Increasing precipitation whiplash in climate change hotspots

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Abstract
Throughout the world, the hydrologic cycle is projected to become more variable due to climate change, posing challenges in semi-arid regions with high water resource vulnerability. Precipitation whiplash results from hydrologic variability, and refers to interannual shifts between wet (≥80th historical percentile) and dry (≤20th historical percentile) years. Using five model large ensembles, we show that whiplash is projected to increase in frequency (25%–60%) and intensity (30%–100%) by 2100 across several semi-arid regions of the globe, including Western North America and the Mediterranean. These changes can be driven by increases in the frequency of wet years or dry years, or both, depending on the region. Moisture budget calculations in these regions illuminate the physical mechanisms behind increased whiplash. Thermodynamic changes generally dominate, with modulations by dynamics, evaporation, and eddies on regional or global scales. These findings highlight increasingly volatile hydrology in semi-arid regions as the 21st Century progresses.

1. Introduction
The global hydrological cycle is projected to transform under a warming climate. The transformation includes a global increase in precipitation, an increasing climatological contrast between wet and dry events (often referred to as 'wet events wetter, dry events drier', Held and Soden 2006, O'Gorman et al 2009, Trenberth 2011, Allen et al 2020, Douville et al 2021), and an increase in many aspects of precipitation variability. For example, simulated increases in the frequency and intensity of extreme precipitation over most of the globe have been thoroughly documented (Trenberth et al 2003, Pendergrass and Hartmann 2014, Westra et al 2014, Donat et al 2016, Thakeray et al 2018). Meanwhile, increases in severe drought risks in the 21st Century across many regions are projected (e.g. Chadwick et al 2016, Dai et al 2018, Cook and Mankin 2019, Ukkola et al 2020). Consistent with these results, the magnitudes of precipitation anomalies are projected to increase over many land areas in response to warming (e.g. Pendergrass et al 2017, Giorgi et al 2019). Such changes are robust across interannual to decadal timescales (Wood et al 2021), albeit with interannual fluctuations between intensification and de-intensification (Koutsoyiannis 2020).

An expected consequence of increasing variability is that certain regions could experience rapid shifts between extreme dry and wet conditions (e.g. the annual precipitation accumulation exceeds the historical 80th percentile and is immediately preceded by a year with precipitation at or below the historical 20th percentile). Swain et al (2018) define this type of hydrologic volatility as a 'whiplash' event. They find that these dry-to-wet events are 25%–100% more frequent across California by 2100 in the Community Earth System Model version 1 Large Ensemble (CESM1-LENS, Kay et al 2015). This effect occurs despite little change in mean precipitation, unlike in other Mediterranean (MED) climate regimes, which are projected to undergo substantial drying. Similar to California, other MED climate regions experience mid-latitude wetness in winter and subtropical dryness in summer (Polade et al 2017, De Luca et al 2020, Ficklin et al 2022). These regions, at the margins between the planet's wet and dry zones, are highly vulnerable to an increased variability of winter precipitation. They tend to coincide with many of the planet's climate change hotspots, regions

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where the impacts of global warming are expected to be particularly harsh (e.g., Giorgi 2006, Diffenbaugh and Giorgi 2012). But a global perspective of change in year-to-year precipitation whiplash remains unexplored. In theory, increasing whiplash could result from a one-sided increase in the occurrence of overall wet years or dry years, or both. An important research goal is to disentangle and quantify the dominant forces that drive precipitation whiplash in different regions.

Natural variability within the climate system introduces large uncertainties in projected future changes (Deser et al., 2012a, 2012b, Dai and Bloecker 2019). To isolate the anthropogenically forced changes in precipitation whiplash requires datasets with sufficient representation of natural variability. Fortunately, besides CESM1-LENS, the US CLIVAR Multi-Model Large Ensemble Archive (MMLEA, Deser et al. 2020) consists of several single model initial condition large ensembles (SMILEs, Lehner et al. 2020). It provides a great opportunity to robustly sample uncertainties associated with both internal variability and model uncertainty across Earth system models (ESMs) (Maher et al. 2019, Wood et al. 2021). Additionally, physical mechanisms for hydrologic changes can be explored using a thermodynamic and dynamic framework (Seager et al., 2014, Norris et al. 2019) where sub-daily data is available.

In this study we seek to address three key questions: (a) which parts of the globe might experience increasing precipitation whiplash in the future? And (b) Are the shifts driven by an increase in dryness or wetness? Lastly, (c) how robust are the projected changes across different SMILEs?

2. Data and methods

2.1. Climate model data

We use daily precipitation from five SMILEs in the MMLEA, including the LENS from the CESM1 (40 members), GFDL-CM3 (20), EC-EARTH (16), CanESM2 (50), and CSIRO-Mk3-6-0 (30). The SMILEs have been shown to capture precipitation variability adequately over most parts of global land areas relative to observations (Wood et al. 2021), adding confidence to future projections. Infinitesimal perturbations to the initial atmospheric state can lead to very different future climates in a model (Kay et al. 2015, Lehner et al. 2018), and such sensitivity can be exploited to quantify internal variability and biases under the same radiative forcing (Kay et al. 2015, Goldenson et al. 2021). The MMLEA also makes comparison across models more robust than traditional CMIP efforts (Deser et al. 2020, Lehner et al. 2020). Considering the volatile nature of precipitation whiplash and its potential sensitivity to internal variability, the MMLEA is well suited for this task.

We analyze simulation output from the twentieth century (20 C, 1950–2005) and RCP8.5 (2005–2100) scenarios. We note that although the current policy pathways likely yield less warming than projected by the RCP8.5 scenario, (e.g., Ritchie and Dowlatabadi 2017), it should capture the upper bound (i.e. worst possible outcome) of future whiplash changes and hence is still informative for adaptation plannings. All data are bilinearly interpolated to a common 2° × 2° (latitude × longitude) grid to reduce data aggregation bias associated with variable model resolution (Chen and Dai 2019). To ensure MMLEA mean precipitation changes equally represent individual SMILEs, we use the first 16 ensemble members from each SMILE to construct an MMLE (80 members). The large size of the MMLE should reduce the underestimation issue noted by Wood et al. (2021). Elsewhere, we utilize all available ensemble members of each individual LENS to understand systematic differences among models, particularly at a regional scale.

2.2. Metric definitions

We define precipitation whiplash events (see figure 1(a) for an observed example) as whenever annual mean precipitation at a given 2° × 2° pixel is equal to or above the 80th percentile (wet year) of the historical climatology (1950–2000) and immediately followed by a year with precipitation equal to or below the 20th percentile (dry year), or vice versa (Swain et al. 2018). The historical climatology is constructed by concatenating the 1950–2000 annual mean precipitation (at each grid point) from all ensemble members for each model individually to obtain a statistically robust distribution. This leads to, for instance, a precipitation distribution with a sample of 2040 years (40 members × 51 years) for CESM1-LENS. The same time period is used for observed threshold in GPCC. We then calculate the frequency (percentage of occurrence) and intensity (absolute values of the precipitation differential between the two consecutive years) of such events at each grid point and each year for individual SMILEs. We also calculate the occurrence of the wet and dry years individually (historical 80th and 20th percentiles, respectively) in the future climate. The Interannual variability in historical (1950–1980) and future (2070–2100) climate is quantified by computing the standard deviation of annual precipitation. The spatial pattern of future changes is calculated by subtracting historical (1950–1980) mean from future (2070–2100) mean at each grid point, normalized by the historical values.

2.3. Regions of Interest

Here, we use the spatial pattern of future whiplash changes from the MMLE mean to select four land regions with robust change signals (figure 1(b)) to better understand the drivers of regional whiplash. These regions include two climate reference regions defined in Iturbide et al. (2020) for the
Figure 1. (a) An example of observed precipitation ‘whiplash’ events over west Australia in GPCC, (b) Historical (1950–1980) frequency of precipitation ‘whiplash’ globally, and (c) relative future change (2070–2100 minus historical normalized by historical values) in ‘whiplash’ year frequency calculated using MMLEs (80 members). The blue dots indicate where 60% of ensemble members agree on the sign of ‘whiplash’ frequency change. The green patches illustrate regions with positive changes in both wet (≥80th percentile) and dry year (≤20th percentile) frequency. The blue boxes indicate four regions with outstanding changes over land.

Intergovernmental Panel on Climate Change Sixth Assessment Report, i.e. the Western North America (WNA, a polygon encompasses 32° N–52° N, 235° E–255° E) and the MED (30° N–45° S, −10° E–40° E) regions. The other two regions we selected are West Australia (WAU, 10° S–35° S, 110° E–130° E) and SouthEast Africa (SAF, 30° S–0, 20° E–50° E). The time series are calculated by aggregating the pixels with positive values over land within these regions. An 11 year running mean is then applied to smooth the time series.

2.4. Moisture budget analysis
To identify drivers of hydrological cycle change in both wet and dry years, we evaluate the moisture budget conditioned on years of ≤20th and ≥80th percentile precipitation separately. Below is a simplified derivation.

The steady-state moisture budget equation may be expressed as:

\[
P = E - \nabla \cdot \{qv\}
\]  

(1)
where $P$ is precipitation, $E$ is evaporation, $q$ is specific humidity, $v$ is the horizontal wind vector, and $\{\}$ denotes a mass-weighted vertical integral.

To average over all time steps, we separate moisture flux convergence into terms representing climatologies of $q$ and $v$ and anomalies at each 6 h time step.

$$
\bar{P} = E - \nabla \cdot \{\bar{qp}\} - \nabla \cdot \{\bar{q}v'\} \quad (2)
$$

where overbars denote means and primes denote anomalies. The second term on the right hand side of (2) represents moisture flux convergence by the climatological moisture and circulation. The final term represents moisture flux convergence by eddies, as calculated in Seager et al (2014), which we denote simply as the eddies term.

Thus, the future change in the moisture budget is given by:

$$
\Delta \bar{P} \approx \Delta \bar{E} - \Delta (\nabla \cdot \{\bar{qp}\}) + \Delta \text{eddies} \quad (3)
$$

where $\Delta$ denotes the change from the historical to future climates. To identify the roles of moisture and circulation separately, we simply divide $-\nabla \cdot \{\bar{qp}\}$ by the climatological column water vapor, $\{\bar{q}\}$, to yield the term, $D$, representing the mean circulation. Thus, neglecting the second-order term, we obtain

$$
\Delta \bar{P} \approx \Delta \bar{E} + D \Delta CWV + CWV \Delta D + \Delta \text{eddies} \quad (4)
$$

Here, the second and third terms on the right represent the changes to moisture flux convergence due to climatological changes in moisture and circulation, respectively, which we may refer to as thermodynamic and dynamic.

Finally, we condition this equation on years of $\leq 20^\text{th}$ and $\geq 80^\text{th}$-percentile precipitation separately, where the percentiles are evaluated at each grid point and identified in each climate separately (1990–1999 versus 2071–2080).

$$
\Delta \bar{P}_{20} \approx \Delta \bar{P}_{20} + D_{20} \Delta CWV_{20} + CWV_{20} \Delta D_{20} + \Delta \text{eddies}_{20} \quad (5)
$$

$$
\Delta \bar{P}_{80} \approx \Delta \bar{P}_{80} + D_{80} \Delta CWV_{80} + CWV_{80} \Delta D_{80} + \Delta \text{eddies}_{80} \quad (6)
$$

Furthermore, we subtract (5) from (6) to reveal how the change in moisture budget differs between wet and dry years, as plotted in figures 6 and S9.

We restrict this analysis to the CESM1 LENS because it is the only one that archives 3D data at 6 h temporal resolution. And for these data the available time periods are limited to 1990–1999 and 2071–2080. For CESM1, changes in frequency of whiplash, wet year, dry year, and interannual variability between these shorter periods and the longer periods analyzed in the rest of the study are highly similar (cf figures 4 and S8). Hence, the moisture budget analysis over the shorter period should be representative. The analysis is performed on CESM1’s native grid ($288 \times 192$ pixels).

3. Results

3.1. Simulated changes

Historically, high interannual precipitation whiplash is seen over regions within the inter-tropical convergence zone, specifically the East Indian Ocean and the central-to-eastern tropical Pacific (figure 1(b)). Whiplash is also frequent in major monsoon regions and along storm tracks in both hemispheres, indicating a key role for large-scale atmospheric circulation in generating whiplash. Individual realizations from each model show comparable magnitudes to those observed in GPCC (figure S1(a)) and CRU (not shown as it is similar to GPCC).

The greatest increases in the occurrence of precipitation whiplash are mainly located over the transition zones between the tropics and mid-latitudes, most noticeably over the subtropical oceans and adjacent land regions (figure 1(c)). This contrasts with the projected changes in interannual variability, which are strongest in the tropics and mid-latitudes (figure 2(a), Seager et al 2012, 2019, He and Li 2019). Here, we chose to focus our analysis on precipitation whiplash over land because it has greater social impacts. Besides the changes across California, which in fact extend to WNA, other land areas including the MED, WAU, and SAF exhibit ~50% increased likelihood of precipitation whiplash according to the MMLE. Most of these regions overlap with areas where there is a projected increase in both historically wet ($\geq 80^\text{th}$ percentile) and dry ($\leq 20^\text{th}$ percentile) years (denoted by green shading; figure 1(c)). While precipitation variability changes (figure 2(a)) share much spatial similarity to the increases in wet years (figure 2(b)), the whiplash metric reflects changes in both the wet and dry frequency (figure 2(c)). Historical whiplash events are most intense (figure S2(a)) over climatologically dry regions (e.g. North Africa and the tropical central-eastern Pacific). The future increases (figure S2(b)) are similar to those of whiplash frequency, except for the values over the tropical eastern Pacific, suggesting that precipitation whiplash might have critical impacts on historically arid regions.

3.2. Whiplash flavors

Since precipitation whiplash describes two-sided changes, seemingly similar changes in whiplash frequency and intensity could be driven by distinct perturbations in the two sides of the precipitation distribution. To better understand the different flavors of precipitation whiplash and how they are projected to unfold over the upcoming decades, we examine temporal changes from 1950 to 2100 in the frequency of precipitation whiplash years, wet years, and dry years (figure 3). Note that the time series for wet years (middle column) and dry years (right column) do not
Figure 2. Relative future change (2070–2100 minus historical normalized by historical values) in (a) interannual precipitation variability, (b) wet year frequency, and (c) dry year frequency. The blue dots indicate where 60% of ensemble members agree on the sign of change.
add up to whiplash (left column) because whiplash events only capture the transition between wet and dry years. The time series are calculated by aggregating the pixels with increasing whiplash over land within the four regions. The MMLE mean projects robust increases in whiplash frequency (figures 3(a)–(d)) during the 21st century across all these regions. The WAU region exhibits the largest increase of 50% ± 120%. This is followed closely by the WNA region, where increases of 35% ± 70% are seen. The MED and SAF regions have more moderate increases of 15% ± 60% and 25% ± 40%, respectively. Such increasing trends generally persist throughout the century. Temporal changes in whiplash intensity (figure S3) show higher magnitudes, reaching a 200% increase in some ensemble members.

The one-sided changes for wet (figures 3(e)–(h)) and dry (figures 3(i)–(l)) year frequency unveil different drivers for regional changes. We identify three different flavors of precipitation whiplash accordingly. The first is driven by an increase in the frequency of wet years with unchanged dry year occurrence, such as the WNA regions (increase of wet-year frequency by 100% ± 100%). This is consistent with what Swain et al. (2018) found across California using only one large ensemble. In contrast, whiplash changes over the MED and WAU regions are mostly driven by increases in dry years (120% ± 100% and 100% ± 100%, respectively), with good ensemble agreement on the sign of dry changes after 2050 or so. Robust decreases of mean precipitation are also projected over these regions in CMIP6 models (Cook and Mankin 2019,
Ukkola et al. 2020), resulting from increased moisture divergence by the mean flow (Seager et al. 2014, D’Agostino and Lionello 2020). The MED region also experiences a drop in the occurrence of wet years after 2050, which translates to a slight reduction in whiplash during the latter decades of the timeseries. The third type occurs as a result of increases in both wet and dry year frequency, as exemplified by the SAF region, where end-of-century wet-year and dry-year frequencies are projected to increase by 50% ± 90% and 60% ± 60%, respectively (figures 3(g) and (k)). This type of whiplash is arguably the most impactful, as it involves an increased tendency for consecutive years of drought and floods, despite even small changes in mean precipitation. Although SAF is the only region where this feature is identified after aggregation, there are many sub-regions, predominantly in the subtropics, where both wet-year and dry-year frequency increase (figure 1(b)).

### 3.3. Intermodel variability

Here, we discuss how the individual SMILEs differ in their regional projections of whiplash change. The 40 ensemble members of CESM1-LENS (figure 4(a)) largely agree with the MMLE on the increased precipitation whiplash over the four regions of interest, albeit with appreciably larger (12%–33% more, table S1) and broader increases than the MMLE. This model also exhibits substantial whiplash changes over south Asia and northeast Brazil, likely associated with increasing volatility of monsoon precipitation. EC-EARTH LENS (figure S4) shows particularly expansive increases in whiplash frequency throughout the tropics and subtropics, with 40%–65% mean increases (table S1). The GFDL-CM3 LENS qualitatively agrees with CESM1 and EC-EARTH, with a striking 75% mean increase in whiplash frequency over WNA near 2100. Changes in CanESM2 and CSIRO-Mk3-6-0 are overall sparser and of lesser magnitudes. Despite these subtle model disagreements, the five SMILEs overall show increasing precipitation whiplash over the four hotspot regions, an indicator of the robustness of the MMLE projection. The spatial patterns of future changes in interannual variability (figures 4(b) and S5), wet-year (figures 4(c) and S6), and dry-year (figures 4(d) and S7) frequency in all SMILEs overall agree with the MMLE. Regional discrepancies likely arise from the systematic differences among different ESMs.

### 3.4. Drivers of change in CESM

In light of the different flavors of whiplash changes, we delve briefly into atmospheric moisture budget analysis (Seager et al. 2014, Norris et al. 2019) to decompose the changes and understand the physical mechanisms. Sub-daily output is needed to close the moisture budget (Seager and Henderson 2013); this is enabled by 3D data at 6 h temporal resolution in CESM1 LENS archives. Besides, the regional trends in CESM1 (figure 5) generally echo the MMLE temporal changes (figure 3) for whiplash, wet-year, and dry-year frequency. Notable differences include...
slightly higher increases in whiplash frequency than the MMLE mean, a moderately less positive dry-year trend over the MED, and a nearly 50% increase in wet-year frequency over WAU. Also, CESM1 shows a small negative trend in dry years and a lower increase in whiplash over WNA. Thus, CESM1-LENS is situated more on the wetting side of the spectrum among the five SMILEs.

Because the CESM1 projections differ only subtly from those of the MMLE mean, we proceed to decompose the moisture budget for CESM1. Precipitation changes are decomposed into changes in evaporation), thermodynamics (Therm; moisture availability), dynamics (Dyn; circulation), and eddies. Here, the thermodynamic and dynamic terms represent changes to the mean moisture and circulation, respectively, whereas the eddy term represents the moisture flux convergence by anomalous moisture and circulation. The differences between wet ($\geq 80$th percentile) and dry ($\leq 20$th percentile) years (figure 6) provide a proxy for increasing whiplash tendency, i.e. where wet years increase by more than dry years.

Among the four hotspots, the thermodynamic dominance is most noticeable for WNA (figure 6(a)), over which wet-led whiplash change is projected. Besides, the thermodynamic term (figures 6(c) and S9) is the leading factor for the increases in precipitation whiplash, as the spatial patterns and the magnitudes are largely similar over many continental areas except the deep tropics (weighted pattern correlation of 0.54 between figures 6(a) and (c). This feature is to be expected from hydrological cycle intensification. Over various MED-type regions, the dynamic term (figure 6(d)) counteracts the thermodynamic-induced tendency to enhance the differential between wet and dry years. There is a pattern correlation of 0.50 between figures 6(a) and (d), illustrating the importance of dynamics in driving interannual variability throughout the globe. This is particularly

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Figure 5. Same as figure 3 but for CESM1-CAM5 large ensemble.
apparent over MED which has dry-led whiplash changes, where the dynamic term is of greater magnitude than the thermodynamic term. This is consistent with Pfahl et al (2017) and Norris et al (2019), who found that the dynamic term tends to offset the thermodynamic wetting tendency in the subtropics for extreme precipitation. Our results suggest that dynamics tend to reduce the differential between wet and dry years, which possibly results from the slowdown of general circulation (Held and Soden 2006). Although SAF and WAU can be classified as both wet and dry-led, the dry tendency over SAF comes from dynamic terms solely, while thermodynamic and dynamic terms both lead to drying over WAU.

The eddy term (pattern correlations of 0.42 between figures 6(a) and (e) is the leading term for increased interannual variability over WAU. It tends to amplify the thermodynamics (i.e. exacerbating the swings between wet and dry years) over MED and SAF, while it counteracts the thermodynamics and amplifies the dynamic changes over WNA. This indicates that, although the change to the mean circulation may be similar between wet and dry years, the wet years are influenced by a much greater enhancement of eddy moisture flux convergence than occurs in dry years. For WAU, the evaporation term also contributes to the increasing differential, although globally it exhibits little resemblance to the precipitation changes.

Figure 6. (a)–(e) The difference between the wet (≥80th-percentile composite) and dry (≤20th-percentile composite) moisture budget changes from 1990–1999 to 2071–2080 in the CESM1-LENS. Regions analyzed earlier in manuscript are highlighted in red boxes. (f)–(h) The change in moisture budget terms between 2071–2080 and 1990–1999 in the CESM1-LENS averaged over all grid cells that experience an increase in whiplash frequency. The years of dry (≤20th-, left column), wet (≥80th-, middle column) percentile precipitation, and their differences are composited over each category.
Moisture budget analysis derived from CESM1-LENS shows that enhanced moisture associated with a warmer climate (i.e. the thermodynamic term) is the main driver behind future increases in precipitation whiplash globally. This is particularly true for regions where the change in wet years drives increased whiplash. In general, the thermodynamic term is most influential for changes on a global scale (Held and Soden 2006, O’Gorman and Schneider 2009, Pfahl et al 2017), while the dynamic component play an important role in modulating regional changes, especially over land (Byrne and O’Gorman 2015, Norris et al 2019). The influences of moisture flux convergence by eddies and evaporative fluxes exacerbate the differential between wet and dry years, thereby increasing whiplash by more than what would occur through moisture increases alone. The affected regions are primarily at the poleward margins of the subtropics, where annual precipitation is typically delivered by a handful of extratropical cyclones each winter. Hence, the influence of the eddies is likely associated with an increasing disparity in extratropical-cyclone activity between wet and dry years over these regions. Meanwhile, the influence of evaporation may reflect memory of the land surface to antecedent wet or dry years. The dynamic term (changes to mean circulation) offsets the other factors, with its importance most apparent over regions with the dry-led changes. This connection may indicate that a slowdown of the mean circulation tends to decrease whiplash. We believe these mechanisms could apply more broadly to other SMILEs, but further investigation of their moisture budget is required.

Regarding regional changes, our results resonate with pioneering studies that highlighted hydrological-cycle changes in several climate change hotspots (Giorgi 2006, Difennaugh and Giorgi 2012, Seager et al 2012). In particular, the expansive changes over WNA may be associated with an eastward shifted North Pacific jet stream and an enhanced meridionally oriented trough therein (Neelin et al 2013, Wang et al 2014, Swain et al 2016, 2018). Similarly, drying and increased precipitation variability over the MED have been attributed to a combination of changes in the upper-tropospheric circulation and a reduction in the temperature difference between land and sea (Tuel and Eltahir 2020). Over SAF, increasing extreme rainfall and drought risk are related to warming as well as large scale circulation shifts (Fauvaucreau et al 2003, Maure et al 2018, Pascale et al 2020).

Overall, our results highlight that precipitation whiplash is expected to increase substantially over many places towards the latter half of the 21st century. Although there are common mechanisms driving this change throughout the globe, there are nuances in the role of each factor over different regions. Given that the results are based on 80 ensemble members from five ESMs, we believe the projections are likely (pattern correlation of 0.10 between figures 6(a) and (b). We further split whiplash changes into wet-to-dry (figure S10(a)) and dry-to-wet (figure S10(b)) shift-type. Overall, spatial distributions are similar over the four focus regions, indicating that neither of the two shift types overpowers total whiplash changes. The strongest differences are mostly over the southern Pacific Ocean, where more dry-to-wet whiplash changes are projected.

The thermodynamic component is the leading contributor to the increasing differential between wet and dry years, averaged over regions experiencing increased whiplash (figure 6(h)). This results from a strong thermodynamic drying of dry years (figure 6(f)) but a slight thermodynamic wetting of wet years (figure 6(g)). The evaporation and eddy terms show secondary importance, while the dynamic term marginally counteracts the effects of the other terms. For dry years (figure 6(f)), changes in evaporation ($\Delta E$) are larger than precipitation ($\Delta P$) and moisture export moves locally evaporated moisture more effectively out of the region, leading to enhanced drying. For wet years (figure 6(g)), changes in precipitation are greater than in evaporation, meaning that there is enhanced moisture import from remote regions. Thus, the differential between wet and dry years dominated by the thermodynamic changes, is intensifying and will continue to intensify hydrological volatility in many regions around the world.

4. Conclusions and discussion

We find that more frequent interannual shifts between wet and dry events are projected by the MMLE simulations in many high-vulnerability regions around the globe. The frequency of whiplash events is projected to increase by between 25% and 60% over several regions, including the MED, WNA, SAF, and WAU by 2100. We identify several different types of whiplash, as characterized by the individual contributions of changing wet and dry years. Increasing whiplash is driven by increased wet years over WNA, increased dry years over MED and WAU, and by both over SAF. The five SMILEs evaluated here generally agree with the MMLE mean, albeit with regional nuances across different ESMs. The regions overall governed by, ED climate regimes are mostly impacted. One exception is coastal Chile, which does not exhibit increased whiplash in most SMILEs, likely due to uniform drying of the distribution. It is worth noting that there might be uncertainty in whiplash changes that is associated with the forcing scenarios, as our results are based on MMLE simulations under the RCP 8.5 scenario. But, given the similar spatial patterns of hydrological-cycle intensification in GCMs across different forcing scenarios (e.g. Tebaldi et al 2021), we believe the results should be qualitatively similar in other scenarios.
to reflect the behavior of the larger CMIP6 ensemble if every model had produced multiple realizations. They warn of an increasingly volatile hydrological cycle over many highly populated and economically influential regions. Such rapid and amplified swings in annual precipitation may have impacts that are not confined to the effects of the extremes themselves, and instead, flow from the sequencing of extremes. For example, during a dry year wildfire may be enhanced by a buildup of fuel in the antecedent wet year; conversely, during a wet year extreme rainfall has a greater tendency to cause debris flows if fires in the antecedent dry year left the ground more impervious. In addition, although we observe similar spatial patterns between wet-to-dry and dry-to-wet whiplash changes, their temporal characteristics may differ, which could be investigated in further work. The intensification of whiplash will increase the complexity of water resources management (e.g. Ficklin et al 2022). This may be exacerbated by multi-year whiplash (e.g. a multi-year drought followed by an extreme wet year), or seasonal whiplash (e.g. an extremely dry winter followed by an extremely wet summer). Future work could investigate how whiplash changes manifest on different timescales. Such information should better inform risk assessment and adaptation practices.

**Data availability statement**

The data that support the findings of this study are openly available at the following URL/DOI: www.cesm.ucar.edu/projects/community-projects/MMLEA/ and https://climatedataguide.ucar.edu/climate-data/gpcc-global-precipitation-climatology-centre and https://crudata.uea.ac.uk/cru/data/hrg/#current.

The data that support the findings of this study are openly available at the following URL/DOI: www.cesm.ucar.edu/projects/community-projects/MMLEA/www.cesm.ucar.edu/projects/community-projects/MMLEA/. A standard data availability statement has been added to your article, based on the information you gave in your submission. This text cannot be changed unless there is an error. Please remove any other data statement if the information is now duplicated. If the standard statement includes a link or DOI, please check that this is also an item in the reference list. If not, please provide the reference details (author, year, data title, repository name, link) and indicate where this reference should be cited in the text of your article.

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**References**

Allan R P et al 2020 Advances in understanding large-scale responses of the water cycle to climate change Ann. New York Acad. Sci. 1472 49–75

Byrne M P and O’Gorman P A 2015 The response of precipitation minus evapotranspiration to climate warming: why the “wet-get-wetter, dry-get-drier” scaling does not hold over land J. Clim. 28 8078–92

Chadwick R, Good P, Martin G and Rowell D P 2016 Large rainfall changes consistently projected over substantial areas of tropical land Nat. Clim. Change 6 177–81

Chen D and Dai A 2019 Precipitation characteristics in the community atmosphere model and their dependence on model physics and resolution. J. Adv. Model. Earth Syst. 11 2352–74

Cook B I and Mankin J S 2019 Twenty-first century drought projections in the CMIP6 forcing scenarios Earth’s Future 8 1–20

D’Agostino R and Lionello P 2020 The atmospheric moisture budget in the Mediterranean: mechanisms for seasonal changes in the Last Glacial Maximum and future warming scenario Quat. Sci. Rev. 241 106392

Dai A and Bloeker C F 2019 Impacts of internal variability on temperature and precipitation trends in large ensemble simulations by two climate models Clim. Dyn. 52 289–306

Dai A, Zhao T and Chen J 2018 Climate change and drought: a precipitation and evaporation perspective Curr. Clim. Change Rep. 4 301–12

De Luca P, Messori G, Faranda D, Ward P J and Coumou D 2020 Compound warm–dry and cold–wet events over the Mediterranean Earth Syst. Dyn. 11 793–805

Deser C et al 2020 Insights from Earth system model initial-condition large ensembles and future prospects Nat. Clim. Change 10 277–86

Deser C, Knutti R, Solomon S and Phillips A S 2012a Communication of the role of natural variability in Nat. Clim. Change 2 273–9

Deser C, Phillips A, Bourdette V and Teng H 2012b Uncertainty in climate change projections: the role of internal variability Clim. Dyn. 38 527–46

Diffenbaugh N S and Giorgi F 2012 Climate change hotspots in the CMIP5 global climate model ensemble Clim. Change 114 813–22

Donat M G, Lowry A L, Alexander L V, Gorman P A O and Maher N 2016 More extreme precipitation in the world’s dry and wet regions Nat. Clim. Change 6 508–13

Douville H et al 2021 Water cycle changes Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change ed V Masson-Delmotte et al (Cambridge: Cambridge University Press) pp 1055–210

Farchione J, Krzysztof S, Rouault M and Richard Y 2003 Rainfall changes consistently projected over substantial areas of tropical land Clim. Dyn. 20 127–38

Fritsma K and Veldhuis R 2012 More extreme precipitation over Europe and its possible attribution to global warming Clim. Change 114 813–22

Giorgetta M, Lohmann O, Roeckner E and Mikolajewicz U 2020 Advances in understanding large-scale responses of the water cycle to climate change Ann. New York Acad. Sci. 1472 49–75

Gloersen P, Gille ST and Collelo GP 1990 A new generation of satellite glaciological oceanography Space. Sci. Rev. 54 345–98

Giorgi F 2006 Climate change hot-spots Geophys. Res. Lett. 33 L08707

Giorgi F, Raffaele F and Coppola E 2019 The response of precipitation characteristics to global warming from climate projections Earth Syst. Dyn. 10 73–89

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Golderson N, Thakkeray C W, Hall A D, Swain D L and Berg N 2021 Using large ensembles to identify regions of systematic biases in moderate-to-heavy daily precipitation Geophys. Res. Lett. 48 1–11
He C and Li T 2019 Does global warming amplify interannual climate variability? Clim. Dyn. 52 2667–84
Held I M and Soden B J 2006 Robust responses of the hydrological cycle to global warming J. Clim. 19 5686
Iturbide M et al 2020 An update of IPCC climate reference regions for subcontinental analysis of climate model data: definition and aggregated datasets Earth Syst. Sci. Data 12 2959–70
Kay J E et al 2015 The Community Earth System Model (CESM) large ensemble project: a community resource for studying climate change in the presence of internal climate variability Bull. Am. Meteorol. Soc. 96 1333–49
Koutsoyiannis D 2020 Revisiting the global hydrological cycle: is it intensifying? Hydrof. Earth Syst. Sci. 24 3899–932
Lehner F, Deser C, Maher N, Marotzke J, Fischer E M, Brunner L, Knutti R and Hawkins E 2020 Partitioning climate projection uncertainty with multiple large ensembles and CMIP5/6 Earth Syst. Dyn. 11 491–508
Lehner F, Deser C, Simpson I R and Terray L 2018 Attributing the U. S. Southwest’s recent shift into drier conditions Geophys. Res. Lett. 45 6251–61
Maher N et al 2019 The Max Planck institute grand ensemble: enabling the exploration of climate system variability J. Adv. Model. Earth Syst. 11 2050–69
Maure G, Pinto I, Ndebele-Murisa M, Muthige M, Lennard C, Nikulin G, Meque A and Meque A 2018 The southern African climate under 1. 5 °C and 2 °C of global warming as simulated by CORDEX regional climate models OPEN ACCESS The southern African climate under 1. 5 °C and 2 °C of global warming as simulated by CORDEX regional climate models Env. Res. Lett. 13 065002
Neelin J D, Langenbrunner B, Meyerson J E, Hall A and Berg N 2013 California winter precipitation change under global warming in the coupled model intercomparison project phase 5 ensemble, J. Clim. 26 6238–56
Norris J, Chen G and Neelin J D 2019 Thermodynamic versus dynamic controls on extreme precipitation in a warming climate from the community earth system model large ensemble J. Clim. 32 1025–45
O’Gorman P A and Schneider T 2009 The physical basis for increases in precipitation extremes in simulations of 21st-century climate change Sciences 106 14773–7
Pascale S, Kapnick S B, Delworth T L and Cooke W F 2020 Increasing risk of another Cape Town “ Day Zero ” drought in the 21st century Proc. Natl Acad. Sci. 117 29495–503
Pendergrass A G et al 2017 Precipitation variability increases in a warmer climate. Sci. Rep. 7 1–9
Pendergrass A G and Hartmann D L 2014 Changes in the distribution of rain frequency and intensity in response to global warming J. Clim. 27 8372–83
Pfahl S, Gorman P A O and Fischer E M 2017 Understanding the regional pattern of projected future changes in extreme precipitation Nat. Clim. Change 7 4230427
Polade S D, Gershunov A, Cayan D R, Dettinger M D and Pierce D W 2017 Precipitation in a warming world: assessing projected hydro-climate changes in California and other Mediterranean climate regions Sci. Rep. 7 1–10
Ritchie J and Dowlabadi H 2017 Why do climate change scenarios return to coal? Energy 140 1276–91
Seager R and Henderson N 2013 Diagnostic computation of moisture budgets in the ERA-interim reanalysis with reference to analysis of CMIP-archived atmospheric model data J. Clim. 26 7876–901
Seager R, Liu H, Henderson N, Simpson I, Kelley C, Shaw T, Kushnir Y and Ting M 2014 Causes of increasing aridification of the Mediterranean region in response to rising greenhouse gases. J. Clim. 27 46554–676
Seager R, Naik N and Vogel L 2012 Does global warming cause intensified interannual hydroclimate variability? J. Clim. 25 3355–72
Seager R, Osborn T J, Kushnir Y, Simpson I R, Nakamura J and Liu H 2019 Climate variability and change of Mediterranean-type climates J. Clim. 32 2887–915
Swain D L, Horton D E, Singh D and Diffenbaugh N S 2016 Trends in atmospheric patterns conducing to seasonal precipitation and temperature extremes in California Sci. Adv. 2 4
Swain D L, Langenbrunner B, Neelin J D and Hall A 2018 Increasing precipitation volatility in twenty-first-century California Nat. Clim. Change 8 427–33
Tebaldi C et al 2021 Climate model projections from the scenario model intercomparison project (ScenarioMIP) of CMIP6 Earth Syst. Dyn. 12 253–93
Thakkeray C W, DeAngelis A M, Hall A, Swain D L and Qu X 2018 On the connection between global hydrologic sensitivity and regional wet extremes Geophys. Res. Lett. 45 20
Trenberth K E 2011 Changes in precipitation with climate change Clim. Res. 47 123–38
Trenberth K E, Dai A, Rasmussen R M and Parsons D B 2003 The changing character of precipitation Bull. Am. Meteorol. Soc. 84 1205–17
Tuel A and Eltahir E A B 2020 Why is the Mediterranean a climate change hot spot? J. Clim. 33 5829–43
Ukkola A M, Kauwe M G, De Roderick L M, Abramowitz G and Pitman A J 2020 Robust future changes in meteorological drought in CMIP5 projections despite uncertainty in precipitation. Geophys. Res. Lett. 47 e2020GL087820
Wang S Y, Hips J, Gillies R R and Yoon J-H 2014 Probable causes of the abnormal ridge accompanying the 2013–2014 California drought: ENSO precursor and anthropogenic warming footprint. Geophys. Res. Lett. 41 3220–6
Westra S, Fowler H J, Evans I P, Alexander L V, Berg P, Johnson F, Kendon E J, Lenderink G and Roberts N M 2014 Future changes to the intensity and frequency of short-duration extreme rainfall Rev. Geophys. 52 522–55
Wood R R, Lehner F, Pendergrass A G and Schlunegger S 2021 Changes in precipitation variability across time scales in multiple global climate model large ensembles Environ. Res. Lett. 16 064022