Mechanisms for an Amplified Precipitation Seasonal Cycle in the U.S. West Coast under Global Warming

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(Manuscript received 1 February 2019, in final form 20 April 2019)

ABSTRACT

The mean precipitation along the U.S. West Coast exhibits a pronounced seasonality change under warming. Here we explore the characteristics of the seasonality change and investigate the underlying mechanisms, with a focus on quantifying the roles of moisture (thermodynamic) versus circulation (dynamic). The multimodel simulations from phase 5 of the Coupled Model Intercomparison Project (CMIP5) show a simple “wet-get-wetter” response over Washington and Oregon but a sharpened seasonal cycle marked by a stronger and narrower wet season over California. Moisture budget analysis shows that changes in both regions are predominantly caused by changes in the mean moisture convergence. The thermodynamic effect due to the mass convergence of increased moisture dominates the wet-get-wetter response over Washington and Oregon. In contrast, mean zonal moisture advection due to seasonally dependent changes in land–sea moisture contrast originating from the nonlinear Clausius–Clapeyron relation dominates the sharpened wet season over California. More specifically, the stronger climatological land–sea thermal contrast in winter with warmer ocean than land results in more moisture increase over ocean than land under warming and hence wet advection to California. However, in fall and spring, the future change of land–sea thermal contrast with larger warming over land than ocean induces an opposite moisture gradient and hence dry advection to California. These results have important implications for projecting changes in the hydrological cycle of the U.S. West Coast.

1. Introduction

From October to April, precipitation along the U.S. West Coast is above the annual mean (Fig. 1), marking the pronounced wet season typical of the Mediterranean climate (Swain et al. 2018). Understanding future changes in precipitation seasonality under global warming carries important implications for projecting regional climate change. In the western United States, changes in seasonal precipitation have large socioeconomic impacts as agriculture and hydropower generation are supported by seasonal runoff fed by precipitation and mountain snowpack and regulated for multiple water uses. In particular, the increasing incidence of drying in the fall may have consequential impacts for ecosystems and wildfire risk, as it extends the already long and dry season, potentially

allowing summer-like vegetation dryness to persist into the peak Santa Ana wind season that begins in November (Guzman-Morales and Gershunov 2019).

California lies in the transitional latitudes between the subtropical dry climate and the midlatitude, storm track–dominated climate. Future changes in California precipitation are subject to the influence of circulation shifts as the climate warms (Seager et al. 2007; Seager and Vecchi 2010; Neelin et al. 2013). This contributes to the large uncertainties in model projections of precipitation changes over California (e.g., IPCC 2013; Choi et al. 2016). The diverse microclimates created by the complex topography further challenge model projections of regional precipitation changes. Hence, there is an unmet need for climate projections to inform future development to support the growing population and economy (Cowling et al. 1996; Swain 2015). To date, there is a broad consensus among climate models that the southwestern United States (SWUS), a region stretching from the southern plains to the Pacific coast, will experience a long-term decline of water availability in the twenty-first century (e.g., Seager et al. 2007;

Supplemental information related to this paper is available at the Journals Online website: <https://doi.org/10.1175/JCLI-D-19-0093.s1>.

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FIG. 1. The two leading (a),(b) EOF patterns (in mm day^{-1}) and (c) standardized principal components (PCs) of climatological monthly mean precipitation over the U.S. West Coast from NARR during 1979–2016. The values given on the top right of (a) and (b) represent the percentage variance explained by each mode. Rectangles in (a) indicate the regions for California (32° – 42°N , 115° – 124°W) and Washington–Oregon (42° – 49°N , 120° – 125°W). The x axis in (c) is from July to June.

Seager and Vecchi 2010; Scheff and Frierson 2012; Seager and Henderson 2013; Gao et al. 2014; Cook et al. 2015). The recent severe droughts and more frequent wildfires in the SWUS forebode the grim projections of mega-droughts in the future (e.g., Griffin and Anchukaitis 2014; Robeson 2015; Williams et al. 2015; Diffenbaugh et al. 2015; Seager et al. 2015; Prein et al. 2016). A seasonally dependent response of surface water availability with a robust spring drying has also been noted for the SWUS in future projections (Seager et al. 2014; Gao et al.

2014). The significant spring drying is reported to be dominated by the thermodynamically driven dry zonal advection (Ting et al. 2018). On the other hand, extension of the North Pacific jet stream and the associated storm tracks have been implicated in the increased winter precipitation in the California coast under warming (Neelin et al. 2013). The distinct sharpening of California's future mean seasonal cycle has been revealed by Swain et al. (2018). However, a detailed mechanistic understanding of the precipitation seasonality response to warming in

California is still missing. Compared with California, future changes of precipitation seasonal cycle in the states of Washington and Oregon (hereinafter simply Washington–Oregon) have received less attention so it is unclear if and why the response in California may be different from that in Washington–Oregon.

Previous studies often focused on precipitation changes in a particular season (winter or summer), but the seasonality of precipitation may also undergo marked changes in response to anthropogenic warming. Song et al. (2018a) found a robust seasonally dependent response of tropical precipitation to warming and attributed the response to the increase in latent energy in a warmer, moister atmosphere that slows down the atmospheric response to the seasonal variation of solar insolation. For the subtropics, Song et al. (2018b) noted the seasonality changes in the North Pacific and North Atlantic subtropical highs that influence moisture transport and precipitation seasonality in the SWUS and central United States, respectively. The seasonality changes in North Pacific atmospheric rivers (ARs), a major cause of extreme precipitation and flooding along the U.S. West Coast (e.g., Ralph et al. 2004, 2006; Leung and Qian 2009; Neiman et al. 2011), have been hinted by Warner and Mass (2017), who noted that the peak in future AR days may shift by about 1 month earlier. Since changes in extreme precipitation are reflections of the changes in monthly-mean precipitation (Lehmann et al. 2018), whether the mean seasonality has similar changes remains unclear.

This study explores the characteristics of seasonality changes in mean precipitation along the U.S. West Coast, and investigates the underlying mechanisms with a focus on quantifying the roles of moisture (thermodynamic) versus circulation (dynamic). We begin by describing the changes in mean monthly precipitation based on global warming experiments, demonstrating that the “wet-get-wetter” response and the sharpened wet season response are distinct over the U.S. West Coast with a dividing latitude along the Oregon–California border. We investigate the thermodynamic and dynamic contributions via moisture advection and divergence process based on a moisture budget analysis. Finally, we explore the sources of seasonality changes in land–sea moisture contrast, which is demonstrated to dominate the sharpened wet season in California, as dictated by the nonlinear Clausius–Clapeyron (CC) relation.

2. Observations, model experiments, and methods

a. Observations and model experiments

In this study, monthly precipitation from the North American Regional Reanalysis (NARR) at a $0.25^\circ \times 0.25^\circ$ resolution during 1979–2016 (Mesinger et al. 2006)

TABLE 1. The 37 CMIP5 models providing outputs for the Hist and RCP8.5 experiments. Among these models, only 25 provide outputs of surface variables for calculating the boundary term. We use four models with daily outputs to calculate the transient eddy effect directly.

No.	Model	Surface variables	Daily data for eddy estimate
1	ACCESS1.0	×	
2	ACCESS1.3	×	
3	BCC-CSM1.1	×	
4	BCC-CSM1.1-m	×	
5	BNU-ESM	×	
6	CanESM2	×	×
7	CCSM4		
8	CESM1-BGC		
9	CESM1-CAM5		
10	CESM1-WACCM		
11	CMCC-CESM		
12	CMCC-CM		
13	CMCC-CMS		
14	CNRM-CM5	×	×
15	CSIRO-Mk3.6.0	×	
16	FGOALS-g2		
17	FIO-ESM		
18	GFDL CM3	×	
19	GFDL-ESM2G	×	
20	GFDL-ESM2M	×	
21	GISS-E2-H	×	
22	GISS-E2-R	×	
23	HadGEM2-AO	×	
24	HadGEM2-CC	×	
25	HadGEM2-ES	×	
26	INM-CM4	×	
27	IPSL-CM5A-LR	×	
28	IPSL-CM5A-MR	×	
29	IPSL-CM5B-LR	×	
30	MIROC5	×	
31	MIROC-ESM-CHEM	×	
32	MIROC-ESM	×	
33	MPI-ESM-LR		×
34	MPI-ESM-MR		
35	MRI-CGCM3	×	×
36	NorESM1-ME		
37	NorESM1-M	×	

is used to analyze the climatological seasonal cycle along the U.S. West Coast. A total of 37 models from phase 5 of the Coupled Model Intercomparison Project (CMIP5) are used to examine the future changes of mean monthly precipitation. We compare simulations between the historical (Hist) and representative concentration pathway 8.5 (RCP8.5) scenario (Taylor et al. 2012) for the current (1962–2005) and future (2056–99) periods, respectively (Table 1). To calculate the multimodel ensemble (MME) mean, all the CMIP5 monthly variables are interpolated to a common 73×144 global grid. The CMIP5 datasets used in this study are available at http://www.ipcc-data.org/sim/gcm_monthly/AR5/Reference-Archive.html.

b. Methods

In free-running coupled simulations, internal variability is not synchronous across the individual simulations in the CMIP5 ensemble, so the ensemble mean can effectively suppress internal variability and isolate the effects of global warming. The ensemble mean is calculated as the arithmetic mean of the equally weighted 37 CMIP5 models. To estimate the statistical robustness, we highlight regions with model agreement from at least 70% of the CMIP5 models on the sign of response, consistent with previous studies (Power et al. 2012; Song et al. 2018a,b). Our main results are not substantially influenced by choosing different thresholds such as 80% model agreement.

We focus on the wet months (October–April) along the U.S. West Coast in this study and contrast the midwinter [December–February (DJF)] with the neighboring spring [March–April (MA)] and fall [October–November (ON)] seasons.

Following Ting et al. (2018), changes in mean precipitation ($\Delta\bar{P}$) can be decomposed into changes in mean moisture convergence, transient eddy moisture convergence, and evaporation as

$$\Delta\bar{P} = \Delta\left(-\frac{1}{g\rho_w}\nabla \cdot \int_0^{p_s} \bar{\mathbf{u}}\bar{q} dp\right) + \Delta\left(-\frac{1}{g\rho_w}\nabla \cdot \int_0^{p_s} \bar{\mathbf{u}}'q' dp\right) + \Delta\bar{E}, \quad (1)$$

where the overbar represents monthly mean and the prime denotes daily deviation from the monthly mean, Δ denotes changes in the future based on the differences between the RCP8.5 and Hist experiments, P is precipitation, E is evaporation, $\mathbf{u}$ is horizontal wind vector, q is specific humidity, g is gravitational constant, ρ_w is density of water, p is pressure, and p_s is its surface value. Equation (1) represents the balance between the changes in the divergence of vertically integrated moisture transport and the changes in $P - E$. Since the changes in evaporation are much smaller than those in precipitation, we focus on the effect of moisture transport on precipitation. We calculate the vertical integrals at 17 standard pressure levels between the surface pressure and the top pressure level, and we use the centered finite difference scheme for the horizontal difference. Since we only use monthly outputs from all 37 CMIP5 models, the transient eddy moisture convergence $[-(1/g\rho_w)\nabla \cdot \int_0^{p_s} \bar{\mathbf{u}}'q' dp]$ is estimated as the residual using Eq. (1). To demonstrate that this method does not lead to misinterpretation of the transient term, we choose four CMIP5 models (CanESM2, CNRM-CM5, MPI-ESM-LR, and MRI-CGCM3) with daily

outputs and a sharpened seasonal cycle in California to calculate the transient eddy effect directly (Fig. S1 in the online supplemental material). The results show a reasonable correspondence between the residual and the transient eddy effect calculated using daily data.

To further quantify the relative roles of dynamic and thermodynamic effects, the changes in mean moisture convergence can be expressed as the sum of changes from the horizontal wind only (dynamic) and changes from specific humidity only (thermodynamic) as follows:

$$\Delta\left(-\frac{1}{g\rho_w}\nabla \cdot \int_0^{p_s} \bar{\mathbf{u}}\bar{q} dp\right) \cong -\frac{1}{g\rho_w}\nabla \cdot \int_0^{p_s} \Delta\bar{\mathbf{u}}\bar{q} dp - \frac{1}{g\rho_w}\nabla \cdot \int_0^{p_s} \bar{\mathbf{u}}\Delta\bar{q} dp. \quad (2)$$

In addition, the changes in mean moisture convergence can also be interpreted as the contributions from the moisture advection, the divergence term, and the boundary term that arises from the surface pressure gradient:

$$\Delta\left(-\frac{1}{g\rho_w}\nabla \cdot \int_0^{p_s} \bar{\mathbf{u}}\bar{q} dp\right) = \Delta\left(-\frac{1}{g\rho_w}\int_0^{p_s} \bar{\mathbf{u}} \cdot \nabla\bar{q} dp - \frac{1}{g\rho_w}\int_0^{p_s} \bar{q}\nabla \cdot \bar{\mathbf{u}} dp - \frac{1}{g\rho_w}\bar{q}_s\bar{\mathbf{u}}_s \cdot \nabla p_s\right). \quad (3)$$

Since not all the 37 CMIP5 models (Table 1) provide outputs of surface variables for calculating the boundary term $[-(1/g\rho_w)\bar{q}_s\bar{\mathbf{u}}_s \cdot \nabla p_s]$, the residual of the difference between the left-hand term and the first two right-hand terms in Eq. (3) has to be used to estimate the boundary term. This approach is confirmed to be reasonable in Fig. S2, in which good agreement is found between the residual (Fig. S2e) and the direct estimate (Fig. S2d) for 25 CMIP5 models with surface variables in their archives (Table 1). Similarly, the mean dynamic and thermodynamic contributions to the response in Eq. (2) can also be partitioned into advection, the divergence term, and the boundary term (as a residual) components, as follows:

$$-\frac{1}{g\rho_w}\nabla \cdot \int_0^{p_s} \Delta\bar{\mathbf{u}}\bar{q} dp = -\frac{1}{g\rho_w}\int_0^{p_s} \Delta\bar{\mathbf{u}} \cdot \nabla\bar{q} dp - \frac{1}{g\rho_w}\int_0^{p_s} \bar{q}\nabla \cdot (\Delta\bar{\mathbf{u}}) dp - \frac{1}{g\rho_w}\bar{q}_s\Delta\bar{\mathbf{u}}_s \cdot \nabla p_s, \quad (4)$$

$$\begin{aligned}
-\frac{1}{g\rho_w} \nabla \cdot \int_0^{p_s} \bar{\mathbf{u}} \Delta \bar{q} dp &= -\frac{1}{g\rho_w} \int_0^{p_s} \bar{\mathbf{u}} \cdot \nabla (\Delta \bar{q}) dp \\
&\quad - \frac{1}{g\rho_w} \int_0^{p_s} \Delta \bar{q} \nabla \cdot \bar{\mathbf{u}} dp \\
&\quad - \frac{1}{g\rho_w} \Delta \bar{q}_s \bar{\mathbf{u}}_s \cdot \nabla p_s. \quad (5)
\end{aligned}$$

The sources of error in the diagnostic evaluation of the moisture budget due to different numerical methods are discussed in detail by [Seager and Henderson \(2013\)](#).

Following the analysis of [Ting et al. \(2018\)](#) for understanding the SWUS spring drying, the CC relation can be used to understand the regional scale changes in California. By comparing the specific humidity from the CMIP5 outputs with that calculated based on the CC relation (Fig. S3), we confirm that the CC relation holds well over California using monthly data and can be used to study the mechanisms for seasonality changes.

3. Results

a. Characteristics of future changes in precipitation seasonality

We begin by clarifying the dominant modes of climatological seasonal cycle of mean precipitation along the U.S. West Coast based on observation using empirical orthogonal functions (EOFs) (Fig. 1). The first dominant mode features an in-phase seasonal cycle along the U.S. West Coast, with a wet season from October to April accounting for ~93% of the seasonal cycle. The second mode features a north–south dipole with a dividing latitude along 42°N between California and Oregon, and its principal component (PC2) depicts a southward progression of the storm track and precipitation as season proceeds from fall to winter. Therefore, we choose California and Washington–Oregon as two representative areas (green rectangles in Fig. 1a) in this study.

Figure 2 depicts the changes in climatological mean seasonal cycle of monthly precipitation under warming. The CMIP5 models reproduce the observed climatological seasonal cycle well with a wet season from October to April (Figs. 2a,b), which provides confidence in using the CMIP5 models to investigate the future seasonality changes. However, the amplitude is not well reproduced by the MME, with overestimation over California. Under warming, California receives more precipitation in winter and less in spring and fall (solid line in Fig. 2c), with >70% model agreement among the 37 CMIP5 models, indicating a robust stronger and narrower wet season in the future. The distinct sharpened seasonal cycle of California precipitation with

wetter winter and drier spring and fall is in concert with previous findings based on the Community Earth System Model Large Ensemble Simulations (CESM-LENS; [Swain et al. 2018](#)) but deviates from the conventional wisdom of the wet-get-wetter mechanism of precipitation changes ([Held and Soden 2006](#)). Following [Song et al. \(2018a\)](#), the wet-get-wetter pattern can be obtained by least-squared fitting the projected changes between RCP8.5 and Hist (solid black line) on the time series of the climatological mean precipitation based on Hist (red line), representing the fractional changes congruent with the current seasonal cycle. By removing the wet-get-wetter pattern from the projected changes, the sharpened wet season is still evident (dashed line in Fig. 2c). Meanwhile, the precipitation response over Washington–Oregon also exhibits a clear seasonal dependence to warming, showing more precipitation in the wet season throughout October to April (solid line in Fig. 2d). Removal of the wet-get-wetter component (current seasonal cycle) diminishes the seasonality change (dashed line in Fig. 2d). Thus, changes over Washington–Oregon can be characterized broadly by the wet-get-wetter pattern, representing an enhancement of the current seasonal cycle.

To further clarify the robustness of the precipitation seasonality change in each model and its time evolution, we define a wet season index as the mean precipitation difference between winter (DJF) and the average of spring (MA) and fall (ON) over California (32°–42°N, 115°–124°W). A sharpened wet season under warming is projected if the ratio of this index between the RCP8.5 and Hist experiments is larger than 1. In California, 30 out of 37 CMIP5 models show a sharpened wet season under warming, with the MME also showing a sharpened wet season (Fig. 3a). There is no significant linear trend in the time series of the wet season index before 2000 based on the MME, but the linear trend is statistically significant at the 95% and 99% confidence levels for 2000–40 and 2040–95, respectively, indicating a sharpening wet season under anthropogenic warming in the twenty-first century (Fig. 3b). We estimated the time when the signal of sharpened wet season emerges from the noise of natural climate variability [the time of emergence (ToE)] for each model. The signal is calculated as the linear trend of the wet season index from 2001 to each year after 2001, and the noise is calculated as one standard deviation of its interannual variability over the reference period 1861–2000 ([Hawkins and Sutton 2012](#); [Quan et al. 2018](#)). The ToE is defined as the year when the signal overwhelms the noise. The results indicate that in 23 out of 37 CMIP5 models, the ToE of the sharpened wet season occurs during the twenty-first century, with the MME emerging around 2022 (Fig. 3c).

FIG. 2. Climatology of monthly mean precipitation averaged over (a) California (32° – 42° N, 115° – 124° W) and (b) Washington–Oregon (42° – 49° N, 120° – 125° W) based on NARR (light blue), the MME of RCP8.5 (blue), and Hist (red). The shading indicates one standard deviation of 37 CMIP5 models. (c), (d) The changes (solid) in mean precipitation between the RCP8.5 and Hist based on the MME of 37 CMIP5 models. Dashed lines indicate the precipitation changes after removing the wet-get-wetter pattern obtained by regression onto the climatological seasonal cycle from the Hist runs. An asterisk indicates that at least 70% of the models agree on the sign of the change. Units: mm day^{-1} .

These CMIP5 results suggest the possibility for detecting the sharpened wet season over California in a few decades. Although the sharpened wet season has not yet emerged in observation (not shown), the drying spring and fall are already underway (Swain et al. 2018).

b. Moisture budget analysis

To determine the extent to which the precipitation response can be explained by the moisture (thermodynamic) and circulation (dynamic) changes via the effects of moisture advection, the divergence term, and the boundary term, we conduct a moisture budget analysis. Based on Eq. (1), the sharpened wet season over California and the wetter wet season over Washington–Oregon are predominantly caused by the changes in mean moisture convergence, which is offset by the transient eddy moisture convergence, while evaporation changes show little seasonality (Figs. 4a,b). Also examined are the effects of dynamic and thermodynamic processes on the total mean moisture convergence changes based on Eq. (2). Both dynamic and thermodynamic effects contribute to the sharpening seasonal

cycle over California, while the wet-get-wetter change over Washington–Oregon is predominantly attributable to thermodynamic effect (Figs. 4c–f). Next, the contributions from moisture advection and the divergence and boundary terms to the total mean moisture convergence, as well as the dynamic and thermodynamic components, are further illustrated following Eqs. (3)–(5).

The results demonstrate that the sharpened wet season over California is dominated by the mean moisture advection (red line in Fig. 5a), especially via the thermodynamic component due to changes in specific humidity (red line in Fig. 5e). For Washington–Oregon, the divergence term mainly accounts for the wetter wet season (blue line in Fig. 5b), which is entirely attributed to the thermodynamic effect via increased moisture (blue line in Fig. 5f). Also suggested is that both the wetter winter and drier spring in California might have a dynamical origin (black line in Fig. 5c), consistent with Gao et al. (2014). Changes in the North Pacific jet stream and subtropical high are further discussed (Fig. 6). The broader area defined by the climatological 30 m s^{-1} zonal wind contour in the future than in the present

FIG. 3. (a) Ratio of the RCP8.5 and Hist wet season index defined as the winter (DJF) minus the average of spring (MA) and fall (ON) $[DJF - (MA + ON)/2]$ precipitation over California (32° – 42° N, 115° – 124° W) for each CMIP5 model. The red dashed line is the value for the MME. A sharpened wet season under warming is projected if the ratio is larger than 1 (black line). (b) Time series of the wet season index (in mm day^{-1}) based on MME of the Hist and RCP8.5 experiments from 37 CMIP5 models. The shading indicates one standard deviation of 37 CMIP5 models. (c) Time of emergence (ToE; in years) of the sharpened wet season in each model. The red dashed line is the ToE year for the MME.

indicates a broadening and strengthening jet in the future. Both the eastward extension of the westerly jet stream (Figs. 6a–c) and the deepening of the Aleutian low pressure (Fig. 6e) favor a wetter California winter by steering storm tracks and increasing moisture advection to the U.S. West Coast. These features appear robust across the CMIP5 models with >70% model agreement although they could be overestimated by the models due to their bias in simulating the intermediate-scale stationary waves (Simpson et al. 2016). On the other hand, the enhancement of the North Pacific subtropical high in spring (Song et al. 2018b) may contribute to the drier spring (Fig. 6f).

The contributions of each process to the seasonality changes over California are further compared quantitatively in Fig. 7. The total mean moisture convergence dominates the increased precipitation in winter (Fig. 7a), the declining precipitation in spring and fall (Figs. 7b,c), and the sharpened wet season (Fig. 7d). More specifically, the dynamic effect dominates the wetter winter (Fig. 7a), the thermodynamic effect dominates the drier fall (Fig. 7c), and both the dynamic and thermodynamic components contribute to the drier spring (Fig. 7b). For the extended wet season, fall has the most robust drier contribution from the total mean moisture convergence via the thermodynamic effect

FIG. 4. Climatology of monthly mean precipitation changes from the contributions of (a),(b) the mean moisture convergence (black) calculated as $\Delta[-(1/g\rho_w)\nabla \cdot \int_0^{p_s} \bar{\mathbf{u}} \bar{q} dp]$, evaporation (purple), and transient eddy moisture convergence (orange) obtained as a residual based on Eq. (1), (c),(d) the dynamic effect $[-(1/g\rho_w)\nabla \cdot \int_0^{p_s} \Delta \bar{\mathbf{u}} \bar{q} dp]$, and (e),(f) the thermodynamic effect $[-(1/g\rho_w)\nabla \cdot \int_0^{p_s} \bar{\mathbf{u}} \Delta \bar{q} dp]$ averaged over (left) California and (right) Washington–Oregon based on Eq. (2). The shading indicates one standard deviation of 37 CMIP5 models. Units: mm day^{-1} .

among the 37 CMIP5 models (Fig. 7c). For the overall interseasonal structure of the sharpened wet season, both dynamic and thermodynamic components have positive contributions (Fig. 7d). In comparison, the thermodynamic component appears to be more robust than the dynamic component among the CMIP5 models via the effect of moisture advection. In view of the dominance of the thermodynamic component and the robustness of the term $[-(1/g\rho_w)\int_0^{p_s} \bar{\mathbf{u}} \cdot \nabla(\Delta \bar{q}) dp]$ in the sharpened wet season, we are prompted to investigate the physical process behind the change of the moisture gradient.

Based on the above analyses, we infer that advection is more important for California, while the divergence term contributes more to Washington–Oregon for the seasonal cycle changes. To further address the causes of the difference between California and Washington–Oregon, the climatological atmospheric circulation is evaluated (Fig. 8). Washington–Oregon lies in a region with strong wind convergence in the lower troposphere (850 hPa) and wind divergence in the upper troposphere (200 hPa) during the entire wet season (October–April). Thus, the mass convergence due to the increased

FIG. 5. The contributions of advection (red), the divergence term (blue), and the boundary term (green) to the (a),(b) changes in total mean moisture convergence (black) based on Eq. (3), (c),(d) dynamic effect (black) based on Eq. (4), and (e),(f) thermodynamic effect (black) based on Eq. (5) to the climatological changes in monthly mean precipitation between the RCP8.5 and Hist experiments over (left) California and (right) Washington–Oregon from the MME of 37 CMIP5 models. Units: mm day^{-1} .

moisture dominates the future changes in precipitation there, inducing a wet-get-wetter change. In contrast, California lies in the transition region between subtropics-type and midlatitude-type hydroclimates with a lower troposphere (850 hPa) wind convergence to the north and wind divergence to the south. As a result, the divergence term for California on average is not as strong as that over Washington–Oregon and plays a secondary role. Overall, since California straddles both the subtropics and midlatitudes, its precipitation has more complicated seasonality changes and mechanisms than that over Washington–Oregon.

c. Mechanism underlying the seasonality changes in land–sea moisture contrast

The thermodynamic effect via mean moisture advection can be partitioned into zonal $[-(1/g\rho_w)\int_0^{p_s}\bar{u} \cdot (\partial\Delta q/\partial x) dp]$ and meridional $[-(1/g\rho_w)\int_0^{p_s}\bar{v} \cdot (\partial\Delta q/\partial y) dp]$ components. An overwhelmingly large fraction ($\sim 82\%$) of the thermodynamic-based moisture advection effect that is responsible for the sharpened wet season over California comes from the zonal component (not shown). Therefore, we focus below only on the zonal moisture advection as a product of the mean zonal wind ($\bar{u}$) and the zonal

FIG. 6. The changes in (a)–(c) zonal wind at 200 hPa (shaded; in m s^{-1}) and (d)–(f) sea level pressure (shaded; in hPa) between the RCP8.5 and Hist experiments based on the MME of 37 CMIP5 models for (a),(d) fall (ON), (b),(e) winter (DJF), and (c),(f) spring (MA). The contours in (a)–(c) are the climatological 30 m s^{-1} zonal wind in the Hist (solid) and RCP8.5 (dashed) experiments. Stippling indicates that at least 70% of the models agree on the sign of changes.

gradient of moisture changes ($\partial\Delta q/\partial x$). In winter, moisture increases more over ocean than over land, inducing a weak wet moisture advection to California driven by the climatological westerly wind (Fig. 9a, black line in

Fig. 10e). In spring and fall, moisture increases more over land than ocean, so the advection of drier air by the climatological westerly favors drying in California. The land–sea moisture contrast is much stronger in fall than

FIG. 7. The changes in mean precipitation (orange), total mean moisture convergence (gray), dynamic effect (gray), and thermodynamic effect (gray), as well as the contributions of advection (red), the divergence term (blue), and the boundary term (green) between the RCP8.5 and Hist experiments over California (32°–42°N, 115°–124°W) based on the MME of 37 CMIP5 models during (a) winter (DJF), (b) spring (MA), (c) fall (ON), and (d) the sharpened wet season [DJF – (MA + ON)/2]. Error bars denote one standard deviation of 37 CMIP5 models. The calculation is the same as in Fig. 5. Units: mm day^{-1} .

spring (Figs. 9b,c, black lines in Figs. 10d,f). The winter minus the average of spring and fall difference gives distinct wet advection anomalies in the lower atmosphere over California (Fig. 9d), driven both by the intensified climatological westerly wind in winter and the larger increase in moisture over land than ocean in spring and fall.

To gain further insights into the physical causes of the seasonally dependent changes in zonal moisture gradient, we examine the effect of land–sea thermal contrast in different seasons following Ting et al. (2018). Based on the CC relation, we calculate the changes in specific humidity due only to the temperature warming at fixed relative humidity (Fig. S4). The results show more moisture increase over land than ocean due to the changes in land–sea thermal contrast with larger warming over land than ocean. The distribution and magnitudes for the sharpened wet season are similar to those of the total changes in specific humidity under warming (Fig. 9d; see also Fig. S4d). Therefore, the changes in moisture gradient are largely captured by the changes in specific humidity due to temperature changes, consistent with Chadwick et al. (2016). There is small but nonnegligible difference between the specific humidity changes due to temperature changes only and the total specific humidity changes. The difference, more noticeable in winter, is indicative of the possible effect of

relative humidity change, which increases slightly over oceans but decreases substantially over land (Byrne and O’Gorman 2016, 2018). Although the changes in relative humidity can be important for the moisture changes over land (Byrne and O’Gorman 2015), they play a secondary role in the sharpened wet season so their effects are ignored in our analysis below.

During the wet season (October–April), the climatological surface temperature over ocean is warmer than that over land in California ($T_{\text{land}} < T_{\text{ocean}}$, shaded in Figs. 10a–c), with the strongest thermal contrast occurring in winter (red line in Fig. 10e). In the future, there is more surface warming over land than ocean ($\Delta T_{\text{land}} > \Delta T_{\text{ocean}}$, contours in Figs. 10a–c and blue line in Figs. 10d–f), which is related to the fundamental difference between land and ocean, such as heat capacity, that determines their energy budgets and response to warming (e.g., Manabe et al. 1991; Sutton et al. 2007). As the CC relation is nonlinear, both the climatological land–sea thermal contrast and the change in land–sea thermal contrast under warming can influence the zonal gradient of the specific humidity changes (Fig. 11). Specifically, a uniform warming over ocean and land ($\Delta T_{\text{land}} = \Delta T_{\text{ocean}}$) on top of the negative zonal gradient of climatological temperature ($T_{\text{land}} < T_{\text{ocean}}$) would lead to a negative zonal gradient of specific humidity

FIG. 8. Climatological divergence ($\times 10^{-5} \text{ s}^{-1}$) patterns of 850- and 200-hPa horizontal wind vectors for (a),(d) fall (ON), (b),(e) winter (DJF), and (c),(f) spring (MA) based on the MME of 37 CMIP5 models. Positive (negative) values denote divergence (convergence). Stippling indicates that at least 70% of the models agree on the sign.

FIG. 9. Longitude–pressure cross section of the changes in zonally asymmetric (zonal mean is removed) specific humidity (shaded; in g kg^{-1}) between the RCP8.5 and Hist experiments and climatological zonal wind (contour; in m s^{-1}) averaged over the latitudes of 32° – 42°N for (a) winter (DJF), (b) spring (MA), (c) fall (ON), and (d) the sharpened wet season $[\text{DJF} - (\text{MA} + \text{ON})/2]$ based on the MME of 37 CMIP5 models. The gray lines indicate the longitudinal boundary of California.

change (i.e., warmer mean temperature would give more moisture increase). However, more warming over land than ocean ($\Delta T_{\text{land}} > \Delta T_{\text{ocean}}$) gives rise to an opposite zonal gradient of specific humidity change to the mean one. Thus, there is a tug of war between the climatological and the changes of land–sea thermal contrast in changing the zonal gradient of specific humidity. As a result of the nonlinear CC relation (Fig. 11), the strong climatological land–sea thermal contrast ($T_{\text{land}} < T_{\text{ocean}}$) dominates the changes in land–sea moisture contrast ($\Delta q_{\text{land}} < \Delta q_{\text{ocean}}$) in winter (Figs. 9a, 10e),

inducing a wetter winter in California via positive moisture advection from the ocean. In contrast, the change in land–sea thermal contrast under warming ($\Delta T_{\text{land}} > \Delta T_{\text{ocean}}$) overwhelms the weaker climatological land–sea thermal contrast ($T_{\text{land}} < T_{\text{ocean}}$) in fall and spring. This induces a larger increase in moisture over land than ocean ($\Delta q_{\text{land}} > \Delta q_{\text{ocean}}$) (Figs. 9b,c, and 10d,f), leading to a drying via negative moisture advection. The larger changes in land–sea thermal contrast under warming (blue line in Fig. 10d) favor stronger changes in land–sea moisture contrast and the related

FIG. 10. (a)–(c) The changes in surface temperature (contour; in $^{\circ}\text{C}$) between the RCP8.5 and Hist experiments and the climatological surface temperature (shaded; in $^{\circ}\text{C}$) for the Hist simulations based on the MME of 37 CMIP5 models for (a) fall (ON), (b) winter (DJF), and (c) spring (MA). (d)–(f) As in (a)–(c), but for the zonal gradient of surface temperature changes (blue; in $\times 10^{-5} \text{ } ^{\circ}\text{C m}^{-1}$), the climatological surface temperature (red; in $\times 10^{-5} \text{ } ^{\circ}\text{C m}^{-1}$), and specific humidity change in lower troposphere (black; in $\times 10^{-8} \text{ m}^{-1}$) averaged over the latitudes of 32°–42°N. Shading indicates one standard deviation of 37 CMIP5 models. The gray lines indicate the longitudinal boundary of California.

FIG. 11. Schematics for the changes in land–sea specific humidity contrast over California based on the Clausius–Clapeyron relation. During the wet season (October–April), the climatological surface temperature over ocean is warmer than that over land ($T_{\text{land}} < T_{\text{ocean}}$). Under a warming climate, there is more surface warming over land than ocean ($\Delta T_{\text{land}} > \Delta T_{\text{ocean}}$). Changes in the land–sea specific humidity contrast (Δq_{land} vs Δq_{ocean}) depend on both the climatological and the warming induced changes in land–sea thermal contrast. This leads to different changes in zonal moisture advection over California in different seasons.

negative moisture advection in fall (Figs. 9c, 10d). These results agree with previous studies (e.g., Byrne and O’Gorman 2015; Ting et al. 2018; Chen et al. 2019) that emphasized the zonal moisture gradient as an important factor in regional precipitation changes under future warming and that the wet-get-wetter scaling does not hold accurately over land. However, Ting et al. (2018) attributed the spring drying to the effect of climatological land–sea thermal contrast with warmer land than ocean, as they focused on the SWUS with larger inland areas including areas east of 110°W, where the zonal gradient is opposite to that over California (red and black lines in Fig. 10f).

4. Discussion

California has a Mediterranean-type climate with wet winter and dry summer. The sharpened seasonal cycle with a more pronounced contrast between winter and summer projected in a warming climate will further challenge the management of the disparate water resources. Examining the future seasonality changes projected around the globe, we found no evidence of a sharpened wet season in other Mediterranean-type

climate regions. Instead drier winters are commonly projected for those regions in the future (Fig. S5) (Goubanova and Li 2007). Thus, California appears rather unique in terms of its changes in precipitation seasonality compared to Washington–Oregon or even other continents. The eastward extension of the strong Pacific jet stream is arguably the root cause for the increase in winter precipitation in California (Neelin et al. 2013). Moreover, the ocean upwelling regime along the California coast (Huyer 1983) may contribute to the unique sharpened wet season in California by modulating the land–sea thermal contrast and how it changes in different seasons.

Although our results are consistent with Seager et al. (2014), who found that the climatological $P - E$ is primarily sustained by mean moisture convergence, the dominance of the mean moisture convergence in the precipitation change of California where winter precipitation mainly comes from storms deserves some discussion. Newman et al. (2012) looked at the mean global atmospheric moisture transport in a global reanalysis and found an important role of low-frequency (>10 days) and synoptic anomalies in moisture transport from ocean to land in the extratropics. Notably, low-frequency anomalies contribute much more to $P - E$ in the U.S. West Coast than synoptic anomalies (see their Fig. 1), suggesting a small role of synoptic eddies in precipitation, consistent with Seager et al. (2014) and our results. However, storm tracks steered by the jet stream and landfalling atmospheric rivers are known to play a key role in the winter extreme precipitation over California (e.g., Ralph et al. 2006; Leung and Qian 2009; Neiman et al. 2011; Neelin et al. 2013; Zheng et al. 2018). By separating the total changes into extreme and non-extreme precipitation, we found that the drier spring/fall is mainly due to the decrease in nonextreme precipitation (not shown), suggesting perhaps a smaller role for the transient eddy during spring/fall. More research is needed to reconcile the role of transient eddy moisture convergence in reanalysis and model simulations. Higher-resolution reanalyses and model simulations may be particularly useful as eddy activities are better resolved at higher resolution.

Last, the use of the residual term in Eqs. (3)–(5) to estimate the boundary term may also lead to biases (Fig. S2). Because of the complex topography along the U.S. West Coast, the boundary term can potentially be an important factor in precipitation changes but CMIP5 models do not resolve the complex terrain to fully capture the boundary effect. High-resolution models are desirable to further elucidate the contribution of the boundary term to precipitation changes in a warming climate.

5. Conclusions

In this study, future changes in the seasonal cycle of mean precipitation during the wet season are investigated based on the Hist and RCP8.5 experiments from 37 CMIP5 models. With a moisture budget framework, we explore the mechanisms for the changes in precipitation seasonality along the U.S. West Coast, with a focus on quantifying the roles of moisture (thermodynamic) and circulation (dynamic) effects via moisture advection and the divergence term. The impact of land–sea thermal contrast on the zonally asymmetric changes in moisture is quantified. Our main findings are summarized as follows:

- 1) During the wet half year (October–April), the change of precipitation is characterized by a sharpened wet season over California in future warming, and a wet-get-wetter pattern over Washington–Oregon. Both changes are dominated by the changes in mean moisture convergence via thermodynamic (moisture) effect.
- 2) The thermodynamic effect due to the mass convergence of increased moisture by mean overturning wind dominates the wet-get-wetter feature over Washington–Oregon where the climatological circulation features a strong convergence in the lower troposphere.
- 3) Both dynamic and thermodynamic effects contribute to the sharpened wet season over California. The thermodynamic effect due to moisture advection mainly accounts for the sharpened wet season, and the dynamic effect from eastward extension of the jet stream and deepening of the Aleutian low also contributes to the wetter winter. Uncertainty associated with the dynamic component is much larger than that associated with the thermodynamic one among CMIP5 models (Fig. 7d).
- 4) Further partitioning moisture advection into the meridional and zonal components, zonal moisture advection via the thermodynamic effect is mainly responsible for the overall interseasonal structure of the sharpened wet season over California. Through the constraint of the nonlinear CC relation, the strong climatological land–sea thermal contrast ($T_{\text{land}} < T_{\text{ocean}}$) dominates the changes in land–sea contrast of specific humidity ($\Delta q_{\text{land}} < \Delta q_{\text{ocean}}$), inducing zonal advection of moister air from ocean to California that contributes to the wetter winter. In fall and spring, the changes of land–sea thermal contrast under warming ($\Delta T_{\text{land}} > \Delta T_{\text{ocean}}$) overwhelm the weaker effect of climatological land–sea thermal contrast, inducing larger increase in specific humidity over land than ocean ($\Delta q_{\text{land}} > \Delta q_{\text{ocean}}$) and

hence zonal advection of drier air from ocean to California.

Acknowledgments. This research is supported by the U.S. Department of Energy Office of Science Biological and Environmental Research as part of the Regional and Global Modeling and Analysis and Multi-Sector Dynamics programs. We appreciate the valuable comments from Dr. Richard Seager and two other anonymous reviewers that helped improve the quality of this work. PNNL is operated for the Department of Energy by Battelle Memorial Institute under Contract DE-AC05-76RL01830. We acknowledge the World Climate Research Program's Working Group on Coupled Modeling, which is responsible for CMIP, and thank the climate modeling groups for producing and making available their model output at http://www.ipcc-data.org/sim/gcm_monthly/AR5/Reference-Archive.html. For CMIP, the U.S. DOE's Program for Climate Model Diagnosis and Intercomparison provides coordinating support and led development of software infrastructure in partnership with the Global Organization for Earth System Science Portals. The authors declare no competing financial interests.

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