Diagnosing Seasonal Vegetation Impacts on Evapotranspiration and Its Partitioning at the Catchment Scale during SMEX04–NAME

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(Manuscript received 6 October 2011, in final form 5 June 2012)

ABSTRACT

A fundamental problem in ecohydrology is diagnosing impacts of vegetation dynamics on the catchment response. This study uses a distributed hydrologic model and remote sensing data to evaluate the effects of seasonal vegetation greening on the basin water balance and the partitioning of evapotranspiration ET into soil evaporation, transpiration, and evaporation of intercepted water. Using remotely sensed data, updates are made to model vegetation parameters related to radiation, interception, and transpiration as ecosystems respond to precipitation during the North American monsoon (NAM). Comparisons of simulations with static and seasonally varying vegetation parameters reveal lower ET but higher vegetation-mediated ET losses because of the greening. Sensitivity analyses indicate that vegetation fraction is the primary control on ET and its partitioning, while interception parameters play a secondary role. As a result, spatial patterns in ET partitioning in the catchment exhibit a strong signature of vegetation fraction, though fine (coarse)-scale influences of soil moisture (radiation) are also observed. Vegetation-mediated ET losses were significant in large fractions of the catchment and exhibited ecosystem-dependent seasonal evolutions. The numerical simulations presented here provide the first spatially explicit estimates of ET partitioning accounting for vegetation dynamics obtained from remotely sensed data at the catchment scale.

1. Introduction

Seasonal greening of drought-deciduous ecosystems in semi-arid regions significantly alters the surface energy balance, including evapotranspiration ET (e.g., Montaldo et al. 2005; Watts et al. 2007; Vivoni et al. 2008). Relatively little is known about the impacts of vegetation dynamics on the catchment response during the North American monsoon (NAM; July–September), despite quantification of these dynamics at regional scales (Forzieri et al. 2011). Quantifying the effects of seasonal greening on the basin water balance is a significant challenge in ecohydrology (e.g., Newman et al. 2006; Voepel et al. 2011). Of particular importance are the roles of vegetation processes on the seasonal evolution of catchment ET and its partitioning into soil evaporation $E$, transpiration $T$, and evaporation of intercepted water $I$ (Reynolds et al. 2000).

Ecological studies during the monsoon typically focus on individual processes at the plot scale (e.g., Maass et al. 1995; Yépez et al. 2007; Watts et al. 2007). Investigations of watersheds (10$^4$–10$^5$ km$^2$), however, are essential to address the role of vegetation phenology on hydrologic responses, leading to a large gap in our understanding of spatiotemporal patterns at the catchment scale (Newman et al. 2006). An approach for testing the role of vegetation on catchment hydrology is via simulations that have been tested against field data (Ivanov et al. 2008; Vivoni et al. 2010). Distributed hydrologic models, for example, allow 1) identifying the impacts of seasonal plant responses on the basin water balance relative to static conditions and its spatial variability, 2) isolating the spatial sensitivity to specific plant processes (and their interactions), and 3) quantifying the spatiotemporal changes in ET and its partitioning into soil evaporation and plant transpiration due to vegetation dynamics.

A major difficulty in diagnosing the impacts of vegetation dynamics on the catchment response has been the lack of reliable simulations. Here, a distributed hydrologic
model, tested against a distributed soil moisture and temperature dataset (Vivoni et al. 2010), is employed. Vegetation changes are captured by linking remote sensing observations to model parameters that influence vegetation processes. This is a first step toward a fully dynamic representation of drought-deciduous ecosystems of the monsoon region (cf. Ivanov et al. 2008). The numerical experiments here are designed to reveal the mechanisms through which seasonally varying vegetation shapes the evolution of the catchment-scale evapotranspiration and its partitioning.

2. Methods

a. Study catchment and observations

A semiarid, mountain (92.5 km²) basin, Sierra Los Locos (SLL; 29.96°N, 110.51°W; Fig. 1), was selected because of its seasonal vegetation greening and the availability of ground data during the Soil Moisture Experiment 2004 (SMEX04)—North American Monsoon Experiment (NAME) (Bindlish et al. 2008). The basin has complex terrain—with elevations ranging from 657 to 1681 m and slopes of 16.4° ± 10°—that organizes soil and ecosystem distributions. Shallow soils (<2 m) range in texture from sandy to sandy clay loam. Three major ecosystems are present: desert scrubland at low elevations, subtropical scrublands at intermediate heights, and oak savannas at higher altitudes (Vivoni et al. 2007). Ecosystems exhibit seasonal greening during the monsoon, accounting for 60%–70% of the annual precipitation, though the magnitude and duration of greening periods vary (Méndez-Barroso et al. 2009).

Remotely sensed (RS) data from the Moderate Resolution Imaging Spectroradiometer (MODIS) were used to map albedo, leaf area index (LAI), and normalized difference vegetation index (NDVI) at 16-day compositing intervals and 250-m or 1-km spatial resolution. MODIS composites were projected and clipped to the basin. Figure 1 presents the seasonal variations of NDVI and albedo observations, including spatial average (squares), ±1 spatial standard deviation (bars), and maximum and minimum (solid lines).

b. Hydrologic modeling with remotely sensed vegetation parameters

Remote sensing data are used to vary vegetation parameters of the Triangulated Irregular Network
Table 1. Vegetation parameters with basin-averaged values (±1 spatial standard deviation) for the static leaf off [day of year (DOY) 177 or 25 Jun 2004] and leaf on (DOY 241 or 28 Aug 2004) cases.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Variable (unit)</th>
<th>Process classification</th>
<th>RS source</th>
<th>Static leaf off (pre-NAM)</th>
<th>Static leaf on (NAM)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vegetation fraction</td>
<td>( v_f ) (-)</td>
<td>All</td>
<td>NDVI</td>
<td>0.05 (±0.05)</td>
<td>0.58 (±0.20)</td>
</tr>
<tr>
<td>Albedo</td>
<td>( a ) (-)</td>
<td>Radiation</td>
<td>Albedo</td>
<td>0.15 (±0.01)</td>
<td>0.14 (±0.01)</td>
</tr>
<tr>
<td>Optical transmission</td>
<td>( K_t ) (-)</td>
<td>Radiation</td>
<td>LAI</td>
<td>0.70 (±0.09)</td>
<td>0.36 (±0.09)</td>
</tr>
<tr>
<td>Free throughfall(^a)</td>
<td>( p ) (-)</td>
<td>Interception</td>
<td>NDVI</td>
<td>0.95 (±0.05)</td>
<td>0.42 (±0.20)</td>
</tr>
<tr>
<td>Canopy field capacity(^b)</td>
<td>( S ) (mm)</td>
<td>Interception</td>
<td>NDVI</td>
<td>0.06 (±0.04)</td>
<td>0.46 (±0.15)</td>
</tr>
<tr>
<td>Stomatal resistance(^c)</td>
<td>( r_s ) (s m(^{-1}))</td>
<td>Transpiration</td>
<td>NDVI</td>
<td>95.61 (±4.33)</td>
<td>53.28 (±15.97)</td>
</tr>
</tbody>
</table>

\(^a\) Free throughfall coefficient obtained as \( p = 1 - v_f \), following Návar et al. (1999).
\(^b\) Canopy field capacity obtained as \( S = v_f S_{\text{max}} + (1 - v_f)S_{\text{min}} \), where \( S_{\text{max}} = 0.77 \text{ mm} \) and \( S_{\text{min}} = 0.02 \text{ mm} \), from Návar et al. (1999).
\(^c\) Minimum canopy-averaged stomatal resistance obtained as \( r_s = v_f r_{s\text{min}} + (1 - v_f)r_{s\text{max}} \), where \( r_{s\text{min}} = 20 \text{ s m}\(^{-1}\) \) and \( r_{s\text{max}} = 100 \text{ s m}\(^{-1}\) \), following ranges in Cox et al. (1999).

(TIN)-based Real-time Integrated Basin Simulator (TIBS) (Ivanov et al. 2004). The model has a spatially explicit treatement of terrain, soils, vegetation, and atmospheric forcing. The distributed model accounts for hydrologic processes that track the catchment response, including ET from bare soil, vegetation, and canopy interception; 2) infiltration and soil moisture redistribution; 3) shallow subsurface transport; and 4) overland and channel flow. Vivoni et al. (2010) conducted a model application in the SLL basin using static vegetation data for the period after full-canopy development. The model application consisted of 34 302 elements with an effective resolution of 52 m obtained from a TIN-based terrain representation. Reliable model performance was obtained against surface layer (0-5 cm) soil moisture and temperature data from a set of ground stations (see Vivoni et al. 2010 for details). Here, three alternative cases are constructed to diagnose the vegetation impact (Fig. 1): 1) static leaf off (pre-NAM), 2) static leaf on (NAM), and 3) seasonally varying or dynamic greening (DYN). All cases considered remotely sensed vegetation data that was coarser in resolution than the original (30 m) land cover data in Vivoni et al. (2010). Model parameters for each case were linked to RS data, updated at the time of available images, and resampled to the model domain (see Table 1).

The approach taken to link the RS data to the model vegetation parameters was based on Carlson and Ripley (1997). For example, vegetation fraction \( v_f \) in a model element, which has important controls on interception, radiation, and ET (Ivanov et al. 2004), was obtained as

\[
v_f = \left( \frac{\text{NDVI} - \text{NDVI}_{\text{min}}}{\text{NDVI}_{\text{max}} - \text{NDVI}_{\text{min}}} \right)^2,
\]

where \( \text{NDVI}_{\text{min}} = 0.18 \) and \( \text{NDVI}_{\text{max}} = 0.75 \) are minimum and maximum basin-averaged values of NDVI in this application. A similar scaling with NDVI was performed for interception parameters \( p \) and \( S \) (Návar et al. 1999, see Table 1). Slowly varying canopy height and interception drainage parameters were kept constant using values in Vivoni et al. (2010). Leaf effects on radiation are captured by 1) the optical transmission coefficient \( K_t \) (following the Beer–Lambert law):

\[
K_t = \exp(-k\text{LAI}),
\]

where \( k = 0.61 \) for a similar ecosystem (Maass et al. 1995), and 2) the observed albedo \( a \). Lizárraga-Celaya et al. (2010) found good agreement between MODIS and ground-based albedo at the EC site. Stomatal resistance \( r_s \) was scaled with NDVI using (1), following the observed linear relation of Vivoni et al. (2008) between \( \text{ET}_{\text{max}} \) and vegetation greenness at a range of field sites. Table 1 reports the relations for \( r_s \) and \( S \) as well as a range of values for each case.

3. Results and discussion

a. Comparison of static and seasonally varying vegetation simulations

Distributed simulations for the three cases were conducted from 14 June to 30 September 2004, to match SMEX04–NAME (Higgins and Goichis 2007), using hourly rainfall forcing from three gauges in the SLL basin and atmospheric data from the EC site. Table 2 compares the seasonal water balance, \( \Delta S/\Delta t = P - \text{ET} - Q \) for the three cases, obtained from basin-averaged quantities. Static leaf off (or pre-NAM) exhibits the highest ET, while static leaf on (or NAM) has the lowest ET, indicating that vegetation supports less total ET over the season. This counterintuitive result is due to the impacts of higher \( v_f \) on 1) light interception resulting in 51.4% ± 14% less radiation and 2) rainfall interception \( p \) leading to 44.2% ± 21% less water reaching the soil surface (Table 1). As expected, dynamic greening ET lies between the other cases and is slightly higher than the \( \text{ET}/P = 0.76 \) of Vivoni et al. (2010) obtained for the
full-canopy period. Low $Q/P$ (~2\%) is consistent with other estimates in the region (Gochis et al. 2006). ET/P differences among the cases are not offset by changes in $Q/P$, but result in storage variations $\Delta S/P$, indicating that a soil moisture comparison can reveal the signatures of seasonally varying vegetation on the basin water balance.

Figure 2 presents the seasonal evolution of the basin-averaged surface (0–5 cm) volumetric soil moisture $\theta_{\text{sur}}$ (m$^3$ m$^{-3}$) and ET (mm h$^{-1}$). Note the excellent match of the DYN and NAM cases with the field data during a long dry down, as reported in Table 2. The pre-NAM case, however, underestimates soil moisture considerably. Large differences between the cases occur during a 2-week period (15–29 July 2004) when vegetation parameters change rapidly in time (Méndez-Barroso et al. 2009). During the season, precipitation leads to increases

Table 2. Characteristics of vegetation cases. The water balance and ET partitioning components include $P$, ET, $Q$, and $\Delta S$, which are basin-averaged precipitation, evapotranspiration, runoff, and change in storage (mm). $\Delta S$ is calculated as a residual. The performance metrics are the mean absolute error (MAE, in units indicated) and bias (unitless), defined as in Vivoni et al. (2006), for the basin-averaged $\theta_{\text{sur}}$ and ET calculated with respect to the ground stations and EC site.

<table>
<thead>
<tr>
<th>Component</th>
<th>Static leaf off (pre-NAM)</th>
<th>Static leaf on (NAM)</th>
<th>Dynamic greening (DYN)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water balance partitioning</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$P$ (mm)</td>
<td>294.82</td>
<td>294.82</td>
<td>294.82</td>
</tr>
<tr>
<td>ET (mm) ($ET/P$)</td>
<td>274.35 (0.93)</td>
<td>221.73 (0.75)</td>
<td>231.02 (0.78)</td>
</tr>
<tr>
<td>$Q$ (mm) ($Q/P$)</td>
<td>6.73 (0.02)</td>
<td>5.40 (0.02)</td>
<td>6.11 (0.02)</td>
</tr>
<tr>
<td>$\Delta S$ (mm) ($\Delta S/P$)</td>
<td>13.74 (0.05)</td>
<td>67.69 (0.23)</td>
<td>57.69 (0.20)</td>
</tr>
<tr>
<td>Evapotranspiration partitioning</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$E$ (mm) ($E/ET$)</td>
<td>271.61 (0.99)</td>
<td>129.18 (0.58)</td>
<td>167.18 (0.72)</td>
</tr>
<tr>
<td>$T$ (mm) ($T/ET$)</td>
<td>2.46 (0.01)</td>
<td>67.81 (0.31)</td>
<td>46.84 (0.20)</td>
</tr>
<tr>
<td>$I$ (mm) ($I/ET$)</td>
<td>0.28 (0.001)</td>
<td>24.74 (0.11)</td>
<td>17.00 (0.07)</td>
</tr>
<tr>
<td>Performance metrics: MAE (bias)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\theta_{\text{sur}}$ (m$^3$ m$^{-3}$)</td>
<td>0.04 (0.50)</td>
<td>0.01 (1.11)</td>
<td>0.01 (1.16)</td>
</tr>
<tr>
<td>ET (mm h$^{-1}$)</td>
<td>0.16 (0.64)</td>
<td>0.15 (0.54)</td>
<td>0.15 (0.51)</td>
</tr>
</tbody>
</table>
in $\theta_{sat}$ that are dissipated through ET, with soil moisture recessions controlled by the vegetation status and its parameterization. Catchment ET rates are comparable to the EC data (Fig. 2b, Table 2), despite the distance between sites and scale discrepancy between the basin-averaged model estimate and the site data (Watts et al. 2007). Overall, the catchment response exhibits a pulse–recession behavior with prolonged dry downs (Vivoni et al. 2010), which characterizes peripheral areas in the semiarid region with low amounts of sustained rainfall (Tang et al. 2012).

Table 2 also shows the basin-averaged ET partitioning for each case. The pre-NAM case is dominated by soil evaporation (≈99% of ET), while the NAM case has a mixture of losses due to vegetation, including a large amount of water lost to interception (≈11% of ET). Note the basin-averaged $y_f$ for NAM is 0.58, matching the observations of Yilmaz et al. (2008), indicating that large bare soil fractions are still present. As expected, the DYN exhibits an ET partitioning that is intermediate to the static cases, with $T/ET$ of 0.20 over the season. This estimate is within the range of $T/ET$ (0.07–0.8) in previous studies (Reynolds et al. 2000). Because of its seasonality, the DYN case warrants a detailed ET partitioning analysis to identify its spatiotemporal variability at the catchment scale. Prior to this, however, it is worthwhile to identify the vegetation processes most responsible for the seasonal evolution of ET partitioning.

b. Sensitivity analysis of spatiotemporal vegetation processes

Comparison of the pre-NAM and NAM cases revealed lower ET/$P$ and higher $T/ET$ for vegetated conditions caused by effects on radiation, interception, and transpiration processes that can be isolated. To do so, simulations were conducted where process parameters (Table 1) were sequentially varied to quantify how the seasonality in each affected the catchment response. Figure 3 presents a sensitivity analysis of ET and its partitioning for different cases depicting the seasonal processes. In VF, only $y_f$ is varied, while other parameters in Table 1 remain as in pre-NAM. In VFR, $y_f$ and radiation ($a$ and $K_r$) parameters are varied, while VFRT includes changes in $y_f$, $a$, $K_r$ and the transpiration parameter $r_s$. Only the DYN case has seasonal variations in all parameters, including $p$ and $S$. Two measures of ET partitioning are shown: basin-averaged ET/$P$ (Fig. 3a) and its spatial standard deviation $\sigma_{ET}/P$ (Fig. 3b) and their components ($E$, $T$, and $I$) accumulated over the season.

Seasonal ET/$P$ considerably varies when vegetation process evolution is allowed for this semiarid region. For example, a decrease of 19% in ET/$P$ occurs between the pre-NAM and VF cases, indicating that $y_f$ is a dominant control on total ET. In comparison, the sensitivity of ET/$P$ to seasonality in radiation (−1%, VFR) and transpiration (+1%, VFRT) parameters is low, while the evolution of interception parameters (DYN) has an important impact on ET/$P$ (+4.2%). The cases also reveal how ET partitioning is affected by seasonality of individual processes, with $y_f$ having the largest impact on increasing $T/ET$ and $p$ and $S$ leading to a greater $I/ET$. The dominant role of $y_f$ stems from affecting all vegetation processes and its wider range of variation (≈1 order of magnitude) between static cases (Table 1). The spatial variability in ET $\sigma_{ET}$ is also affected by the vegetation process seasonality. Interestingly, static conditions promote larger $\sigma_{ET}/P$ as compared to the other cases, indicating that seasonally varying vegetation processes reduce the spatial variations in ET. As with ET/$P$, soil evaporation is the major contributor to $\sigma_{ET}/P$ with an increasing amount from $T/ET$ and $I/ET$ as vegetation processes evolve over the monsoon.

c. Seasonal evolution of catchment evapotranspiration partitioning

Sensitivity analyses revealed the dominant role of $y_f$ on ET and its partitioning when aggregated over the
catchment and season. Figure 4 explores the spatiotemporal evolution of ET and its components for the DYN case. Results for cumulative ET in the pre-NAM and NAM cases are included for reference only. Note the abrupt increases in $T_{ET}$ and $I_{ET}$ during the “green-up” period and their constant fractions during the “stable” period in Fig. 4a. These periods were selected for comparison because of their differences in $v_f$ but similar soil moisture during a prolonged dry down. Hourly estimates of ET partitioning are shown as $E$ and $(T + I)$ for clarity to depict differences between soil- and vegetation-mediated losses (Figs. 4b,c). The green-up period exhibits a shift from $E/ET$ to $(T + I)/ET$ dominance on 27 July 2004 due to 1) sharp increases of $v_f$, and 2) high root zone soil moisture $s_{rz}$, as the combination of higher vegetation fraction and access to soil water by plants promotes higher transpiration. This is consistent with the seasonal shifts in $T/ET$ observed in a desert shrubland (Scott et al. 2006). Over the entire green-up period, the hourly-averaged daytime $(T + I)/ET$ is equal to 0.71,
but 3 days exceed hourly maximum values of 0.92. In contrast, the stable period has daytime average \((T + I)/ET\) of 0.49 with a maximum of 0.58. Interestingly, the drier conditions during the stable period exhibit strong, out-of-phase diurnal cycles in \(E\) and \((T + I)\), with peaks in the early morning and noon, respectively.

The spatial distribution of ET partitioning is illustrated for 2 days selected in each period to represent average midday conditions. Vegetation-mediated losses dominate the spatial distribution in the green-up period (Fig. 4d) with 78% and 53% of the basin area having \((T + I)/ET\) greater than 0.5 and 0.75, respectively. Note that the widespread, but patchy, distribution of high \((T + I)/ET\) follows increased \(v_T\) (Fig. 4f) in subtropical scrublands responding to localized storms. For example, the mountain front (mf) exhibits intense greening that subsides in the stable period, during which \((T + I)/ET\) is significantly reduced (\(-64\%\); Fig. 4e). Other locations, such as the valley bottom (vb), experience little change in \((T + I)/ET\) because of constant low values of \(v_T\) in the desert scrubland. During the stable period, \((T + I)/ET\) has values greater than 0.5 and 0.75 in 47% and 22% of the basin area—a clear reduction in spatial extent. Vegetation-mediated ET losses are also concentrated in certain oak savannas at high elevation. The mountain top (mt) shows an increase in \(v_T\) (Fig. 4g) and \((T + I)/ET\) (+73%) during the stable period, likely due to the delayed greening of this ecosystem (Forzieri et al. 2011). Note that while \(v_T\) (at 250-m resolution) has a strong influence on \((T + I)/ET\), there are other factors affecting the spatial pattern, including finescale soil moisture controls on ET (near 50 m) and the coarse radiation effects of albedo and LAI (at 1 km). As a result, the evolution of ET partitioning aggregated over a large catchment emerges from a complex set of underlying processes that can exhibit strong spatiotemporal variations.

4. Conclusions

Quantifying how ET partitioning varies with vegetation dynamics during a season and within a catchment is a major challenge in ecohydrology (Newman et al. 2006). In this study, a distributed hydrologic model is used to provide the first spatially explicit estimates of ET partitioning at the catchment scale using remotely sensed vegetation conditions. Model estimates are in excellent agreement with available, but limited, observations (Vivoni et al. 2007, 2010) and are consistent with prior available ET partitioning studies (Reynolds et al. 2000; Scott et al. 2006). The numerical study revealed 1) the reduction of ET/P due to seasonal vegetation cover; 2) the dominant role of vegetation fraction on ET and its partitioning, relative to other plant parameters; and 3) the seasonal shift of the spatial distribution of vegetation-mediated ET losses from dominance by subtropical scrublands early in the season to patterns resembling the oak savanna distribution later in the season. While promising, further efforts are required to simulate the biophysical responses of drought-deciduous ecosystems to the monsoon—for example, following Ivanov et al. (2008)—and assess their spatiotemporal impacts on catchment ET partitioning. This will provide a basis for generalization of these results for other model structures. Furthermore, the model-based findings in this study need to be corroborated with field-based ET partitioning estimates that span the seasonal vegetation evolution and sample representative ecosystems in a catchment. Improved estimates of ET and its partitioning obtained from field studies and modeling are necessary for assessing ecological controls on regional hydrology and land–atmosphere interactions during the North American monsoon.

Acknowledgments. Funding from the Army Research Office (Grant 56059-EV-PCS), NOAA Climate Program Office (Grant GC07-019), NSF IRES Program (Grant OISE 0553852), USDA-ARS SMEX04 project, and U.S. Fulbright-Garcia Robles Scholar Program is acknowledged.

REFERENCES


