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The contribution of precipitation recycling to North American wet and dry precipitation extremes

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Abstract

Over the course of a season, a location's precipitation is comprised of moisture sourced from a diverse set of geographic regions. Seasonal extremes in precipitation may arise from changes in the contribution of one or several of these sources. Here, we use the Community Earth System Model with numerical water tracers to quantify the contribution of locally sourced, known as precipitation recycling, versus remotely sourced precipitation to seasonal wet and dry extremes across North America. The greatest impact of recycling on both wet and dry extremes is found in the Interior West of the United States where changes to recycling contribute as much as 25%–30% of drought deficit and pluvial surplus. Recycling contributions are smaller across the eastern U.S., generally less than 8%, highlighting the greater role of imported moisture for explaining hydroclimate extremes in these regions. Robust contributions of precipitation recycling to drought and pluvials across the Interior West are driven by consistent changes to local evaporation and the conversion of local evaporation to local precipitation during extreme hydroclimate conditions. The results are consistent with an energy-limited and water-limited evaporation framework and provide a new estimate of the role of local processes in shaping hydroclimate extremes.

1. Introduction

Precipitation is derived from diverse moisture sources and various atmospheric pathways. The geographic area that contributes evaporation to a location's precipitation is known as the precipitationshed (Keys *et al* 2012). Within the precipitationshed, local evaporation through precipitation recycling, and remote evaporation through transport in the mean and eddy flow can have substantial roles depending on the time of year and region of interest (Dirmeyer and Brubaker 1999, Harrington *et al* 2023). During extreme wet and dry years, the relative contributions of evaporation sources within a precipitationshed can vary considerably from the mean (Brubaker *et al* 2001, Dirmeyer *et al* 2014, Vázquez *et al* 2020), indicating that specific areas of a region's precipitationshed may be more or less directly linked with that region's precipitation extremes. However, quantifying the contribution of different evaporative sources to a region's precipitation anomalies during extreme wet and dry intervals is challenging, and outside of specific regional case studies (e.g. Dirmeyer and Brubaker 1999, Bosilovich and Schubert 2001, Herrera-Estrada *et al* 2019, Roy *et al* 2019), estimates of these contributions are generally lacking. In this study, we demonstrate how numerical water tracers within a climate model can be used to examine the evaporative sources associated with precipitation extremes and develop estimates of the contributions of local versus remote moisture sources to precipitation anomalies during drought and pluvial events across North America.

Wet and dry intervals are often initiated by an anomalous flux of moisture from one or more remote sources. For example, the presence (absence) of atmospheric rivers, which transport water vapor from the subtropical and midlatitude Pacific Ocean, are responsible for most of the winter flooding (drought) events along the western United States (Neiman *et al* 2011, Konrad and Dettinger 2017, Paltan *et al* 2017). Likewise, anomalous moisture advection from the tropical Atlantic and Gulf of Mexico within the southerly flow of a semistationary ridge drives nearly all extreme spring flood events in the Ohio basin (Nakamura *et al* 2013).

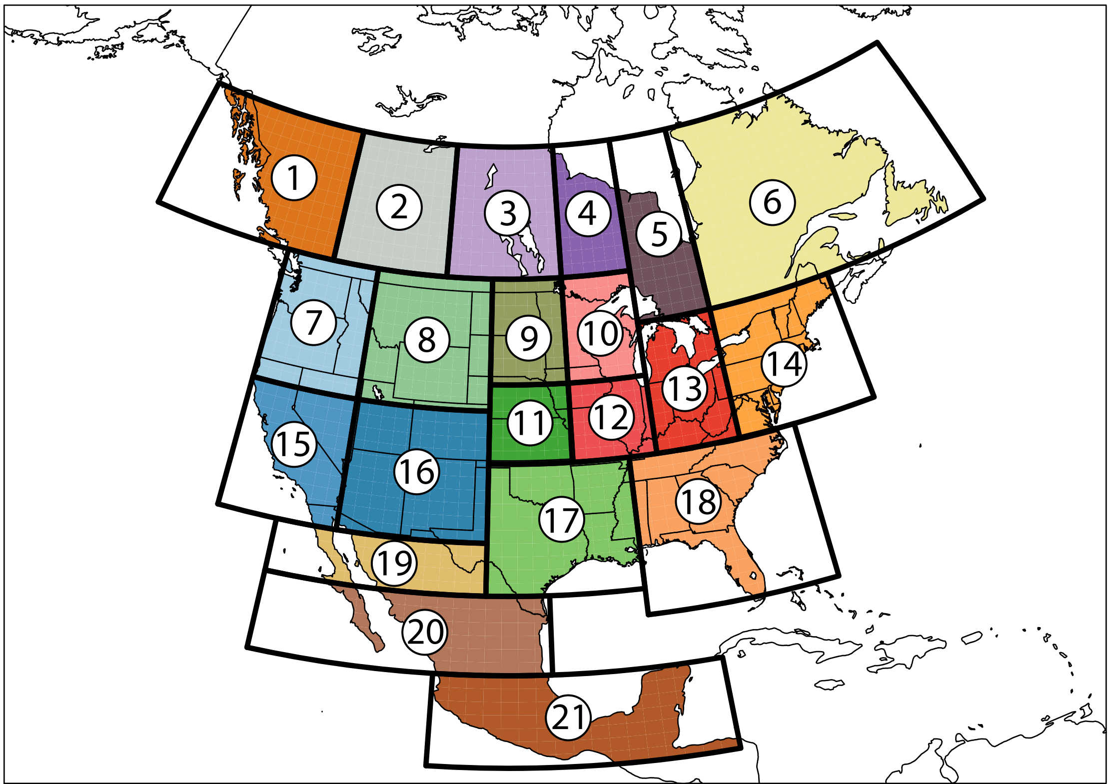
However, local processes, including the recycling of local evaporation to precipitation, can modify the magnitude of the externally sourced precipitation anomaly, especially in regions of strong land-atmosphere coupling. Herrera-Estrada *et al* (2019) estimate that a reduction in precipitation recycling due to a lack of local evaporation and/or local precipitation trigger mechanisms contributed as much as 14% to the precipitation deficit during the 2012 Midwest drought. Bonan and Stillwell-Soller (1998) use idealized model simulations to show that an artificially imposed drying of the local land surface reduced precipitation during the record 1993 Great Plains flood event by 30%–40%, highlighting the important contribution of precipitation recycling to the event's high rainfall rates. Interestingly, Bosilovich and Schubert (2001) find that the magnitude of recycled precipitation decreased (relative to mean conditions) during the 1993 Great Plains flood event due to lower-than-average local evaporation, indicating that precipitation recycling, though still important to the total precipitation anomaly, may become relatively less important during pluvial periods in the region. Likewise, Dominguez *et al* (2008) show that reduced moisture advection to the central U.S. increases recycled precipitation in the region through greater sensible heating and associated increases in buoyancy and convection. More broadly, these and other case studies indicate that the extent to which precipitation recycling will amplify an imported precipitation anomaly will depend on the myriad changes to local evaporation, atmospheric stability, and circulation that arise during anomalous hydroclimate conditions (Giorgi *et al* 1996, Findell and Eltahir 2003, Roy *et al* 2019), and that knowledge of the seasonal mean recycling contribution to total precipitation is likely insufficient to fully understand the recycling contribution to precipitation extremes.

The contribution of different evaporative sources to wet and dry extremes can be estimated using several methods, including isotopic analysis, two-dimensional box models, and numerical water tracers, each of which has benefits and limitations. While box models and offline Lagrangian tracking methods (e.g. back trajectory calculations) can be used on reanalysis data, they require numerous simplifications, including the assumption of a well-mixed atmosphere, a lack of cloud process representation, and relatively large timesteps between calculations, all of which can bias estimates of evaporative sources (Gimeno *et al* 2012, van der Ent *et al* 2013). Moisture tracking-enabled climate models avoid these simplifications by tracing water in real-time throughout its entire path from evaporation to precipitation (Nusbaumer and Noone 2018, Harrington *et al* 2021); this process ensures that the identified evaporative sources of the model precipitation are accurate. However, climate models have biases, and the relationships between moisture sources and sinks in the model may not accurately reflect reality.

Harrington *et al* (2023) compare estimates of climatological evaporative moisture sources from the moisture tracking-enabled Community Earth System Model (CESM) with those of previously published box models and Lagrangian tracking methods (Dominguez *et al* 2006, Dirmeyer *et al* 2009, van der Ent *et al* 2010) and find general agreement across the North American domain, providing confidence in the CESM output and highlighting the utility of each method. Here, we extend the analysis of CESM to examine moisture sources during seasonal precipitation extremes. A description of the water tracers and of the framework used to estimate evaporative source contributions to precipitation extremes are presented in the methods section. A seasonal breakdown of the local and remote moisture contributions to seasonal drought and pluvials in different North American regions is presented in the results section. Lastly, a synthesis of the results within the context of water- and energy-limited climates and of previously published work on moisture sourcing during extremes is presented in the discussion section.

2. Methods

To estimate the contribution of precipitation recycling to seasonal drought and wet extremes, we use the CESM version 1.2 (CESM1.2) with atmospheric water tracers (Hurrell *et al* 2013, Nusbaumer and Noone 2018, Brady *et al* 2019). A detailed description of the water tracing methodology and experimental design of the CESM simulation can be found in Harrington *et al* (2023). Briefly, water tracers in CESM allow the user to identify the geographic evaporation source of modeled precipitation. An overview of the process is provided as a schematic in figure S1. As water evaporates from the surface of a model grid cell (either land or ocean), it is 'tagged' with a label indicating the geographic location of evaporation. The tag remains with the water as it moves through the atmosphere, including through phase changes, until the water precipitates back to the model surface. The water tracing module registers the tag upon deposition to the surface, creating a record of geographic evaporative sources for a location's precipitation. The tag labels are associated with a pre-defined set of geographic regions shown in figure 1. Evaporation from any grid cell within a region is tagged with the same region label. The regions are chosen to balance the need for computational efficiency



1. Pacific Canada	**8. Upper Rockies**	**15. Pacific Southwest**
2. West Canada Prairies	**9. Northern Plains**	**16. Southwest**
3. East Canada Prairies	**10. Upper Midwest**	**17. Southern Plains**
4. West Ontario	**11. Central Plains**	**18. Southeast**
5. East Ontario	**12. Lower Midwest**	**19. Northern Mexico**
6. Atlantic Canada	**13. Great Lakes**	**20. Central Mexico**
7. Pacific Northwest	**14. Northeast**	**21. Southern Mexico**

Figure 1. Moisture tag regions in CESM (see section 2).

(a greater number of regions results in slower model simulation speed and greater data volume) while also representing areas of distinct climate and ecology across North America (Harrington *et al* 2023).

The CESM simulation is run in 'AMIP' mode using active land (Community Land Model version 5 (CLM5)) and atmosphere (Community Atmosphere Model version 5 (CAM5)) components and uncoupled, observed time-variant monthly sea surface temperatures and sea ice concentrations from the Hadley Center Global Sea Ice and Sea Surface Temperature data set (Rayner *et al* 2003). CLM5 uses 15 pre-defined plant functional types and simulates vegetation state (leaf area index and canopy height) prognostically (Lawrence *et al* 2019). The land and atmosphere models have a horizontal resolution of $0.9 \times 1.25°$, while the ocean and sea ice data is prescribed on a 1° degree grid. The simulation is run for the period 1985–2015 using prescribed concentrations of greenhouse gases and aerosols consistent with observations from 1985 to 2006 and RCP4.5 from 2006 to 2015 (Thompson *et al* 2011). We use the 1985 model year as spin-up and focus our analysis on the 30 yr 1986–2015 period. A thorough evaluation of the CESM simulation climate has been conducted in Harrington *et al* (2023). While CESM has been used extensively in climate research (Hurrell *et al* 2013), biases in simulated precipitation (presented here relative to the Climate Prediction Center Merged Analysis of Precipitation product (Xie and Arkin 1997)) are present throughout North America, particularly in the Sierra Madre range in Mexico and the Coast Mountain range in British Columbia (figure S2). Results from the present analysis will be discussed within the context of these biases within the discussion section.

We estimate the contribution of locally sourced precipitation to anomalously dry and wet seasons by calculating the percentage of the total seasonal precipitation anomaly $P_{\text{total\_anom}}$ due to the anomaly in recycled precipitation $P_{\text{recycled\_anom}}$. For instance, if a region receives 100 mm less precipitation than average during a drought ($P_{\text{total\_anom}} = -100$ mm), and 20 mm less precipitation than average due to local recycling ($P_{\text{recycled\_anom}} = -20$ mm), then local recycling contributes 20% to the seasonal drought deficit. This calculation requires that we first calculate seasonal climatologies for total precipitation and recycled precipitation for each region. In addition to precipitation recycling ratios, we also calculate the evaporation recycling ratio. The evaporation recycling ratio is defined as the percentage of regionally averaged evaporation that falls as precipitation within the same region (i.e. the fraction of evaporation that remains within the local region). In this study, unless otherwise noted, the term evaporation is used to represent the combined processes of surface evaporation and transpiration (Miralles *et al* 2020).

Anomalously dry and wet seasons are determined by ranking regional-average 3 month standardized precipitation index (SPI) values (McKee *et al* 1993). SPI values represent the number of standard deviations the 3 month precipitation anomaly deviates from the long-term mean. To create an appropriate probability distribution, a gamma distribution is first fit to the raw 3 month precipitation data. The data is then transformed to a normal distribution. After transformation, the SPI is calculated as:

$$\text{SPI} = \frac{P_{ij} - \overline{P_i}}{\sigma_i}$$

where P_{ij} is equal to the precipitation value during timeframe i (in this case, 3 months) for year j, $\bar{P}_i$ is equal to the 30 yr mean 3 month precipitation, and σ_i is equal to the standard deviation of the 3 month precipitation. The 3 month SPI value for each season (DJF, MAM, JJA, and SON) is calculated for each grid cell in each year. Area-weighted regional averages are then calculated for grid cells with greater than 50% land coverage, and the three lowest and highest values for each region are selected to represent drought (10th percentile and below) and pluvial (90th percentile and above) seasons, respectively. We test the sensitivity of the results to the number of drought and pluvial years by also examining the five lowest and highest SPI values for each region (figure S3).

Water-limited and energy-limited evaporation environments are defined using a climatological aridity index (AI) calculated from the CESM data. The AI is defined as the ratio of a region's annual mean precipitation (P) to potential evaporation (PE):

$$\text{AI} = P/\text{PE}.$$

It measures the extent to which supply (P) matches demand PE and is used widely in climate, hydrology, and agricultural applications (Arora 2002, Roderick *et al* 2015, Zomer *et al* 2022). Low (high) AI values indicate evaporation rates limited by water (energy) availability. Following Milly and Dunne (2016), we adopt a net surface energy-based definition of PE:

$$\text{PE} = 0.8 \cdot R_{\text{net}}/L_{\text{v}}$$

where R_{net} is equal to net surface radiation, and L_{v} is equal to the latent heat of vaporization.

3. Results

Figure 2 shows the average percent contribution of precipitation recycling to the precipitation deficit in the three driest seasons (figures 2(a)–(d)) and to the precipitation surplus in the three wettest seasons (figures 2(e) and (f)). By extension, the average percent contribution from remote evaporation sources can be determined by subtracting the recycling contributions from 100. Similar results are found when using the five driest and wettest years (figure S3). In all seasons and regions, imported moisture is the primary contributor to drought and pluvial precipitation anomalies. However, recycling has a considerable amplifying role in warm months, especially in western portions of the North American domain.

The contribution of recycling to winter precipitation extremes is small across the continent (figures 2(a) and (e)), consistent with relatively low terrestrial evaporative demand and mostly dormant vegetation during the season. The exception is in the far southern U.S. and Mexico, where a lack (abundance) of locally-sourced precipitation contributes 4%–8% (2%–6%) of the negative (positive) precipitation anomaly during drought (pluvials). Along the far western U.S., where most precipitation occurs in winter, recycling has little influence on whether a season is exceptionally dry or wet. Given the relatively minor contribution of precipitation recycling to boreal winter precipitation extremes across the domain, we focus the rest of the analysis on boreal spring, summer, and fall.

In boreal spring, maximum contributions of recycling to drought (14%–18%) are found in the Interior West, including the Southwest and Upper U.S. Rocky Mountain regions, and in far southern Mexico.

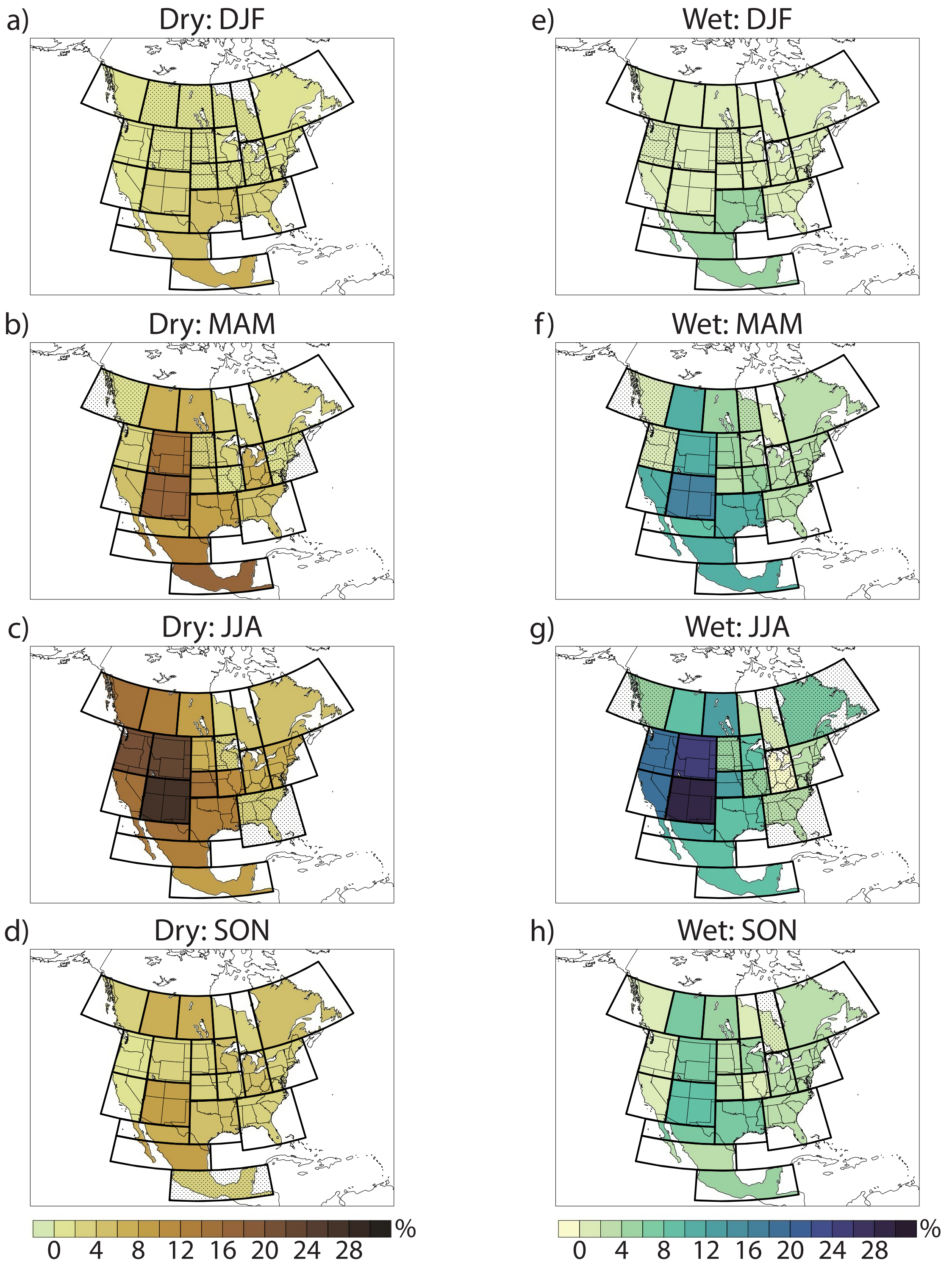


Figure 2. Average percent contribution of precipitation recycling to the seasonal precipitation de_cit (a)–(d) and surplus (e)–(h) in the three driest (a)–(d) and wettest (e)–(h) seasons based on 3 month SPI. Regions with stippling indicate disagreement on the sign of change among the three years.

Maximum contributions to anomalously heavy seasonal precipitation (10%–18%) are also located across the Interior West, stretching from the Canadian Prairies to southern Mexico, and in the Pacific Southwest and Southern Plains. Across the eastern U.S., recycling contributions to spring extremes are less than 8%, indicating a dominant role for imported moisture during anomalously wet and dry years. Several regions (those marked with stippling) with low average recycling contributions exhibit disagreement on the sign of the local recycling contribution to precipitation anomalies in the three extreme years. This indicates that precipitation recycling can be above (below) average during spring droughts (pluvials) depending on the year.

In boreal summer, local recycling contributes substantially to seasonal precipitation extremes across the Interior West. In the Southwest, an average of 28% of the precipitation deficit during droughts and 30% of the precipitation surplus during pluvials are derived from recycled moisture. Similarly, recycling contributes 24% to drought deficit and 26% to pluvial surplus in the Upper Rocky Mountain region. Though recycling contributions are high across the Pacific Northwest and Pacific Southwest, these regions are generally dry during summer and precipitation anomalies are small relative to wetter seasons. Contributions from recycling generally decline from west to east across the continent, comprising on average 2%–8% of drought deficit and −2%–4% of wet extreme surplus across the Southeast, Ohio Valley, and Northeast. The negative value during pluvials in the Great Lakes region indicates that, averaged across the three extremes, local recycling contributes less precipitation than average, slightly dampening the externally derived precipitation surplus. In several of these central and eastern regions (those with stippling), there is an inconsistent response in the sign of the recycling contribution to the summer precipitation extreme across events. Increasing the sample from the three most extreme years to the five most extreme years increases the number of regions in which this is true for pluvials, but does not impact the robust agreement on the sign of the recycling contribution during drought (figures S3(c) and (g)). In boreal fall, the spatial pattern of recycling contributions to seasonal precipitation extremes resembles that of spring, with the largest contributions found in the Interior West stretching from Canada to Mexico, and in the Southern Plains. Local contributions remain relatively low across the eastern U.S. In nearly all regions, local precipitation recycling amplifies fall extreme precipitation anomalies in each of the three years. The sign of the recycling contribution to fall season wet anomalies is less consistent across years when considering the larger and less extreme 5 yr composite, but is largely unchanged for droughts (figures S3(d) and (h)).

Spatial patterns of precipitation recycling responses during wet and dry extremes resemble those of climatological precipitation recycling (figure S4) (Harrington *et al* 2023). For example, climatological recycling rates are highest during the summer months and across the Interior West (figure S4). However, differences between climatological recycling contributions and recycling contributions during drought and pluvials are apparent. For example, averaged across all years, recycling contributes 20% to summer precipitation in the Southwest, but 28% to summer drought deficit. Likewise, recycling contributes 12% of summer precipitation in the Northeast, but only 4% of summer pluvial surplus. These differences highlight the complex and nonlinear changes to moisture sourcing during extreme conditions.

To better understand the varying contributions of recycling to extreme precipitation anomalies, we next examine the change in recycled precipitation amounts during drought and pluvial periods (figures 3 and S5), as well as the overall relationship between recycled precipitation and total precipitation (figure S6). Figure 3 shows the percent change from average in recycled precipitation during the three driest and wettest years. During spring droughts, precipitation recycling is diminished by 40%–70% across the Upper Rockies, Southwest, Southwest Pacific, Mexico and the Southern Plains. Similarly, these areas exhibit the greatest increases in recycled precipitation during wet springs, with values exceeding 80% in the Southwest and northern Mexico. Though recycling increases by 20%–40% across the Midwest and Northeast during anomalously wet springs, these changes have relatively minor influence on the total precipitation surplus (figure 2(f)). In summer, percent recycling changes are greatest (40%–70%) in the Pacific Northwest, Pacific Southwest, Southwest, northern Mexico, and Southern Plains. In the eastern half of North America, average recycling changes are less than 20%, and as noted previously, may be positive or negative during anomalously wet conditions across much of the region depending on the year. The widespread disagreement on the sign change in recycled precipitation during wet summers across much of eastern North America coincides with the period of the year with the greatest fraction of recycled precipitation from convective processes (figures S5(a)–(c)). Excessively wet conditions can suppress local convective activity (figure S5(h)) leading to reductions in summer recycled precipitation in some wet years. The largest changes in fall recycling are in the Southwest and central portions of the domain, similar to the spring pattern.

Consistent with the changes to recycled precipitation during drought and pluvials, the strength of the relationship between recycled and total precipitation, as measured by the Pearson linear correlation coefficient, is strongest across Interior western and central portions of the domain (figure S6). For example, during JJA, the correlation coefficient between recycled and total precipitation is 0.97 in the Southwest, 0.90 in the Upper Rockies, 0.83 in the Southern Plains, and 0.86 in the Central Plains. While the relationship between recycled and total precipitation is positive in all regions and seasons, the strength of the correlation is generally weaker in regions where the average percent change in recycling during extremes is relatively smaller. For example, correlation values are 0.32 in Pacific Canada, 0.30 in the Southeast, 0.50 in the Upper Midwest, and 0.47 in the Great Lakes during summer (figure S6).

The anomalous contribution of recycling to precipitation extremes may manifest through a change in local evaporation amount and/or a change in the magnitude of evaporation recycling (the efficiency that local evaporation is converted to precipitation). Figure 4 shows the average percent change in evaporation for

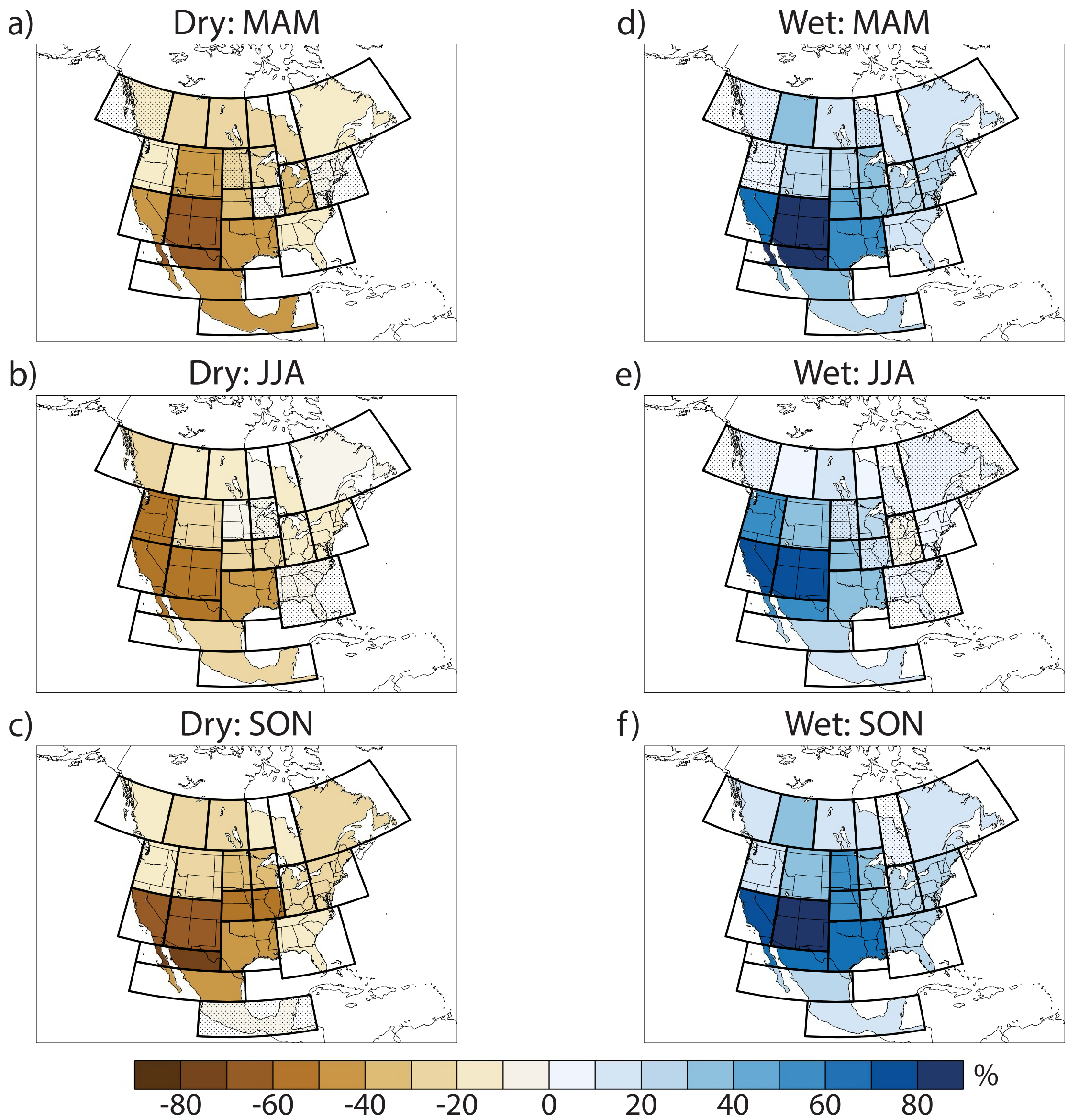


Figure 3. Average percent change in recycled precipitation during (a)–(c) the three driest seasons and (d)–(f) the three wettest seasons based on 3 month SPI. Regions with stippling indicate disagreement on the sign of change among the three years.

each region during extreme dry and wet seasons, along with the agreement in the sign of change across years. In summer drought conditions, average evaporation is reduced across Mexico and the western and central U.S., and slightly enhanced in the eastern U.S. and most of Canada. The opposite pattern emerges during extremely wet summers. Percent changes in evaporation are largest (20%–35%) and consistently of the same sign in the Southwest, northern Mexico, and the Central and Southern Plains. There is some disagreement on the sign of evaporation change among summer drought and among summer pluvial events in much of Canada and the northern and eastern U.S. The average increase (decrease) in evaporation across northern and eastern portions of North America during summer droughts (pluvials) is of the opposite sign to the change in recycled precipitation in these areas (figures 3(b) and (e)), indicating that processes other than total evaporation drive the reduction (enhancement) of locally-derived precipitation during summer drought (pluvials).

During fall, the spatial patterns of average evaporation anomalies are generally similar to summer, with a robust maximum of evaporation change over the Southwest and northern Mexico during anomalously wet and dry years. Large evaporation changes are less widespread in boreal spring and are largely confined to the Southwest U.S. and northern Mexico, though a robust reduction of 10%–15% is also located in the Ohio Valley during drought years, consistent with a regionally elevated contribution of recycling to drought (figure 2(b)).

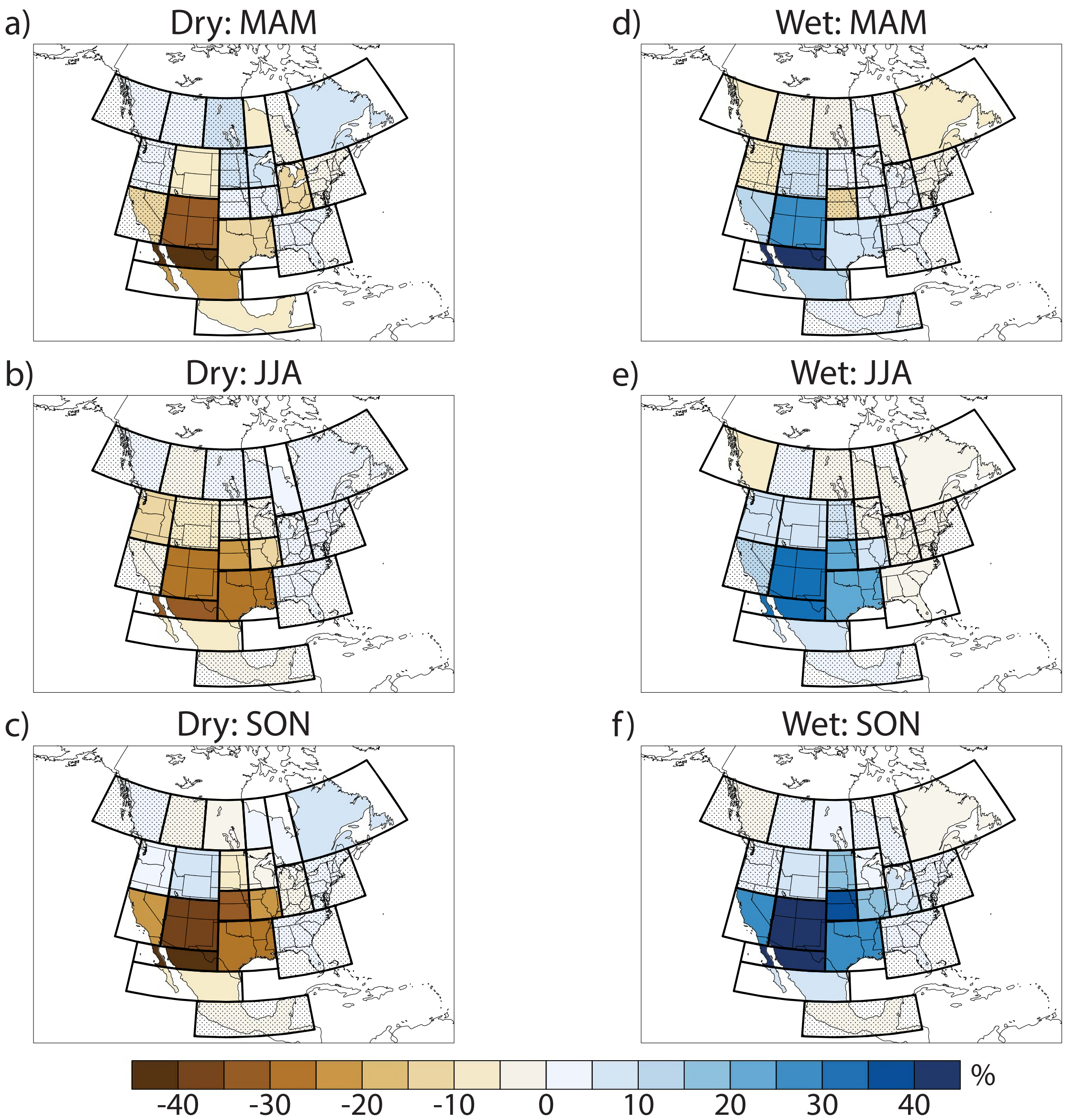


Figure 4. Average percent change in evaporation during (a)–(c) the three driest seasons and (d)–(f) the three wettest seasons based on 3 month SPI. Regions with stippling indicate disagreement on the sign of change among the three years.

Broadly, the spatial pattern of evaporation change during anomalously wet and dry conditions resembles the distribution of energy- and water-limited areas across North America (figure S7). Regions classified as water-limited evaporative environments (low AI values, <0.5) exhibit reduced evaporation during drought and enhanced evaporation during pluvials (figure 5), while energy-limited regions exhibit small increases in evaporation during drought and reduced evaporation during pluvials. Similar to the Budyko framework (Budyko 1974), which suggests a functional relationship between evaporation and AI across catchments, there appears to be a clear relationship between evaporation response during wet and dry extremes and climatological aridity across regions. The distribution of data points for each season in figure 5 follows a similar shape (compare distributions of like colors), indicating that the overall relationship between aridity and evaporation change is generally robust to the timing (season) of the precipitation extreme. Note that though annual mean AI is used here, seasonality can strongly influence aridity in western and central portions of the U.S., making these areas energy- or water-limited depending on the time of year.

Across all seasons and regions, average evaporation recycling decreases during drought and increases during extremely wet seasons, consistent with atmospheric conditions that inhibit and promote precipitation during droughts and pluvials, respectively (figure 6). In general, the largest and most robust changes in evaporation recycling during extremes are found across the Interior West from Canada to Mexico in boreal spring and summer (large percent changes along the West Coast in summer occur during a time of little evaporation recycling), and confined to the Southwest Pacific, Southwest, northern and central Mexico, and

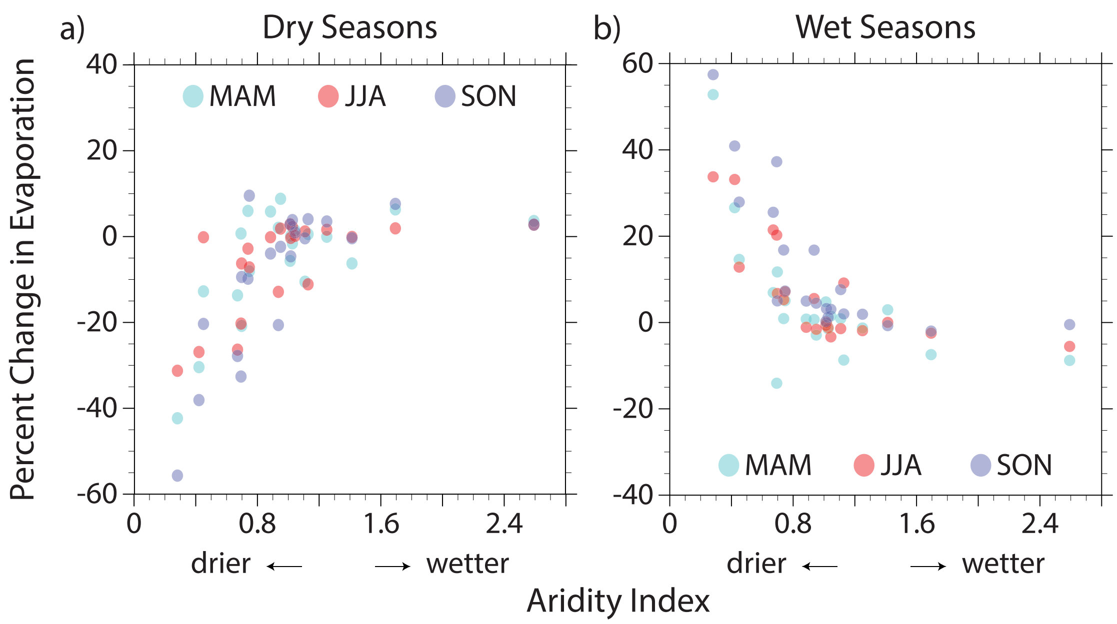


Figure 5. Climatological annual mean aridity index (see section 2) versus percent change in evaporation during (a) the three driest seasons and (b) the three wettest seasons for each of the 21 tagged regions. MAM (blue), JJA (red), and SON (purple).

the Northern Plains during fall droughts and pluvials. Again, there is disagreement on the sign of the evaporation recycling change among individual extreme seasons in several of the northern and eastern portions of the North American domain, especially during summer pluvials (e.g. the Southeast, Ohio Valley, Lower Midwest) (figure 6(e)). However, the average reduction (increase) in evaporation recycling in eastern and northern North America during drought (pluvials) helps to explain the mismatch between the sign of evaporation change (figure 4) and the sign of recycled precipitation change (figure 3). Across the Interior West of North America, changes to evaporation recycling and evaporation generally work in the same direction to drive robust changes in precipitation recycling and amplification of extreme wet and dry seasons.

4. Discussion

Moisture tracking with CESM indicates that most of the anomalous precipitation during seasonal drought and pluvial periods in North America is sourced from remote, as opposed to local, areas (figure 2). This is consistent with observed links between dry and wet precipitation extremes and atmospheric rivers along the U.S. West Coast (Paltan *et al* 2017), tropical cyclones in the Southeast (Knight and Davis 2009, Prat and Nelson 2013), the Great Plains low level jet in the central U.S. (Mo *et al* 1997), etc, all of which drive anomalous moisture transport. However, the results indicate that precipitation recycling can also change considerably during these dry and wet periods (figure 3), particularly in Interior western and central portions of North America resulting in substantive contributions to drought and pluvial precipitation anomalies (figure 2). A schematic of the moisture flux anomalies for two regions with strong (weak) and consistent (inconsistent) local contributions to extreme wet and dry summer seasons is shown in figure 7. In regions with large local contributions (e.g. the Upper Rockies and Southwest), imported precipitation anomalies are enhanced through changes in precipitation recycling via modifications to evaporation and evaporation recycling. In regions with small local contributions (e.g. the Great Lakes and Southeast), changes to evaporation and evaporation recycling do little to enhance imported precipitation anomalies, and, as outlined below, may counteract the precipitation anomaly.

The extent to which local recycling contributes to drought and pluvial anomalies appears to be determined in part by the degree of regional aridity (figure 5). In severely and moderately water-limited regimes, including northern Mexico, the Interior West of the U.S., and the Southern and Central U.S. Plains, evaporation consistently declines during drought and increases during pluvials, enhancing the potential for extreme event amplification (figure 4). This potential is realized further because the atmospheric processes that convert local evaporation to precipitation (quantified via evaporation recycling) in these regions robustly decrease during drought and increase during pluvials (figure 6). In energy-limited regimes like the eastern U.S. and Canada, evaporation changes during dry and wet intervals are generally smaller and of inconsistent sign (positive or negative depending on the year) (figure 4). This leads to the possibility of either

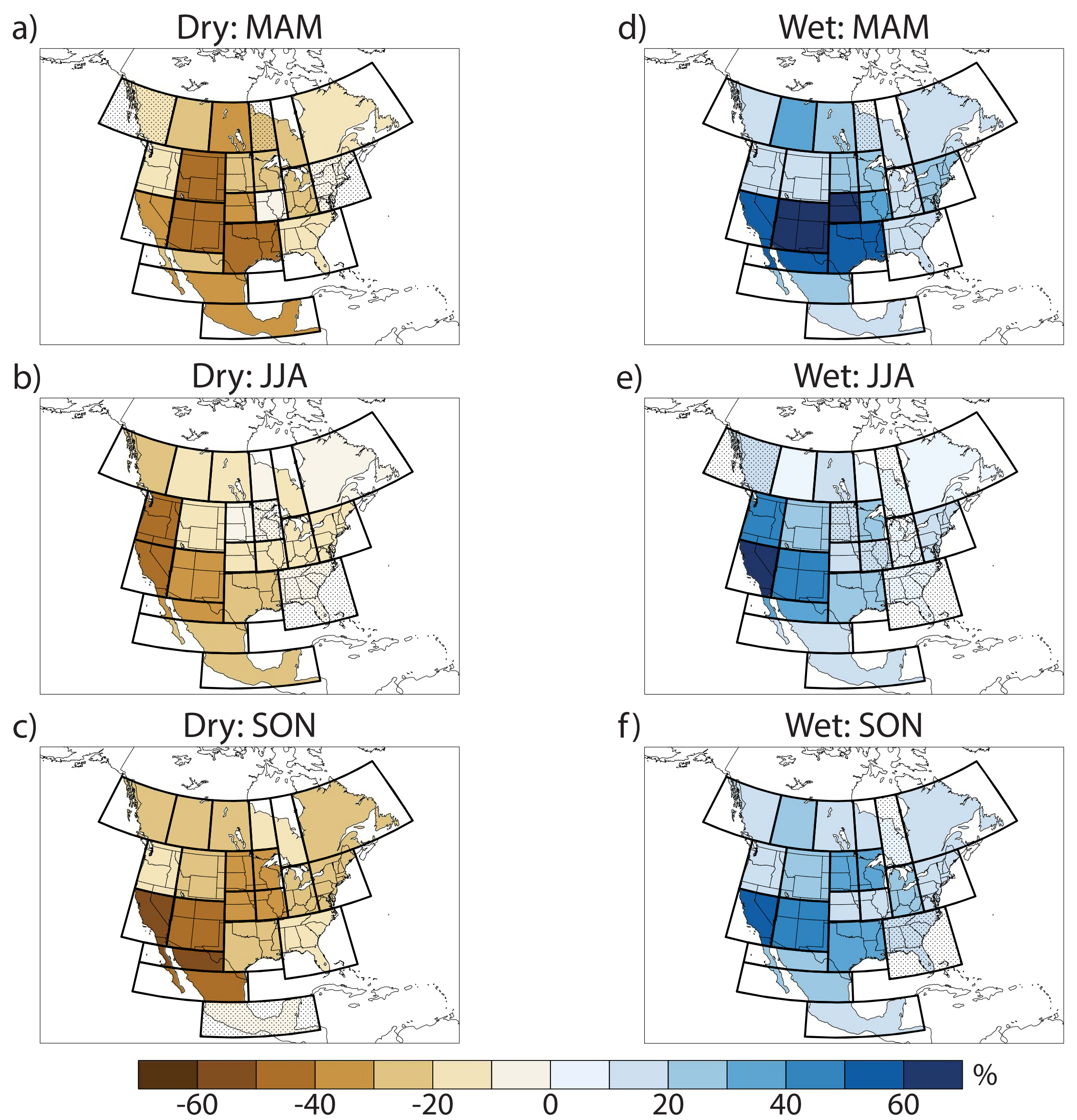


Figure 6. Average percent change in evaporation recycling during (a)–(c) the three driest seasons and (d)–(f) the three wettest seasons based on 3 month SPI. Regions with stippling indicate disagreement on the sign of change among the three years.

a relatively small amplification or small dampening of the externally sourced precipitation extreme. In these energy-limited domains, changes in the efficiency in which local evaporation is converted to local precipitation generally amplify the externally driven precipitation anomaly, though instances of reduced evaporation recycling during pluvials, which counteracts wet conditions, are common during summer (figure 6).

The simulated evaporation changes during extreme wet and dry seasons are consistent with concepts of water-limited and energy-limited evaporation (Seneviratne *et al* 2010). In water-limited areas, evaporation closely follows precipitation, allowing for strong land-atmosphere feedbacks and an important role for precipitation recycling in amplifying precipitation extremes. In energy-limited areas, the response of evaporation to dry and wet anomalies is less consistent. The presence of vegetation in these energy-limited areas facilitates the movement of deeper soil moisture to the surface, sustaining transpiration during periods of relatively low precipitation and high vapor pressure deficit (Teuling *et al* 2013, O'Connor *et al* 2021). However, in some dry events, evaporation in traditionally energy-limited regions behaves similar to water-limited regimes, and decreases. This is likely the case during exceptionally prolonged dry periods when root-zone soil moisture falls well below average. In pluvial periods, evaporation may decrease in energy-limited regimes if increased cloud coverage reduces incoming radiation, temperatures cool, and vapor pressure deficit decreases. However, given sufficient energy, evaporation may increase in response to

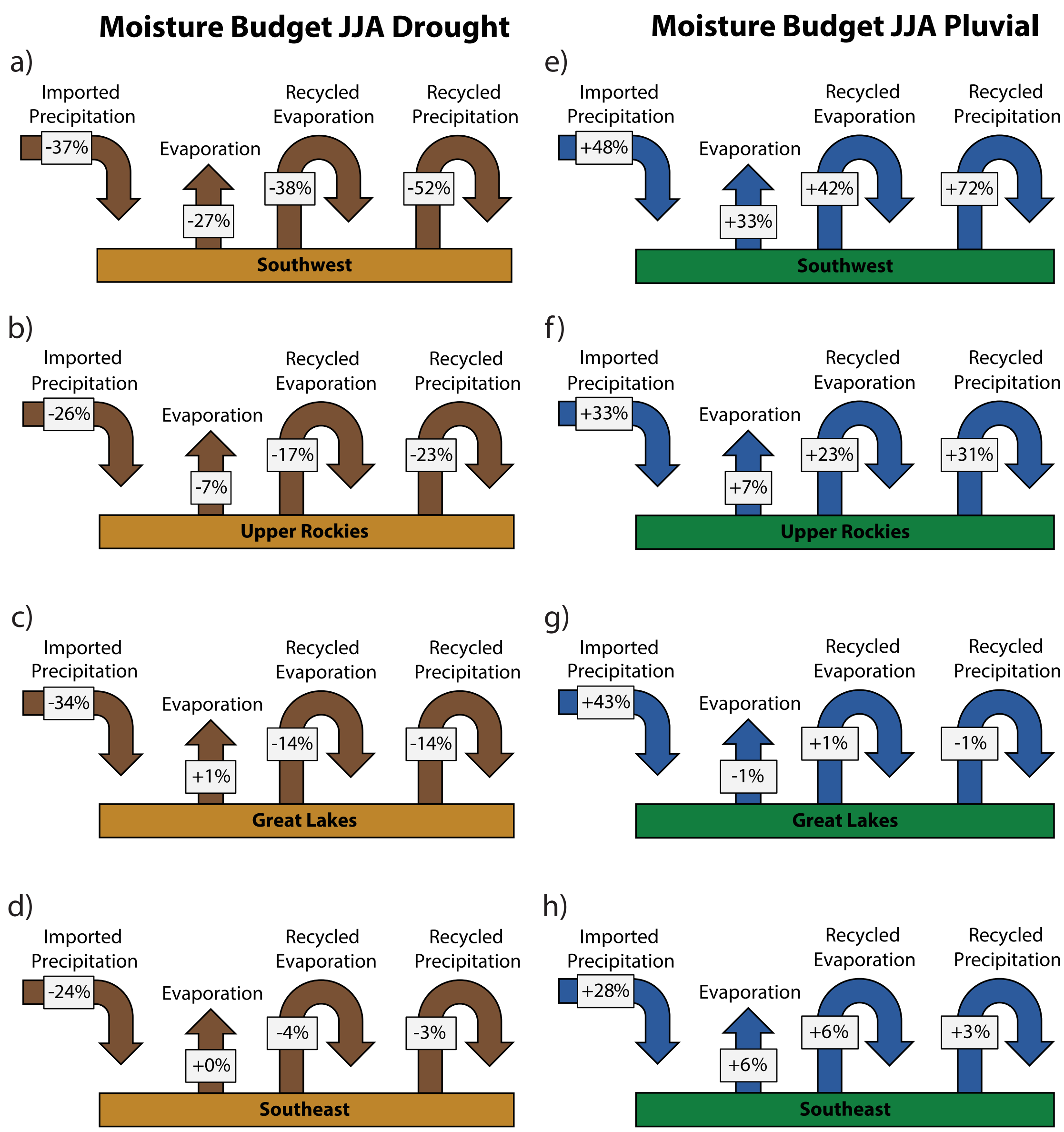


Figure 7. Schematic of the regional moisture budget anomalies during the three driest (a)–(d) and wettest (e)–(h) summer (JJA) seasons based on 3 month SPI for (a), (e) the Southwest, (b), (f) the Upper Rockies, (c), (g) the Great Lakes, and (d), (h) the Southeast (see figure 1 for locations on map). Numbers indicate the percent change from average.

greater precipitation and soil moisture. Overall, the evaporation changes in these areas are smaller and do not support strong amplification of precipitation extremes.

The simulated reductions in the fraction of local evaporation that falls as precipitation during drought, and vice versa during pluvials, are consistent with observed changes to relative humidity and atmospheric stability during these times. In drought, high pressure and subsidence promote stable, relatively dry atmospheric conditions that limit cloud formation and precipitation (Zhuang *et al* 2020). Wet periods are generally characterized by high relative humidity, instability, and forcing mechanisms that promote lift and convergence (Kunkel *et al* 2012). However, the reduction in evaporation recycling during some anomalously wet summers in energy-limited regimes somewhat contradicts this traditional view. In these years, convective processes, which account for the vast majority (in some cases >90%) of summer precipitation recycling (figure S5), are slightly inhibited by reduced incoming radiation and cooler temperatures from enhanced cloud cover and evaporation, resulting in lower conversion rates of local evaporation to precipitation—somewhat limiting the total precipitation anomaly.

The response of precipitation recycling during wet and dry extremes in CESM resembles that from several regional case studies. For example, Roy *et al* (2019) and Herrera-Estrada *et al* (2019) use reanalysis data with an offline moisture tracking analytical model and find that precipitation recycling decreased considerably during the 2012 summer Midwest drought, contributing 14.4% to drought deficit. The equivalent area in our study, a combination of the Central Plains and Lower Midwest, (regions 11 and 12; figure 1) exhibits an average 13% contribution of precipitation recycling to drought deficit during the three driest summer seasons (figure 2(c)). Similarly, our finding that recycled precipitation amounts decrease relative to average conditions during some pluvial periods across the central and eastern U.S. (figure 3(e)) is consistent with the analysis from Bosilovich and Schubert (2001) who used reanalysis data and a bulk diagnostic recycling model to study the 1993 Great Plains flood event.

Despite these similarities, biases in CESM (e.g. figure S2) likely influence the relative contributions of local versus remote moisture during mean and extreme hydroclimate conditions. For example, the summer wet anomaly along the Rocky Mountains in CESM may reflect unrealistically high precipitation recycling amounts in the region, perhaps linked to overly active convective triggering in the model (e.g. Zhen *et al* 2019). More broadly, biases in the simulated frequency and intensity of precipitation may bias the relative contributions of local and remote evaporative sources. The convective parameterization scheme in CESM, like most general circulation models, simulates light precipitation too frequently (Chen *et al* 2021), which may impact the precipitation recycling ratio as well as soil water infiltration rates and therefore evaporation. Repeated analysis with high resolution models will help to tease out the impact of spatial resolution on model estimated precipitation sourcing.

Furthermore, while the model results presented here are generally consistent with the well-established concepts of water- and energy-limited evaporation regimes, recent work has shown that climate models tend to underestimate evaporation during drought across semi-arid and arid regions (Zhao *et al* 2022). Based on Gravity Recovery and Climate Experiment satellite data, Zhao *et al* (2022) find that evaporation increases relative to the climatological mean during 44.4% of drought months globally. Even in water-limited regimes like the Interior western U.S., nearly 40% of drought months exhibit positive evaporation anomalies during drought. Averaged across a subset of the Coupled Model Intercomparison Project Phase 6 (CMIP6), models simulate evaporation increases during 25% of drought months globally, with even smaller values in arid regions. Model biases are attributed primarily to the representation of plant responses to water stress, and soil structure effects on soil hydraulic conductivity (Zhao *et al* 2022). In our analysis, CESM simulates increases in evaporation during some drought events across most regions (figure 4), though not in northern Mexico, the Southwest, and the Southern Great Plains. This may indicate that the negative response of evaporation during drought, and therefore the large contribution of reduced precipitation recycling to drought deficit, is overestimated in the Interior West and Southern Great Plains in our analysis. However, it is worth noting that our analysis focuses on seasonal-scale drought, rather than drought months as in Zhao *et al* (2022), and the longer timescale of dry conditions may lead to a greater likelihood of negative evaporation anomalies. Future work will examine the possible sensitivity of evaporation to drought timescale in CESM.

The large contribution of precipitation recycling to extreme precipitation anomalies (10%–30%) across the Interior West and Southern Plains suggests that monitoring land surface conditions such as soil moisture will assist in seasonal forecasting of precipitation extremes. The results also suggest that changes to local surface characteristics, such as land use type and vegetation physiology, could have important implications for seasonal precipitation extremes in these areas. On the other hand, local sources of moisture are of relatively minor importance (<10%) in amplifying seasonal extremes across much of the northern and eastern portions of North America, highlighting a greater need to focus on understanding variability in atmospheric circulation and its relation to moisture transport in these regions. A shift towards more water-limited regimes in response to increases in atmospheric CO_2 (Denissen *et al* 2022) could drive an increasing role for precipitation recycling in amplifying wet and dry extremes in the future.

Data availability statement

The data that support the findings of this study are openly available at the following URL/DOI: https://app.globus.org/file-manager?origin_id=3c432d8b-5427-4fff-9ed7-fb6d6f24dcc8&origin_path=%2F.

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