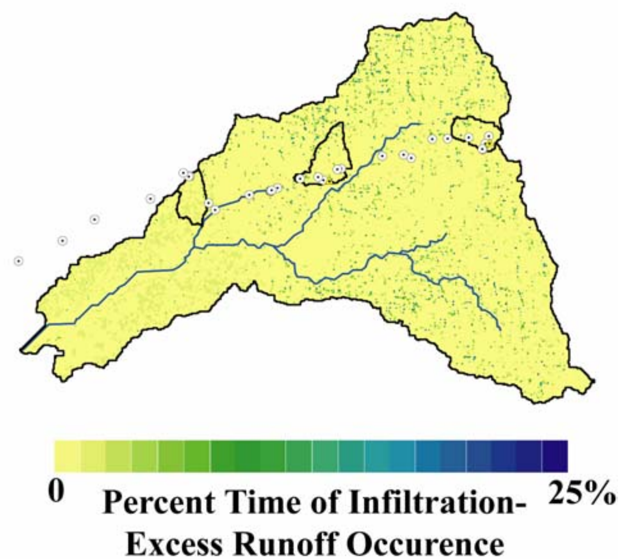
Basin –Averaged Soil Moisture



Basin Discharge and Saturated Area



<u>Distributed Runoff Production</u>



How does vegetation seasonality affect the basin runoff response?

> On-going work on hydrological modeling

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

Concluding Remarks

Ecohydrology of Seasonally-Green Deserts:

1. The NAMS is characterized by strong seasonality in ecohydrological processes modulated by mountainous terrain.

   Understanding in this system has broad implications to other semiarid monsoon systems (e.g., Australia, Africa).

2. Seasonally-green vegetation has important controls on soil moisture conditions and land-atmosphere interactions.

   Further studies are required to identify parameterizations that can improve hydroclimatological models in the region.

3. Latitudinal variability of the NAMS provides an organizing principle for studies of seasonally-varying ecohydrology.

   Field and remote sensing analyses will form the foundation for atmospheric and hydrological modeling across this gradient.

FIN