The Role of Circulation and Its Changes in Present and Future Atmospheric Rivers over Western North America

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ABSTRACT

Performance in simulating atmospheric rivers (ARs) over western North America based on AR frequency and landfall latitude is evaluated for 10 models from phase 5 of the Coupled Model Intercomparison Project among which the CanESM2 model performs well. ARs are classified into southern, northern, and middle types using self-organizing maps in the ERA-Interim reanalysis and CanESM2. The southern type is associated with the development and eastward movement of anomalous lower pressure over the subtropical eastern Pacific, while the northern type is linked with the eastward movement of anomalous cyclonic circulation stimulated by warm sea surface temperatures over the subtropical western Pacific. The middle type is connected with the negative phase of North Pacific Oscillation–west Pacific teleconnection pattern. CanESM2 is further used to investigate projected AR changes at the end of the twenty-first century under the representative concentration pathway 8.5 scenario. AR definitions usually reference fixed integrated water vapor or integrated water vapor transport thresholds. AR changes under such definitions reflect both thermodynamic and dynamic influences. We therefore also use a modified AR definition that isolates change from dynamic influences only. The total AR frequency doubles compared to the historical period, with the middle AR type contributing the largest increases along the coasts of Vancouver Island and California. Atmospheric circulation (dynamic) changes decrease northern AR type frequency while increasing middle AR type frequency, indicating that future changes of circulation patterns modify the direct effect of warming on AR frequency, which would increase ARs (relative to fixed thresholds) almost everywhere along the North American coastline.

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1. Introduction

Atmospheric rivers (ARs) are long, narrow plume structures with strong water vapor transport that cover 10% or less of the globe but account for most of the poleward water vapor transport across the midlatitudes (Newell et al. 1992; Zhu and Newell 1998). A typical AR is associated with an extratropical cyclone and is located in the warm sector of the pre-cold-front region (Ralph et al. 2004). The detailed characteristics of ARs can be found in the mini-review by Gimeno et al. (2014). ARs may induce significant natural disasters and socioeconomic damage due to their links with extreme precipitation (Leung and Qian 2009; Rivera et al. 2014; Jeon et al. 2015; Mahoney et al. 2016; Gershunov et al. 2019), floods (Neiman et al. 2008; Konrad and Dettinger 2017), and strong winds (Waliser and Guan 2017). ARs also affect the water vapor budget in the polar regions (Nash et al. 2018). Previous studies (e.g., Guan and Waliser 2015) investigated the global spatial distribution of AR frequency and showed that the west coast of North America is one of the areas where ARs make landfall most frequently, especially in winter (Mundhenk et al. 2016a). Indeed, most of the winter precipitation over coastal western North America is contributed by ARs (Gershunov et al. 2017).

ARs making landfall over western North America on different time scales in the current climate have recently been studied extensively, with many studies considering dynamical influences on ARs. Mundhenk et al. (2016b) revealed that the positive height anomaly over the northeast Pacific increased AR activity over the Gulf of Alaska while decreasing it over the U.S. West Coast. On the decadal time scale, Liu et al. (2016) demonstrated that the combination of the Pacific decadal oscillation and the North Pacific Gyre Oscillation modulated the AR frequency over the western coastal regions of North America. On the interannual time scale, Kim et al. (2019) explored the influence of El Niño–Southern Oscillation (ENSO) diversity on AR frequency and found higher AR frequency over western North America and the southwestern United States during central Pacific El Niño and the eastern Pacific El Niño events, respectively, and that fewer ARs reached the United States during La Niña events. Zhang and Villarini (2018) classified ARs into three clusters according to their tracks and discussed their linkage to climate modes such as ENSO, the Pacific–North America teleconnection pattern, the Pacific–Japan teleconnections, and the East Asian subtropical jet stream. Guirguis et al. (2018) indicated that the interaction between different pressure anomaly modes explained the interannual variability of land-falling ARs. Guirguis et al. (2019) classified ARs

landfalling in Northern California into two distinct types and discussed the role ENSO plays in modulating the synoptic evolution and orientation of ARs. On the synoptic time scale, Luo and Tung (2015) found that oceanic convection affects ARs by modifying moisture transport and heat balance. Jiang and Deng (2011) showed that East Asian cold surges modulate ARs mainly through slow moving baroclinic disturbances that are evident at 500-hPa geopotential height anomalies on time scales > 12 days. From a fundamental physical perspective, Hu et al. (2017) found that approximately two-thirds of landfalling ARs are associated with Rossby wave breaking, with anticyclonic and cyclonic wave breaking corresponding to ARs oriented in westerly and southwesterly directions, respectively. Payne and Magnusdottir (2016) showed that ARs that persist for more than 63 h over the coastline were more likely to be accompanied by larger moisture content and inland shift of the location of Rossby wave breaking compared to all ARs.

Fewer studies have concentrated on the influence of dynamical changes on ARs in the future climate. In the context of global warming, thermodynamic processes will undoubtedly increase AR frequency and intensity. The global-mean atmospheric water vapor content is expected to increase at the Clausius–Clapeyron rate of approximately $7\%^{\circ}\text{C}^{-1}$ with increasing global-mean temperature (Held and Soden 2006), which would be conducive to increased AR frequency. On the other hand, ARs will also be affected by changes in atmospheric circulation patterns such as the widening of the tropics (Lu et al. 2007; Son et al. 2018) and the poleward shift of jet streams (Barnes and Polvani 2013) and storm tracks (Seiler and Zwiers 2016a). Previous studies focused on the changes in ARs in a warming climate show that the projected changes vary with different definitions of ARs (Gao et al. 2015; Payne and Magnusdottir 2015; Warner et al. 2015; Hagos et al. 2016; Shields and Kiehl 2016; Warner and Mass 2017). Some studies discuss the roles of thermodynamic and dynamic processes in projected AR change (Gao et al. 2015; Payne and Magnusdottir 2015; Hagos et al. 2016; Shields and Kiehl 2016) with most finding that the thermodynamic contribution is dominant. However, disagreements exist regarding the dynamic contribution. Gao et al. (2015) concluded that available model simulations did not provide evidence of a significant dynamical effect on ARs in the winter season owing to uncertainties among phase 5 of the Coupled Model Intercomparison Project (CMIP5) models in projecting winter circulation patterns. Previous studies (Payne and Magnusdottir 2015; Shields and Kiehl 2016) demonstrated that the dynamic response is more dominant

in the equatorward portion of moisture flux peak distribution in the extended winter.

Given the uncertainties of the dynamical influence on ARs in the future climate, this study investigates the dynamical contribution to the changes in ARs in a warming climate considering that it plays an important role in altering the latitudinal distribution of AR events (Payne and Magnusdottir 2015). We will consider spatial distributional changes in ARs due to total and dynamic influences by considering changes in AR type frequency in a warming climate in combination with AR definitions that use fixed and temperature-dependent thresholds, respectively. We also answer several further questions. How many types of ARs can be classified and what are the characteristics of atmospheric circulation patterns that are associated with each type in the current climate? How does each type of AR respond to the warming climate? How do dynamical changes contribute to these changes?

The remainder of this paper is organized as follows. Section 2 introduces the data from reanalysis and CMIP5 climate model simulations that were used as well as the AR definition and methods used in this study. In section 3, CMIP5 model performance in simulating ARs in a recent historical period is evaluated, and CanESM2 is chosen for further analysis based on its performance. In section 4, three types of ARs and the associated circulation patterns in both observations and CanESM2 are described. Section 5 discusses the changes in each AR type in the future climate and the influence of dynamical changes. A summary and discussion complete the paper in section 6.

2. Data and methods

a. Data

We analyze the ARs that occur between 1 December and 28 February each year. Even though the peak of AR activity in Canada and Alaska areas often occurs in the fall, our choice to study AR activity in DJF was deliberate. First, circulation patterns are different in DJF and SON since the latter reflects the transition from JJA to DJF. Second, the probability of flooding when ARs occur is higher in DJF than that in SON (Konrad and Dettinger 2017), suggesting that DJF ARs are of greater concern from an impacts perspective. Previous studies (Guan and Waliser 2017; Ralph et al. 2019) indicate that AR events selected from different reanalyses have substantial agreement, especially for ERA-Interim (ERA-I) and MERRA-2. Therefore, we use daily data from the ERA-I reanalysis (Dee et al. 2011) at $1^\circ \times 1^\circ$ horizontal resolution over the period 1980–2004. Variables include 2-m air temperature (T_2m), specific humidity (q), geopotential height (z), and zonal

(u) and meridional (v) winds at the levels in accordance with those in models. We also use daily data from 10 CMIP5 climate models from different model groups listed in Table 1 for the same period (1980–2004) forced by historical forcings and for the projected future period (2075–99) forced by representative concentration pathway 8.5 (RCP8.5) emissions scenario (van Vuuren et al. 2011; Taylor et al. 2012). We use the first model ensemble member (r1i1p1) from each of the CMIP5 models except for CCSM4, for which r6i1p1 is used since the first ensemble member is not archived in CMIP5. We also use ensemble members r2i1p1 to r5i1p1 from CanESM2.

b. Definition of ARs

We focus on the ARs making landfall over the coastline of western North America (see Fig. 1), using integrated water vapor (IWV) and integrated vapor transport (IVT) to define ARs. The IWV over a grid point is calculated by vertically integrating the specific humidity from 1000 to 500 hPa, including the levels at 1000, 850, 700, and 500 hPa:

$$IWV = \frac{1}{\rho g} \int_{1000}^{500} q dp, \quad (1)$$

where g is the gravitational acceleration and ρ is the density of water. The IVT over a grid point is calculated similarly by vertically integrating the product of specific humidity and wind speed:

$$IVT = \frac{1}{g} \sqrt{\left(\int_{1000}^{500} qu dp \right)^2 + \left(\int_{1000}^{500} qv dp \right)^2}. \quad (2)$$

IWV and IVT are in units of meters (m) and kilograms per meter per second ($\text{kg m}^{-1} \text{s}^{-1}$), respectively. To facilitate the analysis of differences between reanalysis and model simulations, we bilinearly interpolate IWV and IVT in CMIP5 models to the $1^\circ \times 1^\circ$ longitude/latitude ERA-I grid.

ARs are identified following a series of steps. In keeping with many other studies, we first select areas with higher water vapor content on a given day by identifying locations that satisfy the following inequalities:

$$IWV_{ij} \geq IWV_{zmean} + A \times (IWV_{zmax} - IWV_{zmean}), \quad \text{and} \quad (3)$$

$$IWV_{ij} \geq IWV_{mmean} + B \times (IWV_{mmax} - IWV_{mmean}), \quad (4)$$

where IWV_{ij} is the IWV value at grid point at latitude i and longitude j , IWV_{zmean} refers to the zonal average

TABLE 1. Details of 10 models used, including their resolutions (number of grid cells in the zonal x and meridional y directions), institutes, and IVT thresholds corresponding to the 96th percentile of 1980–2004 December–February IVT values at 66 grid points along the coastline of western North America marked in Fig. 1. For comparison, the IVT threshold for the ERA-I reanalysis is $250 \text{ kg m}^{-1} \text{ s}^{-1}$.

Model names	Native resolution (longitude $\times$ latitude)	Th_Hist_IVT ($\text{kg m}^{-1} \text{ s}^{-1}$)	Institute
ACCESS1.3	192×144	243	Commonwealth Scientific and Industrial Research Organization (CSIRO) and Bureau of Meteorology (BOM), Australia
BCC_CSM1.1(m)	320×160	350	Beijing Climate Center, China Meteorological Administration
CanESM2	128×64	260	Canadian Centre for Climate Modeling and Analysis
CCSM4	288×192	312	National Center for Atmospheric Research
HadGEM2-CC	192×144	216	Met Office Hadley Centre
GFDL-ESM2M	144×90	255	NOAA Geophysical Fluid Dynamics Laboratory
IPSL-CM5A-LR	96×96	282	Institute Pierre-Simon Laplace
MIROC5	256×128	273	Atmosphere and Ocean Research Institute (The University of Tokyo), National Institute for Environmental Studies, and Japan Agency for Marine-Earth Science and Technology
MPI-ESM-LR	192×96	297	Max Planck Institute for Meteorology
NorESM1-M	144×96	324	Norwegian Climate Centre

of IWV along the entire latitude circle at latitude i , $\text{IWV}_{\text{mmean}}$ indicates the meridional average of IWV along between 0° and 90°N at longitude j , IWV_{zmax} and IWV_{mmax} denote the maximum IWV found along the entire latitude and the longitude between 0° and 90°N , respectively, and A and B are parameters with values 0.3 and 0.1, respectively, which were chosen to best capture the structures of ARs (Zhu and Newell 1998; Jiang and Deng 2011).

Second, in order to ensure that features with poleward water transport are identified, the high water-content areas selected from step one must intersect the coastline of western North America, with the grid points being retained only if the integrated vapor transport comes from the southwest. That is, the potential AR is retained if the correlation between the latitudes and longitudes of the grid points across the area under consideration is positive.

Third, the total area of the potential AR selected from step two has to be larger than 50 contiguous $1^\circ \times 1^\circ$ grid cells (Mundhenk et al. 2016a). Based on the methods for calculating the length, width, and axis of ARs in (Guan and Waliser 2015), sufficiently large ARs with a length-to-width ratio > 1.6 that are longer than 1600 km are retained.

Last, in potential ARs in observations, IVT at the landfall location and its area average are required to be larger than $250 \text{ kg m}^{-1} \text{ s}^{-1}$. This threshold represents the 96th percentile of IVT along the coastline that is considered. Thus, the corresponding IVT threshold for each model is set as the 96th IVT percentile of that model along the coastline. These thresholds are listed in Table 1. Similarly, IWV at the landfall location and its area average are required to be larger than 20 mm.

Figure 1 illustrates an example of an AR based on our definition that occurred on 22 January 2005. The shading indicates the IVT values and the black line denotes the axis of AR. Ralph et al. (2019) show that the choice of AR definition has a stronger effect on AR frequency than the choice of reanalysis because no single definition can be perfect for every application. The ARs identified with our definition were compared with ARs identified in previous studies (Neiman et al. 2008; Jiang et al. 2014;

FIG. 1. The west coast of North America. The 66 blue circles along the coastline mark the studied AR landfall locations in reanalysis and CMIP5 models. An AR event that occurred on 22 Jan 2005, identified based on the definition in this study, is displayed. Shading indicates integrated vapor transport (IVT) ($\text{kg m}^{-1} \text{ s}^{-1}$), and the black line indicates the axis of the AR event.

Zhang and Villarini 2018). The time series of AR annual frequency in our study (Fig. 2a) exhibits similar inter-annual variability as that in Zhang and Villarini (2018), and the percentage of landfall dates in agreement with Neiman et al. (2008) is 71% in DJF during 1997–2004. Their study finds 63 days with AR conditions intersecting the coastline from 32.5° to 52.5°N. We find 55 days with AR conditions in our study considering the same period and locations. Differences are likely due to the use of different definitions and data sources. Neiman et al. (2008) only considered IWV based on Special Sensor Microwave Imager satellite observations when selecting ARs whereas we use both IVT and IWV derived from ERA-I, following previous studies (e.g., Rutz et al. 2014) that indicate that IVT correlates better with precipitation than IWV. Last, the spatial distribution of AR activity is similar with that of Jiang et al. (2014).

c. Methods

1) IDENTIFYING THE INFLUENCE OF DYNAMICAL CHANGES ON AR STATISTICS

We differentiate the influence of dynamical changes on ARs under the RCP8.5 scenario by using two types of thresholds. In the one case the thresholds for IVT and IWV are fixed at the level used for the historical period, while in the other the thresholds vary with temperature at the Clausius–Clapeyron rate, thus controlling for the expected increases in water vapor content associated with warming. Changes in AR statistics when using a fixed threshold reflect the combined effects of warming and dynamical changes, whereas, after controlling for the effect of warming on water vapor content, changes in AR statistics should only reflect the effects of dynamical changes. The temperature-dependent thresholds are calculated as follows:

$$\text{Th_CC_IWV} = (\text{Th_Hist_IWV}) \times (1 + r\Delta T), \quad (5)$$

$$\text{Th_CC_IVT} = (\text{Th_Hist_IVT}) \times (1 + r\Delta T), \quad (6)$$

$$r = \frac{L_V}{R_V \bar{T}^2}, \quad \text{and} \quad (7)$$

$$\Delta T = T - \bar{T}, \quad (8)$$

in which Th_Hist_IWV and Th_Hist_IVT are fixed thresholds for IWV and IVT in the historical period, Th_CC_IWV and Th_CC_IVT are temperature-dependent thresholds for IWV and IVT in the future period, r and ΔT are the Clausius–Clapeyron scaling factor and temperature change that can be calculated from formulas (7) and (8) according to Chan et al. (2016). Here ΔT indicates the difference in the global-annual-mean near-surface air

FIG. 2. (a) Time series of 1980–2004 (December–February) AR frequency over the coastline of western North America in the ERA-I reanalysis (black line) and in CMIP5 models (color lines). (b) AR frequency bias in each model relative to the ERA-I reanalysis.

temperature between the future and that in climatology from 1980 to 2004 for each model. R_V and L_V are water vapor gas constant and vaporization enthalpy of water vapor, respectively.

2) MODEL EVALUATION

Model performance is evaluated using root-mean-square error (RMSE) and model bias (B) in Eqs. (9) and (10). The strip indicated by 66 grid points in Fig. 1 is widened by including adjacent grid points to produce a domain of 202 grid points in total that are considered along the coast of North America. AR activity probability at each grid point is calculated from the number of times an AR covers that point divided by the total number of winter season days in 25 years. The simulation performance of AR activity probability over the 202 locations in models is analyzed using

$$\text{RMSE} = \left[\frac{\sum_{k=1}^{202} (\text{model}_k - \text{obs}_k)^2}{\sum_{k=1}^{202} (\text{obs}_k)^2} \right]^{1/2}, \quad \text{and} \quad (9)$$

$$B = \frac{\sum_{k=1}^{202} (\text{model}_k - \text{obs}_k)}{\sum_{k=1}^{202} \text{obs}_k}, \quad (10)$$

where model_k and obs_k represent AR activity probability at grid k along the coastline in models and reanalysis, respectively.

3) SELF-ORGANIZING MAPS

Self-organizing map (SOM) analysis is a type of cluster analysis that is widely applied in climate science (Cavazos 1999; Hewitson and Crane 2002; Sheridan and Lee 2011) to obtain spatial patterns (nodes) that are characteristic of each cluster. SOM analysis is distinct from methods such as k -means cluster analysis in how the central points in the clusters (nodes) are organized and allowed to evolve through the iterative clustering process. We utilize SOM analysis to differentiate different types of ARs making landfall over the coastline of western North America and their associated atmospheric circulation patterns.

We apply SOM analysis to IVT fields on days with ARs occurring in the area 15° – 65°N and 180° – 100°W and classify them into K types ($K = 2, 3, \dots, 15$) using a $1 \times K$ grid array. SOM analysis can be performed using either a one-dimensional or two-dimensional grid array, where the choice describes how the distance between nodes is evaluated. Heuristically, a given node can have more close neighbors in a two-dimensional grid than in a one-dimensional grid. For our purposes it was useful to consider a $1 \times K$ grid array rather than, for example, a $2 \times (K/2)$ array because we wanted to objectively determine a suitable number of nodes, and thus sought a sequence of classifications with monotonically increasing complexity as represented by the number of nodes, as will be seen in the following subsection. The nodes are determined through an iterative learning process. At each iteration, an input IVT field is matched with the “winning” node that best matches the input field according to a similarity measure. The winning node and the surrounding nodes are updated to reflect the distribution of IVT field distances from the winning node and between the surrounding nodes. This process is repeated, cycling repeatedly through all of the input IVT fields, until there is no further appreciable change in the nodes. To measure the similarity between the input data and each node, we use Euclidean distance, consistent with many other studies (Cavazos 1999; Hewitson and Crane 2002; Harrington et al. 2016). Two parameters, the learning rate and neighborhood radius, control how quickly nodes can change from one iteration to the next. We set the learning rate to decline linearly from 0.05 to 0.01 over the maximum number of iterations, which is prescribed as 10000, and set the neighborhood radius to initially cover 2/3 of the nodes of the node array. This radius determines how changes in one node affect other nodes. It is gradually reduced to a value such that eventually changes to a given node do not affect other nodes. More details about choosing parameters can be found in Liu et al. (2006).

We found that our results were not sensitive to these parameter settings, or the choice of distance function. The SOM calculations are performed with the R SOM package (Wehrens and Buydens 2007).

We use SOM analysis to find K node patterns representing different AR types in the ERA-I AR day IVT fields. IVT fields on individual AR days in the best performing model are then classified as corresponding to one of the K AR types identified in ERA-I for both the historical and future periods based on their Euclidean distance. The best performing model is chosen based on the following analysis in section 3.

4) DETERMINING THE NUMBER OF NODES K

We use a field significance test (Johnson 2013; Guo et al. 2017) that controls the “false discovery rate” (FDR) to determine how many distinct types of ARs can be classified on the basis of historical period as represented ERA-I. False discovery is an expected consequence of any statistical test since such tests operated by comparing values of a test statistic against values that would be considered, but not impossible, unusual under the null hypothesis. Thus, when repeating a test multiple times, we should expect false rejection of the null hypothesis to occur in proportion to the number of tests performed.

We follow the approach for controlling the FDR that is proposed by (Wilks 2006) and applied by Johnson (2013). The latter study combines SOM analysis with a one-dimensional grid array of sea surface temperatures (SST) with field significance testing with a controlled FDR to determine the number of distinguishable flavors of ENSO. Here, for a given K , the clusters of IVT fields closest to each of the SOM nodes are compared pairwise with a significance test for each of the $C_K^2 = K(K-1)/2$ pairs of SOM patterns. The significance test involves the use of Student's t tests that are conducted independently at each grid point. The resulting field of p values is interpreted using the FDR approach of (Wilks 2006) to ensure that field significance is assessed at the 5% level. These pairwise field significance tests are conducted across nodes for increasing levels of K and the largest value of K for which there are no statistically indistinguishable patterns (i.e., no rejections of the pairwise field significance tests) is considered as a potential indication of the optimal number of AR types. This provides an upper bound for the possible number of distinguishable AR types, which are then further assessed according to whether they are associated with distinct interpretable circulation patterns are distinguishable.

5) EXPLAINED VARIANCE

A useful metric for comparing models with observations is the fraction of the total variance in the IVT field on AR days that can be projected onto the K IVT

patterns obtained from the SOM analysis of the ERA-I reanalysis. Explained IVT variance is calculated separately in the reanalysis and models, respectively. Ideally, models would simulate a similar fraction of the total IVT variance in the space spanned by the K patterns as is seen in observations. Let $\mathbf{P}_1, \mathbf{P}_2, \dots, \mathbf{P}_K$ be K n -dimensional vectors that represent the K IVT patterns where n is the number of grid points in the IVT field. Let $\mathbf{P}_K$ be the $n \times K$ matrix that has $\mathbf{P}_1, \mathbf{P}_2, \dots, \mathbf{P}_K$ in columns 1, 2, $\dots$, K . Also, let $\mathbf{\Sigma}$ be the $n \times n$ covariance matrix calculated from the IVT fields from which the patterns are derived (since 203 AR days are selected in ERA-I, $\mathbf{\Sigma}$ is calculated from 203 IVT fields). The total variance in the IVT field on AR days v_{tot} is therefore the trace of the covariance matrix $\mathbf{\Sigma}$, that is, $\text{tr}(\mathbf{\Sigma})$, which is the sum of the diagonal elements of $\mathbf{\Sigma}$. This can be compared with the total IVT variance that can be represented in the space spanned by K IVT patterns, which is given by Eq. (11). The explained variance is calculated in Eq. (12):

$$v_{p,k} = \text{tr}[\mathbf{\Sigma} \mathbf{P}_k (\mathbf{P}_k^T \mathbf{P}_k)^{-1} \mathbf{P}_k^T], \quad \text{and} \quad (11)$$

$$v_{\text{exp}} = \frac{v_{p,k}}{v_{\text{tot}}}. \quad (12)$$

3. Model performance in simulations of landfalling ARs

a. AR frequency

The total AR frequencies are shown in Fig. 2a, in which the black line indicates yearly frequencies in the ERA-I reanalysis while other lines indicate frequencies in 10 models. The 10 CMIP5 models we consider generally simulate the interannual variability of AR frequency well. Figure 2b shows the bias in AR frequency for each model relative to the reanalysis. The average total AR frequency along the coastline is approximately 8.1 days yr^{-1} in reanalysis. Among the 10 models, BCC_CSM1.1(m) and CCSM4 overestimate the total frequency while the other 8 models underestimate frequency, which is consistent with the tendency of most of models to underestimate extratropical cyclone frequency and intensity in the current climate (Seiler and Zwiers 2016b). The lower overall frequency than reported in some other studies (Guan and Waliser 2015; Mundhenk et al. 2016a; Gershunov et al. 2017) may be explained by the more stringent definition used in our study that considers the higher IWV and IVT values as well as by differences in data sources, seasons and the periods considered. The magnitude and sign of the AR frequency bias in models appears to be related to bias in the model's IVT climatology, as shown in Fig. S1 in the

online supplemental material, although there is considerable spread among models. Note, for example, that the IVT thresholds for BCC_CSM1.1(m) and CCSM4 rank first and third among the 10 models (Table 1), indicating that they overestimate climatological IVT; these models also overestimate AR frequency despite the use of relative thresholds. In contrast, HadGEM2-CC has the lowest IVT threshold and also exhibits strong negative bias in AR frequency. Among all models, CanESM2 has the AR frequency that is closest to that in reanalysis.

b. Spatial distribution of AR activity probability

Figure 3 depicts the climatology of AR activity probability at each location along the coastline of western North America for DJF based on 1980–2004. Figure 3a shows that the observed peak AR climatological frequency is about 5%–8% of days in DJF, which occurs over the coastal region between 40° and 45°N . As noted above, this is lower than frequencies reported in other studies, for reasons that were noted. Nevertheless, the spatial distribution is basically in agreement with previous studies (e.g., Jiang et al. 2014; Rutz et al. 2014; Gershunov et al. 2017). Note also that no ARs are detected in the Gulf of Alaska with our definition. Potential reasons include the use of more stringent thresholds involving both IVT and IWV, and the fact that the Gulf of Alaska exhibits strong AR seasonality with ARs occurring more frequently during summer and autumn than during winter (Mundhenk et al. 2016a), along with Canada and the northwest United States (Gershunov et al. 2017).

The AR activity probability climatologies in the 10 models are exhibited in Figs. 3b–k. Most models reproduce the basic structure of the spatial distribution of AR frequency seen in reanalysis. This is particularly the case for ACCESS1.3, CanESM2, CCSM4, MIROC5, and IPSL-CM5A-LR, which are mostly in line with the high-performance models in simulating ARs identified in previous studies (Payne and Magnusdottir 2015). The ratio of AR activity probability in the 10 models to that in reanalysis is shown in Fig. 4. Almost all models overestimate AR activity over Southern California and the Baja California peninsula except for ACCESS1.3, and underestimate it over Vancouver Island, which is possibly due to model bias in simulating IVT and IWV (Figs. S3 and S4).

c. Root-mean-square error and model bias

The spatial RMSE and model biases in AR activity probability calculated over the 202 gridpoint coastal strip [see Eqs. (8) and (9)] are listed in Table 2 in order of the absolute value of climatological frequency bias. The NorESM1-M, MIROC5, GFDL-ESM2M, ACCESS1.3, and HadGEM2-CC have negatively biased climatological AR activity probability while the other five models show positive biases, indicating that the five models produce ARs

FIG. 3. Climatology of 1980–2004 winter (December–February) AR activity probability over the coastline of western North America in the (a) ERA-I reanalysis and (b)–(k) CMIP5 models.

having a larger area of impact than that in ERA-I even though some underestimate the total AR frequency in Fig. 2b. HadGEM2-CC and BCC_CSM1.1(m) have the largest negative and positive biases, respectively. NorESM1-M has the lowest bias among the 10 models and the second lowest RMSE; as can be seen from Fig. 4, NorESM1-M generally overestimates the AR activity probabilities in the lower and higher latitudes while underestimating those in the midlatitudes. Compared to the other nine models, CanESM2 has the lowest RMSE and low model bias. CanESM2 performs better than other models when simultaneously considering IVT and AR frequency biases relative to the ERA-I reanalysis (Fig. S1), consistent with previous studies that have also evaluated the performance of this model positively relative to others (Payne and Magnusdottir 2015; Gershunov et al. 2019). Therefore, we use 5 runs from CanESM2 for our further analysis of projected changes. Results for the historical period from the ensemble of five CanESM2 simulations for AR frequency and AR activity probability can be found in Fig. S2, where it can be seen that the latter exhibits a similar pattern to that in Fig. 4c.

4. AR types and their associated circulation patterns in reanalysis and CanESM2

a. AR types

SOM analysis is used to classify AR day IVT fields into three types. We limited the analysis to three types

for two reasons. First, results from the field significance tests show that three patterns are statistically distinguishable. Second, the circulation patterns associated with the three patterns are also clearly distinct.

The left panel in Fig. 5 shows the composite IVT pattern for each of the three AR types identified in reanalysis, indicating that the three types of ARs have different water sources and make landfall in different parts of the coast. The number on the top of each panel is AR frequency of the corresponding type. We refer to the three AR types shown in Figs. 5a–c as the southern, northern, and middle types, respectively. Southern ARs make landfall over the southern coast and mainly influence Southern California, Baja California, and also the inland Southwest (Rutz and Steenburgh 2012; Rutz et al. 2014; Gershunov et al. 2017). The northern type is characterized by the highest frequency, with water vapor originating from northeast of Hawaii and tending to affect southwest Canada and Washington State. Finally, middle type ARs mostly affect British Columbia, Washington State, Oregon, and Northern California, with the center of maximum water transport occurring north of Hawaii. Even though the northern and middle type ARs make landfall at similar latitudes, ARs from the two types have different shapes (not shown), water sources, and associated circulation patterns that are discussed in the rest of this paper.

ARs were also classified into three types in CanESM2 using three patterns trained from the reanalysis. The

Ratio of AR activity probability 1980–2004 (DJF)

FIG. 4. Ratio of climatological 1980–2004 winter (December–February) AR activity probability over the coastline of western North America in CMIP5 models to that in the ERA-I reanalysis. Red points indicate positive bias and blue points indicate negative bias relative to ERA-I.

CanESM2 composite mean IVT fields for each AR type are exhibited in the right-hand panels of Fig. 5. It can be seen that the frequencies of the southern and middle types are underestimated in CanESM2 while that of the northern type is overestimated, which is basically consistent with the result in Fig. S2b. The total variance explained by the three patterns is approximately 37% in reanalysis (34% in CanESM2), indicating that three features represent comparable, substantial proportions

of variability of the IVT field across the entire North Pacific domain in both the reanalysis and the model.

b. Possible mechanisms associated with different types of ARs

Given the distinct nature of each AR type, we conducted a composite analysis to identify the circulation patterns associated with each type and investigated the processes corresponding to each pattern.

TABLE 2. Biases and root-mean-square errors (RMSE) of AR activity probability of climate models sorted according to increasing absolute value of bias and RMSE, respectively. The difference of temperature for each model between the future period 2075–99 and historical period 1980–2004 is shown in column 6.

Models	Model bias	Models	RMSE	Models	ΔT (°C)
NorESM1-M	−0.01	CanESM2	0.42	GFDL-ESM2M	2.6
MPI-ESM-LR	0.04	NorESM1-M	0.46	NorESM1-M	3.1
CanESM2	0.07	CCSM4	0.48	BCC_CSM1.1(m)	3.2
CCSM4	0.10	ACCESS1.3	0.49	MIROC5	3.3
MIROC5	−0.11	IPSL-CM5A-LR	0.62	CCSM4	3.4
GFDL-ESM2M	−0.14	MIROC5	0.64	MPI-ESM-LR	3.5
IPSL-CM5A-LR	0.21	MPI-ESM-LR	0.71	ACCESS1.3	3.9
ACCESS1.3	−0.25	GFDL-ESM2M	0.79	IPSL-CM5A-LR	4.4
BCC_CSM1.1(m)	0.52	BCC_CSM1.1(m)	0.91	CanESM2	4.4
HadGEM2-CC	−0.61	HadGEM2-CC	0.93	HadGEM2-CC	4.6

COMP IVT (1980-2004)

FIG. 5. Composite IVT patterns for three AR types identified via SOM analysis in the (left) ERA-I reanalysis and (right) CanESM2 simulations for 1980–2004. (a),(d) Southern types; (b),(e) northern types; and (c),(f) middle types. Shading represents IVT magnitude ($\text{kg m}^{-1} \text{s}^{-1}$) and vectors indicate IVT direction. The number above each panel indicates the frequency of the corresponding AR type in December–February of 1980–2004.

For each AR type, we calculated the circulation difference between days with ARs of that type and all days in DJF, considering the wind field at 250 and 850 hPa, the 500-hPa geopotential, and 2-m air temperature (Fig. 6). As can be seen, for the southern type in Figs. 6a and 6d, anomalous cyclonic circulation is located in the midcoast of North America at 850 hPa while anomalous anticyclonic circulation is seen over the Gulf of Alaska. The anomalous southerly wind on the southeast side of the anomalous cyclonic circulation

transports water vapor to the southern coast, which is conducive to the occurrence of ARs in that area, together with accompanying anomalously warm air temperatures. The northwestern side of this feature shows significant outflow of cold continental air onto the northeastern Pacific. At 250 hPa, a tripolar anomaly pattern is seen in the wind field over the northeastern Pacific, which is consistent with the anomalous geopotential height at 500 hPa, which in turn is indicative of cooling of the lower troposphere due to

COMP ERAI (1980 - 2004)

FIG. 6. (a)–(c) Composite of the wind field anomaly at 250 hPa (vectors; m s^{-1}) and geopotential height anomaly (shading; m) at 500 hPa and (d)–(f) composite of the wind field anomaly (vectors; m s^{-1}) at 850 hPa and 2-m air temperature anomaly (shading; $^{\circ}\text{C}$) in the ERA-I reanalysis of 1980–2004. The three rows correspond to the southern, northern, and middle AR types, respectively. The areas enclosed by red contours in (a)–(c) and (d)–(f) denote the regions where the geopotential height and 2-m air temperature anomalies are significantly different from zero at the 10% significance level, respectively. The thick vectors indicate where the wind speed anomalies are significantly different from zero at the 10% significance levels. The black shading indicates the topography that extends above the corresponding pressure levels.

the continental outflow that accompanies the southern AR.

For the northern type in Figs. 6b–e, At 250 and 850 hPa, contrasting to that in the southern type, the anomalous anticyclonic and cyclonic circulations are located over the midcoast of North America and Gulf of Alaska, respectively, which leads to the anomalous southerly wind blowing from oceans to the northern coasts and an associated warm temperature anomaly over most of North America except for Alaska. The resulting transport of water vapor from lower latitudes is conducive to ARs. In addition, the warm air temperature anomaly along the

pathway of the anomalous southerly wind to the northern coast implies greater atmospheric water vapor content, which is also conducive to the occurrence of ARs over this region. The tropospheric circulation that enhances moisture transport onto the continent also moves cold air into the Gulf of Alaska, decreasing the 500-hPa geopotential surface. The combination of tropospheric heating from latent heat release to the south and cold air advection to the north generates an anomalous dipole circulation aloft near the tropopause.

Figures 6c and 6d show that the middle type seems to be associated with larger circulation patterns than the other

FIG. 7. (a)–(c) Composite wind field anomaly for the southern type ARs at 250 hPa (vectors; m s^{-1}) and geopotential height anomaly at 500 hPa (shading; m) and (d)–(f) composite wind field anomaly at 850 hPa (vectors; m s^{-1}) and 2-m air temperature anomaly (shading; $^{\circ}\text{C}$) in the ERA-I reanalysis of 1980–2004. The three rows correspond to results for 5 days, 3 days, and 1 day prior to the landfalling AR day, respectively. Red contours in (a)–(c) and (d)–(f) depict areas where the geopotential height and 2-m air temperature anomalies are significantly different from zero at the 10% significance level, respectively. The thick vectors mark where wind speed anomalies are significantly different from zero at the 10% significance levels. The black shading indicates topography that extends above the corresponding pressure levels.

two types. Different from the anomalous SST pattern in the northern type, negative SST anomalies are found over the subtropical central Pacific (not shown), consistent with the wind patterns. The SST pattern is similar to that associated with the negative phase of the North Pacific Oscillation–west Pacific teleconnection pattern (NPO/WP) (Linkin and Nigam 2008). At the lower level, there is a broad anomalous cyclonic circulation over the northeast Pacific. The anomalous southerly wind drives water vapor from a longer distance in the central Pacific compared to the northern type. At the upper level, an anomalous tripolar circulation pattern that enhances the westerly wind speed over the equatorward flank of the East Asia

westerly jet stream and decreases that over the poleward flank extends from eastern Russia to Southern California. The intensifying westerly jet stream over the equatorward flank, which can act as a “westerly duct” (Webster and Holton 1982) providing steering winds (Shields and Kiehl 2016), is favorable to the circulation patterns at the lower level. Additionally, the middle type is linked to anomalous negative temperature over most of North America except part of the western United States.

To further understand the mechanisms associated with each AR type, we conduct a composite analysis for atmospheric circulation on days 5, 3, and 1 prior to the day of AR landfall. Figure 7 exhibits the results for

FIG. 8. As in Fig. 7, but for the northern type of AR.

the southern type. An anticyclonic–cyclonic circulation pattern appears over the northeast Pacific 5 days ahead and then amplifies while moving eastward. The anomalous anticyclonic circulation over the southern coast emerges 3 days ahead and strengthens after that, accompanied by strengthening southerly wind over the southern coast that provides favorable water vapor transport conditions. The southern type is therefore associated with the development of a local low pressure system over the subtropical Pacific that may be linked to synoptic disturbances.

The evolution of atmospheric circulation patterns for the northern type is shown in Fig. 8. This type occurs in the presence of anomalously warm SSTs over the East China Sea and the Sea of Japan (not shown) and positive surface temperature anomalies over northeastern Asia are apparent 5 days ahead. An anomalous cyclonic circulation over the Sea of Japan stimulated by the warm SST anomaly is apparent 3 days ahead and moves

eastward as the AR landfalling day approaches, favoring a deepening of the eastern flank of the Aleutian low and the development of anomalous anticyclonic circulation over the midcoast. The southerly wind to the northwestern side of the anticyclonic circulation transports water vapor to the northern coast, which favors the formation of northern type of ARs. The development of explosive extratropical cyclones over the Kuroshio (Roebber 1984) may contribute to deepening of the Aleutian low, which would also tend to enhance moisture transport onto the northern coast.

For the middle type of ARs, there exists an equivalent barotropic meridional dipole structure that is apparent in the wind anomaly fields at both levels and in the midlevel geopotential height anomaly field. This feature strongly resembles the negative phase of the NPO/WP, indicating this AR type may be linked with that teleconnection. The corresponding anomalous SST pattern (not shown), which is similar to the anomalous T2m

FIG. 9. As in Fig. 7, but for the middle type of AR.

distribution in Fig. 9, is consistent with the equivalent-barotropic structure in the wind field. Southwesterly winds are present on the southeastern side of the anomalous cyclonic circulation over the subtropical eastern Pacific at 850 hPa 5 days ahead, which weakens trade winds in the eastern basin and induces less evaporation over this region, resulting in warmer SSTs. On the other hand, westerly wind over the southwest side of the anomalous cyclonic circulation intensifies westerlies and leads to more evaporation, resulting in cold SST anomalies. The development of warm SST anomalies in the eastern subtropical Pacific and cold SST anomalies in western subtropical Pacific increases the meridional SST gradient, which is conducive to the intensification of westerlies on the southern edge of the anomalous cyclonic circulation over the subtropical eastern Pacific at lower level and the subtropical jet stream at 30°N at the upper level. The intensification of the subtropical jet stream may play a role as a “westerly duct” (Webster

and Holton 1982) that provides steering winds (Shields and Kiehl 2016), which in turn are favorable for Rossby wave breaking over the eastern Pacific (Payne and Magnusdottir 2014), resulting in ARs moving toward to the midcoast of North America.

Having investigated the possible mechanisms corresponding to the three AR types in reanalysis, we examined CanESM2 to determine if the model exhibits similar mechanisms in its climate for the historical period. It is clear from Fig. 10 that CanESM2 can well simulate the anomalous circulation patterns associated with the three types that we described using reanalysis. One difference is that the anomalous atmospheric features are generally more statistically significant in CanESM2, which is likely due to the larger sample size compared to reanalysis given that five ensemble members are available. The evolution of circulation patterns for each type from CanESM2 in Figs. S5–S7 also supports the features that we

FIG. 10. As Fig. 6, but based on the five-member CanESM2 ensemble rather than the ERA-I reanalysis.

identified by examining the reanalysis. The differences of anomalous circulation patterns associated with three types of ARs between CanESM2 and ERA-I are shown in Fig. S8.

5. Future changes in ARs and the influence of dynamical changes

How does each type of ARs change in a warming climate and what role do the dynamical changes play in these changes? To answer these questions, we analyze the changes in total AR frequency and AR activity probability at each location influenced by the total changes and the dynamical changes, respectively, based on five-member CanESM2 ensemble under RCP8.5 forcing. As discussed in section 2, we use AR definitions with fixed and temperature-dependent IVT and IWV

thresholds (see Fig. S9) in order to distinguish the impact of dynamical changes from dynamical and thermodynamic changes in the future, respectively. Results are displayed in Table 3. CanESM2 simulates approximately $6.9 \text{ AR days yr}^{-1}$ in the historical period and roughly double that number, $16.0 \text{ days yr}^{-1}$, in the future climate. About 28% of that doubling is attributable to dynamical changes, which on their own would have increased frequency to around 9.5 days yr^{-1} , suggesting that dynamical changes do not play a dominant role in increasing the total frequency. Nevertheless, we could ask whether dynamical changes affect ARs in particular areas.

Figure 11 presents ratios of AR activity probability in the future period to that in the current period, influenced by total and dynamical changes. First, considering the impact of the total changes, AR activity probability

TABLE 3. Frequency of different AR types based on the CanESM2 five-member ensemble during the historical period 1980–2004 and future period 2075–99. For the future period, AR frequency influenced by total changes and dynamical changes is displayed separately. Values in parentheses show the percentage changes of AR frequency relative to the historical period. The middle row uses fixed IVT and IWV thresholds, while the bottom row uses temperature-dependent thresholds in order to isolate changes due to dynamical changes rather than thermodynamic and dynamical changes combined.

Period	Total frequency (days yr ⁻¹ ± 1 standard deviation)	Southern type (days yr ⁻¹)	Northern type (days yr ⁻¹)	Middle type (days yr ⁻¹)
1980–2004	6.9 ± 3.5	1.9	3.7	1.3
Total 2075–99	16.0 ± 5.7	3.8 (100%)	5.1 (38%)	7.1 (446%)
Dynamical only 2075–99	9.5 ± 4.7	2.4 (26%)	2.5 (–32%)	4.6 (254%)

increases along the coastline especially for Vancouver Island and the California area, which is consistent with the results from previous studies that indicate a strikingly large increase of AR occurrence at the end of the twenty-first century (Gao et al. 2015; Payne and Magnusdottir 2015). In contrast, AR frequency decreases over the northern coast and southernmost coastline but increases over the midcoast, especially California, when controlling for the impact of thermodynamic changes, which indicates that the dynamical response is dominant on the southern side of the moisture transport peak, consistent with Payne and Magnusdottir (2015). Figure S10 is the same as Fig. 11 except that differences in AR activity probability are shown. Even though the largest increase of AR activity probability influenced by total changes occurs over Washington State and Oregon, the relative changes in these regions are lower than those in Vancouver Island and California due to the higher probability over Washington State and Oregon in historical climatology.

How does the frequency of the different types of ARs change in the future? The ARs in the future are also classified into three types according to their similarity to the SOM node patterns obtained from ERA-I. This assumes that the three types identified from ERA-I are sufficient to group ARs, irrespective of the level of warming. The assessment of this hypothesis is based not only on statistical results but also on an evaluation of whether the associated circulation patterns are similar to those in the current climate. The composite mean IVT field corresponding to each AR type in the future climate is shown in Figs. 12a–c. Figures 12d–f show the difference of composite mean IVT field associated with each AR type in the future climate relative to that in the historical climate. The total IVT variance explained by the three patterns in the future climate is approximately 37%, close to that in the current climate. Compared to the current climate, ARs in future climate become stronger, which may be attributed to the increasing water vapor due to global warming. Also, the

circulation patterns associated with southern type ARs favor ARs that concentrate more strongly on California in the future period as can be seen in Fig. 12d. The composite circulation patterns associated with the three AR types in the future climate (Fig. S11) are very similar to those in the current climate but with weaker amplitude in 500-hPa geopotential height and surface air temperature, which is due to differences in the reference of climatologies.

To further understand how the dynamical changes affect each of the three AR types in the future climate, we estimate AR frequency changes due to total and dynamical changes (Table 3). Considering the influence of the total changes, the frequency of all three patterns increases especially for the middle type, which increases 446% relative to the historical period, consistent with Nusbaumer and Noone (2018) who showed more long-distance moisture transport for ARs in the future epoch. In contrast, dynamical influences reduce the frequency of northern type while increasing that of middle type, supporting the result in Fig. 11b.

To better understand how AR frequency is influenced by dynamical changes in the future climate, differences in winter circulation patterns between the future and historical periods during wintertime are shown in Fig. 13. At the lower level, the surface air temperature warms most in the polar region, which is consistent with extensive studies (Holland and Bitz 2003; Barnes and Polvani 2015). The Aleutian low deepens and extends to the southeast (not shown), which favors anomalous southerly winds over the midcoast of North America at 850 hPa. At midlevels, 500-hPa geopotential height increases over the entire area we focus on. Geopotential height increases more over the polar region, consistent with changes in the surface air temperature, while it increases least over the northeastern of Pacific. At the upper levels, intensification of the subtropical jet stream at ~30°N is consistent with the distribution of surface air temperature gradient. These circulation pattern changes are similar to the circulation features associated with the

Ratio of AR activity probability (2075-2099)/(1980-2004) CanESM2

FIG. 11. Ratios of AR activity probability influenced by (a) total changes and (b) dynamical changes between future and historical periods based on the five-member CanESM2 simulations with historical and RCP8.5 forcings.

middle AR type, indicating their potential to enhance the formation of such ARs.

6. Summary and discussions

This study has investigated the influence of dynamical changes on the ARs that make landfall over western North America. Model performance in simulating landfalling ARs was evaluated and several high-performing models such as ACCESS1.3, CanESM2, CCSM4, and MIROC5 were identified. Consequently, a five-member ensemble of CanESM2 runs was selected for further analysis.

SOM analysis is used to classify ARs into three types, which we refer to as the southern, northern, and middle types. Southern type ARs make landfall over the southern coast of North America, mainly influencing Southern California and the Baja California peninsula. The northern type is characterized by water vapor originating from northeast of Hawaii and tends to affect the southwestern Canada and Washington State. Middle

type ARs mostly affect British Columbia, Washington State, Oregon, and Northern California, with the center of maximum water transport lying to the north of Hawaii.

A composite analysis was used to understand the possible mechanisms for AR changes. The southern type is associated with the development and eastward movement of an anomalous low pressure system over the subtropical eastern Pacific. The northern type is linked with the eastward movement of anomalous cyclonic circulation stimulated by warm SSTs over the subtropical western Pacific, which may be associated with storm activity in the vicinity of Kuroshio. Middle type ARs appear to be associated with the negative phase of NPO/WP pattern. Also, the westerly jet stream at $\sim 30^\circ\text{N}$ may serve as the westerly duct that modulates ARs moving toward the midcoast of North America by providing steering winds and inducing Rossby wave breaking over the eastern Pacific. A previous study (Zhang and Villarini 2018) has also classified ARs into

COMP IVT CanESM2 (2075-2099)

FIG. 12. (a)–(c) As in Fig. 5, but for the future period 2075–99, based on the five-member CanESM2 simulations with historical and RCP8.5 forcing. (d)–(f) Differences of IVT (shading; %) in three types of ARs in the future period 2075–99 relative to that in the historical period 1980–2004 and differences of IVT direction between the future period and the historical period (vectors; $\text{kg m}^{-1} \text{s}^{-1}$).

three types in reanalysis, but their associated circulation patterns seem to be different from those identified in this study, due possibly to the use of different analysis periods, seasons, time scales, and data sources. We further analyzed the mechanisms for each type in CanESM2, and found them to be very similar to those deduced from the ERA-I reanalysis, both in the historical and future climates.

We further analyzed the impact of dynamical changes on AR frequency late in the twenty-first century under RCP8.5 forcing and compared with the combined (total) effect of thermodynamic and dynamical changes. The frequency of ARs affected by total changes increases along the coastline, especially for the Vancouver Island and California areas. The total frequency is projected to double compare to that in the historical period, mainly due to the increasing frequency of the middle AR type. Dynamical changes decrease AR frequency over the northern coast while increasing that over the midcoast, especially California, consistent with circulation changes that would be expected to reduce the frequency of northern type ARs and increase that of middle type ARs.

We also investigated the future AR changes in other high-performing models such as ACCESS1.3, CCSM4, and MIROC5, results from CCSM4 (not shown) strongly resemble those from CanESM2 while results from the other models (not shown) are substantially different when considering the distribution of AR activity probability, indicating that good performance in simulating ARs in the current climate does not necessarily lead to agreement on future projections. Further study of AR producing mechanisms in different models and their stability under forcing may help to increase confidence in some model results more than others.

A further question is whether model biases might affect AR frequency changes in the future period. The AR frequencies influenced by total changes increase in all models except BCC_CSM1.1(m). However, as shown in Fig. S12, the magnitude of the change in AR frequency influenced by total changes seems unrelated to the AR frequency bias. Figure S13 shows the links between AR frequency biases and the changes in different types. Six models overestimate the frequency of southern type ARs while eight and nine models underestimate that of

FIG. 13. (a),(b) The difference in December–February circulation patterns between future (2075–99) and historical (1980–2004) periods in the five-member CanESM2 simulations. Vectors in (a) and (b) indicate the wind field (m s^{-1}) at 250 and 850 hPa, respectively, while shading denotes 500-hPa geopotential height (m) and 2-m air temperature ($^{\circ}\text{C}$), respectively. The black shading indicates topography that extends above the corresponding pressure levels.

northern type and middle type ARs, respectively, which supports our previous conclusion that most models overestimate ARs at the lower latitudes while underestimating those at the higher latitudes. Considering the impact of the total changes, AR frequencies of three types increase in almost all models except for the southern type in MIROC5 and BCC_CSM1.1(m) and the middle type in BCC_CSM1.1(m). When controlling for the impact of thermodynamic changes, the AR frequencies of the middle type increase in eight models while those of the southern and northern types decrease in eight and six models, respectively. However, we cannot infer from this figure how the biases of those models might affect the future changes in different AR types. Nevertheless, the signs of changes in most models basically coincide with the results from CanESM2.

In this study, we have only focused on the possible circulation mechanisms associated with the three AR

types at the synoptic scale. There remain many broader questions, such as whether the large-scale modes of climate variability modulate the different types of ARs and their associated circulation mechanisms on the interannual and interdecadal time scales, and whether these modulating effects will change in a warming climate. Such questions are largely beyond the scope of current study and thus remain for future study. We did briefly consider the impact of ENSO on the relative frequency of the three AR types at the interannual time scale but did not find a significant relationship. This could be due to the relatively short reanalysis record considered in this study or may just indicate that ENSO affects the moisture transport or other characteristics of all three types of ARs. In a previous study (Kim et al. 2019) found that ENSO modulates moisture transport over western North America. Also, results in Guirguis et al. (2019) have suggested that ARs impacting Northern California are modulated by a combination of climate modes on the interannual and subseasonal time scales. Therefore, the effects of the modes of climate variability on AR activity and properties remain a largely open question that will be the subject of future studies. Also, considering the strong link between ARs and extreme precipitation, it will be useful to understand the relationship between different AR types and extreme precipitation and how that relationship may change in the future.

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REFERENCES

- Barnes, E. A., and L. Polvani, 2013: Response of the midlatitude jets, and of their variability, to increased greenhouse gases in the CMIP5 models. *J. Climate*, **26**, 7117–7135, <https://doi.org/10.1175/JCLI-D-12-00536.1>.
- , and —, 2015: CMIP5 projections of Arctic amplification, of the North American/North Atlantic circulation, and of their relationship. *J. Climate*, **28**, 5254–5271, <https://doi.org/10.1175/JCLI-D-14-00589.1>.

- Cavazos, T., 1999: Large-scale circulation anomalies conducive to extreme precipitation events and derivation of daily rainfall in northeastern Mexico and southeastern Texas. *J. Climate*, **12**, 1506–1523, [https://doi.org/10.1175/1520-0442\(1999\)012<1506:LSCACT>2.0.CO;2](https://doi.org/10.1175/1520-0442(1999)012<1506:LSCACT>2.0.CO;2).
- Chan, S. C., E. J. Kendon, N. M. Roberts, H. J. Fowler, and S. Blenkinsop, 2016: Downturn in scaling of UK extreme rainfall with temperature for future hottest days. *Nat. Geosci.*, **9**, 24–28, <https://doi.org/10.1038/ngeo2596>.
- Dee, D. P., and Coauthors, 2011: The ERA-Interim reanalysis: Configuration and performance of the data assimilation system. *Quart. J. Roy. Meteor. Soc.*, **137**, 553–597, <https://doi.org/10.1002/qj.828>.
- Gao, Y., J. Lu, L. R. Leung, Q. Yang, S. Hagos, and Y. Qian, 2015: Dynamical and thermodynamical modulations on future changes of landfalling atmospheric rivers over western North America. *Geophys. Res. Lett.*, **42**, 7179–7186, <https://doi.org/10.1002/2015GL065435>.
- Gershunov, A., and Coauthors, 2019: Precipitation regime change in western North America: The role of atmospheric rivers. *Nat. Sci. Rep.*, **9**, 9944, <https://doi.org/10.1038/s41598-019-46169-w>.
- , T. Shulgina, F. M. Ralph, D. A. Lavers, and J. J. Rutz, 2017: Assessing the climate-scale variability of atmospheric rivers affecting western North America. *Geophys. Res. Lett.*, **44**, 7900–7908, <https://doi.org/10.1002/2017GL074175>.
- Gimeno, L., R. Nieto, M. Vázquez, and D. A. Lavers, 2014: Atmospheric rivers: A mini-review. *Front. Earth Sci.*, **2**, 1–6, <https://doi.org/10.3389/feart.2014.00002>.
- Guan, B., and D. E. Waliser, 2015: Detection of atmospheric rivers: Evaluation and application of an algorithm for global studies. *J. Geophys. Res. Atmos.*, **120**, 12 514–12 535, <https://doi.org/10.1002/2015JD024257>.
- , and —, 2017: Atmospheric rivers in 20 year weather and climate simulations: A multimodel, global evaluation. *J. Geophys. Res. Atmos.*, **122**, 5556–5581, <https://doi.org/10.1002/2016JD026174>.
- Guirguis, K., A. Gershunov, R. E. S. Clemesha, T. Shulgina, A. C. Subramanian, and F. M. Ralph, 2018: Circulation drivers of atmospheric rivers at the North American west coast. *Geophys. Res. Lett.*, **45**, 12 576–12 584, <https://doi.org/10.1029/2018GL079249>.
- , —, T. Shulgina, R. E. S. Clemesha, and F. M. Ralph, 2019: Atmospheric rivers impacting Northern California and their modulation by a variable climate. *Climate Dyn.*, **52**, 6569–6583, <https://doi.org/10.1007/s00382-018-4532-5>.
- Guo, Y., M. Ting, Z. Wen, and D. E. Lee, 2017: Distinct patterns of tropical Pacific SST anomaly and their impacts on North American climate. *J. Climate*, **30**, 5221–5241, <https://doi.org/10.1175/JCLI-D-16-0488.1>.
- Hagos, S. M., L. R. Leung, J. Yoon, J. Lu, and Y. Gao, 2016: A projection of changes in landfalling atmospheric river frequency and extreme precipitation over western North America from the Large Ensemble CESM simulations. *Geophys. Res. Lett.*, **43**, 1357–1363, <https://doi.org/10.1002/2015GL067392>.
- Harrington, L. J., P. B. Gibson, S. M. Dean, D. Mitchell, S. M. Rosier, and D. J. Frame, 2016: Investigating event-specific drought attribution using self-organizing maps. *J. Geophys. Res. Atmos.*, **121**, 12 766–12 780, <https://doi.org/10.1002/2016JD025602>.
- Held, I. M., and B. J. Soden, 2006: Robust responses of the hydrological cycle to global warming. *J. Climate*, **19**, 5686–5699, <https://doi.org/10.1175/JCLI3990.1>.
- Hewitson, B., and R. Crane, 2002: Self-organizing maps: Applications to synoptic climatology. *Climate Res.*, **22**, 13–26, <https://doi.org/10.3354/cr022013>.
- Holland, M. M., and C. M. Bitz, 2003: Polar amplification of climate change in coupled models. *Climate Dyn.*, **21**, 221–232, <https://doi.org/10.1007/s00382-003-0332-6>.
- Hu, H., F. Dominguez, Z. Wang, D. A. Laversa, G. Zhang, and F. M. Ralph, 2017: Linking atmospheric river hydrological impacts on the U.S. West Coast to Rossby wave breaking. *J. Climate*, **30**, 3381–3399, <https://doi.org/10.1175/JCLI-D-16-0386.1>.
- Jeon, S., Prabhat, S. Byna, J. Gu, W. D. Collins, and M. F. Wehner, 2015: Characterization of extreme precipitation within atmospheric river events over California. *Adv. Stat. Climatol. Meteor. Oceanogr.*, **1**, 45–57, <https://doi.org/10.5194/ascmo-1-45-2015>.
- Jiang, T., and Y. Deng, 2011: Downstream modulation of North Pacific atmospheric river activity by East Asian cold surges. *Geophys. Res. Lett.*, **38**, L20807, <https://doi.org/10.1029/2011GL049462>.
- , K. J. Evans, Y. Deng, and X. Dong, 2014: Intermediate frequency atmospheric disturbances: A dynamical bridge connecting western U.S. extreme precipitation with East Asian cold surges. *J. Geophys. Res. Atmos.*, **119**, 3723–3735, <https://doi.org/10.1002/2013JD021209>.
- Johnson, N. C., 2013: How many ENSO flavors can we distinguish? *J. Climate*, **26**, 4816–4827, <https://doi.org/10.1175/JCLI-D-12-00649.1>.
- Kim, H.-M., Y. Zhou, and M. A. Alexander, 2019: Changes in atmospheric rivers and moisture transport over the northeast Pacific and western North America in response to ENSO diversity. *Climate Dyn.*, **52**, 7375–7388, <https://doi.org/10.1007/s00382-017-3598-9>.
- Konrad, C. P., and M. D. Dettinger, 2017: Flood runoff in relation to water vapor transport by atmospheric rivers over the western United States, 1949–2015. *Geophys. Res. Lett.*, **44**, 11 456–11 462, <https://doi.org/10.1002/2017GL075399>.
- Leung, L. R., and Y. Qian, 2009: Atmospheric rivers induced heavy precipitation and flooding in the western U.S. simulated by the WRF regional climate model. *Geophys. Res. Lett.*, **36**, L03820, <https://doi.org/10.1029/2008GL036445>.
- Linkin, M. E., and S. Nigam, 2008: The North Pacific Oscillation–west Pacific teleconnection pattern: Mature-phase structure and winter impacts. *J. Climate*, **21**, 1979–1997, <https://doi.org/10.1175/2007JCLI2048.1>.
- Liu, X., X. Ren, and X.-Q. Yang, 2016: Decadal changes in multiscale water vapor transport and atmospheric river associated with the Pacific decadal oscillation and the North Pacific Gyre Oscillation. *J. Hydrometeorol.*, **17**, 273–285, <https://doi.org/10.1175/JHM-D-14-0195.1>.
- Liu, Y., R. H. Weisberg, and C. N. K. Mooers, 2006: Performance evaluation of the self-organizing map for feature extraction. *J. Geophys. Res.*, **111**, C05018, <https://doi.org/10.1029/2005JC003117>.
- Lu, J., G. A. Vecchi, and T. Reichler, 2007: Expansion of the Hadley cell under global warming. *Geophys. Res. Lett.*, **34**, L06805, <https://doi.org/10.1029/2006GL028443>.
- Luo, Q., and W. Tung, 2015: Case study of moisture and heat budgets within atmospheric rivers. *Mon. Wea. Rev.*, **143**, 4145–4162, <https://doi.org/10.1175/MWR-D-15-0006.1>.
- Mahoney, K., and Coauthors, 2016: Understanding the role of atmospheric rivers in heavy precipitation in the southeast United States. *Mon. Wea. Rev.*, **144**, 1617–1632, <https://doi.org/10.1175/MWR-D-15-0279.1>.
- Mundhenk, B. D., E. A. Barnes, and E. D. Maloney, 2016a: All-season climatology and variability of atmospheric river frequencies over the North Pacific. *J. Climate*, **29**, 4885–4903, <https://doi.org/10.1175/JCLI-D-15-0655.1>.

- , —, —, and K. M. Nardi, 2016b: Modulation of atmospheric rivers near Alaska and the U.S. West Coast by northeast Pacific height anomalies. *J. Geophys. Res. Atmos.*, **121**, 12 751–12 765, <https://doi.org/10.1002/2016JD025350>.
- Nash, D., D. Waliser, B. Guan, H. Ye, and F. M. Ralph, 2018: The role of atmospheric rivers in extratropical and polar hydroclimate. *J. Geophys. Res. Atmos.*, **123**, 6804–6821, <https://doi.org/10.1029/2017JD028130>.
- Neiman, P. J., F. M. Ralph, G. A. Wick, J. D. Lundquist, and M. D. Dettinger, 2008: Meteorological characteristics and overland precipitation impacts of atmospheric rivers affecting the west coast of North America based on eight years of SSM/I satellite observations. *J. Hydrometeorol.*, **9**, 22–47, <https://doi.org/10.1175/2007JHM855.1>.
- Newell, E., N. E. Newell, Y. Zhu, and C. Scott, 1992: Tropospheric rivers?—A pilot study. *Geophys. Res. Lett.*, **19**, 2401–2404, <https://doi.org/10.1029/92GL02916>.
- Nusbaumer, J., and D. Noone, 2018: Numerical evaluation of the modern and future origins of atmospheric river moisture over the West Coast of the United States. *J. Geophys. Res. Atmos.*, **123**, 6423–6442, <https://doi.org/10.1029/2017JD028081>.
- Payne, A. E., and G. Magnusdottir, 2014: Dynamics of landfalling atmospheric rivers over the North Pacific in 30 years of MERRA reanalysis. *J. Climate*, **27**, 7133–7150, <https://doi.org/10.1175/JCLI-D-14-00034.1>.
- , and —, 2015: An evaluation of atmospheric rivers over the North Pacific in CMIP5 and their response to warming under RCP 8.5. *J. Geophys. Res. Atmos.*, **120**, 11 173–11 190, <https://doi.org/10.1002/2015JD023586>.
- , and —, 2016: Persistent landfalling atmospheric rivers over the west coast of North America. *J. Geophys. Res. Atmos.*, **121**, 13 287–13 300, <https://doi.org/10.1002/2016JD025549>.
- Ralph, F. M., P. J. Neiman, and G. A. Wick, 2004: Satellite and CALJET aircraft observations of atmospheric rivers over the eastern North Pacific Ocean during the winter of 1997/98. *Mon. Wea. Rev.*, **132**, 1721–1745, [https://doi.org/10.1175/1520-0493\(2004\)132<1721:SACAOO>2.0.CO;2](https://doi.org/10.1175/1520-0493(2004)132<1721:SACAOO>2.0.CO;2).
- , and Coauthors, 2019: ARTMIP-early start comparison of atmospheric river detection tools: How many atmospheric rivers hit northern California's Russian River watershed? *Climate Dyn.*, **52**, 4973–4994, <https://doi.org/10.1007/s00382-018-4427-5>.
- Rivera, E. R., F. Dominguez, and C. L. Castro, 2014: Atmospheric rivers and cool season extreme precipitation events in the Verde River basin of Arizona. *J. Hydrometeorol.*, **15**, 813–829, <https://doi.org/10.1175/JHM-D-12-0189.1>.
- Roebber, P. J., 1984: Statistical analysis and updated climatology of explosive cyclones. *Mon. Wea. Rev.*, **112**, 1577–1589, [https://doi.org/10.1175/1520-0493\(1984\)112<1577:SAAUCO>2.0.CO;2](https://doi.org/10.1175/1520-0493(1984)112<1577:SAAUCO>2.0.CO;2).
- Rutz, J. J., and W. J. Steenburgh, 2012: Quantifying the role of atmospheric rivers in the interior western United States. *Atmos. Sci. Lett.*, **13**, 257–261, <https://doi.org/10.1002/asl.392>.
- , —, and F. M. Ralph, 2014: Climatological characteristics of atmospheric rivers and their inland penetration over the western United States. *Mon. Wea. Rev.*, **142**, 905–921, <https://doi.org/10.1175/MWR-D-13-00168.1>.
- Seiler, C., and F. W. Zwiers, 2016a: How will climate change affect explosive cyclones in the extratropics of the Northern Hemisphere? *Climate Dyn.*, **46**, 3633–3644, <https://doi.org/10.1007/s00382-015-2791-y>.
- , and —, 2016b: How well do CMIP5 climate models reproduce explosive cyclones in the extratropics of the Northern Hemisphere? *Climate Dyn.*, **46**, 1241–1256, <https://doi.org/10.1007/s00382-015-2642-x>.
- Sheridan, S. C., and C. C. Lee, 2011: The self-organizing map in synoptic climatological research. *Prog. Phys. Geogr.*, **35**, 109–119, <https://doi.org/10.1177/0309133310397582>.
- Shields, C. A., and J. T. Kiehl, 2016: Atmospheric river landfall-latitude changes in future climate simulations. *Geophys. Res. Lett.*, **43**, 8775–8782, <https://doi.org/10.1002/2016GL070470>.
- Son, S. W., S. Y. Kim, and S. K. Min, 2018: Widening of the Hadley cell from Last Glacial Maximum to future climate. *J. Climate*, **31**, 267–281, <https://doi.org/10.1175/JCLI-D-17-0328.1>.
- Taylor, K. E., R. J. Stouffer, and G. A. Meehl, 2012: An overview of CMIP5 and the experiment design. *Bull. Amer. Meteor. Soc.*, **93**, 485–498, <https://doi.org/10.1175/BAMS-D-11-00094.1>.
- van Vuuren, D. P., and Coauthors, 2011: The representative concentration pathways: An overview. *Climatic Change*, **109**, 5–31, <https://doi.org/10.1007/s10584-011-0148-z>.
- Waliser, D., and B. Guan, 2017: Extreme winds and precipitation during landfall of atmospheric rivers. *Nat. Geosci.*, **10**, 179–183, <https://doi.org/10.1038/ngeo2894>.
- Warner, M. D., and C. F. Mass, 2017: Changes in the climatology, structure, and seasonality of northeast Pacific atmospheric rivers in CMIP5 climate simulations. *J. Hydrometeorol.*, **18**, 2131–2141, <https://doi.org/10.1175/JHM-D-16-0200.1>.
- , —, and E. P. Salathé, 2015: Changes in winter atmospheric rivers along the North American west coast in CMIP5 climate models. *J. Hydrometeorol.*, **16**, 118–128, <https://doi.org/10.1175/JHM-D-14-0080.1>.
- Webster, P. J., and J. R. Holton, 1982: Cross-equatorial response to middle-latitude forcing in a zonally varying basic state. *J. Atmos. Sci.*, **39**, 722–733, [https://doi.org/10.1175/1520-0469\(1982\)039<0722:CERTML>2.0.CO;2](https://doi.org/10.1175/1520-0469(1982)039<0722:CERTML>2.0.CO;2).
- Wehrens, R., and L. M. C. Buydens, 2007: Self- and super-organizing maps in R: The kohonen package. *J. Stat. Software*, **21**, 1–19, <https://doi.org/10.18637/jss.v021.i05>.
- Wilks, D. S., 2006: On “field significance” and the false discovery rate. *J. Appl. Meteor. Climatol.*, **45**, 1181–1189, <https://doi.org/10.1175/JAM2404.1>.
- Zhang, W., and G. Villarini, 2018: Uncovering the role of the East Asian jet stream and heterogeneities in atmospheric rivers affecting the western United States. *Proc. Natl. Acad. Sci. USA*, **115**, 891–896, <https://doi.org/10.1073/pnas.1717883115>.
- Zhu, Y., and R. E. Newell, 1998: A proposed algorithm for moisture fluxes from atmospheric rivers. *Mon. Wea. Rev.*, **126**, 725–735, [https://doi.org/10.1175/1520-0493\(1998\)126<0725:APAFMF>2.0.CO;2](https://doi.org/10.1175/1520-0493(1998)126<0725:APAFMF>2.0.CO;2).