Observed relation between evapotranspiration and soil moisture in the North American monsoon region

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Soil moisture control on evapotranspiration is poorly understood in ecosystems experiencing seasonal greening. In this study, we utilize a set of multi-year observations at four eddy covariance sites along a latitudinal gradient in vegetation greening to infer the ET-θ relation during the North American monsoon. Results reveal significant seasonal, interannual, and ecosystem variations in the observed ET-θ relation directly linked to vegetation greening. In particular, monsoon-dominated ecosystems adjust their ET-θ relation, through changes in unstressed ET and plant stress threshold, to cope with differences in water availability. Comparisons of the observed relations to the North American Regional Reanalysis dataset reveal large biases that increase where vegetation greening is more significant. The analysis presented here can be used to guide improvements in land surface model parameterization in water-limited ecosystems. Citation: Vivoni, E. R., H. A. Moreno, G. Mascaro, J. C. Rodríguez, C. J. Watts, J. Garatuza-Payan, and R. L. Scott (2008), Observed relation between evapotranspiration and soil moisture in the North American monsoon region, Geophys. Res. Lett., 35, L22403, doi:10.1029/2008GL036001.

1. Introduction

[2] Evapotranspiration (ET) links the surface water and energy balances with plant physiological activity, especially for water-limited ecosystems [Rodríguez-Iiturbe and Porporato, 2004]. In the southwest U.S. and northwest Mexico, the strong seasonal coupling of radiation and precipitation during the North American monsoon (NAM, July-September) leads to dramatic ecosystem responses in terms of vegetation greening [e.g., Matsui et al., 2005; Watts et al., 2007; Vivoni et al., 2007]. While the influence of vegetation greening on the surface energy balance has been recognized, little is known of its effects on the relation between soil moisture (θ) and evapotranspiration.

[3] ET is controlled by several factors, including atmospheric, soil moisture and vegetation conditions. A common approach to simulating ET is to compute the potential evapotranspiration (ETp) and then apply a function accounting for soil moisture (i.e., ET = f(θ)ETp) [e.g., Mahfouf et al., 1996]. These equations typically assume time-constant plant parameters. Matsui et al. [2005] found that the soil moisture control on ET was a large source of uncertainty in NAM simulations, even when accounting for vegetation greening. As a result, the effects of seasonal greening on the ET-θ relation need to be further investigated for improved parameterizations in land surface models.

[4] A major difficulty in identifying the effect of vegetation dynamics on the ET-θ relation has been the lack of observations in water-limited ecosystems. The semiarid NAM region is well suited to explore the effects of vegetation greening since: (1) seasonal rainfall accounts for 40 to 70% of the annual precipitation; (2) ecosystems respond vigorously to NAM rainfall; and (3) latitudinal gradients exist in the NAM rainfall amounts and vegetation response. Here, we demonstrate that vegetation greening impacts the observed soil moisture control on evapotranspiration and evaluate its possible influence on a land surface model applied across a set of water-limited ecosystems.

2. Observations

[5] The NAM is characterized by an abrupt increase in rainfall over the southwest U.S. and northwest Mexico, starting in June or July depending on latitude. While interannual variations of NAM precipitation are substantial, regional analyses reveal spatial patterns following geographic position and elevation [e.g., Gochis et al., 2007]. Figure 1 shows the percent of annual precipitation during the NAM using monthly rain gauge data [Chen et al., 2002]. Note the strong seasonality, with 65 to 75% of rainfall occurring during NAM in western Mexico. Excellent correspondence is observed between precipitation and the spatial distribution of vegetation greening. This is quantified as the seasonal change (September minus June) in Normalized Difference Vegetation Index (NDVI), obtained from the SPOT VEGETATION sensor [Ducharmin et al., 2002], averaged over the 2004–2006 summers.

[6] To sample across the latitudinal gradient in vegetation greening, we use multi-year records (2004–2007) from four sites in Arizona, USA, and Sonora, Mexico, representing broad ecoregions in the NAM domain (Figure 1). Table 1 describes the study sites, which include a semiarid mesquite savanna (SR) and grassland (KN), subtropical scrubland (STS) and tropical deciduous forest (TDF). At each site, we used 30-min volumetric soil moisture (θ in % at 5 cm) and evapotranspiration (mm/day) from the eddy covariance method (EC) to derive daily values of the ET-θ relation. Soil moisture depths were selected based on available data and for consistency with tight coupling of soil moisture...
control and the surface energy balance. Watts et al. [2007] provides descriptions of the EC method and the study sites.

3. Evapotranspiration and Soil Moisture Relation

3.1. Transition During North American Monsoon

[7] For water-limited ecosystems, a piecewise-linear equation has been proposed to depict daily evapotranspiration as [Rodriguez-Iturbe and Porporato, 2004]:

\[
ET(\theta) = \begin{cases} 
0 & 0 < \theta \leq \theta_b \\
E_w \frac{\theta - \theta_h}{\theta_w - \theta_h} & \theta_h < \theta \leq \theta_w \\
E_w + (ET_{max} - E_w) \frac{\theta - \theta_w}{\theta^* - \theta_w} & \theta_w < \theta \leq \theta^* \\
ET_{max} & \theta^* < \theta \leq n
\end{cases}
\]

where \( E_w \) is soil evaporation, \( ET_{max} \) is un-stressed evapotranspiration, \( \theta_h, \theta_w \) and \( \theta^* \) are volumetric soil moisture contents at the hygroscopic, wilting and plant stress thresholds, and \( n \) is soil porosity. Equation (1) is similar to the \( ET = f(\theta)ET_r \) functions used in a range of land surface models [e.g., Mahfouf et al., 1996] and is used here only to quantify the \( ET-\theta \) relation and estimate parameters. Typically, soil moisture parameters of (1) are assumed constant in time and related to soil and vegetation properties.

[8] For monsoon-dominated ecosystems, the \( ET-\theta \) relation parameters may vary with time depending on vegetation greening. For example, Figure 2 presents the observed \( ET-\theta \) relation for the SR site for pre-monsoon (MJ) and NAM (JAS) periods. Higher \( ET \) rates and \( \theta \) typically occur during the NAM, with little overlap of the two periods. Low (high) \( ET \) and \( \theta \) are coincident with minimum (maximum) greening, as indicated by low (high) NDVI in MJ (JAS). Note the peak NDVI of ~0.4 occurs ~1 month after the precipitation peak (~100 mm), due to the delay in biomass production. Large variations in the \( ET-\theta \) relations between pre-monsoon and NAM periods also take place at the other sites, although the \( ET \) and \( \theta \) ranges vary. In contrast, Matsui et al. [2005] only found minor differences in the simulated \( ET-\theta \) relation between pre-monsoon and NAM periods, since their transpiration parameterization was severely limited at low soil moisture values.

[9] To quantify the shift in the \( ET-\theta \) relation, we used a nonlinear optimization algorithm [Gill et al., 1981] to obtain parameters of (1) and its goodness of fit for all sites. Table 2 presents the variations in \( ET_{max}, E_w \) and \( \theta^*/\theta_{max} \) from pre-monsoon to NAM conditions, as well as All Data (MJIAS). Regressions of the observed data with (1) yield increases in \( ET_{max} \) and \( E_w \) and reductions in \( \theta^*/\theta_{max} \) as precipitation \( (P) \) and NDVI increase during the NAM. These trends suggest plant phenology plays a role in varying maximum \( ET \) and lowering plant stress threshold, \( \theta^* \). An example of the differences in the regressions is shown in Figure 2 for SR. At low \( \theta \) (~2 to 6%), stressed \( ET \) in the NAM is greater than for the pre-monsoon, while unstressed \( ET \) is only observed during the NAM for high \( \theta \) (~9 to 12%). As expected, however, equation (1) is a simplification of the observed variations of \( ET \) with \( \theta \) in monsoon-dominated ecosystems.

3.2. Seasonal, Interannual and Ecosystem Variability

[10] Observed variations in the soil moisture control on \( ET \) are further explored in Figure 3, presented as the
regression of (1) for clarity. Figure 3a shows the seasonal evolution of the ET-θ relation for the SR site for May to September. Clearly, ET increases in time as the NAM promotes vegetation greening. Pre-monsoon conditions in May and June are characterized by low, stressed ET. The rapid onset of vegetation greening in July leads to an increase in the stressed ET, but a similar form of (1). During the peak biomass in August, a minimum in θ* and the appearance of unstressed ET_max are identified, leading to a transition in the form of (1). In September, the ecosystem experiences higher plant stress (increase in θ*), but can sustain larger ET_max due to the available plant biomass. The seasonal evolution of the ET-θ relation was also observed at the other sites, indicating that this phenomenon is widespread for monsoon-dominated ecosystems.

[11] This seasonal evolution suggests that ET_max and θ* can be directly linked to the vegetation phenology. Figure 3a (inset) presents linear regressions of monthly ET_max and θ*/θ_max with monthly NDMI for all ecosystems, indicating that ET_max increases and the plant stress threshold decreases with higher NDMI. Similar regressions are shown in Figures 3b (inset) and 3c (inset) for the annual ET_max and θ*/θ_max with NDMI. The phenological control on ET_max is significant (R^2 = 0.51 and 0.38 at annual and monthly scales), supporting the use of a vegetation index to modify (1) [e.g., Williams and Albertson, 2004]. Regressions between θ*/θ_max and NDMI are negative, but relatively weak due to varying trends in individual ecosystems (R^2 = 0.03 and 0.18 at annual and monthly scales). This suggests that ecosystem-dependent stress threshold changes occur during the NAM, which are not considered in land surface models [e.g., Chen et al., 1996; Matsui et al., 2005].

[12] In addition to seasonal changes, the observed ET-θ relation has high interannual variability as shown in Figure 3b for KN and STS, which represent a gradient in vegetation greening from a grassland to a subtropical scrubland. Clearly, ET_max varies from year to year, with a narrow range of 2.22 to 2.71 mm/day for KN and a wider range of 2.06 to 3.60 mm/day for STS. Interestingly, yearly changes in θ*/θ_max show opposite behavior, with a wider range at KN (0.55–0.80) and narrower changes at STS (0.77–0.86). In addition, interannual variations in the ET-θ relation are tied to total precipitation and its seasonal distribution, as this controls plant phenology. In general, wetter summers lead to higher NDMI, which induces greater ET_max and lower θ*/θ_max (insets for Figures 3b and 3c). This suggests these ecosystems adjust their ET-θ relation, by changes in plant biomass (ET_max) and/or stress threshold (θ*), to cope with interannual changes in NAM precipitation.

[13] To compare the ecosystems, Figure 3c presents the ET-θ relations for SR, KN, STS and TDF based on all available data. ET_max increases from 2.52 mm/day at KN to 4.03 mm/day at TDF, closely following the degree of vegetation greening (NDMI in Table 2). The SR and STS sites have similar ET_max and θ*/θ_max perhaps due to sharing a similar vegetation type, though NDMI is higher at STS. Furthermore, a progressive increase in the slope of the

Table 2. Parameters of the Observed ET-θ Relation^a

<table>
<thead>
<tr>
<th>Site</th>
<th>Period</th>
<th>P (mm)</th>
<th>ET_max (mm/day)</th>
<th>E_n (mm/day)</th>
<th>θ*/θ_max</th>
<th>NDMI</th>
<th>RMSE (mm/day)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SR</td>
<td>Pre-monsoon</td>
<td>10.4 ± 5.1</td>
<td>2.97</td>
<td>0.44</td>
<td>1.00</td>
<td>0.21 ± 0.02</td>
<td>0.21</td>
</tr>
<tr>
<td></td>
<td>NAM</td>
<td>208.4 ± 48.1</td>
<td>3.16</td>
<td>1.11</td>
<td>0.82</td>
<td>0.34 ± 0.07</td>
<td>0.68</td>
</tr>
<tr>
<td></td>
<td>All Data</td>
<td>218.9 ± 52.2</td>
<td>3.02</td>
<td>0.80</td>
<td>0.70</td>
<td>0.29 ± 0.09</td>
<td>0.58</td>
</tr>
<tr>
<td>KN</td>
<td>Pre-monsoon</td>
<td>7.5 ± 4.9</td>
<td>2.35</td>
<td>0.36</td>
<td>0.88</td>
<td>0.19 ± 0.03</td>
<td>0.30</td>
</tr>
<tr>
<td></td>
<td>NAM</td>
<td>158.3 ± 73.9</td>
<td>2.51</td>
<td>0.62</td>
<td>0.59</td>
<td>0.31 ± 0.12</td>
<td>0.55</td>
</tr>
<tr>
<td></td>
<td>All Data</td>
<td>165.8 ± 70.6</td>
<td>2.52</td>
<td>0.41</td>
<td>0.57</td>
<td>0.26 ± 0.11</td>
<td>0.47</td>
</tr>
<tr>
<td>STS</td>
<td>Pre-monsoon</td>
<td>31.6 ± 24.6</td>
<td>2.83</td>
<td>0.43</td>
<td>0.65</td>
<td>0.50 ± 0.11</td>
<td>0.91</td>
</tr>
<tr>
<td></td>
<td>NAM</td>
<td>301.2 ± 206.5</td>
<td>2.83</td>
<td>0.43</td>
<td>0.65</td>
<td>0.38 ± 0.15</td>
<td>0.91</td>
</tr>
<tr>
<td></td>
<td>All Data</td>
<td>335.2 ± 254.5</td>
<td>2.83</td>
<td>0.43</td>
<td>0.65</td>
<td>0.38 ± 0.15</td>
<td>0.91</td>
</tr>
<tr>
<td>TDF</td>
<td>Pre-monsoon</td>
<td>46.4 ± 48.7</td>
<td>3.74</td>
<td>0.49</td>
<td>1.00</td>
<td>0.31 ± 0.03</td>
<td>0.67</td>
</tr>
<tr>
<td></td>
<td>NAM</td>
<td>440.3 ± 94.5</td>
<td>4.74</td>
<td>2.12</td>
<td>0.83</td>
<td>0.72 ± 0.11</td>
<td>1.21</td>
</tr>
<tr>
<td></td>
<td>All Data</td>
<td>476.9 ± 180.1</td>
<td>4.03</td>
<td>1.28</td>
<td>0.59</td>
<td>0.56 ± 0.22</td>
<td>1.17</td>
</tr>
</tbody>
</table>

^aThe θ_max is the maximum θ for the period of interest. P and NDMI depict the interannual mean ± 1 standard deviation. The root mean square error (RMSE) measures the goodness of fit of (1) to the observations. A dash denotes data were unavailable.

^bDenotes significant data loss.
stressed ET (between $\theta_{\text{m}}$ and $\theta^*$) is observed in the following order: KN, SR, STS, TDF. As a result, ecosystems with more intense greening have higher ET responses for a unit change in soil moisture under stressed conditions and can achieve higher levels of unstressed ET. Clearly, the impact of vegetation greening on the representation of the ET-\theta relation should be captured in land surface models applied across the NAM region.

### 3.3. Comparison to a Land Surface Model

[14] To test if a land surface model represents the impact of vegetation greening on the ET-\theta relation, we inspect simulations from the North American Regional Reanalysis (NARR) [Mesinger et al., 2006]. NARR uses the Noah model [Chen et al., 1996] to simulate land surface states and fluxes. To match the observations, we extracted daily ET (mm/day) and soil moisture in the top 0–10 cm ($\theta$ in %, valid at 5 cm) from the 32-km NARR pixels co-located at each site. We selected NARR for this comparison since: (1) the product is used to assess land-atmosphere interactions [Luo et al., 2007]; (2) soil moisture control on potential ET, estimated through the Penman equation, is prescribed by a form similar to (1) [see Chen et al., 1996, pp. 7254–7256 and Figure 1]; and (3) vegetation greening is captured by a monthly (interpolated to daily), 15-km NDVI data set which does not account for interannual variability [Mesinger et al., 2006].

[15] Figure 4a compares the ET-\theta relations derived from observations (OBS) and NARR simulations at the SR site, as an example. Large differences in soil moisture ($\theta_{\text{m}}$) indicate that NARR has a significant wet bias in the NAM region. Minimum $\theta$ for NARR vary from 12.4% (STS) to 13.0% (SR), while maximum values ($\theta_{\text{max}}$) are from 31.1% (KN) to 33.8% (TDF). Despite the soil moisture overestimation, NARR captures the range of observed ET (~0 to 5 mm/day) as well as the transition in the ET-\theta relation from pre-monsoon to NAM conditions, including the increase in ET and $\theta$. In addition, the interannual and ecosystem variations, related to vegetation greening, are consistent with observations (not shown), suggesting improvements with respect to Matsui et al. [2005]. Despite these encouraging results, parameters of (1) derived from NARR differ with respect to OBS, with a trend of lower ET$_{\text{max}}$ and higher $\theta^*/\theta_{\text{max}}$ for NARR (Table 3).

[16] To explore this discrepancy, Figure 4b compares ET observations ($ET_{\text{OBS}}$) and simulations ($ET_{\text{NARR}}$) for 2004 at each site, selected to match the North American Monsoon Experiment [Higgins and Gochis, 2007]. Clearly, NARR over- (under-) estimates ET for days with low (high) $ET_{\text{OBS}}$. These important discrepancies are related to variations in the parameters of (1) for NARR. Figure 4c summarizes the OBS and NARR comparison as a conceptual diagram, highlighting that misrepresentations are likely due to not fully capturing increases in ET$_{\text{max}}$ and decreases in $\theta^*/\theta_{\text{max}}$ induced by vegetation greening during the NAM. The agreement between $ET_{\text{NARR}}$ and $ET_{\text{OBS}}$ also deteriorates from SR, KN, STS to TDF; as quantified by the SEE (Table 3). This suggests that ET simulations in NARR worsen further south in the NAM region, where seasonal precipitation and vegetation greening are more significant.

### 4. Conclusions

[17] Observations in four monsoon-dominated ecosystems indicate the ET-\theta relation: (1) evolves during the NAM in response to plant phenology; (2) exhibits interannual changes due to vegetation differences; and (3) varies across a latitudinal gradient in vegetation greenness. Similar characteristics were observed in NARR simulations, though we found: (1) a wet bias in soil moisture; and (2) an over- (under-) estimation of ET for low (high) observations. Differences are attributed to not fully capturing the impact of vegetation greening on the ET-\theta relation. Improvements could be achieved by propagating vegetation changes to the unstressed ET and plant stress threshold. Enhanced parameterizations of the ET-\theta relation are necessary to constrain land-atmosphere interactions and their role in precipitation recycling in the NAM.
Figure 4. (a) Comparison of OBS and NARR ET-θ relations for SR. (b) Comparison of $ET_{OBS}$ and $ET_{NARR}$ for SR, KN, STS and TDF. Regressions of $ET_{OBS}$ and $ET_{NARR}$ depicted as red, dashed lines. (c) Conceptual diagrams of (left) the observed NAM transition in the ET-θ relation due to changes in $ET_{max}$ and $θ/θ_{max}$ and (right) the misrepresentation of the ET-θ relation in NARR relative to OBS. $θ/θ_{max}$ in NARR has been scaled to match OBS.
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