Land-Atmosphere Interactions and Hydrologic Response in the NAME experiment

Enrique R. Vivoni

School of Earth and Space Exploration

School of Sustainable Engineering and the Built Environment

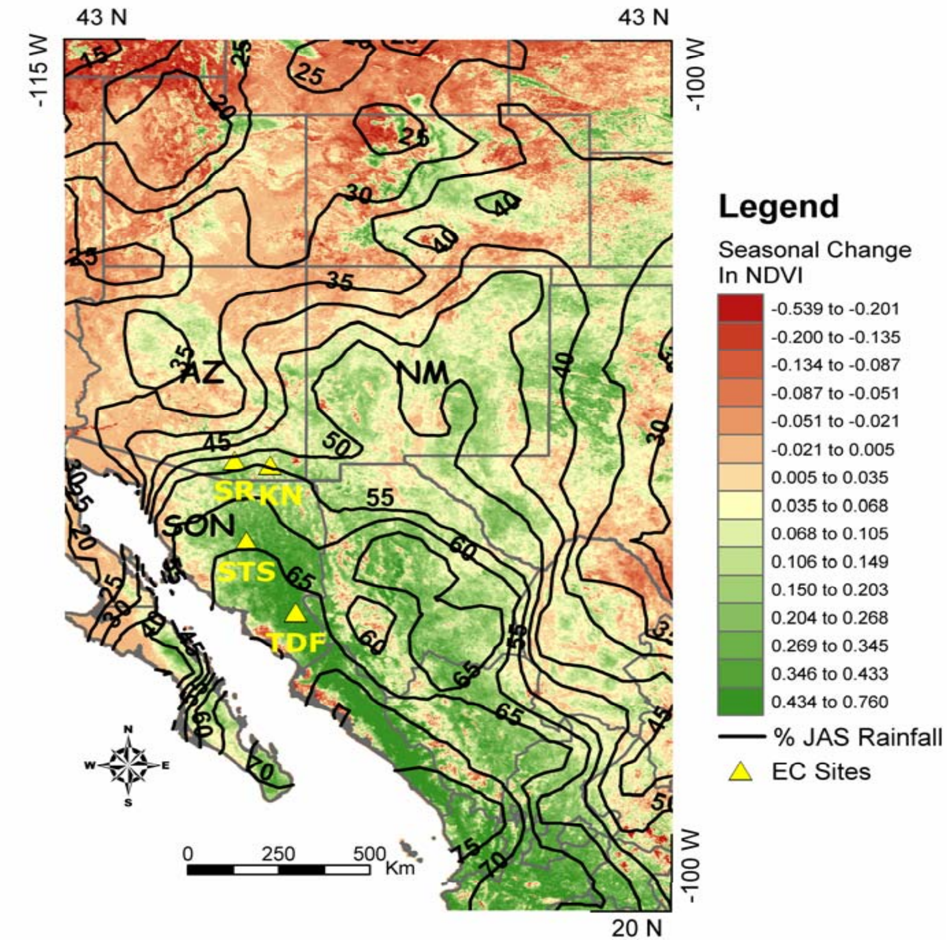
Arizona State University

Tempe, Arizona

WCRP/CLIVAR/VAMOS Panel (VPM12) June 4, 2009

Motivation

The North American Monsoon (NAM) leads to a dramatic vegetation response in southwestern US and northwestern Mexico.



CPC Daily Gridded Precipitation Analysis, 1970-1999.
SPOT VEGETATION, 10-day composite NDVI

Motivation

Prior observations indicate that transitions in ET occur during NAM. However, these are not captured well in previous modeling studies.

Transition in *ET* and *NDVI* at Two Tower Sites (TDF, SR)

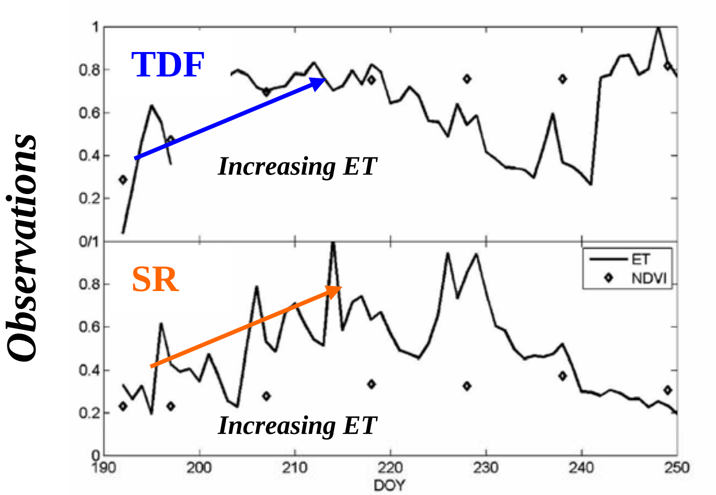


FIG. 8. Evaporative fraction (EF) and NDVI at the TDF near Tesopaco, Sonora, for the period July–September 2004.

Watts et al. (2007) Journal of Climate

Lack of Comparable Transition in *ET* in NAM Simulations

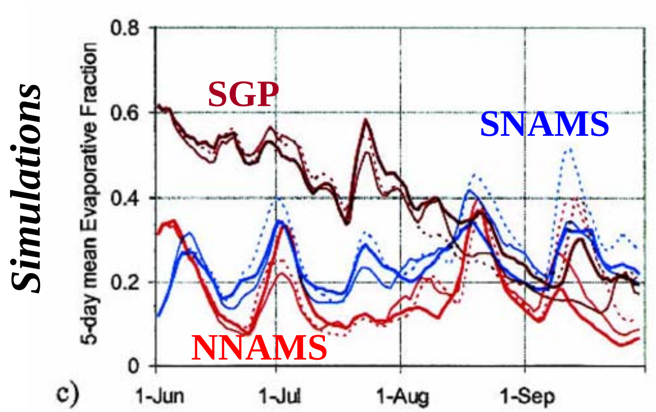


FIG. 7. Time series of simulated cumulative precipitation, soil moisture, and 5-day running mean EF over the NNAMS, SNAMS, and SGP in the three experiments. The transitions of three variables are analogous to each other, demonstrating the land–atmosphere interaction.

Matsui et al. (2005) Journal of Climate

- Vegetation greening (increase in *NDVI*) observed to relate to higher *ET* rates.
- Numerical modeling of NAM does not capture greenup effect on *ET* rates.
- Soil moisture control on *ET* is a likely source of uncertainty in the simulations.

Regional Study Sites

Santa Rita (SR)

Semiarid Mesquite Savanna
Operated by R. Scott (USDA)

Kendall (KN)

Semiarid Grassland
Operated by R. Scott (USDA)

Rayon (STS)

Subtropical Scrubland
Operated by C. Watts (UNISON)

Tesopaco (TDF)

Tropical Deciduous Forest
Operated by J. Garatuza (ITSON)

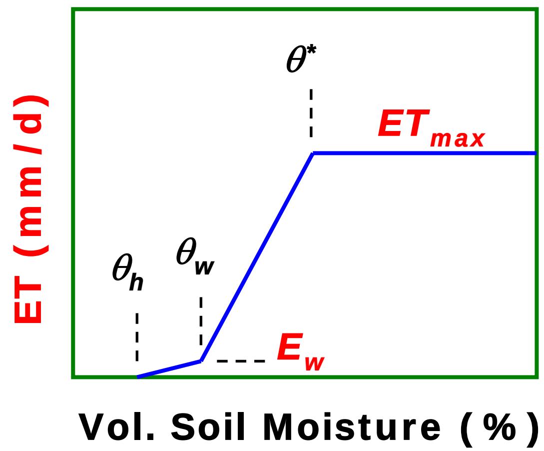
Eddy Covariance (EC) Tower Measurements of *ET* and θ

- We use measurements of actual *ET* and surface soil moisture (θ) at four EC tower sites in NAM region.
- Gradient in vegetation type and summer greening at different sites.
- Measurements at 30-min resolution used to obtain daily average values:
  - Surface soil moisture (0 to 10 cm).
  - Actual *ET* (1-2 m above canopy).
  - Precipitation accumulation.
- Soil surface characteristics obtained from analysis at each tower site.
- Three year record period at each site (May to September):
  - 2004 to 2006 (SR, KN, TDF).
  - 2004, 2006, 2007 (STS).
  - Coincide with NAME 2004 experiment.

Additional Details in Vivoni et al (2008), GRL

ET-Soil Moisture Relation

ET-θ Relation



Analytical Form

$$ET(\theta)=\begin{cases} 0 & 0<\theta\le\theta_h \\ E_w\dfrac{\theta-\theta_h}{\theta_w-\theta_h} & \theta_h<\theta\le\theta_w \\ E_w+(ET_{\max}-E_w)\dfrac{\theta-\theta_w}{\theta^*-\theta_w} & \theta_w<\theta\le\theta^* \\ ET_{\max} & \theta^*<\theta\le n \end{cases}$$

Unstressed ET

Stressed ET

Soil Moisture Control on Actual Evapotranspiration

- Most land surface models use a relation to restrict *ET* due to moisture availability, also known as moisture stress functions.
- The functional form varies, but in general, can be expressed as:

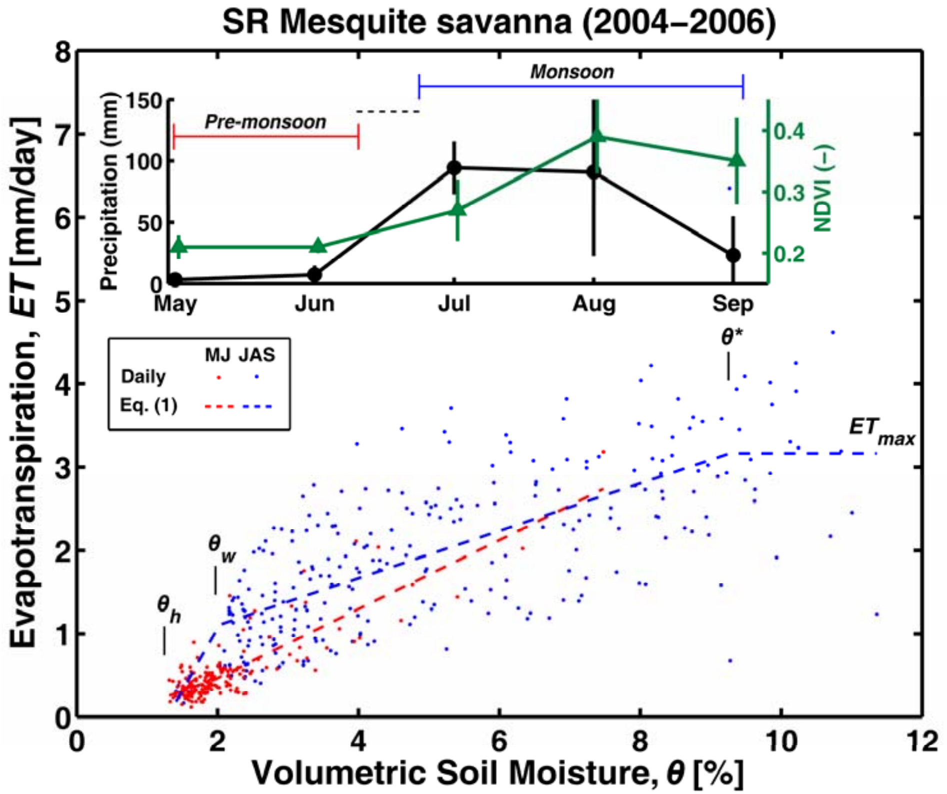
$$ET = f(\theta)ET_{\max}$$

where ET_{max} is the potential *ET* (dependent on other factors except soil moisture) and *ET* is the actual evapotranspiration.

- We use a similar form here consisting of a soil evaporation (E_w), stressed *ET* and unstressed *ET* (ET_{max}) segments.
  - θ_h is the hygroscopic point.
  - θ_w is the wilting point.
  - θ^* is the plant stress threshold.
  - n is soil porosity.
- <u>We use this piecewise linear relation to extract relevant parameters.</u>

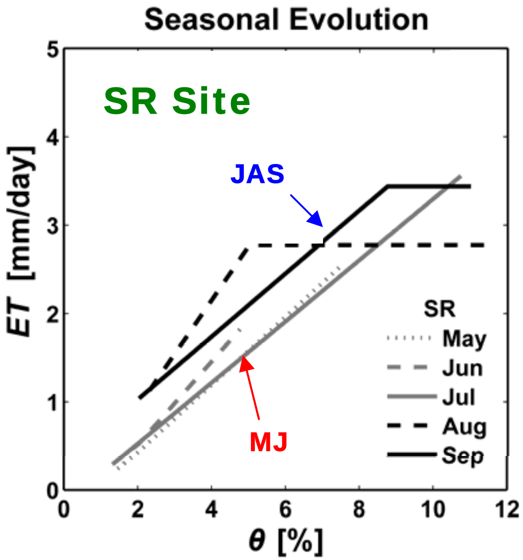
ET-Soil Moisture Relation

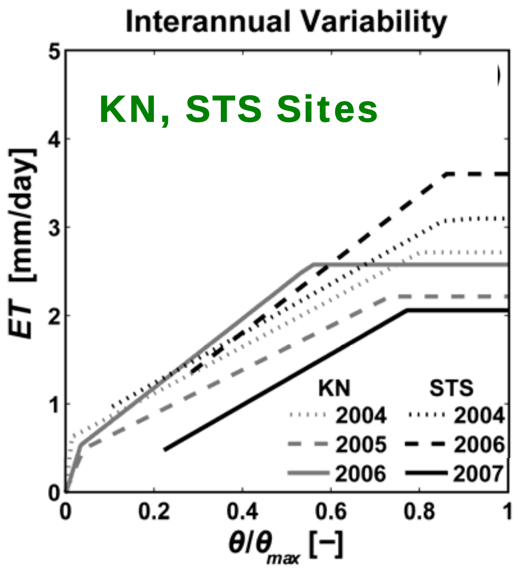
Observed ET-θ relation at SR, classified into pre-monsoon (red) and NAM (blue) periods, with optimized piecewise linear regressions.



- Separate *ET*-θ relations for pre-monsoon and NAM periods.
- Low (high) *ET* and are coincident with minimum (maximum) greening, indicated by low (high) *NDVI*, observed from MODIS monthly data.
- Note ~1 month lag between maximum precipitation (July) and maximum *NDVI* (Aug).

Temporal Variability





<u>Seasonal Evolution and Interannual Variability of *ET*-θ Relation</u>

- Observations at each site revealed that the *ET*-θ relation evolves during the season:
  - Pre-monsoon has low, stressed *ET*.
  - July experiences an increase in stressed *ET*.
  - August has unstressed ET_{max} and lower θ^*.
  - September has higher ET_{max} and θ^*.

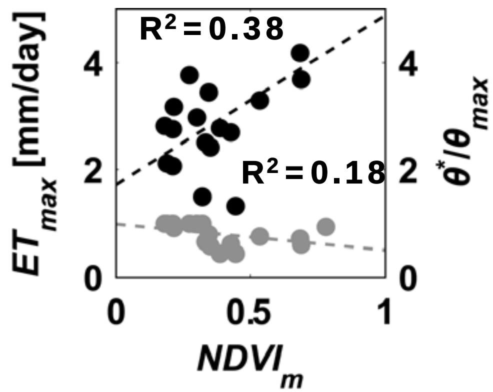
- <u>Widespread seasonal evolution</u> of *ET*-θ relation at all sites due to plant greening.

- Large interannual differences also observed between three years (2004-2007):
  - Wetter summers inducing higher *NDVI*, lead to higher ET_{max} and lower θ^*.
  - Larger yearly changes in ET_{max} for STS.
  - Larger yearly changes in θ^* for KN.

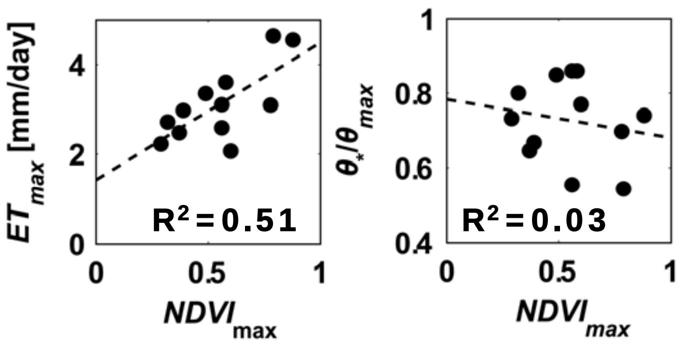
- <u>Ecosystems adjust biomass (ET_{max}) and/or stress threshold (θ^*) to cope with seasonal and interannual changes in precipitation.</u>

Controls of Vegetation Greening

Monthly Relations



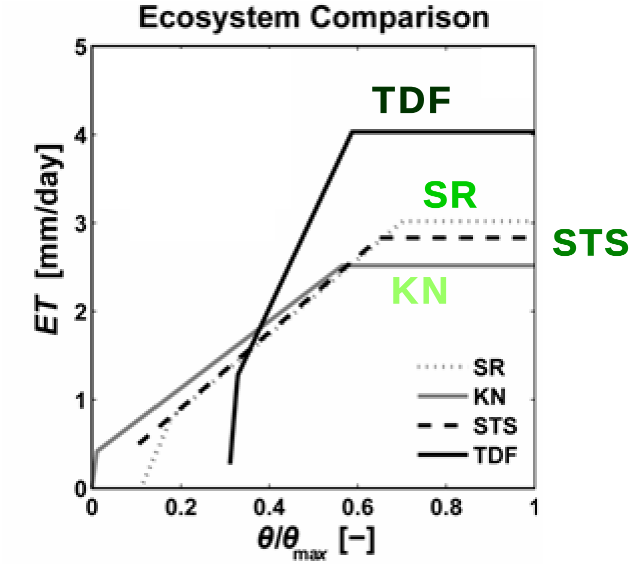
Annual Relations



Vegetation Dynamics (*NDVI*) Control Parameters of *ET*-θ Relation

- Relationships between unstressed *ET* and vegetation greenness reveal ET_{max} is highly dependent on *NDVI*.
  - ET_{max} increases with higher plant biomass.
  - Stronger dependence at annual scale.
- Dependence of ET_{max} occurs for all ecosystems and indicates importance of interannual variability in greenness.
- Relations between plant stress threshold θ^* reveal weaker dependence on *NDVI*.
  - θ^*/θ_{max} decreases with higher greenness.
  - Stronger dependence at monthly scale.
  - Ecosystem-dependent adjustments of θ^*/θ_{max}.
- Changes in θ^*/θ_{max} are due to osmotic adjustments in response to water stress that are ecosystem or species specific.

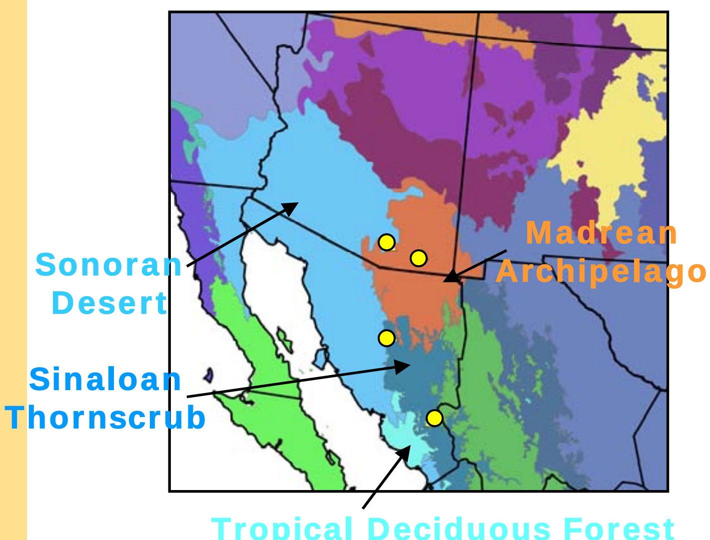
Ecosystem Comparison



Variation of *ET*-θ Relation Across Gradient in Vegetation Greening

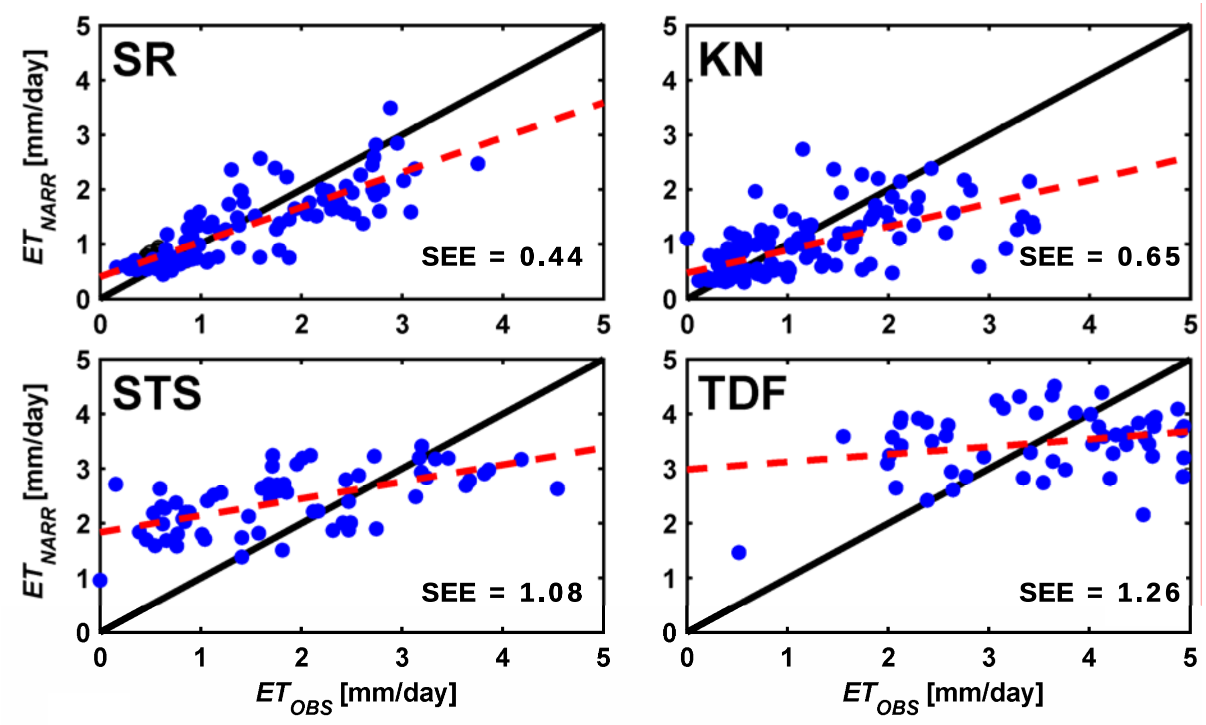
- Cross-site comparisons indicate ecosystem type is important for the *ET*-θ relation.
  - Higher ET_{max} for sites with more greening.
  - Lower θ^*/θ_{max} for sites with more greening.
  - Similar relations when common plant species are observed in sites (SR and STS).
- Range of ET_{max} from 2.52 mm/day for KN to 4.03 mm/day for TDF.
- Slope of the stressed *ET* is steeper for ecosystems with higher greening. Implies greater sensitivity to soil moisture changes.
- Since sites are representative for the broad ecoregions in NAM domain:
  - May be possible to upscale EC tower site observations to similar plant assemblages.
  - Apply regressions with remotely-sensed *NDVI* data to obtain *ET*-θ relation across region.

NAM Ecoregions



Comparison to Reanalysis

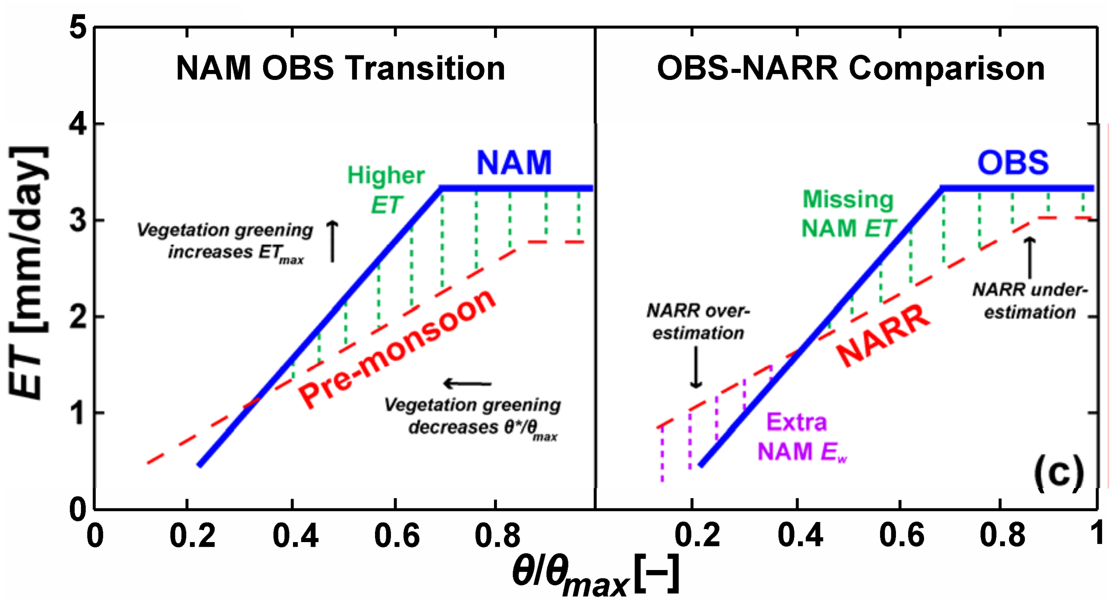
We compare daily ET from NARR data set to observations (OBS) for 2004 (May to September) and found large inconsistencies.



- NARR over- (under-) estimates of low (high) observed *ET.*
- The correspondence between NARR and observations worsens for ecosystems with higher vegetation greening, as quantified by the standard error of estimates (SEE).

Comparison to Reanalysis

The following conceptual diagram attempts to explain why NARR ET predictions are different from ET observations at the range of sites.



- Observed transition (pre-monsoon to NAM) in ET-θ relation is composed of increase in ET_{max} and lowering of $\theta^*/\theta_{\max}$ due to greening. Thus, higher *ET* is observed in NAM.

- A similar pattern is observed when comparing NARR and OBS, with a higher ET_{max} and lower $\theta^*/\theta_{\max}$ in the observations.

- This suggests NARR does not capture greening accurately. Thus, excess soil evaporation (E_w) and deficient transpiration (ET_{max}) occur in the simulations.

Observational Summary

ET and Soil Moisture Relation in NAM Region:

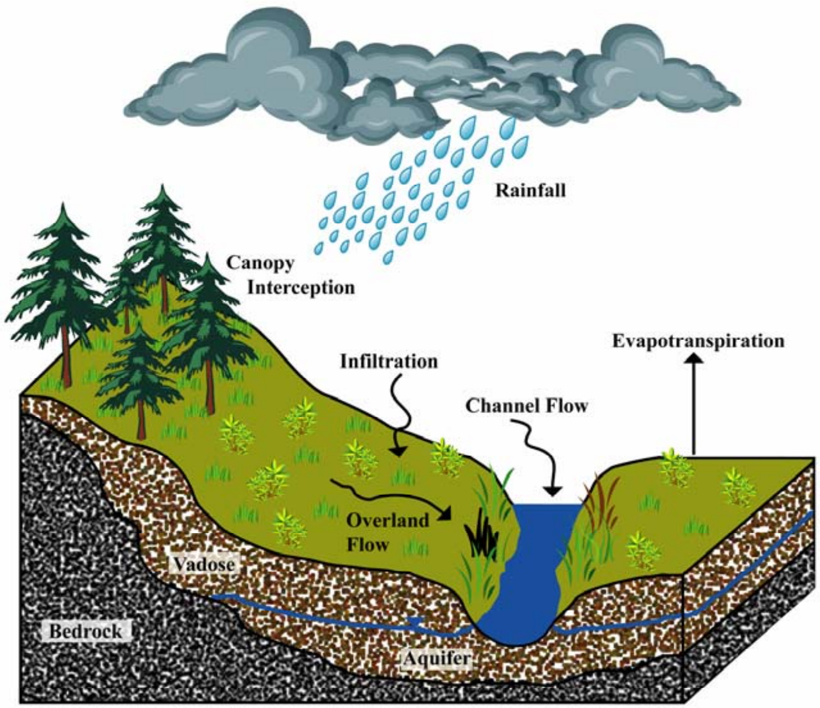
1. *ET*-θ relation evolves during the NAM, exhibits interannual and ecosystem variations, due to vegetation greening.

2. Inconsistencies in NARR simulations are primarily due to not fully capturing impact of greening on *ET*-θ parameters.

3. Enhanced parameterizations of *ET*-θ relation necessary for improved simulation of land-atmosphere interactions.

Hydrologic 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.

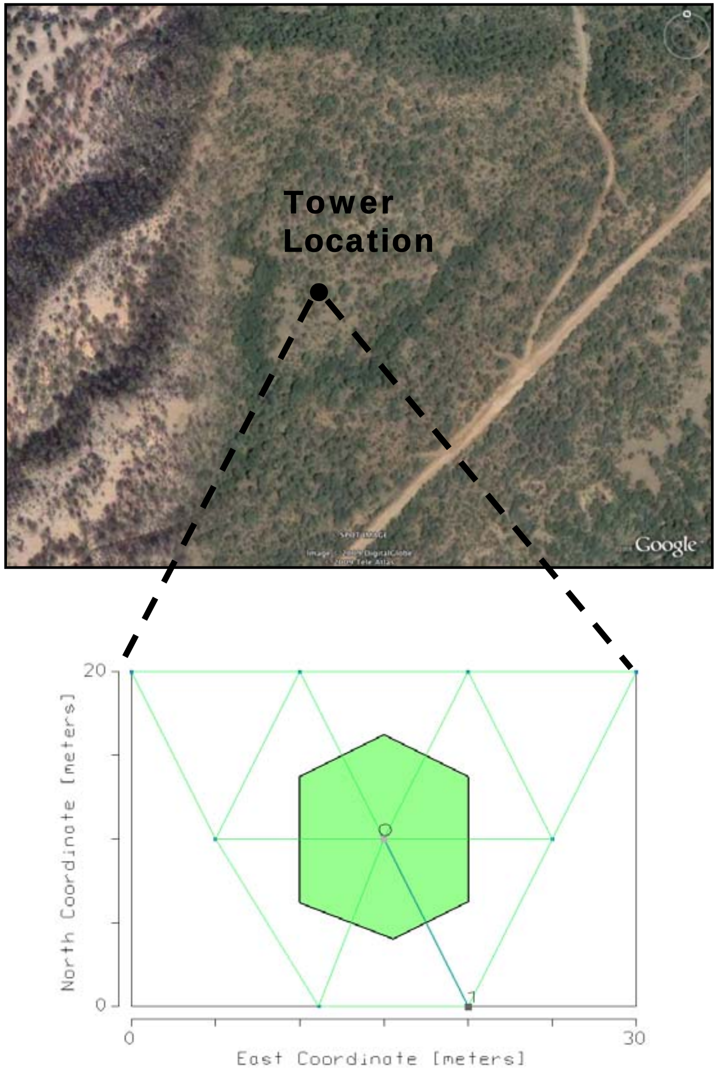
Distributed Hydrologic Modeling

- 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

Point-scale Simulations

Subtropical Scrubland (STS)
Eddy Covariance Site



Eddy Covariance (EC) Tower Site Simulations

- A 100 m^2 hexagonal Voronoi polygon used to depict region around EC tower.

- Measurements at EC tower include:
  - Precipitation (2 sensor types).
  - Soil moisture (3 depths at 1 site).
  - Net Radiation and components.
  - Ground and Sensible Heat Fluxes.
  - Latent Heat Flux.

- Soil profile characteristics from pit:
  - Sandy loam (0 – 30 cm).
  - Loamy sand (30 – 60 cm).

- Subtropical scrubland ecosystem, known as *Sinaloan Thornscrub*, occupies large regions in northern Mexico.

- Cactus, shrub and tree species include:
  - Mesquite (*Prosopis juliflora*).
  - Tree Ocotillo (*Fouquieria macdougalii*).
  - Palo Verde (*Cercidium sonorae*).
  - Whiteball Acacia (*Acacia angustissima*).

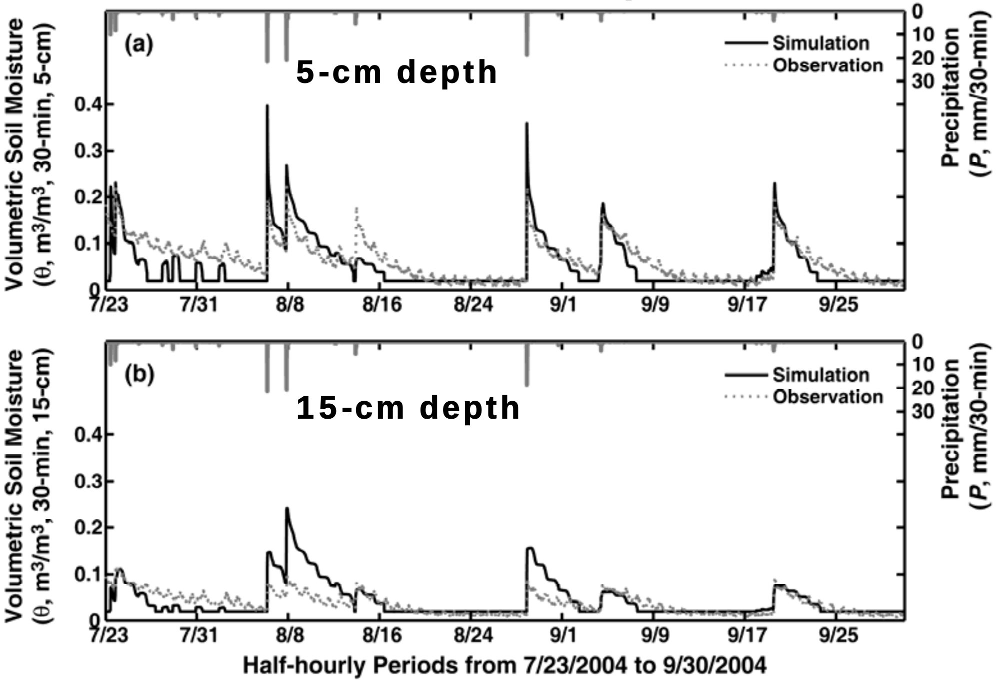
Soil Moisture Comparison

Half-hourly simulations conducted using EC tower forcing from July 23 to September 30, 2004 with well developed plant canopies.

Model Parameters

Parameter	Variable	Value
Saturated hydraulic conductivity	K_s (mm/hr)	225.0
Soil Porosity	n (–)	0.45
Saturated soil moisture content	θ_s (–)	0.41
Residual soil moisture content	θ_r (–)	0.02
Stress soil moisture content	θ^* (–)	0.18
Pore size distribution index	m (–)	0.85
Soil heat conductivity	k_s (J/msK)	0.2
Soil heat capacity	C_s (J/m^{3}K)	1.61×10^6
Soil depth	Z_r (m)	1.0
Surface emissivity	E_s (–)	0.98
Vegetation fraction	v (–)	0.60
Albedo	a (–)	0.16
Vegetation height	h (m)	6.0
Vegetation transmission	K_t (–)	0.95
Minimum stomatal resistance	r_{min} (s/m)	20

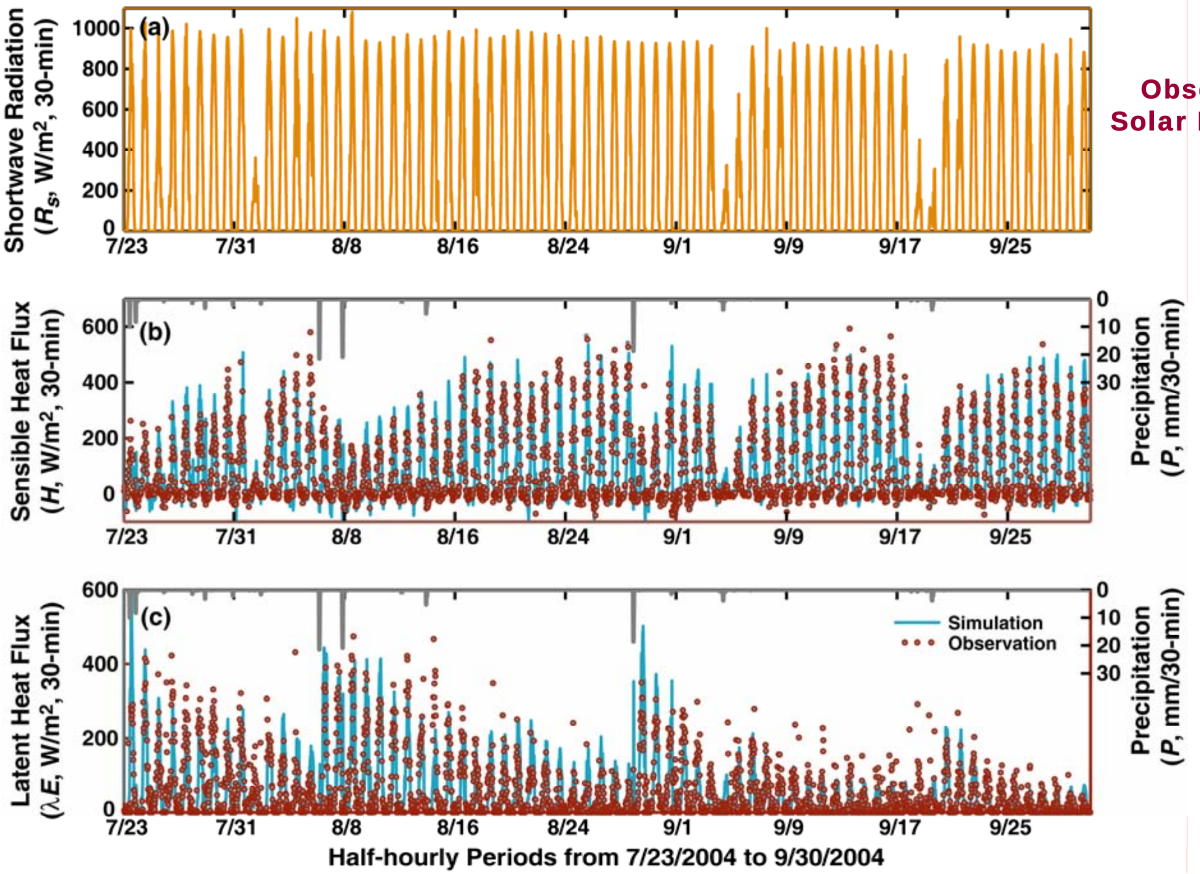
Soil Moisture Comparisons



- Observed response to precipitation pulses captured in point-scale simulations at both shallow (5-cm) and deeper (15-cm) soil layers. Overall, adequate model representation.
- The simulated soil moisture response, however, exhibits some differences in the maximum soil moisture during rain events and the recession characteristics.

Surface Flux Comparison

Capturing the soil moisture data was an essential step in simulating the surface heat fluxes (sensible and latent heat) at 30-min resolution.

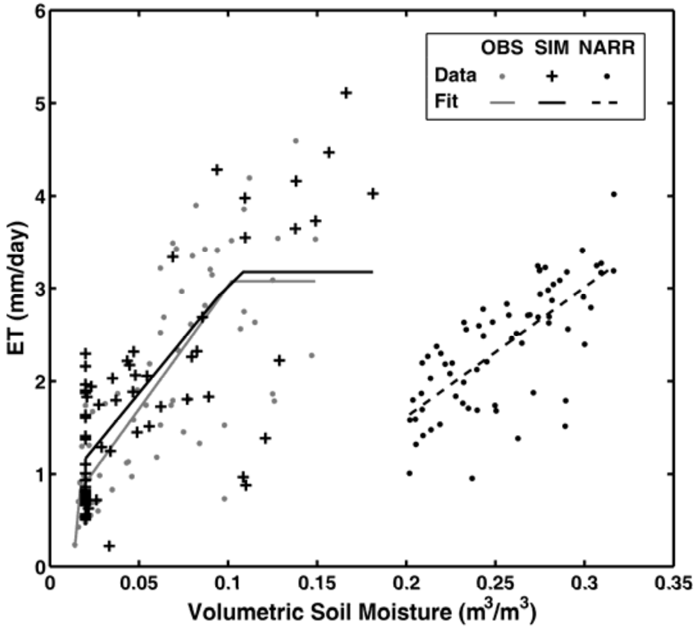


Observed Incoming Solar Radiation (W / m2)

- The diurnal cycle of sensible (H) and latent (λE, evapotranspiration) heat fluxes are simulated very well. Change in the magnitude of the fluxes with wetting and drying is caputured. Maximum *ET* values can be underestimated during dry periods.

ET-Soil Moisture Relation

Observed and Simulated Daily ET-Soil Moisture Relation



Simulation Performance

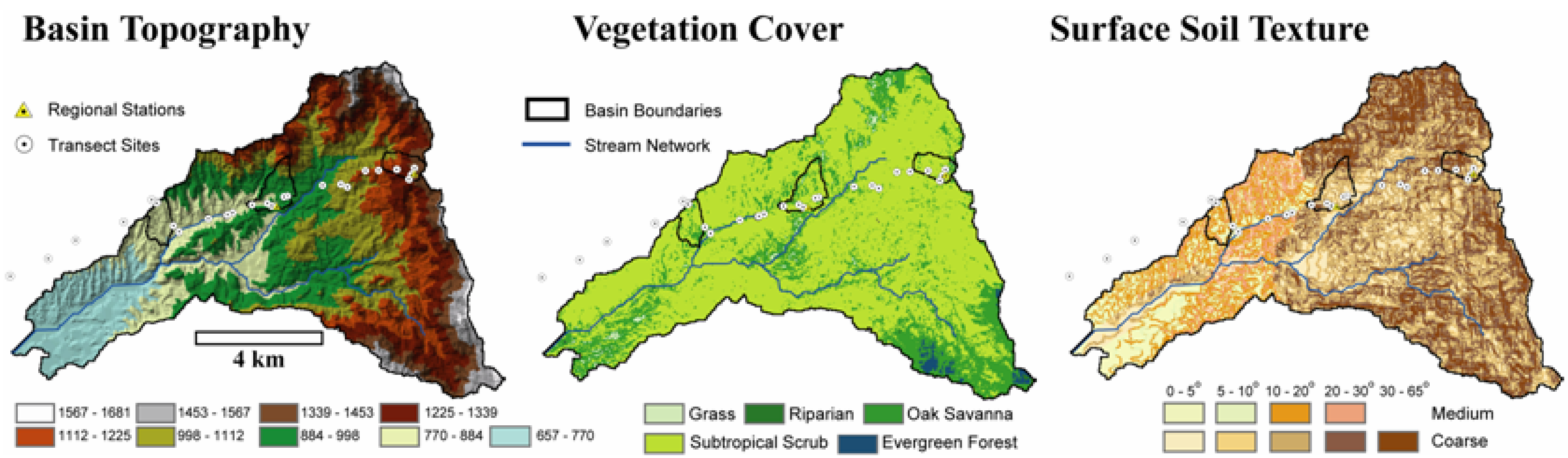
Metric (Unit)	θ_{sur}	θ_{top}	*H*	λE
Bias (–)	0.82	1.16	0.92	0.93
MAE (m^3/m^3, W/m^2)	0.02	0.02	43.29	32.33
CC (–)	0.76	0.65	0.86	0.74

Overall Point-Scale Simulation Results at EC Site

- High temporal resolution simulations indicate the evapotranspiration and soil moisture dynamics are captured well.
- Simulated *ET*-θ relation using tRIBS lends strong support for possible improvements in the NARR reanalysis.
- Further model testing at the EC tower site will include:
  - Use of 2006, 2007, 2008 summers.
  - Addressing footprint-scale soil moisture variabilty using distributed sampling.
  - Identifying model sensitivity to vegetation greening during NAMS.

Catchment-scale Simulations

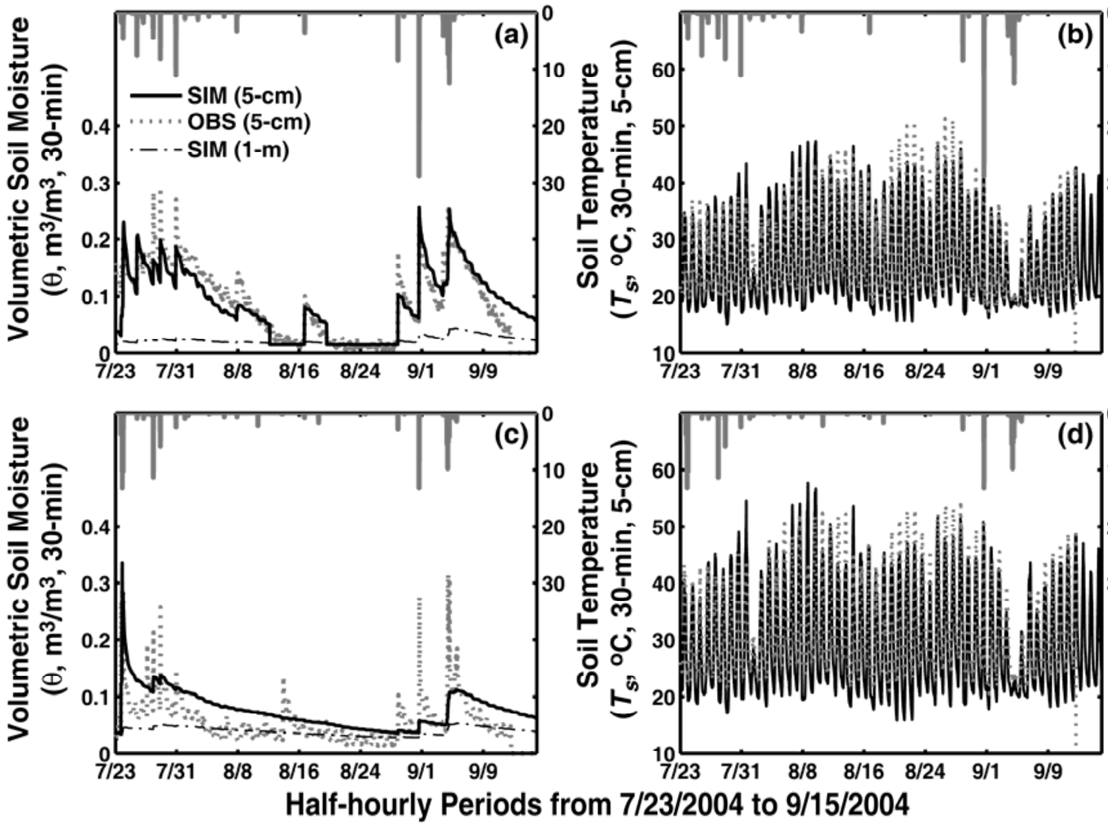
Model setup included the topographic domain, vegetation classification and surface soil texture properties in the Sierra Los Locos basin (92.5 km^2).



- 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 (Yilmaz 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.

Station Comparison

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



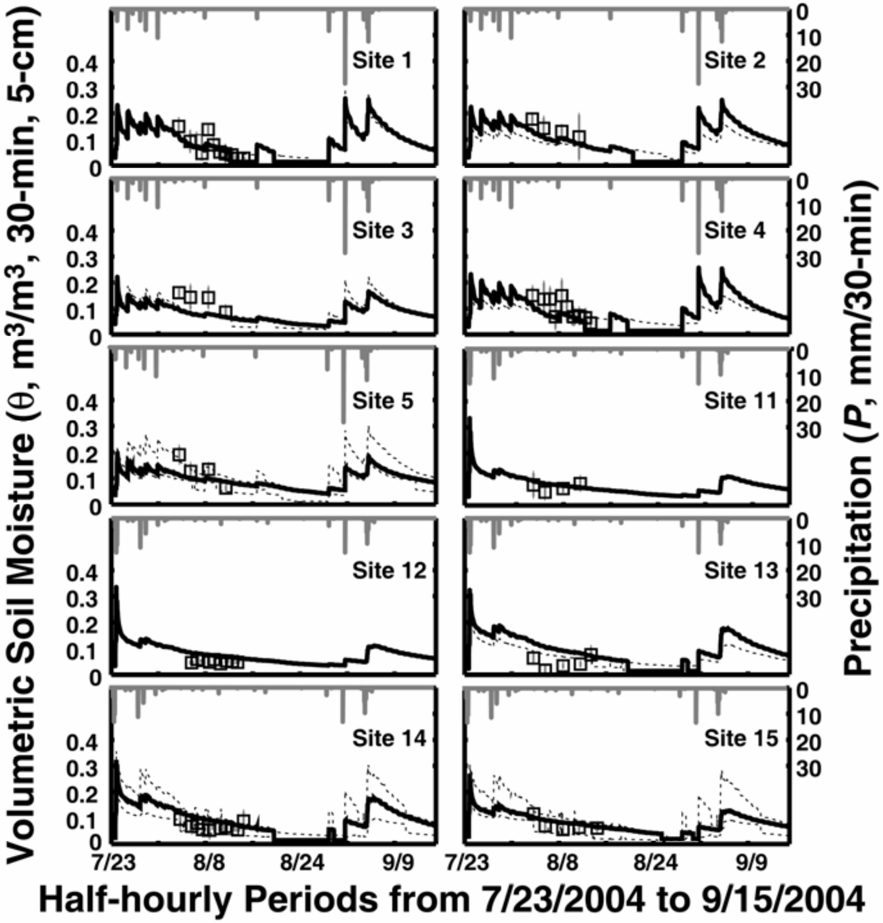
Site 1: Oak Savanna

Site 12: Subtropical Scrub

- Model is not capturing some soil moisture peaks at subtropical scrubland site (possibly due to rainfall errors), whereas performance at the oak savanna is excellent.

Transect Site Comparison

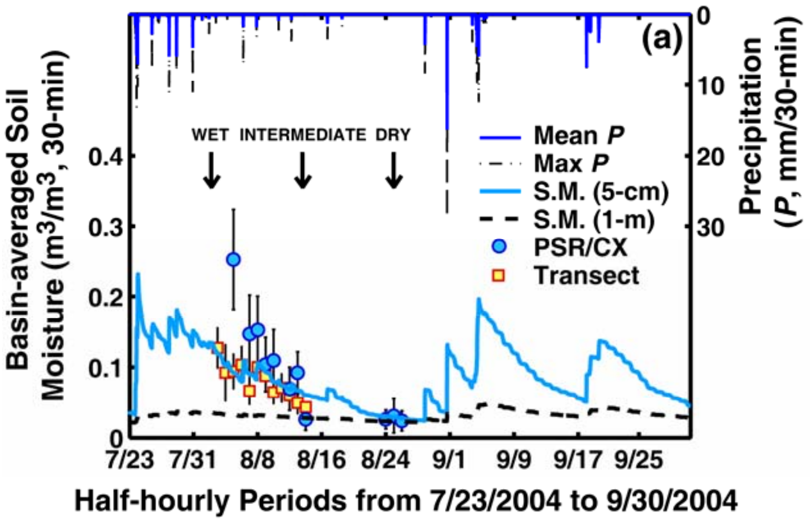
Uncalibrated simulations at distributed locations along the transect indicate good representation of surface soil moisture along the range of sites.

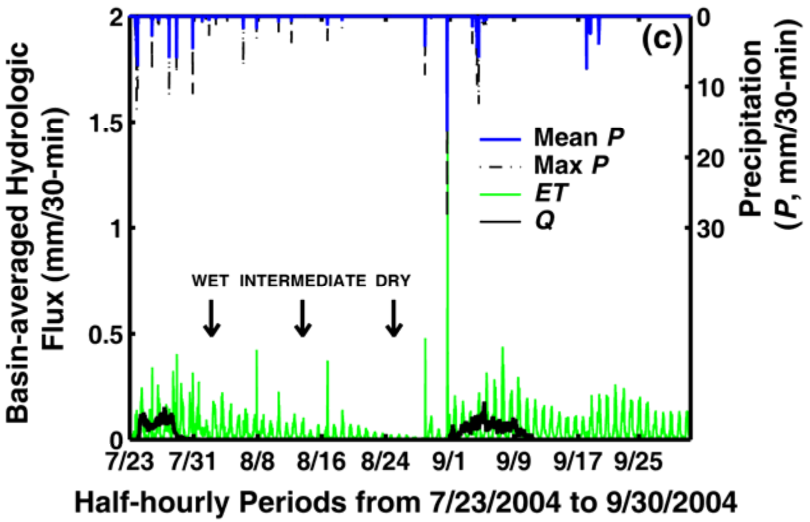


Distributed Soil Moisture Comparison in Basin

- Distributed model yields correct soil moisture recession characteristics during the drying period.
- Differences exist at some particular sampling sites (with certain over and underestimations), though in general adequate performance is obtained.
- The distributed testing of the model with distributed soil moisture observations is a strong constraint on the model behavior in the catchment.

Catchment Comparison



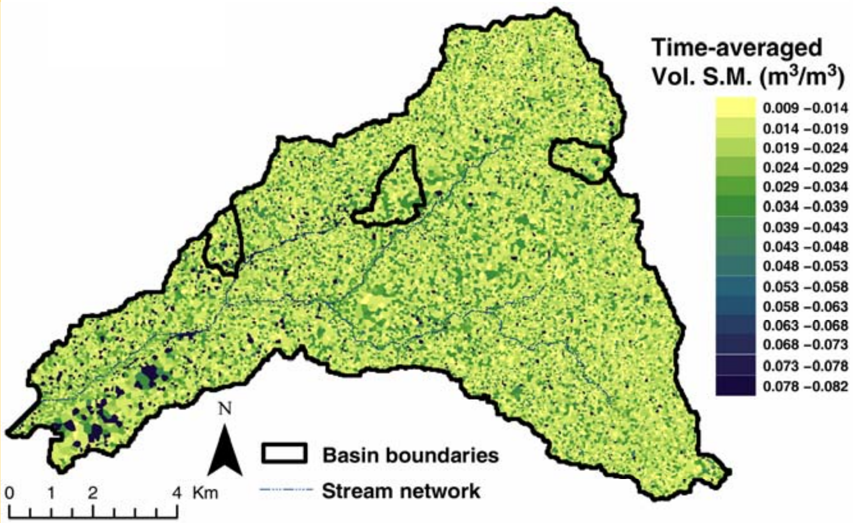


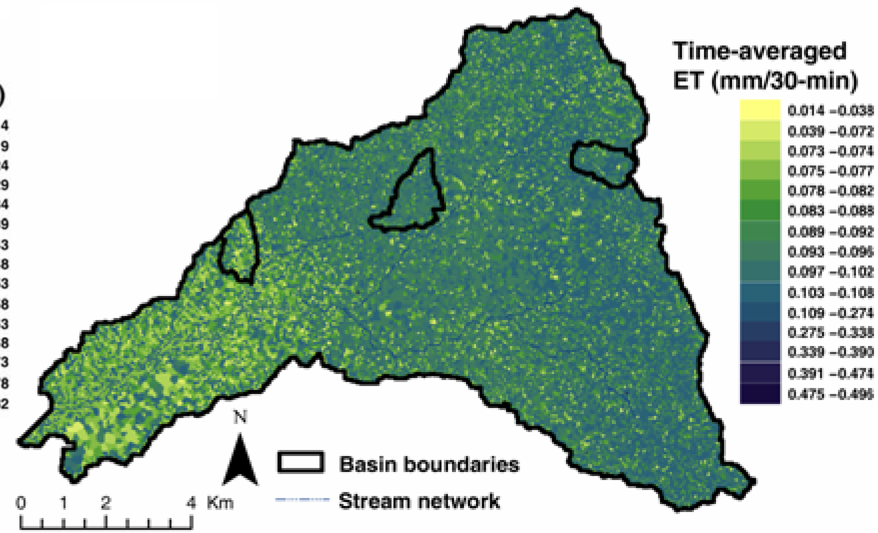
Basin-Averaged Comparison and Water Balance Estimates

- Comparison of the basin-averaged soil moisture time series to data:
  - Averaged ground data matches basin-average soil moisture very well.
  - Remotely-sensed data overestimates model simulations during wet period, improved match in dry periods.
- Basin water balance consists of:
  - Evapotranspiration ratio (*ET*/*P*) = 0.76
  - Runoff ratio (*Q*/P) = 0.21
  - Remainder is increases in soil moisture.
- Streamflow occurs primarily during periods of intense precipitation (Hortonian runoff) and when surface saturation increases (Dunne runoff).

Spatial Patterns

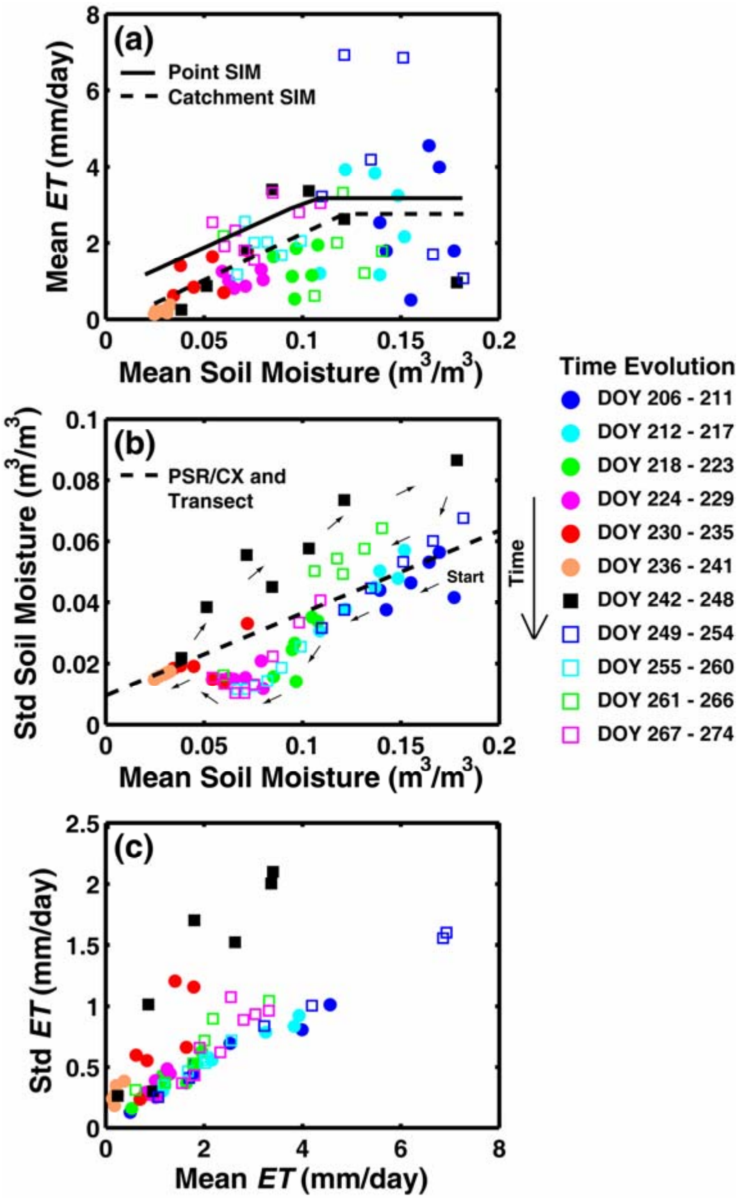
Catchment-scale simulations allow exploration of spatial patterns in soil moisture and evapotranspiration to quantify land surface dynamics.





- Average surface soil moisture (%) and *ET* (mm/hr) over the entire simulation period (1680 hrs) reveals patterns related to topography, soil and vegetation conditions.
    - High average soil moisture along valley bottoms and in particular soil classes.
- While *ET* and soil moisture are strongly linked, their temporal patterns reflect different spatial controls.
    - For example, *ET* spatial variability is smoother and depends on vegetation cover and elevation-dependence of temperature and precipitation.

Emergent Behavior



***ET*-θ Relation and Catchment-Scale Variability**

- The *ET*-θ relation evolves in time as a function of the hydrologic basin wetness
  - Model simulations capture stressed and unstressed *ET* periods.
  - The catchment-averaged relation does not precisely match point scale results, with respect to ET_{max}.
- The spatial variability of soil moisture and ET exhibits hysteresis:
  - Good correspondence in soil moisture spatial variability with observations, except during intermediate wetness.
  - Nonlinearity and hysteresis in the soil moisture makes it difficult to estimate basin-scale variations from mean state.
  - Strong linearity in *ET* spatial variations suggest easier to estimate from mean state (when rainfall days excluded).
- <u>These patterns emerge from complex underlying hydrologic dynamics.</u>

Modeling Summary

<u>ET and Soil Moisture Relation in NAM Region:</u>

1. Tailored hydrologic simulations at study sites with available field data allow matching the *ET*-θ relation well at point scale.

2. Aggregation of landscape heterogeneity leads to a basin-averaged *ET*-θ relation that does not match point results.

3. Seasonal variations of the *ET*-θ relation need to be captured in model simulations by ingesting remote sensing datasets.

Recommendations

1\. Detailed field observations on land-atmosphere and hydrologic dynamics should be focused on comparisons to and improvements upon land surface model parameterizations.

A. Match field investigators and modelers to team on testing and improving land surface parameterizations.

2\. Hydrologic studies should be focused on sites that can help understand behavior as a function of a particular land surface or climate gradient (e.g., elevation, vegetation greenness).

A. Select field sites along a gradient and invest in the necessary (limited) instrumentation and model applications.

1\. Improvements in hydrologic models are necessary in order to be able to transfer new knowledge into the water resources application area (e.g., prediction of flood and droughts).

A. Ensure that model applications are performed after careful testing with field data and have the predictive capabilities.

FIN