Spatial extent of the North American Monsoon: Increased cross-regional linkages via atmospheric pathways

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[1] The North American monsoon is a key feature affecting summer climate over Southwestern North America. During the monsoon, evapotranspiration from the Southwest promotes transference of water to the atmosphere which is subsequently distributed across the continent - linking the SW to other regions via atmospheric hydrologic connectivity. However, the degree to which atmospheric connectivity redistributes monsoonal terrestrial moisture throughout the continent and its sensitivity to climate disturbances such as drought is uncertain. We tracked the trajectory of moisture evapotranspired within the semiarid Southwest during the monsoon season using a Lagrangian analytical model. Southwest moisture was advected north-east accounting for ~15% of precipitation in adjacent Great Plains regions. During recent drought (2000–2003), this amount decreased by 45%. Our results illustrate that the spatial extent of the North American monsoon is larger than normally considered when accounting for hydrologic connectivity via soil moisture redistribution through atmospheric pathways. **Citation:** Dominguez, F., J. C. Villegas, and D. D. Breshears (2009), Spatial extent of the North American Monsoon: Increased cross-regional linkages via atmospheric pathways, *Geophys. Res. Lett.*, *36*, L07401, doi:10.1029/2008GL037012.

1. Introduction

[2] The advent of the North American Monsoon (NAM) during the summer months brings an abrupt precipitation increase to a large region of Southwestern North America. Monsoon rains account for the majority of annual precipitation in the region [*Douglas et al.*, 1993]. While the current consensus encloses the area of influence of the North American Monsoon to the southwest (SW) and nearby regions of northern Mexico, the spatial extent of the monsoon is larger following relocation of terrestrial moisture via atmospheric pathways. In semiarid ecosystems such as the SW, evapotranspiration (ET) is estimated to be more than 90% of incoming precipitation [*Wilcox et al.*, 2003]. SW-ET produced during the monsoon season supports vertically integrated moisture flux divergence from the region [*Anderson et al.*, 2004], making the SW region one of the largest upper-air sources of moisture for the North American continent during the summer [*Anderson and Roads*, 2001]. This moisture can be relocated via atmospheric pathways and eventually fall as precipitation either in the region (recycling) or elsewhere (export). However, the fate of NAM ET and its contribution to downstream precipitation has been uncertain due to the difficulty in quantifying and tracking atmospheric flows.

[3] Recent advances in our understanding of hydrologic systems, along with the availability of computational resources, enable the delineation of hydrologic connectivity associated with atmospheric pathways that determine source-sink regions of evapotranspired moisture at regional to global scales [*Brubaker et al.*, 2001; *Bosilovich et al.*, 2003; *Sudradjat et al.*, 2003; *Stohl and James*, 2005; *Dominguez et al.*, 2006]. Consequently, the extent to which the ecohydrological dynamics of one region affect moisture transport and subsequent precipitation in remote locations can now be assessed. This advance extends the traditional precipitation recycling approach which focuses only on the contribution of local evapotranspiration (ET) to local precipitation [*Budyko*, 1974], – by looking at land-atmosphere connectivity at the continental scale.

[4] Our overall goal was to delineate and quantify the spatio-temporal variability of atmospheric pathways that hydrologically link the SW to other regions in North America. Our specific objectives were 1) to evaluate the suitability of a large existing ET data set (North American Regional Reanalysis, or NARR) for addressing our overall goal; 2) to delineate the pathways and quantify the seasonal progression of precipitation that originates as ET from the SW, differentiating the locally recycled and cross-regionally exported components; and 3) to assess how such relationships are altered by severe, protracted drought. We discuss how monsoonal precipitation has a much larger spatial impact than previously thought due to relocation of moisture from the region through atmospheric pathways.

2. Data and Methodology

[5] The SW drought of the early 2000s was one of the most severe on instrumental record. Therefore, we conducted our analysis for a period from 1996–2006, spanning three types of temporal intervals related to the ecohydrological dynamics of the semi-arid SW: pre-drought (1996–1999), drought (2000–2003) and drought transition (2004–2006). We calculate the amount of precipitation falling over North America originating as ET from the SW using the Dynamic Recycling Model (DRM) [*Dominguez et al.*, 2006]. This model estimates source and sink regions of evapotranspired moisture, and has been used to study the

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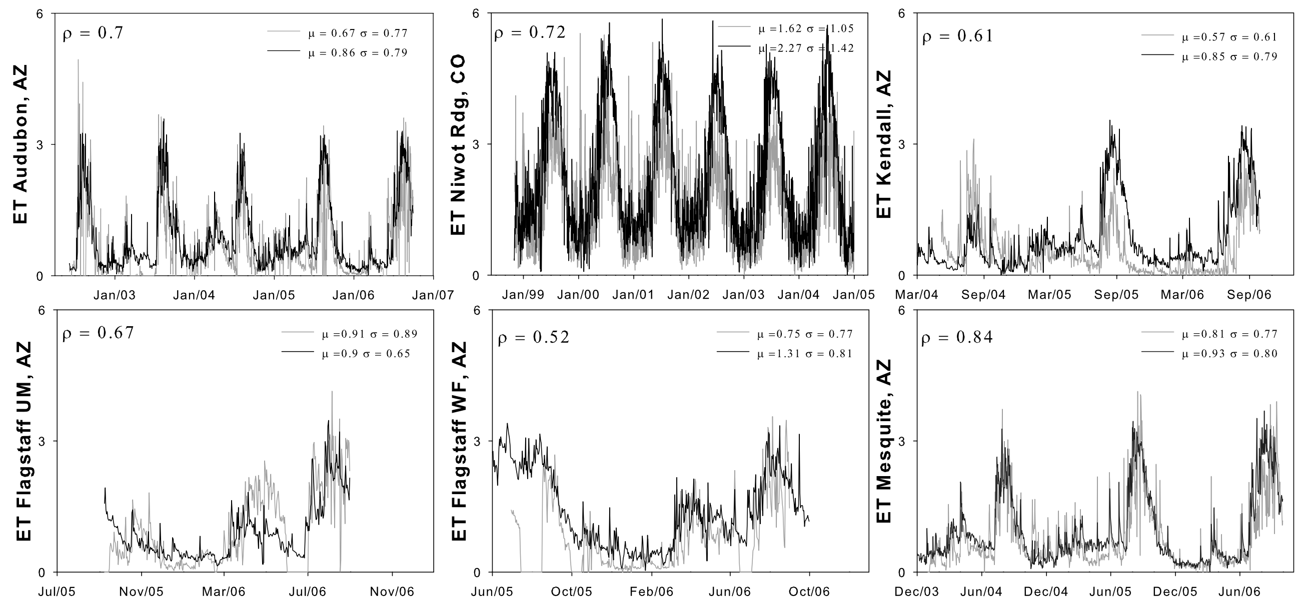

Figure 1. Daily ET (mm/day) estimates of each of the observation stations and the NARR-ET at the corresponding pixel. The gray lines correspond to observations, while the black line is the NARR estimate. At the top right we present the mean (μ) and standard deviation (σ) of the NARR and observation data, with the corresponding correlation coefficient between the two (ρ) in the left corner.

driving mechanisms of recycling variability in the NAM Region and the Central US Plains [*Dominguez et al.*, 2008; *Dominguez and Kumar*, 2008]. As with all bulk recycling models, the DRM is derived from the conservation equation for water vapor of recycled origin. The model requires gridded mean and transient values of specific humidity and zonal and meridional winds in the vertical column, and also evapotranspiration and precipitation estimates. The DRM uses a Lagrangian coordinate system that enables us to follow the trajectory of the advected moisture. The model provides an expression for the local recycling ratio ρ which accounts for the fraction of precipitation falling in one specific cell originating as ET from within the entire region of analysis. The value of ρ is a function of ET, precipitable water and time, calculated by following the trajectory of the air [see *Dominguez et al.*, 2006]. The DRM can also be used to calculate the contribution of ET originating from certain sub-regions to local and remote precipitation. We used this capability of the model to tag the moisture originating from the SW. Like most analytic recycling models, the DRM assumes that the atmosphere is fully mixed. This assumption is justified by the argument that most of the water vapor in the atmospheric column is contained within the planetary boundary layer (PBL) where the moisture is well mixed as a result of convective processes (see *Eltahir and Bras* [1996] for reference data and detailed explanation). However, this assumption might not be always valid, as previously discussed from results based on water vapor tracers [*Bosilovich*, 2003].

[6] We used daily derived variables from the NARR data set for July through September between 1996 and 2006. The NARR product [*Mesinger et al.*, 2006] improves upon the earlier global reanalysis, particularly in terms of hydrologic modeling. Unfortunately land surface observations of variables such as soil moisture and ET are extremely limited, and are currently not assimilated into NARR estimates. Nevertheless, NARR is currently the best long-term, consistent, high-resolution climate data set for North America, providing a much better estimate of land-surface processes than the global reanalyses.

[7] When using assimilated data, the water balance equation must be modified to take into account the residual term α that arises from closure problems and is not part of the natural physics. The residual term can be as large as the other terms in the equation. Unfortunately, there is no way to systematically account for the residual term in our analyses; however, ET is the only term in the water balance equation that is completely model-derived and has significant uncertainty [see also *Nigam and Ruiz-Barradas*, 2006]. Because our analysis relies heavily on ET estimates, we compared NARR ET with estimations of ET from six AMERIFLUX sites within the Southwest. The six sites are: Niwot Ridge LTER (40.03°N, 105.56°W), Audubon Research Ranch (31.59°N, 110.51°W), Walnut Gulch-Kendall (31.74°N, 109.94°W), Flagstaff Unmanaged (35.09°N, 111.76°W), Flagstaff Wildfire (35.45°N, 111.72°W) and Santa Rita Experimental Range - Mesquite (31.82°N, 110.87°W). We assumed that tower observations for specific locations were comparable to ET estimates for a 32km NARR pixel.

3. Results

3.1. NARR ET Suitability Assessment

[8] In our comparisons of NARR-ET to flux tower observations, average NARR-ET was slightly greater than the observed value at each of the six locations (Figure 1); however, the standard deviation from both estimates at a given location was very similar and presents no clear bias. The result was a high correlation between the two daily time series at each location, ($0.52 \leq \rho \leq 0.84$; two-tailed statistical significance >0.999), indicating that the temporal

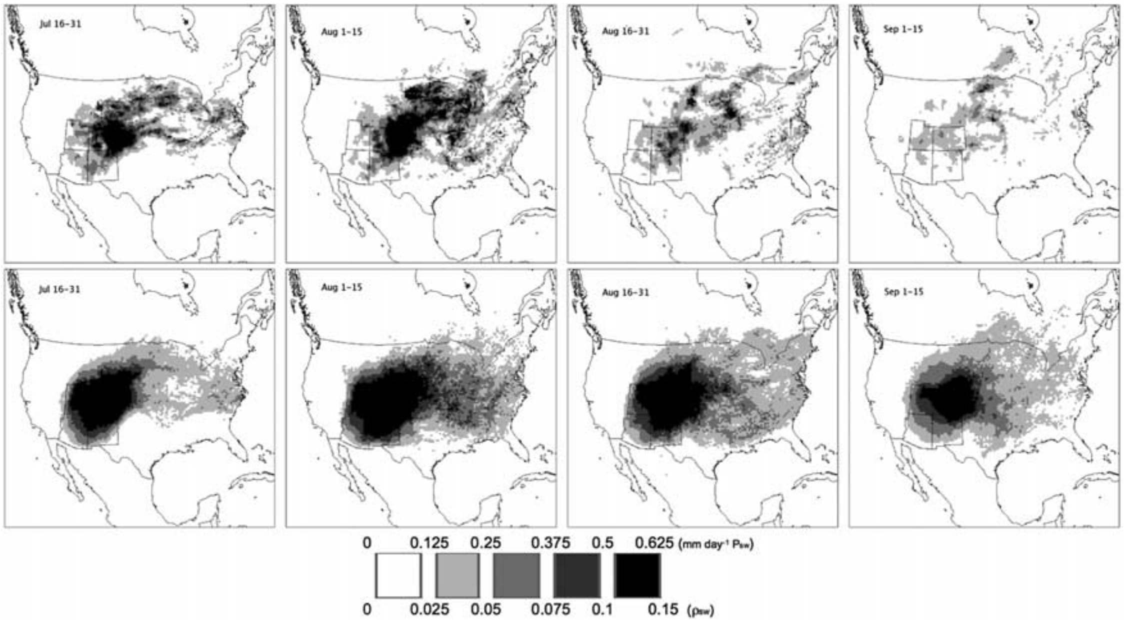

Figure 2. (top) Average precipitation originating as ET from the SW (P_{sw}) for the period 1996–1999. (bottom) Fraction of the total precipitation falling in each pixel that originates as ET from the SW (ρ_{sw}) for the period 1996–1999.

variability of ET is accurately captured by the NARR estimates, making them suitable for subsequent analyses.

3.2. Seasonal Variability of Precipitation Originating as Evapotranspiration From the Southwest

[9] Our estimates of precipitation recycling within the SW and the associated export of ET to other regions indicates that ET from the semi-arid SW region is subsequently advected throughout North America (Figure 2). Precipitation originating as ET from the SW (P_{sw}) contributes to total precipitation throughout the central and eastern US extending to southeastern Canada. Intraseasonal variability of P_{sw} averaged over 1996–1999 (Figure 2 (top)) highlights a predominantly north-east trajectory of the moisture in accordance with the dominant seasonal winds, and shows large temporal variability. As SW-ET increases with the monsoon, so does the subsequent moisture export. The exported moisture peaks during early August, and slowly decreases as the monsoon season tapers off. On average 15% of the rainfall in the northeast part of the Four Corners and adjacent areas originates in the SW (Figure 2 (bottom)). As the moisture moves east, it contributes less to total precipitation, decaying to only about 2% in the eastern seaboard. In our calculations, the value of P_{sw} is obtained by multiplying ρ_{sw} by the total precipitation falling in each pixel; for this reason the distribution of P_{sw} shows a more heterogeneous pattern than ρ_{sw}.

3.3. Interannual Variability: The Effect of Drought

[10] The temporal dynamics of NARR-ET were consistent with the overall precipitation changes over the SW for the three study periods (Figure 3a). Throughout the 11-year analysis average Jul-Sep ET is higher than precipitation, a difference also seen in observations (not shown). This reflects long-term memory in the system as winter or spring surface storage is subsequently evapotranspired in summer. The ratio of local to non-local P_{sw} highlights that the amount of moisture exported from the region is larger than the recycled precipitation (Figure 3b). Whether falling locally (recycled) or non-locally (exported), P_{sw} decreased 45% during the years of severe drought (Figure 3b). While pre-drought SW-ET contributed an average 10% of the rainfall in US Great Plains states (Nebraska, South Dakota, Wyoming and Kansas), this value decreased to 6% during the drought (Figure 3c), and has since increased due to increases in SW precipitation and ET. The large regional spatial signature of exported moisture also shrank dramatically during the severe drought, and then expanded in the drought transition periods (Figure 3d). Despite the decrease in P_{sw}, drought in the SW did not cause significant precipitation anomalies throughout the US Great Plains, and only affected immediately adjacent regions. This is due to the fact that the US Great Plains receives its warm-season moisture primarily from the Mississippi River basin, the Gulf of Mexico and the Caribbean Sea [*Brubaker et al.*, 2001] and to the out-of-phase relationship between the Southwest and the Great Plains precipitation [*Higgins et al.*, 1997]. Drought in the SW and adjacent regions is characterized by precipitation anomalies between −0.1 and −0.3 mm/day (Figure 3e (middle)), indicating that the changes in export of moisture from the region, which are on the order of 0.1 to 0.2 mm/day, are of the same order of magnitude as precipitation anomalies.

4. Discussion

[11] Our results delineate the extended region of influence of the NAM following relocation of soil moisture through atmospheric pathways. They highlight how such relocation can be modified by changes in the ecohydrology of the source region. We used the DRM to quantify the contribution of SW ET to precipitable water throughout North America. Because of its assumption of a well-mixed atmosphere, the DRM will likely underestimate the contri-

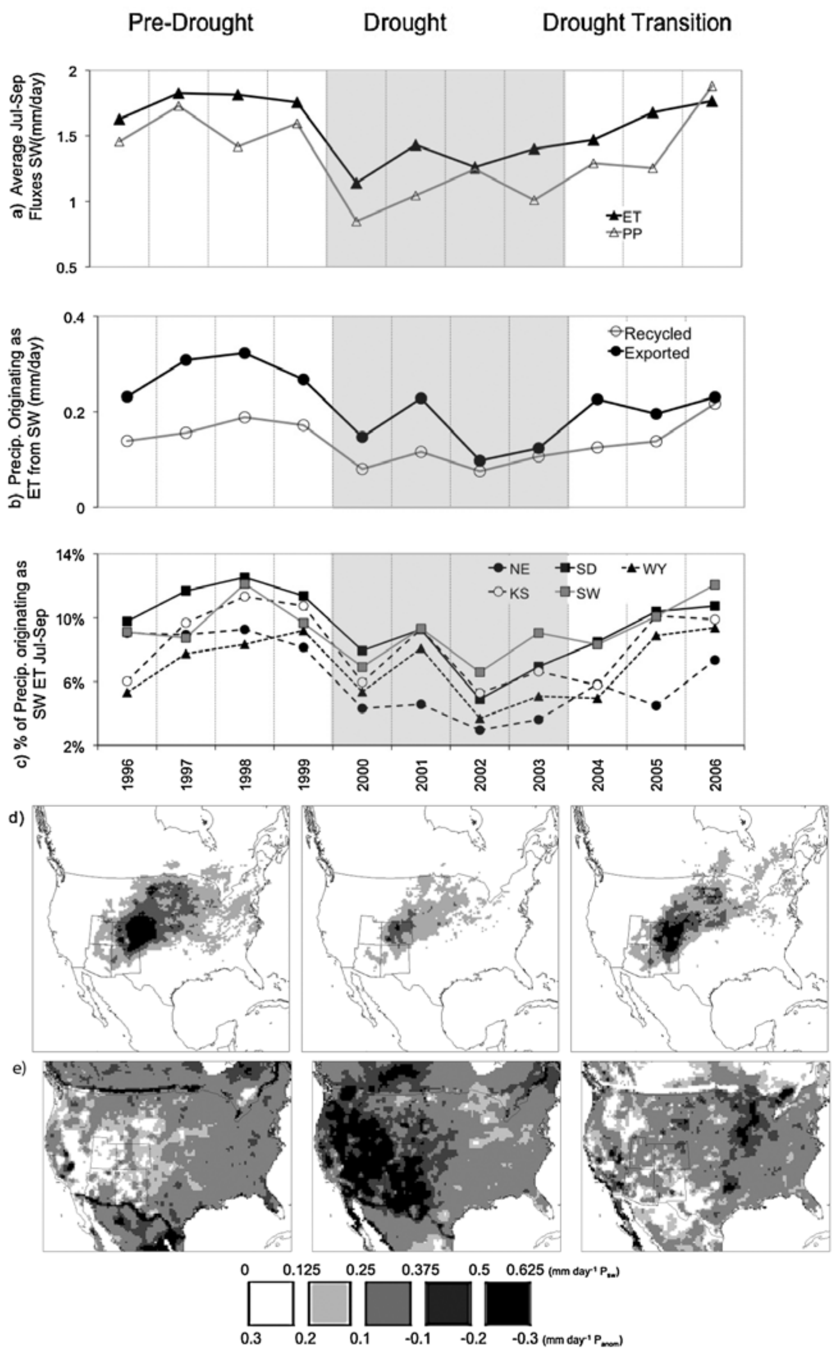

Figure 3. (a) Summer (JAS) P and ET for the period 1996–2006. (b) P_{sw} falling within the SW region (Recycled) and outside the SW region (Exported). (c) P_{sw} as a percentage of total P falling in the states of NE, SD, WY, KS, and within the SW (equal to the recycling ratio) for Jul–Sep. (d) Average Jul–Sep P originating as ET from the SW (P_{sw}) during (right) pre-drought (1996–1999), (middle) severe drought (2000–2003) and (left) drought transition (2004–2006) periods. (e) Precipitation anomalies during the same three periods.

bution of ET to total recycled and remote precipitation in the Southwest [see *Dominguez et al.*, 2008]. The suitability assessment comparing NARR-ET estimates to field observations from six sites indicates that although NARR slightly overestimates the mean ET value, the temporal variability of NARR-ET estimates is strongly correlated with field observations. This indicates that our estimates of exported ET reflect key aspects of intra-and inter-annual variability of ET production and transport via atmospheric pathways of hydrologic connectivity.

[12] Our work was targeted to assess relationships of recycled and exported moisture when the potential for land-surface effects on atmospheric connectivity is greatest (i.e., during the NAM, when the vast majority of precipitation is balanced by evapotranspiration and subsequent moisture flux divergence from the region). We illustrate that the moisture originating from the SW contributes to precipita-

tion throughout North America. Notably, the amount of recycled precipitation was substantial for some locations within the region (as much as 15%), and perhaps even more importantly, the SW exports more moisture than is recycled back into region. The states of Nebraska, South Dakota, Wyoming and Kansas are the primary beneficiaries of SW ET. Consequently, our results highlight that, due to indirect effects associated with relocation of moisture through atmospheric pathways, the spatial influence of the NAM is more extensive than is normally accounted for. More generally, our approach expands the existing body of work related to hydrologic connectivity in the Southwest which has focused almost exclusively on connectivity associated with surface or subsurface pathways to include key land-surface to atmosphere pathways of hydrologic connectivity. This type of hydrologic connectivity may also be relevant to atmospheric science and ecology [*Peters et al.*, 2008].

[13] Temporal changes in atmospheric pathways of hydrological connectivity may also be important. The recent SW drought resulted in a dramatic decrease in regional soil moisture and evapotranspiration. Consequently during the drought, precipitation in other regions originating as SW-ET dropped to less than half that of pre-drought conditions. Further, the spatial signature of exported moisture was muted during the drought years, and has since slowly recovered. Although the drought did not necessarily cause decreased precipitation in other regions, it certainly affected the export of moisture to them from the SW. Other features of the mean-climatological circulation over North America, such as the out-of-phase relationship between the Southwest and the Great Plains, where wetter monsoons are related to drier great Plains (and vice-versa) [*Higgins et al.*, 1997] might compensate for decreased incoming moisture from the SW and explain the lack of correspondence between the SW drought and precipitation anomalies in adjacent regions. However, our results illustrate that hydrologic connectivity through atmospheric pathways is sensitive to changes in the hydrology of source regions.

[14] The recent drought was severe enough to trigger tree die-off and subsequent changes in vegetation across the SW [*Breshears et al.*, 2005; *Rich et al.*, 2008]. These changes in vegetation are not accounted for in NARR-ET [*Gutman and Ignatov*, 1998]. However, we expect that these large-scale changes in land surface conditions and associated ET fluxes could potentially amplify the strength of connectivity from land surface to atmosphere, and should be considered in future assessments of hydrologic connectivity.

[15] In conclusion, our results illustrate the importance of a key type of hydrological connectivity in addition to that associated with surface and subsurface pathways: relocation of terrestrial moisture via atmospheric pathways. This hydrologic connectivity produces cross-regional linkages, and shows how a regional phenomenon such as the North American Monsoon extends to a much larger region when relocation of moisture is taken into account.

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References

Anderson, B. T., and J. O. Roads (2001), Summertime moisture divergence over the southwestern US and northwestern Mexico, *Geophys. Res. Lett.*, *28*, 1973–1976.

Anderson, B. T., H. Kanamaru, and J. O. Roads (2004), The summertime atmospheric hydrologic cycle over the southwestern United States, *J. Hydrometeorol.*, *5*, 679–692.

Bosilovich, M. G. (2003), On the vertical distribution of local and remote sources of water for precipitation, *Meteorol. Atmos. Phys.*, *80*, 31–41.

Bosilovich, M. G., Y. C. Sud, S. D. Schubert, and G. K. Walker (2003), Numerical simulation of the large-scale North American monsoon water sources, *J. Geophys. Res.*, *108*(D16), 8614, doi:10.1029/2002JD003095.

Breshears, D. D., et al. (2005), Regional vegetation die-off in response to global-change-type drought, *Proc. Natl. Acad. Sci. U. S. A.*, *102*, 15,144–15,148.

Brubaker, K. L., P. A. Dirmeyer, A. Sudradjat, B. S. Levy, and F. Bernal (2001), A 36-yr climatological description of the evaporative sources of warm-season precipitation in the Mississippi River Basin, *J. Hydrometeorol.*, *2*, 537–557.

Budyko, M. I. (1974), *Climate and Life*, Academic, New York.

Dominguez, F., and P. Kumar (2008), Preciptation recycling variability and ecoclimatological stability: A study using NARR data. Part I: Central USA plains, *J. Clim.*, *21*, 5165–5186.

Dominguez, F., P. Kumar, X. Liang, and M. Ting (2006), Impact of atmospheric moisture storage on precipitation recycling, *J. Clim.*, *19*, 1513–1530.

Dominguez, F., P. Kumar, and E. R. Vivoni (2008), Precipitation recycling variability and ecoclimatological stability: A study using NARR data. Part II: North American monsoon region, *J. Clim.*, *21*, 5187–5203.

Douglas, M. W., R. A. Maddox, and K. Howard (1993), The Mexican monsoon, *J. Clim.*, *6*, 1665–1677.

Eltahir, E. A. B., and R. L. Bras (1996), Precipitation recycling, *Rev. Geophys.*, *34*, 367–378.

Gutman, G., and A. Ignatov (1998), The derivation of the green vegetation fraction from NOAA/AVHRR data for use in numerical weather prediction models, *Int. J. Remote Sens.*, *19*, 1533–1543.

Higgins, R. W., Y. Yao, E. S. Yarosh, J. E. Janowiak, and K. C. Mo (1997), Influence of the great plains low-level jet on summertime precipitation and moisture transport over the central United States, *J. Clim.*, *10*, 481–507.

Mesinger, F., et al. (2006), North American regional reanalysis, *Bull. Am. Meteorol. Soc.*, *87*, 343–360.

Nigam, S., and A. Ruiz-Barradas (2006), Seasonal hydroclimate variability over North America in global and regional reanalyses and AMIP simulations: Varied representation, *J. Clim.*, *19*, 815–837.

Peters, D. P. C., P. M. Groffman, K. J. Nadelhoffer, N. B. Grimm, S. L. Collins, W. K. Michener, and M. A. Huston (2008), Living in an increasingly connected world: A framework for continental-scale environmental science, *Frontiers Ecol. Environ.*, *6*, 229–237.

Rich, P. M., D. D. Breshears, and A. B. White (2008), Phenology of mixed woody-herbaceous ecosystems following extreme events: Net and differential responses, *Ecology*, *89*, 342–352.

Stohl, A., and P. James (2005), A Lagrangian analysis of the atmospheric branch of the global water cycle. Part II: Moisture transports between Earth's ocean basins and river catchments, *J. Hydrometeorol.*, *6*, 961–984.

Sudradjat, A., K. L. Brubaker, and P. A. Dirmeyer (2003), Interannual variability of surface evaporative moisture sources of warm-season precipitation in the Mississippi River basin, *J. Geophys. Res.*, *108*(D16), 8612, doi:10.1029/2002JD003061.

Wilcox, B. P., D. D. Breshears, and M. S. Seyfried (2003), Rangelands, water balance, in *Encyclopedia of Water Science*, edited by S. W. Trimble, B. A. Stewart, and T. A. Howell, pp. 791–794, Marcel Dekker, New York.

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