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Reduced Moisture Transport Linked to Drought Propagation Across North America

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Key Points:
- Agricultural droughts in upwind regions amplify agricultural droughts downwind via decreased moisture exports
- Decreases in recycled precipitation within a region are positively correlated with decreases in imported precipitation into the region
- Reduced moisture contributions from land areas accounted for 62% of the precipitation deficit in the Midwest during the 2012 drought

Supporting Information:
- Supporting Information S1
- Data Set S1

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Abstract Droughts can have devastating societal impacts. Yet, we do not fully understand the mechanisms that control their development, possibly affecting our ability to predict them. Here we run a moisture-tracking analytical model using reanalysis data between 1980 and 2016 to explore the role of reduced moisture transport in drought propagation. We find that agricultural droughts in multiple subregions across North America may be amplified by decreased moisture transport from upwind land areas, which we link to reduced evapotranspiration and dry soil moisture upwind. We also find that decreases in precipitation recycling are correlated with decreases in moisture arriving from upwind areas. We estimate that decreases in moisture contributions from land areas accounted for 62% of the precipitation deficit during the 2012 Midwest drought. Our results suggest that the land surface may contain useful information for drought prediction and highlight the importance of sustainable land use and of regional cooperation for drought risk management.

Plain Language Summary Droughts reduce the availability of water, which affects communities and ecosystems worldwide. Recent studies have shown that droughts may travel up to thousands of kilometers across continents, but it is still unclear what are the reasons behind these observed drought displacements. While there may be several reasons, we study one particular way in which droughts may be able to travel across continents. Our idea is that a drought in one area may decrease evaporation locally, which will reduce water vapor in the air. As the wind blows, it will transport drier air, which may lead to less precipitation downwind. We find links between droughts that take place in different regions across North America, suggesting that droughts may travel in this way, for example, from the U.S. Southwest to the U.S. Midwest. We also show that the lower evaporation that took place over the western United States, likely due to droughts in the region in 2012, increased the severity of the drought in the U.S. Midwest that year. Our study highlights the importance of sustainable land use management and the need for coordination between communities in upwind and downwind regions to reduce drought risks. It may also help improve future drought predictions.

1. Introduction

Droughts may cause severe damages to communities and ecosystems. However, we do not fully understand their underlying mechanisms, which limits our ability to predict them and understand how climate change may affect them (Berg & Sheffield, 2018; Roy et al., 2019; Wood et al., 2015). Two mechanisms that have been linked to drought development are precipitation recycling and moisture transport (Rodriguez-Iturbe et al., 1991; Eltahir & Bras, 1996; Dirmeyer & Brubaker, 1999; Giannini et al., 2003; Dominguez et al., 2009; D'Odorico et al., 2013; van der Ent et al., 2010; Gimeno et al., 2012; Miralles et al., 2019; Roundy et al., 2013, 2014; Roundy & Wood, 2015; Roy et al., 2019; Santanello et al., 2017; Sud et al., 2003; Wu & Kinter, 2009). Precipitation recycling is the contribution of evapotranspiration to precipitation regionally (Eltahir & Bras, 1996). High rates of precipitation recycling imply a positive feedback, where high evapotranspiration increases atmospheric water vapor, generally leading to more precipitation, increasing soil moisture, and evapotranspiration. Moisture transport refers to moisture that originates as evapotranspiration and is advected downwind, where it may eventually fall as precipitation (Dominguez et al., 2009; Roy et al., 2019).

Studying moisture transport's contributions to flooding is an active research area, especially regarding atmospheric rivers (Dirmeyer & Brubaker, 1999; Dirmeyer & Kinter, 2010; Gimeno et al., 2012; Wei et al., 2016). However, the role of moisture transport in drought development is poorly understood (Miralles et al., 2019). Recently, droughts have been shown to travel long distances and reduced moisture transport has been proposed as a mechanism (Dominguez et al., 2009; Herrera-Estrada et al., 2017; Kam, Sheffield, & Wood, 2014; Keys et al., 2018; Roy et al., 2019). The hypothesis is that droughts reduce moisture exports downwind, possibly amplifying drought conditions downwind.

Several modeling approaches, including analytical models, have been developed to study moisture transport and precipitation recycling (Gimeno et al., 2012). We use the analytical model developed by Dominguez et al. (2006) and extended by Martinez and Dominguez (2014) to perform the first climatological analysis over North America that investigates how moisture transport may be linked to drought propagation. We also use this framework to diagnose the development of the U.S. Midwest drought in 2012.

2. Methods

2.1. The Dynamic Recycling Model

The Dynamic Recycling Model (DRM; Dominguez et al., 2006; Martinez & Dominguez, 2014) estimates how much precipitable water and precipitation that falls daily throughout the domain originates from evapotranspiration over defined subregions. We then calculate the volumes of precipitation that fall each month in each subregion that originate from evapotranspiration within and outside that subregion. The subregions have different areas, so we use these volumetric rates (km^3/month) throughout our study instead of recycling ratios. Supporting information Text S1 includes further information on the DRM.

2.2. Data

The DRM is designed to run using daily precipitation, evapotranspiration, and vertically integrated water vapor, and 6-hourly eastward and northward vertically integrated water vapor fluxes (Dominguez et al., 2006; Martinez & Dominguez, 2014). We run the DRM between 1980 and 2016 using ERA-Interim data (Dee et al., 2011) at 0.75° resolution. ERA-Interim's hydrological cycle has been validated (Balsamo et al., 2015) and shown to be more accurate than other reanalysis products (Lorenz & Kunstmann, 2012). Numerous studies have driven moisture transport models using ERA-Interim (e.g., Agudelo et al., 2018; Keys et al., 2014; Martinez & Dominguez, 2014; Pathak et al., 2016; van der Ent et al., 2010). We also use ERA-Interim's monthly volumetric soil water (0–1 m) to characterize agricultural drought.

2.3. Domain

We select a large domain to capture the possible moisture sources of the region of interest. The full domain lies within 170–140°W and 0–70°N (Figure 1a). The core land domain, between 130–60°W and 16–51.5°N, includes Mexico, the contiguous United States, and southern Canada. The core domain is divided into 15 subregions, while land areas at lower and higher latitudes are divided into 5. The Pacific Ocean is divided into four subregions and the Atlantic Ocean into three. Table S1 displays the subregions' names and areas.

2.4. Spatial Propagation

We define agricultural droughts as the instances when soil moisture falls below the 20th percentile (calculated following Andreadis et al., 2005). We call “precipitation exports” the precipitation that falls outside of a subregion but originates from evapotranspiration within it (Dirmeyer, Brubaker, et al., 2009; Zemp et al., 2014). Conversely, we call “precipitation imports” the precipitation that falls within a subregion but originates from evapotranspiration outside of it.

We identify pairs of upwind-downwind land subregions between which agricultural drought may have propagated via decreased moisture transport between 1980 and 2016. For each land subregion, we calculate monthly time series of the following: soil moisture, evapotranspiration, total precipitation exports from that subregion, total precipitation imports into that subregion, and precipitation exports-imports between that subregion and the other land subregions. We identify the instances when soil moisture, evapotranspiration, total exports, and total imports fall below their respective 20th percentiles. For each subregion in the core domain, we also calculate the monthly anomalies of total precipitation imports and the monthly anomalies

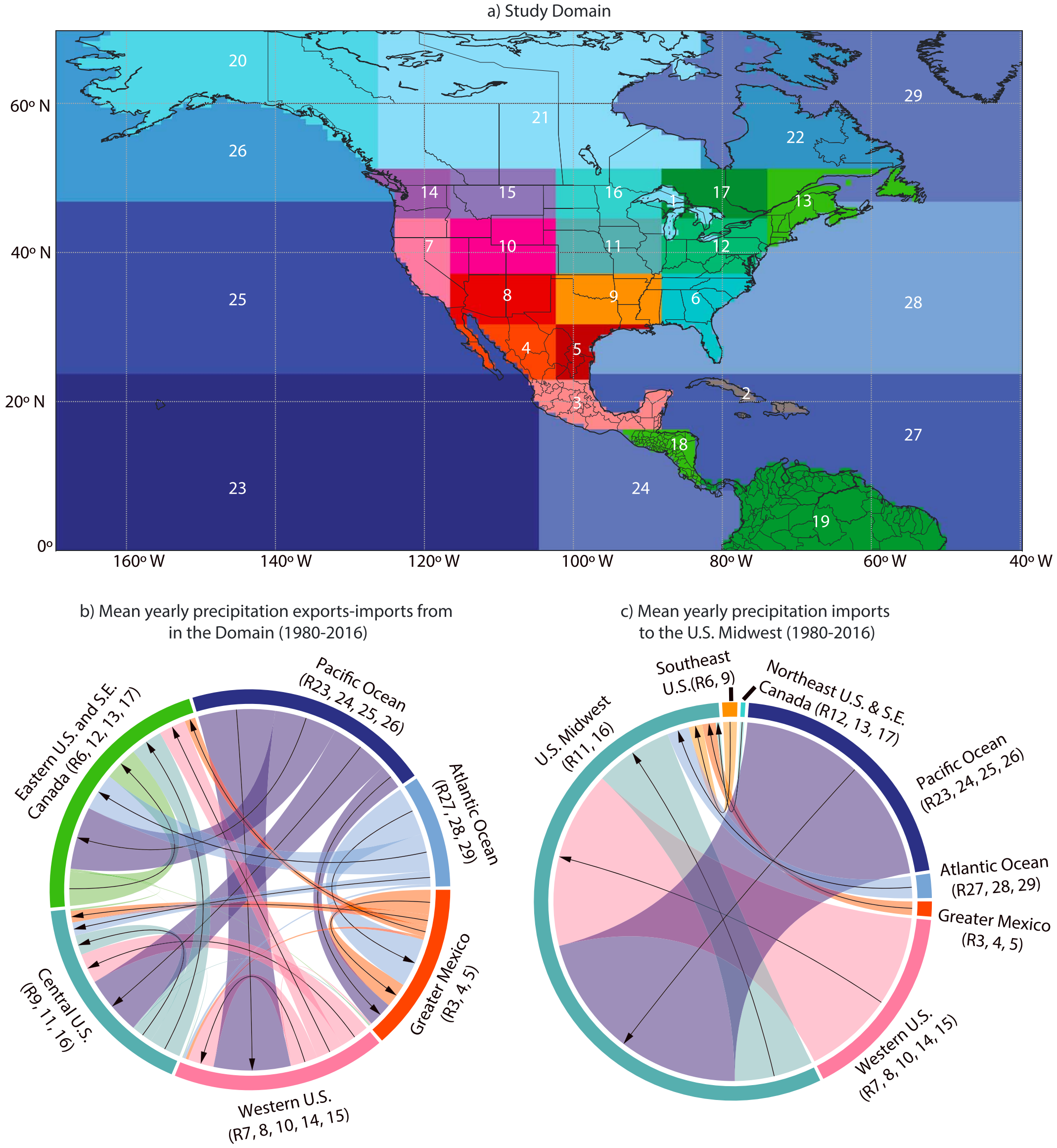

Figure 1. (a) Study domain. (b) Mean yearly precipitation exports-imports between aggregated land and ocean regions (1980–2016; contributions from R1, R2, and R18–R22 are not shown for clarity). (c) Mean yearly precipitation in the Midwest from imports and recycling. In (b) and (c), arrows represent directions from source to sinks, and the links' widths represent the relative volumes of precipitation exports-imports, presented in Tables S3 and S4, respectively.

of precipitation imports from each other land subregion. We calculate monthly anomalies by subtracting the respective monthly mean from each individual monthly value.

During each month between 1980 and 2016 and for each pair of land subregions, A (upwind) and B (downwind), we check if the following conditions are met:

1. Soil moisture values in the two subregions are below their respective 20th percentiles;
2. evapotranspiration over A and total exports from A are below their respective 20th percentiles;
3. total precipitation imports into B are below the 20th percentile;
4. there is a negative anomaly of total precipitation imports into B that is larger in magnitude than the negative anomaly of precipitation exports from A to B; and
5. the negative anomaly of precipitation exports from A to B is at least 30% of the negative anomaly of total precipitation imports into B.

Condition #1 confirms that there is an agricultural drought in both subregions, while condition #2 checks whether the decreased precipitation exports from A to B may be linked to a decrease in evapotranspiration associated with the agricultural drought in A. Condition #3 checks that there is a meteorological drought over B, and condition #4 checks that the reduced exports from A to B are a fraction of the total deficit. Condition #4 also checks that the precipitation deficit from A is not offset by precipitation from other subregions, which would make the total precipitation deficit over B smaller than the precipitation deficit from A to B. Finally, condition #5 ensures that the fraction of the deficit attributed to decreased moisture exports from A to B is substantial. If all conditions are met during at least 1 month, we suggest that a drought may have propagated from A to B, draw a link between the two regions, and record the season of occurrence.

We repeat this analysis for all land subregions as upwind sources and land subregions in the core domain as downwind sinks. To test our results' sensitivity, we repeat this analysis using combinations of 10th and 20th percentile thresholds to define agricultural drought and 10%, 30%, and 50% thresholds for condition #5.

2.5. Regional Intensification

We analyze how reductions in precipitation imports into a subregion may be linked to precipitation recycling. We calculate monthly anomalies of precipitation recycling and normalize them by the monthly means of recycling. Thus, each value represents the deviation from average conditions as a fraction of average conditions. Similarly, we calculate monthly normalized anomalies of total precipitation imports into each subregion in the core domain. To estimate the empirical relationship between decreases in imported and recycled precipitation, we calculate the following linear regression for the months when normalized anomalies of imported precipitation are negative:

$$P_{R,j} = \beta_{0,j} + \beta_{1,j} P_{\mathrm{Im},j} + \varepsilon \tag{1}$$

where $P_{R,j}$ represents the monthly normalized anomalies of precipitation recycling within subregion j, $P_{Im,j}$ represents the normalized anomalies of total precipitation imports into subregion j, $\beta_{0,j}$ and $\beta_{1,j}$ are the regression coefficients for subregion j, and ε is an error term. $\beta_{1,j}$ represents the percentage change in recycled precipitation correlated to 1% decrease in imported precipitation into subregion j.

2.6. U.S. Midwest Drought (2012)

We study the changes in moisture transport and precipitation recycling during the 2012 meteorological and agricultural droughts in the Midwest within a climatological context. Our hypothesis is that reduced precipitation recycling and moisture transport from upwind land sources may have amplified the Midwestern drought. Using the DRM, we identify the precipitation deficits over the Midwest associated to precipitation recycling and to reduced moisture transport from upwind subregions. We repeat this analysis for land areas upwind from the Midwest that were under agricultural drought to track the development of the meteorological and agricultural droughts over the broader region.

We define the Midwest by subregions 11 and 16 (Figure 1a) and define the start of the agricultural drought as the month when soil moisture in both Midwestern subregions falls below the 20th percentile. We define the agricultural drought's peak as the month with the lowest soil moisture percentile in both subregions and the drought's end as the month when soil moisture increases above the 20th percentile. We analyze the evolution of the meteorological drought within these fixed time periods of agricultural drought onset and recovery.

We calculate the total precipitation deficit over the Midwest subregions by adding the precipitation anomalies from the start to the peak of the agricultural drought. We then find the subregions that accounted for at least 10% of the total precipitation deficit over each Midwestern subregion. If the identified upwind land subregions also experienced agricultural drought during this period, we repeat the analysis by calculating the total precipitation deficits over the subregions and identifying what subregions accounted for at least 10% of their respective total deficits. We use a 10% threshold (instead of 30% as in section 2.4) to identify more upwind subregions that contributed to the deficits. We explore possible drivers of the reduced precipitation recycling and moisture transport by examining the time series of soil moisture percentiles, total evapotranspiration, and total precipitation exports from the upwind land subregions that accounted for at least 10% of the total precipitation deficit over the Midwest.

We analyze the drought's recovery by calculating the total precipitation that fell over the Midwest between the peak and the end of the agricultural drought and finding the subregions that accounted for at least 10% of the total precipitation during this period. If other land subregions are identified, we repeat the analysis to identify the subregions that contributed to their recovery. We use absolute precipitation amounts instead of positive precipitation anomalies because any precipitation contributes to the recovery of an agricultural drought.

3. Results

Figure 1b and Tables S2 and S3 show the mean yearly precipitation exports-imports (1980–2016) between four aggregate land regions and imports from the oceans. Greater Mexico and the western United States receive ~70% of precipitation from the oceans and ~23% from internal recycling. Upwind land sources provide the remainder (7% and 8%, respectively). In central and eastern United States, 45–51% of the precipitation comes from the oceans, 35–39% from upwind land regions, and 14–15% is internally recycled. Table S2 displays these percentages for each subregion, and Figure S1 shows the monthly means of precipitation exports, imports, and recycling for each subregion. Figure 1c and Table S4 show the mean precipitation imports into the Midwest, highlighting that the top contributors are the Pacific Ocean (40% of yearly precipitation), the western United States (30%), and internal recycling (13%).

3.1. Spatial Propagation

Figure 2 summarizes the results from the methodology of section 2.4. These maps show the upwind and downwind subregions between which agricultural droughts may have propagated between 1980 and 2016. For example, droughts may have propagated from the U.S. Southwest (R8) and the Pacific Coast (R7 and R14) to the Central Rockies (R10). Subsequently, droughts in the Central Rockies (R10) may have propagated to the Upper Rockies (R15), the Midwest (R11 and R16), the U.S. Southeast (R6), the Mid-Atlantic (R12), and Southeast Canada (R17). Also, linked subregions tend to be adjacent. For example, the Northwest of Mexico (R4) is linked to the U.S. Southwest (R8), which is linked to the Central Rockies (R10). Figure S2 shows the sensitivity of the identified links to the chosen thresholds. While some links are not highlighted in Figure 2 (e.g., R9 upwind from R11), they appear in this sensitivity analysis.

Figure S3 shows how frequently these links were drawn during each season. We found 19 links of agricultural drought propagation between June and August, 12 between March and May, 6 between September and November, and 3 between December and February. Thus, drought propagation via decreased moisture transport appears to be primarily a warm-season phenomenon. The number of links between each pair of subregions indicates the link's strength (e.g., recurring links between the Upper Rockies [R15] and the Upper Midwest [R16]).

3.2. Regional Intensification

Precipitation recycling has a multiplier effect (Savenije, 1995; van der Ent et al., 2010), amplifying an anomaly of imported precipitation. The DRM partitions the precipitation that falls within a subregion as originating from evapotranspiration within the subregion (recycled) or outside the subregion (imported). We quantify the empirical relationship between reductions in recycled and imported precipitation.

Figure 3 shows the percentage decreases in precipitation recycling correlated to a 1% decrease in imported precipitation. Values between 0.9 and 1 represent an almost equal relative decrease in imported and recycled precipitation. Values above 1 represent larger decreases in recycling relative to decreases in imported precipitation, suggesting an amplification effect. Figures 3 and S4 show that there are significant decreases in recycling correlated with decreases in imported precipitation in the Pacific Southwest (R7), U.S. Southwest (R8), Central Rockies (R10), and Upper Rockies (R15). Decreases in recycling may be driven by reduced atmospheric water vapor due to low evaporation or by inhibition of precipitation triggers due to dry soils (Findell & Eltahir, 2003a, 2003b; Roundy et al., 2013). Our framework cannot isolate the specific mechanisms that reduce recycling, so their identification is beyond this study's scope.

3.3. Midwest Drought (2012)

We calculate the moisture transport and recycling changes during the 2012 Midwest drought (Hoerling et al., 2014; Kam et al., 2014) using the framework introduced by Herrera Estrada (2017) and implemented by Roy

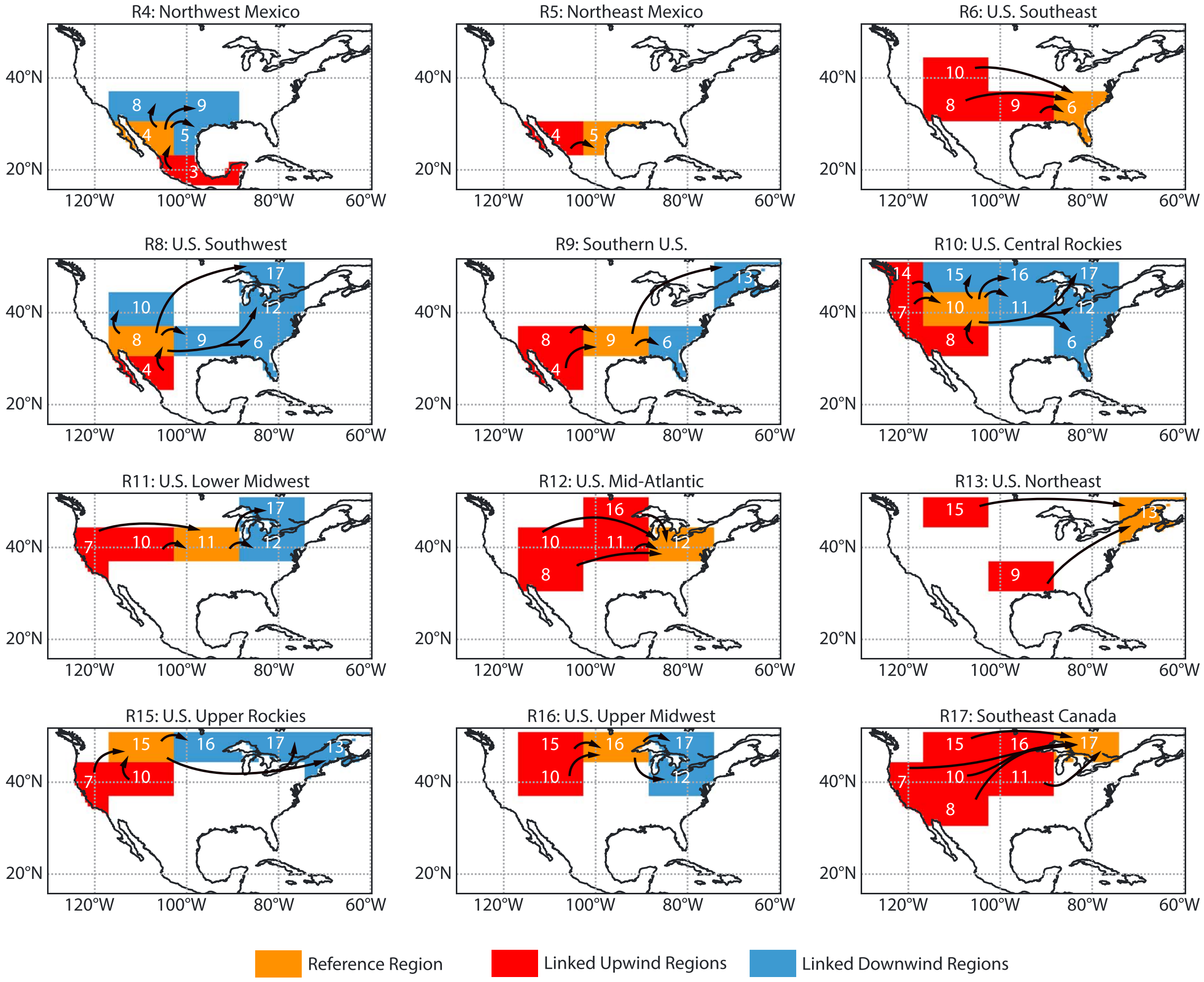

Figure 2. Subregions between which agricultural droughts may have propagated via decreased moisture transport. For each reference subregion (orange), upwind subregions are shown in red and downwind in blue. Agricultural droughts are defined by soil moisture instances below the 20th percentile. Subregions are linked if upwind subregions contribute at least 30% of the deficit of total precipitation imports over the reference region. See Figure S2 for sensitivity to these thresholds.

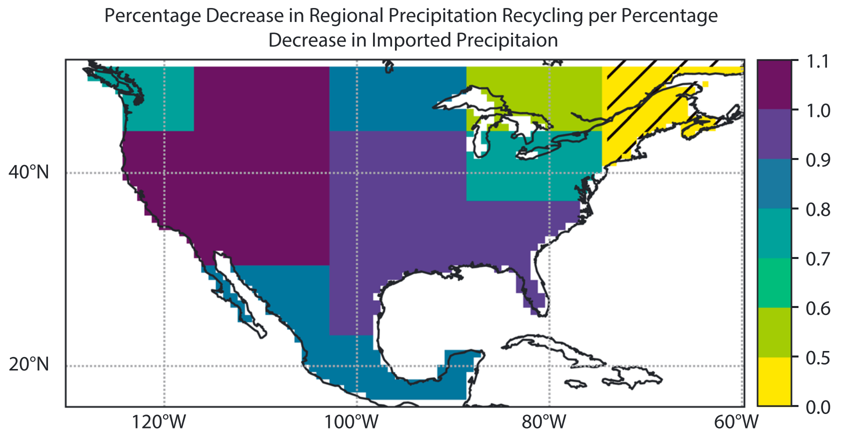

Figure 3. Percentage decrease in precipitation recycling per 1% decrease in imported precipitation into each subregion. Only negative normalized anomalies of total precipitation imports are used to calculate the regressions given by equation (1) ($n = 222–266$ depending on the subregion). Hatched subregions represent nonstatistically significant values (p values > 0.05).

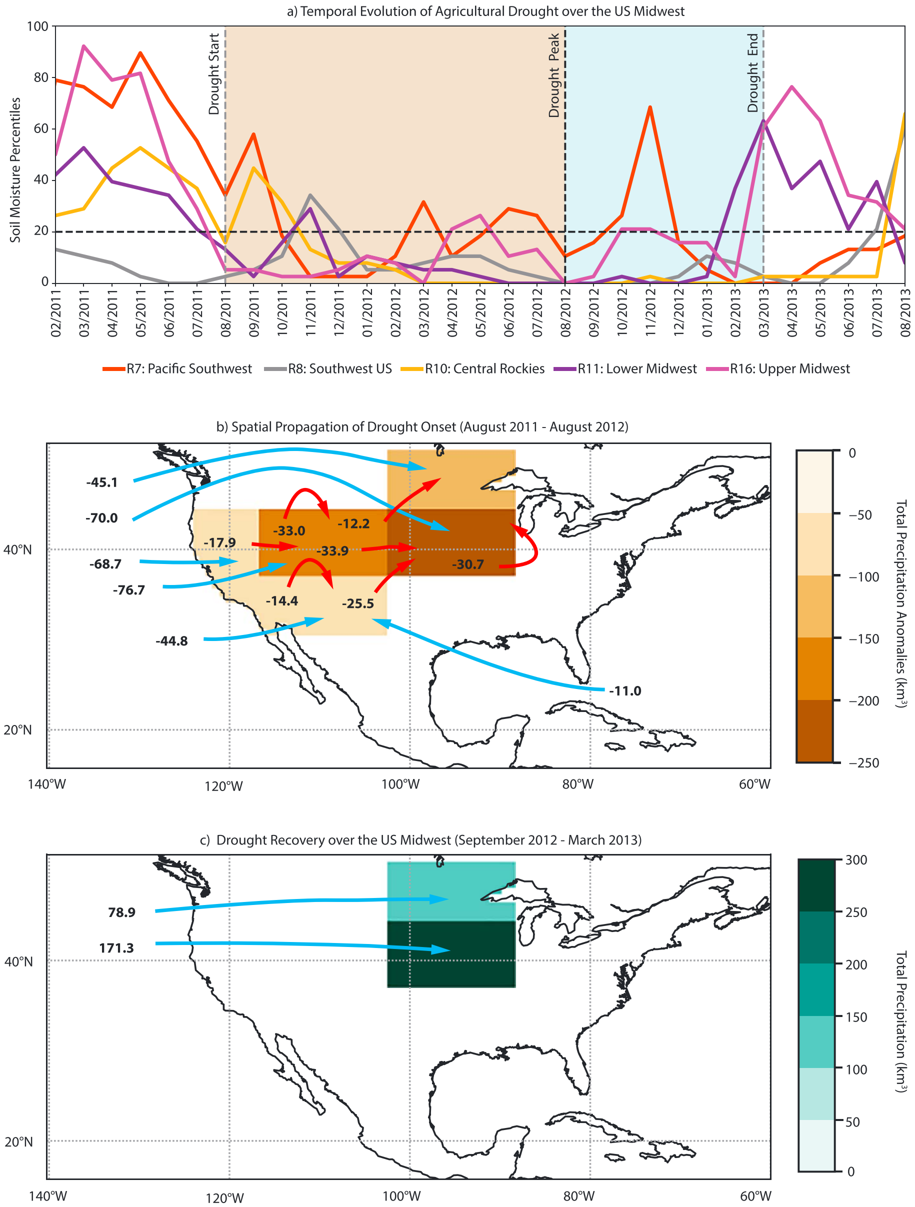

Figure 4. (a) Time series between February 2011 and August 2013 of soil moisture percentiles over the Midwest and three other subregions that contributed to the Midwest's meteorological drought. (b) Spatial propagation of the meteorological drought signal. Shaded colors represent total precipitation deficits (August 2011 to August 2012) relative to climatology. Values indicate the cumulative precipitation deficits in cubic kilometers attributed to land subregions (red arrows) and to aggregated ocean regions (blue arrows). (c) Contributions to the agricultural drought's recovery. Shaded colors represent total precipitation between September 2012 and March 2013. In (b) and (c), only precipitation deficits/totals that amounted to at least 10% of the total deficits/total precipitation are shown for clarity.

et al. (2019). This drought caused substantial agricultural damages and was not adequately predicted (Hoerling et al., 2014; Kam, Sheffield, Yuan, et al., 2014; Roy et al., 2019).

Figure 4a shows time series of soil moisture percentiles for the two Midwestern subregions and three other land subregions that played key roles during the drought onset (Figure 4b). We find that the agricultural drought in the two Midwestern subregions started in August 2011, peaked in August 2012, and recovered by March 2013. Figure 4b shows the accumulated precipitation deficits over the Midwest and the land subregions that contributed directly and indirectly to the Midwest's deficit during the onset period. The Lower Midwest (R11) experienced the largest deficit (−233.1 km^3) over the 13-month period leading to the agricultural drought's peak. Deficits from the Pacific Ocean (R23–R26, −70.0 km^3), Central Rockies (R10, −33.9 km^3), and U.S. Southwest (R8, −25.5 km^3) accounted for most of the Lower Midwest's deficit. Decreased recycling added −30.7 km^3 and smaller contributions from 22 regions contributed the remaining −73.0 km^3 of the total deficit.

Figure 4a shows that these upwind land subregions were also under agricultural drought. The Pacific Ocean, the Pacific Southwest (R7), and decrease recycling accounted for most of the precipitation deficit in the Central Rockies (R10). Similarly, reduced precipitation from the Pacific Ocean and from recycling contributed the most to the precipitation deficit in the U.S. Southwest (R8). Examining time series of the anomalies in evapotranspiration, total exports, total imports, and recycling over each of these land subregions (Figure S5) suggests that the decreases in precipitation exports from the land subregions upwind from the Midwest may be linked to lower-than-average evapotranspiration, possibly due to the agricultural drought (Figure 4a).

Decreased precipitation from the Pacific Ocean contributed directly and indirectly to the development of the meteorological and agricultural droughts over the Midwest and the western United States. However, decreased moisture transport from the land surface and precipitation recycling may have played an important role in amplifying drought conditions. Figure S6a shows the precipitation deficits from each subregion to the two Midwestern subregions combined. Decreased precipitation originating from upwind land subregions and from recycling accounted for 47.5% and 14.4%, respectively, of the total precipitation deficit. Overall, reduced precipitation from land sources amounted to 61.9% of the total deficit compared to 37.9% from the oceans.

The drought's recovery in the Midwest was driven mostly by precipitation arriving directly from the Pacific Ocean, which may have restarted recycling (Figures S5 and S6). Although the agricultural drought in the Midwest recovered by March 2013, droughts in the western United States persisted (Figure 4a).

4. Discussion and Conclusions

We identify subregions across North America between which agricultural droughts may have propagated through decreased moisture transport. We find that droughts in the western United States may amplify droughts in downwind subregions including the Midwest, consistent with Dominguez et al. (2009). Further, linked subregions tend to be adjacent to each other, providing a possible mechanism by which droughts may travel across continents (Herrera-Estrada et al., 2017). Displacement of high-pressure systems and shifts in general circulation patterns may be other possible mechanisms of drought propagation (Hoerling et al., 2014; Wei et al., 2012; Wei et al., 2016). Further work is needed to understand the effects of large-scale circulation on moisture transport and drought propagation (Kam, Sheffield, & Wood, 2014; Wei et al., 2012).

We show that in the western United States, decreases in precipitation recycling are strongly correlated with reductions in imported precipitation, supporting the hypothesis that regional positive feedbacks may amplify decreases in moisture transport into a region. We also find that precipitation recycling may increase as moisture begins to arrive from the surroundings. During the recovery of the 2012 Midwest drought, most of the precipitation arrived from the Pacific Ocean, possibly helping restart recycling.

The DRM assumes a well-mixed atmosphere because most of the recycled moisture is found within the planetary boundary layer, which efficiently mixes the air via turbulent processes (Eltahir & Bras, 1996). However, the well-mixed assumption is generally not met in regions of strong vertical wind shear and where the contribution of water vapor from a certain vertical level to precipitation is very different from that level's mixing ratio (Bosilovich, 2002; Dominguez et al., 2016; Goessling & Reick, 2013; van der Ent et al., 2013). In our study, this assumption may overestimate the precipitation that the model tracks across mountainous regions, particularly in the western United States, leading to uncertainties in the relative contributions from the oceans to inland regions. Qualitative comparisons with Dirmeyer and Brubaker (1999), Dirmeyer, Brubaker, et al. (2009), and Duerinck et al. (2016) show that our study potentially overestimates the precipitation contributions from the Pacific Ocean to the Midwest (not shown). Thus, our estimates of the land-surface's contributions to moisture exports to the Midwest are possibly conservative. A more accurate representation of moisture fluxes across mountains would likely increase the relative importance of precipitation originating from land compared to that from the Pacific Ocean. The DRM is a computationally efficient tool comparable in many cases to sophisticated three-dimensional methods (e.g., Hoyos et al., 2017), but generally provides first-order estimates of moisture sources and sinks.

We use simultaneous occurrences of hydroclimatological conditions to link upwind and downwind regions, and linear regressions to quantify the empirical relationships between changes in imported and recycled precipitation. While circumstantial evidence and correlations are certainly not equivalent to causation, our methodology is built on hypotheses derived from our understanding of moisture transport and precipitation recycling allowing us to draw insights into their role regarding drought propagation. To further isolate the land-surface's effect on drought propagation and intensification, future studies can involve climate modeling experiments that compare the spatiotemporal dynamics of agricultural droughts when soil moisture is fixed to climatology and when it is allowed to evolve dynamically.

Our results suggest that multiple droughts over a continent should not necessarily be conceived as resulting from random atmospheric variability (e.g., Seager et al., 2013). Instead, there may be important teleconnections across the land surface that can propagate and amplify droughts. Our analysis focuses on North America but we expect that moisture transport may play a similarly important role in the spatial propagation of droughts in other regions (e.g., Zemp et al., 2014). This novel conceptualization of drought development may help diagnose past droughts and improve seasonal forecasts (Dirmeyer, Schlosser, et al., 2009; Findell & Eltahir, 1997; Guo et al., 2012; Roundy et al., 2014; Roundy & Wood, 2015; Roy et al., 2019; Wood et al., 2015). Our results raise the importance of sustainable land use practices in upwind regions on which downwind communities rely for precipitation (DeAngelis et al., 2010; Findell et al., 2009; Findell et al., 2017; Keys et al., 2016, 2018; Mahmood et al., 2014; Wang-Erlandsson et al., 2017; Yang et al., 2017). These results also raise questions regarding governance of transboundary precipitationsheds (Dirmeyer, Brubaker, et al., 2009; Keys et al., 2012, 2014, 2017, 2018) and cooperation between upwind and downwind communities for drought risk management.

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