Vegetation greening mitigates the impacts of increasing extreme rainfall on runoff events

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Abstract

Future flood risk assessment has primarily focused on heavy rainfall as the main driver, with the assumption that projected increases in extreme rain events will lead to subsequent flooding. However, the presence of and changes in vegetation have long been known to influence the relationship between rainfall and runoff. Here, we extract historical (1850-1880) and projected (2070-2100) daily extreme rainfall events, the corresponding runoff, and antecedent conditions simulated in a prominent large Earth system model ensemble to examine the shifting extreme rainfall and runoff relationship. Even with widespread projected increases in the magnitude (78% of the land surface) and number (72%) of extreme rainfall events, we find projected declines in event-based runoff ratio (runoff/rainfall) for a majority (57%) of the Earth surface. Runoff ratio declines are linked with decreases in antecedent soil water driven by greater transpiration and canopy evaporation (both linked to vegetation greening) compared to areas with runoff ratio increases. Our results suggest that simulated interactions between vegetation greening, increasing evaporative demand, and antecedent soil drying are projected to diminish runoff associated with extreme rainfall events, with important implications for society.
**Significance statement**

Climate change is leading to increases in the magnitude and number of extreme rainfall events. These increases in extreme rainfall events are often assumed to lead to an increase in extreme flooding events. However, using a climate model ensemble, our results indicate that changes in vegetation and atmospheric water demand may alter the relationship between extreme rainfall and extreme runoff. Notably, for a majority of the Earth surface, we find that projected changes in atmospheric aridity and vegetation lead to drier soil conditions prior to the extreme rainfall event that reduces the amount of hydrologic runoff generated. These findings have important implications for water resources management.

**Introduction**

Hydrologic extremes have severe consequences for human, environmental, and economic sectors. One of the well-established outcomes of ongoing climate change is an increase in the number and magnitude of extreme precipitation events even with minimal changes in annual or seasonal precipitation (1-3). Even for areas that are projected to experience a decline in annual precipitation, the number and intensity of short duration heavy precipitation events are likely to increase (4). This increase in precipitation extremes has already been observed throughout the world (5, 6), with sub-daily extreme precipitation changes generally aligning at or above the Clausius-Clapeyron relationship (~7% °C^{-1})(7) and a lower precipitation sensitivity (2-3% °C^{-1}) for longer time intervals due to energetic constraints (7, 8). Climate model projections agree with these observations and suggest that precipitation extremes will continue to increase into the future with increases in air temperature (7, 9) with high confidence (4).

It is often assumed that extreme precipitation increases also will lead to increases in extreme runoff. However, previous work has suggested that this is not always the case (10-13), resulting in uncertain regional runoff and subsequent flooding trends under increasing extreme precipitation (12-16). Prior work suggests that these discrepancies might stem from changes in
the extreme runoff generation mechanisms, where increases in rain-induced extreme runoff events are offset by decreases in snowmelt-induced extreme runoff events (13, 17). However, there remains a lack of consensus of runoff trends from extreme precipitation events (12, 15), suggesting that [1] we lack a thorough understanding of how the interaction between climate and biotic factors affect precipitation partitioning into runoff and soil-water infiltration, and [2] mechanistic drivers of the changes in antecedent conditions need to be examined in more detail. Additionally, given that extreme runoff events in many colder climates are transitioning from snowmelt- to rain-driven (13, 17), we need an improved understanding of the relationship between future extreme precipitation and runoff in multiple environmental and climatic settings.

Antecedent soil water content is the largest modulator of the amount of runoff from precipitation (10, 16, 18). With climate change, declines in surface-layer soil water content are expected, even with increases in precipitation (19, 20), stemming from increases in vegetation water use due to greening (21-24)) and atmospheric demand due to higher temperatures (25, 26). Additionally, vegetation greening can increase canopy interception, which increases canopy evaporation and results in further declines in soil water content (21). Much of this work, however, has been on the seasonal or annual scale, masking how these changes alter the event-based relationship between extreme precipitation and runoff that makes up a substantial portion of flooding events (27). An increased understanding of this relationship is crucial for water resource and hazard planning.

Here, we address this knowledge gap by investigating the changing relationship between projected changes in daily extreme precipitation events and the corresponding runoff. Specifically, we analyze daily precipitation and runoff from 30 members of the state-of-the-art Community Earth System Model version 2 – Large Ensemble (CESM2-LE (28)) under historical
and projected medium-to-high scenario climate forcing (SSP3-7.0 (29)). Using a large ensemble allows for robust sampling of extreme precipitation and runoff events while also controlling for radiative forcing and model uncertainty or biases (20, 30-32). Although data from multiple large ensembles are publicly available, only the CESM2-LE output provides relatively high temporal (daily) and spatial (~1°) resolutions, includes all the required variables needed for the analysis, and has a relatively large ensemble size (see Materials and Methods). To ensure that the CESM2-LE adequately simulates the historical time period, we compare the mean state and variability against multiple gridded monthly observations compiled by the International Land Model Benchmarking project (ILAMB (33)) for runoff, surface soil moisture, evapotranspiration, and leaf area index (see Supporting Information text, Figures S1-S8, and Tables S1-S2).

Additionally, we compare monthly projections from the CESM2-LE against an ensemble of CMIP6 projections to ensure that the CESM2-LE projections are consistent with other CMIP6 models (see Supporting Information text, Figures S9-S12, and Table S3). Although this monthly comparison allows us to contextualize the overall spatial patterns of hydrologic and land surface variables in CESM2-LE, sufficient daily data availability for other CMIP6 models would have allowed for more relevant comparisons for our study.

We define extreme precipitation days or “events” as days when liquid precipitation (hereafter rainfall) exceeds the 95th percentile of historical (pre-industrial time period: 1850-1880) daily rainfall totals (dry days removed) and occurs on a snow-free surface (snowpack depth less than 1 mm (16)). We define [1] the probability of extreme runoff as the probability of a runoff event greater than the historical 95th percentile runoff (calculated with zero runoff days removed) generated from a 95th percentile or greater precipitation event and [2] event runoff ratio as the runoff depth/extreme rain event depth. The extracted simulated runoff is the maximum runoff on
the day of or the day after the extreme rainfall event. For each extreme rainfall event in the historical and projected time periods (end of the 21st century: 2070-2100), we extract the mean state of antecedent conditions for the 5 days prior to the extreme rainfall event (34) that influence the event-based runoff ratio (runoff/rainfall). These factors include surface-layer soil-water content (top 10 cm of the soil column), which is highly sensitive to runoff and ground evaporation (35), evapotranspiration (separated into its components: ground evaporation + canopy evaporation + plant transpiration), leaf area index (LAI), vapor-pressure deficit (VPD), and total rainfall. We examine surface-layer soil water content because the event-based runoff examined in this study is mostly driven by stormflow (rapid surface and subsurface flow) while baseflow levels (between rainfall events) are mainly influenced by deep soil and groundwater flow (35-38). We take the median of each antecedent variable across all events in each analysis time period, and change statistics are based on these time periods. We acknowledge that the antecedent time period can vary depending on the time of year and location (39, 40). Here, we use a 5-day antecedent time period commonly used in hydrologic studies (34) that includes shorter-duration events while also comparing the 5-day antecedent results with a longer antecedent time period (14 days) in the Supporting Information. Moreover, future climate projections often indicate a widespread occurrence of time-mean surface soil drying (19), suggesting that changes in antecedent soil water content may not be affected by the length of the antecedent time period.

Results and Discussion

Changes in extreme rainfall and corresponding runoff
The CESM2-LE projects widespread projected increases in both the magnitude and number of extreme rainfall events, consistent with previous work (2, 41). Figure S13 displays the ensemble mean of the number of extreme rainfall events assessed for the historical and projected time periods. On average, the number of extreme rainfall events and their magnitudes increased across the land surface relative to the historical time period, with robust agreement among CESM2-LE members (defined as an agreement on the sign of the change for 2/3 of the ensemble members; Figure 1a-b). The largest percent increases in the numbers of extreme rainfall events were found in the northern hemisphere, with large changes in western North America, and western Asia (ensemble mean >150% increase), while portions of Central America, South America, the Mediterranean, and Africa showed slight decreases (~10 to 20%). Similarly, we found increases in extreme rainfall magnitude using the CESM2-LE, with large (>10%) increases found throughout the global land surface. In general, changes in the numbers of extreme rainfall events were much larger than those in the extreme rainfall magnitude (Figure 1a-b), likely due to energy limitations (10, 42). In addition to the increases in extreme rainfall magnitude, the number of extreme rainfall events is projected to increase due to warming-driven transitions from snow to rain (number of historical and projected events shown in Figure S13). With a declining snowpack, more rainfall events also occur on a snow-free land surface (43, 44). We recognize that the interpretation of an extreme precipitation event can vary between studies (45). The 95th percentile used in this study allows for a robust sampling of rainfall-runoff events compared to events farther into the upper tail. We do, however, compare the runoff ratio using the 99th percentile as a threshold and have found no substantial differences (Figures S14 and S15).

While we find increases in ensemble mean rainfall extremes for much of the land surface, these increases do not lead to concomitant increases in runoff extremes simulated by the CESM2-LE.
We see declines in both the probability of extreme runoff and the event-based runoff ratio (projected runoff ratio/historical runoff ratio < 1) for 43.5% and 56.9% of the land surface, respectively, for the ensemble mean (Figure 1c-d), with declines in the runoff ratio more widespread than declines in runoff magnitudes (Figure S16). There is widespread robust agreement among CESM2-LE members for the widespread declines in the runoff ratio, suggesting that declines in extreme runoff occur in the same places where extreme rainfall is projected to increase. These declines in event-based runoff ratio are largely concentrated in the northern high latitudes and Amazon region; however, we also find declines for portions of western North America and Central America (Figure 1c-d). Large increases in runoff ratio following extreme rainfall events are found in central Africa and western Asia (Figure 1c-d). We also find a weak correlation (area-weighted Spearman correlation $r_s = 0.31$) between changes in extreme rainfall magnitude and extreme runoff magnitude across all land grid cells ($n \sim 14,000$) in the ensemble mean field.

**Drivers of runoff ratio changes**

We observe that areas with projected declines in event-based CESM2-LE simulated runoff ratios are linked to reduced antecedent soil water content ($r_s = 0.56$), even in locations experiencing increases in rainfall extremes (Figure 2a-b) and with an extended antecedent time period of 14 days (see Figure S17). Previous studies have also highlighted that this contrasting relationship under historical and projected changes in climate is largely controlled by simulated changes in antecedent soil water conditions (10-12), particularly for frequent rainfall extremes where the rainfall rate does not exceed the top soil layer maximum infiltration rate (46). Building on this, we find widespread, robust declines in antecedent soil water content for the land surface.
(ensemble average decline for 62% of land surface area; Figure 2a). The largest declines (-40% or less) are found in the northern latitudes, but other regions such as the western United States and the Amazon region also exhibit robust declines (-25 to -15%).

Antecedent rainfall and the role of vegetation via transpiration and canopy evaporation are the dominant controls on antecedent soil water content (47) and therefore the runoff ratio. Antecedent soil water content has often been equated with antecedent rainfall (48), but ongoing climate change increases evaporative and vegetation water demand, with sometimes rapid decreases in soil water content (49, 50). Here, we find minimal changes in CESM2-LE simulated antecedent rainfall (ensemble average +0.13%) with declines for 62% of the land surface area (Figure 3a), a further indication of hydrologic intensification whereby extreme events are preceded by drier than usual periods (9). The changes are spatially variable, with areas such as the Amazon region, western Africa, and western Asia exhibiting declines (-30 to -20%), while increases are found in regions such as western North America and portions of northern Africa and southern South America (25 to 40%). The Spearman correlation between changes in antecedent rainfall and antecedent soil water content is +0.42 for all land grid cells, suggesting that changes in antecedent rainfall exhibit some control on antecedent soil water content, but changes in evapotranspiration are likely important as well.

Overall, we find that the global land surface average simulated antecedent evapotranspiration increased by 0.67% for the projected time period, with increases found for 42.3% of the area (Figure 3b). There is an upper limit on how much evapotranspiration can occur, with some regions being water-limited or energy-limited, which results in high spatial variability (51). It is
not surprising, then, that the correlation between projected changes in antecedent soil water
content and evapotranspiration for all land grid cells was weak ($r_s = 0.07$) and the correlation
between antecedent rainfall and evapotranspiration was moderate ($r_s = 0.30$).

*closer look at antecedent conditions*

Extreme rainfall events can be preceded by smaller antecedent rainfall events that replenish soil
water content and alter evapotranspiration, resulting in changes to the runoff ratio. To address
this, we perform an additional analysis separating areas where the CESM2-LE mean projected
runoff ratio increases (projected runoff ratio/historical runoff ratio > 1) or decreases (ratio < 1).
We additionally extract areas where antecedent rainfall changes minimally (+/- 10%) compared
to the historical time period, thus allowing for a consistent comparison of antecedent soil water
content inputs (i.e., rainfall) between the historical and projected time periods. Taken together,
this allows for a comparison of changes in the runoff ratio while controlling for changes in
antecedent rainfall. Runoff ratio increases for 28% of the land surface (excluding Greenland and
Antarctica) and decreases for 30% of the land surface, while controlling for minimal changes in
antecedent rainfall. Diverse environments are represented in each category (Figure 4a,b).

After controlling for changes in antecedent rainfall, differences in the antecedent conditions that
drive CESM2-LE simulated runoff changes between areas with runoff ratio increases or
decreases emerge, largely driven by changes in vegetation (Figure 4). As expected, we find a
significant difference (Mood’s median test) in the medians of antecedent soil water content
changes between areas with runoff ratio increase (area-weighted median for soil water change:
+0.81%) and areas with decrease (-3.5%). Similarly, we find slight increases in antecedent
evapotranspiration associated with decreases in runoff ratio (+0.97%) compared to increases in runoff ratio (-4.6%), where both medians are significantly different from each other (Figure 4c).

**The role of vegetation greening in changes in runoff ratio and soil water content**

To further understand the cause of antecedent evapotranspiration changes and the role of vegetation greening, we now assess changes in individual evapotranspiration components simulated by the CESM2-LE (Figure S18). Even though we find a weak correlation between changes in antecedent soil water content and evapotranspiration ($r_s = 0.07$), we find slightly higher correlations across all land grid cells between antecedent soil water changes and changes in antecedent transpiration ($r_s = -0.22$), canopy evaporation ($r_s = -0.11$), and ground evaporation ($r_s = 0.37$). Changes in antecedent transpiration and canopy evaporation are negatively correlated with soil water content because increases in transpiration and canopy evaporation driven by vegetation greening lead to declines in antecedent soil water content. Changes in antecedent soil water content, then, are positively correlated with antecedent ground evaporation because the declines in antecedent soil water content drive declines in ground evaporation.

As before, we analyze the changes in individual CESM2-LE simulated evapotranspiration components for areas of increases or decreases in runoff ratio and minimal antecedent rainfall change (Figure 4a,b). We find a clear shift to higher antecedent transpiration for areas with decreases in runoff ratio (land surface median: -12.1%) as compared to areas with increases in runoff ratio (median: -35.9%; Figure 4f). We additionally perform a partial area-weighted Spearman correlation analysis ($r_{sp}$) to quantify the relationship of each antecedent evapotranspiration component to changes in soil water content. After controlling for the other variables using the partial correlation analysis, we find that antecedent transpiration was the
component with the second strongest relationship to changes in soil water content in areas of decreased runoff ratios \( (r_{sp} = -0.15) \) and third strongest in areas of increased runoff ratios \( (r_{sp} = -0.12) \). Projected antecedent transpiration generally declined for both groups compared to the historical time period, even though we find widespread vegetation greening (52) (defined here as \( \text{LAI}_{\text{proj}}/\text{LAI}_{\text{hist}} > 1 \); Figure 3c), indicating increased CO\(_2\)-induced water-use efficiency (21, 53-55) (average CO\(_2\) for the projected time period is \(~780\) ppm). However, we find a strong positive correlation between \( \text{LAI}_{\text{proj}}/\text{LAI}_{\text{hist}} \) and change in antecedent transpiration across all land grid cells \( (r = 0.81; \text{Figure S19}) \), suggesting that increased LAI causes transpiration to increase prior to heavy rainfall events (56). The shift from a decrease in antecedent transpiration to an increase occurs at approximately a \( \text{LAI}_{\text{proj}}/\text{LAI}_{\text{hist}} \) value of 2.5 (Figure S19), perhaps indicating a threshold where transpiration increase due to higher LAI overrides reductions due to water use efficiency (57, 58). In addition, we also find projected increases in antecedent VPD for nearly the entire land surface (Figure 3d and Figure 4e), further decreasing stomatal conductance and limiting transpiration (59). Increased LAI and/or earlier leaf-out can also produce warmer conditions (and hence VPD), especially in the northern latitudes (60).

While projected antecedent transpiration generally decreases, simulated antecedent canopy evaporation increases for a majority of the land surface (Figure S18), even when controlling for minimal change in antecedent rainfall (Figure 4g). Larger projected increases in canopy evaporation are found for areas with runoff ratio decreases (median: 38.5\%) compared to areas with runoff ratio increases (median: 17.9\%; Figure 4g). Based on the partial correlation analysis, changes in antecedent canopy evaporation was the variable most strongly related to soil-water content changes in areas of decreases \( (r_{sp} = -0.20) \) and increases \( (r_{sp} = -0.15) \) in runoff ratio. Increased LAI can lead to increased annual canopy evaporation due to increased interception.
but canopy evaporation also has been shown to decline due to less frequent and more intense rainfall events (61). While we show increased extreme rainfall and frequency, we also find that increasing LAI will increase future canopy evaporation across all land grid cells ($r_s = 0.63$). In addition to greening, the substantial increase in evaporative demand from higher VPD (Figure 4e), as well as increased surface roughness from higher LAI values (60), would further result in increased canopy evaporation. While we find increases in VPD across nearly all (~87%) of the land surface, the correlation between antecedent VPD and antecedent canopy evaporation is weak ($r_s = -0.05$) and might be explained by growing season lengthening in areas with defined growing seasons. However, while some differences in the median dates of extreme rainfall event timing (e.g., median day of the year) between areas with an increase or decrease in runoff ratio exist (Figure S20), the difference is minimal, with a shift in +1.8 days for areas with runoff ratio increases and +2.5 days for areas with runoff ratio decreases (Figure S21).

In contrast to antecedent canopy evaporation, we find that projected decreases in the simulated runoff ratio are largely associated with slight decreases in antecedent ground evaporation (median = -1.3%; Figure 4h). Increases in runoff ratio, however, are associated with increases in antecedent ground evaporation (median = +18.2%), driven by larger negative shifts in antecedent transpiration and canopy evaporation from an overall lower probability of large antecedent LAI increases (Figure 4d). The partial correlation analysis further confirms this, where, after controlling for all other variables, antecedent canopy evaporation is the only variable with a positive, significant relationship with antecedent soil water changes in areas of runoff ratio decreases ($r_{sp} = 0.15$) and increases ($r_{sp} = 0.14$). With a large increase in LAI, more of the antecedent evapotranspiration would shift to occur via transpiration and canopy evaporation rather than ground evaporation (22, 62). Our results show this as well, with a moderately strong
negative correlation between changes in antecedent ground evaporation and LAI ($r_s = -0.46$) across all land grid cells. This is further highlighted by a moderate negative correlation between antecedent ground evaporation and canopy evaporation ($r_s = -0.31$). Additionally, increases in runoff ratio are associated with increases in antecedent soil water content, thus allowing for a larger soil water pool for antecedent ground evaporation to occur.

**Summary and Implications**

Runoff generation from extreme rainfall is a complex, dynamic mechanism that depends on antecedent conditions and vegetation status. Here, using a prominent and state-of-the-art large climate model ensemble, we shed light on this complexity and show that even with climate-change-induced increases in the magnitude and number of extreme rainfall events, the runoff ratio during these events is projected to decline for the majority of the land surface, in spite of general increases in the amount of runoff. These simulated declines in projected runoff ratio are largely attributed to projected decreases in antecedent soil water content. For areas where the model projects declines in the runoff ratio with minimal changes in antecedent rainfall, the decrease in antecedent soil-water content is associated with vegetation-greening-induced increases in canopy evaporation and increased antecedent atmospheric water demand. Additionally, antecedent transpiration is a key variable associated with projected changes in soil-water content in areas of decreased runoff ratios. Our results suggest that vegetation greening combined with increased evaporative demand will play an important role in the dampening of runoff from extreme rainfall in the future.

While this work uses a large ensemble from a single climate model to understand mechanisms of simulated change in the event rainfall-runoff ratio, the results fall in line with recent empirical
work on these mechanisms (63-66). This work is a first step to understand how climate change may alter the relationship between extreme rain and extreme runoff. Moving forward, analyses should be performed on additional sophisticated land surface and climate models that produce the output used in this work at a high temporal resolution. In summary, planning for the impacts of extreme rainfall events should increasingly consider the responses of vegetation to changing climate and the resultant effect on antecedent soil moisture conditions.

Materials and Methods

Community Earth System Model version 2 – Large Ensemble

The Community Earth System Model (CESM) is a fully coupled, global-scale climate model with a current grid resolution of 0.9424° latitude X 1.25° longitude. CESM uses the Community Land Model (CLM (67)) to simulate land surface processes. We use individual members of the CESM2 Large Ensemble (CESM2-LE (28)) to assess whether the probability of extreme runoff from extreme rainfall will change in the future. The CESM2-LE is a 100-member ensemble that was run from 1850 to 2014 under historical forcing and from 2015 to 2100 under the high-emission SSP3-7.0 scenario. We use the first 30 of these ensemble members, which allows us to balance computational time/effort for analyzing multiple global daily time series while also sufficiently capturing the impact of forced changes in climate variability on extreme rainfall and runoff events (68). CLM simulates runoff using a combination of surface and subsurface runoff. Surface and subsurface runoff are derived from soil moisture (e.g., saturation, saturated thickness) and topographic characteristics (e.g., slope (67)). Full details on the CESM2-LE model and initializations can be found in the model documentation (28, 69).
From the CESM2-LE, we extracted daily rainfall (specified as RAIN in the CESM2-LE model output naming convention), total runoff (QRUNOFF; a variable used in previous work (70)), and snow depth (SNOWDP; used to assess whether snow was present on the ground at the time of the extreme rainfall event). The extracted daily antecedent variables were liquid water in the top 10cm of the soil (SOILWATER_10CM), transpiration (QVEGT), canopy evaporation (QVEGE), ground evaporation (QSOIL), total projected leaf area index (TLAI), and reference height (2m) air temperature (TREFHT) and relative humidity (RHREFHT) used to calculate vapor pressure deficit.

**Observational Comparisons**

To assess the historical performance of the CESM2-LE, we compare relevant output variables against multiple monthly gridded observations compiled by the International Land Model Benchmarking project (ILAMB (33); Table S1). These include runoff from the Conserving Land-Atmosphere Synthesis Suite (CLASS v1.1 (71)) and Linear Optimal Runoff Aggregate (LORA v1.0 (72)), surface soil moisture (73), evapotranspiration from the Global Land Evaporation Amsterdam Model (GLEAM (74)) and MOD16A2 (75), and LAI from MODIS (76), AVHRR (77), and AVH15C1 (78). Other relevant variables such as precipitation, temperature, and snowpack from the CESM2-LE have been validated in previous work (44, 67, 79-81).

The validation datasets listed in Table S1 are linearly interpolated to the same spatial resolution as the CESM2-LE. Due to the lack of gridded, daily observations, the CESM2-LE daily data are aggregated to a monthly time period for direct comparison with the monthly observations. Between the CESM2-LE ensemble mean and gridded observations, we compare spatial biases in
the mean state and the variability (using the interquartile range (IQR)) of all months (January
through December) during the direct time period overlap; see Table S1). For the mean and IQR,
spatial biases are calculated by subtracting the observations from the CESM2-LE ensemble
mean. Area-weighted Pearson correlations, area-weighted mean absolute errors, and kernel
density scatterplots are calculated between the observations and the CESM2-LE ensemble mean.
Results from this analysis are shown in the Supporting Information.

Runoff ratio and antecedent analyses

For each CESM2-LE member, we find the 95th percentile of rainfall and runoff (with dry days
removed; defined as < 0.01 mm) occurring on a snow-free surface for the historical (1850-1880)
time period for each land surface grid cell and ensemble member. Based on these definitions, we
then extract every rainfall event that meets or exceeds the historical 95th percentile of rainfall for
the historical and projected (2070-2100) time periods that also occurs on a snow-free surface.
For consecutive days with rainfall >= 95th percentile, the rainfall, runoff (day of or day after),
and antecedent conditions corresponding to the first day are extracted. The maximum runoff,
defined as the maximum runoff on the day of or the day after the extreme rainfall event, is then
extracted for each extreme rainfall event. Runoff ratio is estimated by dividing the maximum
runoff depth by the extreme rainfall event depth. The probability of extreme runoff is estimated
by dividing how many extreme runoff events occurred (based on its historical 95th percentile) by
the total number of extreme rainfall events.

For the antecedent analyses, we extract the antecedent variables (see above) for each extreme
rainfall event for the historical and projected time periods. To match up with rainfall, runoff, and
runoff ratio, we take the mean of each antecedent variable for the 5 days preceding the extreme
rainfall event, a commonly used time period for rainfall-runoff analyses (34). The 14-day antecedent analysis is shown in the Supporting Information. The median of the extreme precipitation event depth, subsequent runoff depth, and antecedent variable is calculated across each time period (historical or projected). Changes (percent or ratio) are based on these values.

Statistical analyses

Due to the variety of relationships between rainfall, runoff, and antecedent variables, Spearman’s rank correlations are estimated using probability-weighted bootstrap sampling \( n = 1000 \) to account for differential grid-box areas and are presented as the mean of the bootstrapped correlations. To control for the influence of changing rainfall on antecedent conditions, we extract all land surface areas with minimal changes in ensemble mean antecedent precipitation (+/- 10%) from the historical to projected time periods for all land surface grid cells. In addition to minimal changes in antecedent precipitation, areas with ensemble mean increases (projected runoff ratio/historical runoff ratio > 1) and decreases (< 1) are further extracted for analyses. This results in two spatial units (one with increases in runoff ratio and one with decreases) with minimal projected changes in antecedent rainfall. For these separated regions, we use the nonparametric Mood’s median test to assess whether the medians are significantly different between regions of increasing and decreasing runoff ratio. Additionally, for these separated regions we perform a Spearman rank partial correlation analysis weighted by area using bootstrap sampling \( n = 1000 \) and presented as the mean of bootstrap sample partial correlations for each variable. All calculations reported here use areal weighting or areal percentiles (Willmott et al., 2007), including the histograms summarizing the mapped results. When presenting our statistical results, we place a strong emphasis on effect size rather than
significance tests, driven by the widespread recognition that significance testing should receive less attention (82, 83).

CMIP6 monthly comparisons

To ensure that the CESM2-LE projections are consistent with other CMIP6 models, we compare monthly projections of surface soil moisture (CMIP6 variable ID mrsos), runoff (mrro), evapotranspiration (evspsbl), and LAI (lai). Historical and projected (SSP3-7.0) CMIP6 data are downloaded from the Center for Environmental Data Analysis (CEDA) Archive (https://data.ceda.ac.uk/badc/cmip6/data) and are listed in Table S3. Daily data are not available for a large number of GCMs, so we assess the CESM2-LE projections using monthly data (the CESM2-LE daily data are aggregated to monthly data). All GCM data are linearly interpolated to the same spatial resolution of the CESM2-LE (0.9424° latitude X 1.25° longitude). Using similar metrics as the CESM2-LE analysis, we compare changes from the historical to the projected time period. Results from this analysis are shown in the Supporting Information.

Data availability

All data used in this analysis are freely available at https://www.cesm.ucar.edu/community-projects/lens2/data-sets and via the Center for Environmental Data Analysis (CEDA) Archive (https://data.ceda.ac.uk/badc/cmip6/data). These data should be cited if used.

Code availability
Codes used to extract individual rainfall/runoff events and their antecedent conditions can be found on Zenodo here: https://github.com/dficklin/CESM2-LE_event_extraction.git or via contacting the corresponding author.

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Figure 1. Ensemble mean of projected (2070-2100) changes from the historical time period (1850-1880) for (a) extreme rainfall magnitude (%), (b) number of extreme rainfall events (%), (c) probability of an extreme runoff event occurring from an extreme rainfall event (%), and (d) change in the event-based runoff ratio (projected/historical). The stippling indicates a non-robust ensemble agreement (defined as < 2/3 of the ensemble members agree on the sign of the change). The histograms for each subpanel show the distribution of percent of the land surface with an increase (for a and b) or a decrease (for c and d) in the projections across the individual CESM2 members and the distribution of area-weighted land surface averages across the ensemble.
**Figure 2.** Ensemble mean of projected (2070-2100) changes from the historical time period (1850-1880) for (a) % change in antecedent surface soil water content and (b) a binned scatterplot of the relationship between changes in event runoff ratio and antecedent soil water for each land grid cell. The histograms in panel a show the projections from each individual member of the CESM2 large ensemble of area with a decrease and the area-weighted land surface average. The stippling indicates a non-robust ensemble agreement (defined as < 2/3 of the ensemble members agree on the sign of the change). The size of the filled circles in b is proportional to the area of the terrestrial surface in each bin. The percentages in b represent the percent of the total area in each quadrant.
Figure 3. Ensemble mean of projected (2070-2100) changes from the historical time period (1850-1880) for (a) % changes in antecedent rainfall, (b) % changes in antecedent evapotranspiration, (c) change in antecedent LAI (defined as projected antecedent LAI/historical antecedent LAI), and (d) % changes in antecedent vapor pressure deficit. The stippling indicates a non-robust ensemble agreement (defined as < 2/3 of the ensemble members agree on the sign of the change). The histograms for each subpanel show the distribution of percent of the land surface with a decrease (for a) or an increase (for b-d) in the projections across the individual CESM2 members and the distribution of area-weighted land surface averages across the ensemble.
Figure 4. Summary of changes in antecedent conditions for areas with minimal projected antecedent rainfall change (+/- 10%) but with increases or decreases in runoff ratio. The maps indicate the delineated areas for runoff ratio decreases (panel a; red color) and increases (b; blue color). The specific antecedent conditions assessed include evapotranspiration (c), leaf area index (LAI; defined as projected antecedent LAI/historical antecedent LAI; d), vapor pressure deficit (VPD; e), transpiration (e), canopy evaporation (f), and ground evaporation (g). Vertical lines represent the area-weighted median for each grouping.


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