Evaluating NA-CORDEX historical performance and future change of western U.S. precipitation patterns and modes of variability

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Abstract
The western U.S. precipitation climatology, simulated by the NA-CORDEX regional climate model ensembles, with spatial resolutions of 0.44°C (14 model members) and 0.22°C (15 model members), is examined to evaluate the capability of these ensembles to reproduce (1) the annual and semi-annual precipitation cycle of several hydrologically-important western U.S. regions and (2) localized seasonality in the amount and timing of precipitation. Similar to previous organized downscaling projects, NA-CORDEX ensembles continue to over-simulate wintertime precipitation over mountainous regions. However, both NA-CORDEX ensembles showed improvements to the Desert Southwest’s summertime precipitation associated with the North American Monsoon. Furthermore, the predominant dry bias found throughout the 0.44°C ensemble was improved in many of the higher resolution 0.22°C ensemble members; associated with enhanced mesoscale processes and improved thermodynamics driving the model’s convective parameterizations. When compared against observation-based gridded precipitation, the ability to capture the annual and semi-annual modes of variability was starkly improved in the higher resolution 0.22°C ensemble. The higher resolution members reproduced more consistent spatial patterns of variance featuring lower errors in magnitude—especially with respect to the winter-summer and spring-fall seasonality. A great deal of spread in model performance was found for the semi-annual cycles, although both NA-CORDEX ensembles showed improvements to the Desert Southwest’s summertime precipitation associated with the North American Monsoon. Furthermore, the predominant dry bias found throughout the 0.44°C ensemble was improved in many of the higher resolution 0.22°C ensemble members; associated with enhanced mesoscale processes and improved thermodynamics driving the model’s convective parameterizations. When compared against observation-based gridded precipitation, the ability to capture the annual and semi-annual modes of variability was starkly improved in the higher resolution 0.22°C ensemble. The higher resolution members reproduced more consistent spatial patterns of variance featuring lower errors in magnitude—especially with respect to the winter-summer and spring-fall seasonality. A great deal of spread in model performance was found for the semi-annual cycles, although the higher-resolution ensemble exhibited better clustering of performance metrics. Ultimately, NA-CORDEX model performance is still tied to the fidelity of the large-scale parent model although we found performance is also closely related to which regional climate model was used while the future trend was more related to the parent GCM. Additionally, the value-added via finer domain grid spacing is clear. Lastly, future projections of precipitation patterns were analysed to examine trends in the seasonality of precipitation intensity and modes of variability.
1 | INTRODUCTION

In the face of growing demand on the western United States (U.S.) water resources (Brookshire et al., 2002), significant positive temperature trends (Cavazos et al., 2020), and a proclivity for extensive drought (Cook et al., 2004), scientific efforts spanning a diverse collection of disciplines have engaged the question of how future climate change will impact a wide spectrum of water-related topics. Studies have examined changes to the region’s snowpack (McCabe and Wolock, 1999) and snowmelt (Ficklin et al., 2019), impacts to runoff/infiltration rates (Pierce et al., 2013), and groundwater recharge rates (Meixner et al., 2016), streamflow extremes and reservoir inflows (Naz et al., 2018), as well as attempts to quantify the uncertainty of future projections of hydrologic impacts (Shen et al., 2018). No matter the particular focus of these studies, future climate change impact studies are unified in their reliance on future projection data provided by coarse-resolution global climate models (GCM). These GCM projections are typically provided by the World Climate Research Programme’s Coupled Model Inter-comparison Project (CMIP). The fifth phase of CMIP (i.e., CMIP5; Taylor et al., 2012) provided the model projection data for many of the climate projection studies conducted since its release in the early 2010s. Initial climate projection output from the next CMIP phase (i.e., CMIP6) is now becoming available, with studies investigating the latest round of projected changes beginning to be published (e.g., Jin et al., 2020). With grid spacing on the order of 100-km or more, many important small-scale interactions associated with the western U.S.’s complex terrain are unresolved by CMIP5 and CMIP6 models; as illustrated by their documented biases in temperature and precipitation patterns (Sheffield et al., 2013a; Sheffield et al., 2013b; Liu et al., 2014; Mehran et al., 2014; Koutroulis et al., 2016). Most climate-impact studies focusing on hydrologic questions require greater data fidelity than what CMIP5 and other GCM’s can provide. As such, these climate-impact studies often turn to a form of either statistical or dynamical downscaling (commonly referred to as regional climate modelling [RCM]), both of which are designed to improve the spatial resolution of climate data (e.g., temperature, precipitation, humidity, etc.). Statistical downscaling increases data resolution through statistical relationships with higher resolution historical observations, and is computationally far less demanding than dynamical downscaling. Statistical downscaling neglects the physical processes involved in the many non-linear interactions shaping a region’s climate. These non-linear processes are much better resolved by the process-based numerical RCMs with a long history of historical evaluations having demonstrated their added value over GCMs (Antic et al., 2004; Mearns et al., 2012; Bukovsky et al., 2013; Lucas-Picher et al., 2017); despite RCMs themselves introducing their own source of uncertainty (Christensen et al., 2007). It should be noted here that recent improvements to the statistical downscaling approach referred to as ‘weather generators’ have proven capable of capturing certain historical spatial and temporal traits of small-scale patterns (Fatichi et al., 2011; Li and Babovic, 2019).

Ideally, future RCM-based climate impact studies should employ a multi-member ensemble approach in order to better consider the range of model uncertainty and range of potential future outcomes. Unfortunately, the heavy computational demands associated with ensemble RCM studies is a significant hurdle. To better equip the scientific community with a robust ensemble of future climate projections, large coordinated efforts to produce high-resolution RCM ensembles have been undertaken across the globe. To this point, North America has been the focus of two coordinated RCM ensemble projects. The first project, named the North American Regional Climate Change Assessment Program (NARCCAP; Mearns et al., 2009) used six RCM models to downscale four GCM members from the third CMIP phase (CMIP3; Meehl et al., 2007). Like many RCM applications (Leung et al., 2003; Randall et al., 2007; Zhang et al., 2009), the improvements to terrain fields in the ~½-degree (~50 km) resolution NARCCAP ensemble produced more accurate surface temperature fields compared to the parent GCM output. However, the RCM-GCM linkage to large-scale dynamics via the lateral boundary conditions means that the seasonal precipitation cycles in NARCCAP remained similarly biased to the parent GCM (Gao et al., 2011). Mearns et al. (2009) used Analysis of Variance to assess the improvements of seasonality made by NARCCAP RCMs. They found a general tendency for RCMs to outperform GCMs during summer months when mesoscale processes dominate.
precipitation patterns, while GCMs outperformed during the winter months dominated by synoptic-scale precipitation processes. An investigation into the historical precipitation climatology simulated by the NARCCAP ensemble by Wang et al. (2009) found systematic winter-time wet biases throughout the western U.S. along with an amplified annual cycle; however, semi-annual modes of climate variability were generally better simulated by NARCCAP.

Following the completion of the CMIP5, the Coordinated Regional Climate Downscaling Experiment (NA-CORDEX; Giorgi et al., 2009) was conducted. NA-CORDEX features a greater number of downscaled members simulating domains at three increasing resolutions (0.44°, 0.22°, and 0.11°). The bulk of NA-CORDEX evaluation studies have examined either specific western U.S. regions/seasonal phenomena (Tripathi and Dominguez, 2013; Cerezo-Mota et al., 2016; Poan et al., 2018; Ganguli and Coulibaly, 2019) or specific NA-CORDEX member performance (Lucas-Picher et al., 2013; Martynov et al., 2013; Šeparović et al., 2013). Recently, Bukovsky and Mearns (2020) assessed future projection sensitivity of GCMs downscaled by the complete NA-CORDEX ensemble while Prein et al. (2019) examined the general ability of NA-CORDEX members to resolve specific weather types in order to assess sources of RCM bias. Despite the collection of evaluation studies and basic online model performance evaluations (Rendfrey et al., 2018; NOAA Web Atlas, 2021), a more complete and systematic evaluation of the NA-CORDEX ensemble’s precipitation performance is currently lacking. Such evaluations are crucial in identifying individual RCM ensemble members that simulate a more credible historical climatology; the assumption being that a greater degree of confidence exists in these member’s future climate projections. It is the goal of this study to provide some perspective to subsequent hydrologic climate impact studies on the historical skill and future projections of precipitation cycles and modes of variability within each NA-CORDEX ensemble member.

Analysis presented here evaluates the NA-CORDEX ensemble following the methodology outlined by Wang et al. (2009); hereafter referred to as Wang09. Through this work we ask the following questions: (a) Do the systematic biases found in the NARCCAP ensemble persist in the NA-CORDEX ensemble and (b) Do finer domain grid resolutions improve the ability to the NA-CORDEX RCMs to resolve precipitation patterns and modes of variability? In addition to the historical evaluation, we also explore future changes within the NA-CORDEX ensemble based on several of the representative concentration pathways (RCP) (Van Vuuren et al., 2011). An overview of the data sources used for this study is provided in Section 2. Section 3 highlights the historical precipitation evaluation with Section 4 examining the future precipitation projections. A discussion of results and concluding remarks are provided in Section 5.

2 | DATA

2.1 | NA-CORDEX output

The NA-CORDEX ensemble is comprised of seven RCM members operating at domain grid spacings of 0.44° (~50 km) and 0.22° (~25 km); a higher 0.11° (~12 km) grid is available but with only a single RCM member, is omitted from this study. NA-CORDEX RCMs evaluated here consist of the CanRCM4, two separate configurations of the CRCM model (CRCM5-UQAM, CRCM5-OUR), the HIRHAM5 model, the RCA4 model, the RegCM4 model, and the WRF model. Readers should refer to Mearns et al. (2017) for a description of the specific NA-CORDEX RCM model configurations. We note that because of the model-specific architecture of each RCM, the 0.44° and 0.22° domain grids are all unique to a small degree. To ensure a uniform evaluation across the ensemble, analysis performed in this study was conducted on the available ‘interpolated’ RCM output standardized to a uniform grid.

Over historical periods, NA-CORDEX guidelines require all participating members produce a set of simulations driven with lateral boundary conditions from ERA-Interim reanalysis (Dee et al., 2011) spanning the years 1989–2009. Historical CMIP5 downscaling covers 1950–2005. CMIP5 GCMs downscaled by NA-CORDEX members include the CanESM2, CNRM-CM5, EC-EARTH, GEMatm-Can, GEMatm-MPI, GFDL-ESM2M, HadGEM2-ES, and the MPI-ESM-LR models. Table 1 supplies the various pairings of RCM and parent GCM members evaluated in this study and the specific grid spacings available for each combination of the historical and various future RCP projections.

2.2 | Historical gridded precipitation data

To evaluate the historical skill of NA-CORDEX precipitation, we used the Climate Prediction Centers Unified gauge-based analysis (CPCU; Chen et al., 2008) provided by NOAA/OAR/ESRL PSD from their website at https://www.esrl.noaa.gov/psd/. CPCU offers monthly precipitation between 1948-present on a 0.25° domain over the conterminous U.S. While not first-order observations, for simplicity, CPCU gridded precipitation will be referred to as
‘observation’ throughout this study. Because western U.S. precipitation patterns are so closely linked to the terrain, historical evaluations are best conducted with as little interpolation between the modelled and observed precipitation fields. As such, CPCU and its comparable grid resolution relative to the NA-CORDEX ensembles offered the most appropriate evaluation data set versus other gridded precipitation data sets. The observation by Gillies et al. (2012) that CPCU’s precipitation trend in Utah is in good agreement with the station records also lends support to using this data set. Figure 1 shows (a) the 0.22° NA-CORDEX representation of western U.S. terrain height (meters) and (b) the historical annual long-term mean of CPCU observed precipitation (mm-day⁻¹). Given the primary role the region’s terrain plays on the spatial and seasonal patterns of precipitation, the region’s major mountain ranges are delineated with red lines in Figure 1a.

### 3 NA-CORDEX HISTORICAL EVALUATION

#### 3.1 Annual cycle of historical precipitation

Based on each of the six regions of interest denoted in Figure 1b, Figure 2 shows the monthly climatological precipitation from CPCU (box chart and solid black lines) along with the NA-CORDEX RCM members driven by the ERA-Interim reanalysis boundary conditions. This highlights the ability of these RCM models to reproduce the annual cycle of precipitation when provided a ‘perfect LBC framework’ through the observation-based reanalysis. Overall, systematic wet biases in wintertime precipitation highlighted by Wang09 remain across the mountainous regions throughout the western U.S. along
with dry biases in the summertime precipitation. Many of the same patterns of bias in each region’s annual cycle are preserved (e.g., year-long wet biases over the Colorado Rockies, a limited Monsoon in the Desert Southwest; wintertime wet bias and summertime dry bias in the Intermountain West; comparable summertime precipitation in the northern Rockies but wintertime wet bias). However, the ensemble average of these systematic biases in the NA-CORDEX ensemble have been reduced compared to NARCCAP (Wang09). The reduction in overall biases is likely a result of a combination of improvements to the models themselves as well as the higher resolution of NA-CORDEX ensembles as the 0.22° ensemble does show slight improvements to the annual cycle compared to the 0.44° ensemble. Continuing to evaluate the historical annual cycle, Figure 3 focuses on the NA-CORDEX RCMs driven by the collection of CMIP5 GCMs shown in Table 1. For the most part, NA-CORDEX members capture the general annual cycle within each domain, but similar to the NARCCAP annual cycle (Wang09) and ERA-Interim driven NA-CORDEX members, the amplitude continues to be over-estimated with the vast majority of members producing some degree of wet bias over the mountainous regions. The most egregious biases were found over the Intermountain West and interior mountain ranges, where simulated precipitation was two to three times the observations. We note one limitation of gridded precipitation data sets over complex terrain is the lack of observations in remote areas. It is possible that because of a lack of observation, these gridded precipitation data sets are themselves dry biased meaning that the RCM models appear wet biased due to their ability to more accurately capturing the local precipitation heterogeneities driven by local orographic processes. Regardless, the difference in historical model performance when downscaling GCMs versus ERA-Interim reanalysis reiterates the well-known negative influence GCM biases can have on the performance of the RCM (Warner et al., 1997; Noguer et al., 1998; Bukovsky et al., 2013; Meyer and Jin, 2016).

One noteworthy area of improvement relative to the NARCCAP ensemble is found for the Desert Southwest region’s summertime precipitation. The NA-CORDEX ensemble greatly improves the amplitude of the June–September North American Monsoon (NAM) season. This improvement is likely a function of (a) NA-CORDEX preferentially selecting to downscale better-performing CMIP5 members, (b) the finer resolution of the better-performing CMIP5 forcing data better capturing remote and large-scale processes, and (c) the NA-CORDEX RCMs further improving local effects. When compared with the CPCU gridded precipitation, the importance of RCM grid spacing is highlighted by the July–August months where a consensus dry bias produced by the GCM-driven 0.44° ensemble shown in Figure 3 (similar to that found within NARCCAP; Wang09) shifts towards a wet bias within the 0.22° ensemble.

### 3.2 Modes of precipitation variability

In this section, we explore the capability of NA-CORDEX members to reproduce the various seasonal modes of variability. Using a Fourier filter, the first two harmonics (wavenumbers) of the 12-month precipitation climatology from the CPCU precipitation and each NA-CORDEX member were isolated. The first and second wavenumbers

![Figure 1](https://example.com/fig1.png)

**FIGURE 1** (a) Terrain (m) across the western U.S. are resolved by the 0.22° CORDEX domain and (b) 1951–2005 climatology of CPCU gridded precipitation (mm day⁻¹). Solid red line in (a) represents a rough approximation of the region’s terrain. Dashed boxes in (b) represent the six regions of focus throughout the study with (1) Pacific northwest, (2) Sierra Nevada, (3) Northern Rockies, (4) intermountain west, (5) Colorado Rockies, and 6) desert southwest [Colour figure can be viewed at wileyonlinelibrary.com]
represent the annual and semi-annual modes, respectively (Wang09). Using Empirical Orthogonal Function (EOF) analysis, the first two principal components (PC) of the annual and semi-annual filtered 12-month climatology were examined. These PCs represent physical modes of the annual climate cycle with the first and second PCs of the annual cycle (wavenumber 1) representing the winter-summer mode and the spring-fall mode, respectively. Wang09 documented that the winter-summer mode is in response to the seasonal maximum (minimum) in the strength of the mid-latitude westerlies during the wintertime (summertime) influencing orographic precipitation as well as the position and intensity of the sub-tropical jet (e.g., Luna-Niño et al., 2020), while the spring-fall mode reflects the seasonal passage of the sub-tropical jet. The first and second PCs of the semi-annual mode (wavenumber 2) represent the semi-annual cycles and are associated with numerous seasonal cycles of circulation but primarily a mixture of the onset, development, and dissipation of the North American Monsoon (NAM) circulation and the resulting split of the jet stream into a subtropical jet and polar jet. All in all, the decomposition of annual/semi-annual cycles coupled with the EOF analysis offers an optimal balance between

**FIGURE 2** Monthly climatological precipitation (mm day$^{-1}$) simulated by CORDEX members driven by ERA-INT reanalysis over the six domains outlined with dashed lines in Figure 1. Colour-filled bars and thick black line coincide with the monthly climatology of gridded observations provided by CPCU with coloured lines representing RCM members [Colour figure can be viewed at wileyonlinelibrary.com]
delineating important seasonal evolutions in this mountainous region and the vastly localized climate details (Wang09).

The focus of this study is to evaluate the historical skill of NA-CORDEX ensembles in order to provide context into the degree of confidence for future projections by individual members of the ensembles. With that in mind, our primary focus here is on the evaluation of the GCM-driven ensembles, which due to the sheer number of ensemble members is split between Figures 4 and 5 for the 0.44° ensemble and Figures 6 and 7 for the 0.22° ensemble. However, we acknowledge the scientific value that comes from the evaluation of the ERA-Interim driven RCMs when provided the ‘perfect’ lateral boundary condition framework, so we have included these comparisons in Figures S1 and S2 for the 0.44° and 0.22° ensembles, respectively. We note that the general findings and historical performance comparisons discussed about the GCM-driven ensembles are the same conclusions drawn for the ERA-Interim driven ensemble shown in the supplemental figures. The percent of variance explained by each PC is listed in the lower-left corner of
FIGURE 4  Eigenvectors of the annual and semi-annual modes representing (a) winter-summer mode, (b) spring-fall model, (c) first semi-annual mode, and (d) second semi-annual mode for a portion of the 0.44° CORDEX members. Percentage of variance shown in the lower left corner represents the variance of the first and second harmonics, which are isolated before being subjected to EOF analysis. Model names to the left of each row list the RCM first and the parent GCM below [Colour figure can be viewed at wileyonlinelibrary.com]
At first glance, the NA-CORDEX ensemble produced realistic phases for each annual mode, but with some noteworthy inconsistencies relative to the CPCU data set (top row). Consistent with the NARCCAP ensemble, the preponderance of NA-CORDEX models to systematically over-simulate wintertime precipitation is readily apparent in each PC—especially in the intermountain west regions of Utah, Idaho, and Wyoming. Along with the CanRCM4
FIGURE 6  Same as Figure 4 but for a portion of the 0.22° CORDEX members [Colour figure can be viewed at wileyonlinelibrary.com]
member, all three of the WRF simulations produce far too extreme of a winter-summer mode. CRCM5 RCMs generally perform well, although the CRCM5-UQAM members stand alone in their performance.

A striking difference between the 0.44° NA-CORDEX ensemble members and the CPCU observations is found for the spring-fall mode, with NA-CORDEX members uniformly simulating too strong of an east–west dipole.
signal between the Great Plains and the West Coast (reflecting the Great Plains spring precipitation) and too weak of the north–south dipole signal between the northern Rockies and the desert Southwest (reflecting the North American Monsoon). This mode, along with the semi-annual modes, are associated with the varying timing of the NAM’s impacts on different areas. Except for the RCA4, the HIRHAM5, and the three WRF members, NA-CORDEX ensemble struggles to resolve the NAM’s spatial signature across the desert southwest (corroborating the direct evidence for the lack of a NAM signal shown in Figure 2). We also mention that the WRF models tended to over-estimate the NAM precipitation compared to CPCU observations.

Pertaining to the semi-annual modes, the full complement of the 0.44° NA-CORDEX ensemble exhibits too strong of amplitude. Individual members that stand out in their ability to reproduce more accurately the spatial pattern of the first semi-annual mode are isolated to the CRCM5 and WRF models, while the RegCM4 struggles to capture this mode. Compared to the CPCU observations, further inconsistent performance is found for the second semi-annual mode with none of the NA-CORDEX RCMs standing out and very little member-to-member spatial consistency.

Examining the 0.22° NA-CORDEX ensemble (Figures 6 and 7) shows an improvement to the amplitude of both annual modes along with a much-improved Intermountain West signal. For the most part, the intermodel performance comparisons highlighted for the 0.44° members carry over to the 0.22° members, with CRCM5 and WRF models rounding out the best-performing members for both the winter-summer and spring-fall modes. This applies to the NAM domain as well, although many members within the ensemble exhibit too small of amplitude. Compared with the 0.44° ensemble, the first semi-annual mode throughout the 0.22° ensemble is strikingly improved. Despite a systematic improvement in amplitude of the second semi-annual mode, there continues to be a large degree of model-to-model variance in the spatial pattern.

### 3.3 Impact of grid spacing on variability

Here we examine the impact grid spacing has on the reproduction of the modes of climate variability. Figure 8 shows the normalized eigenvalues (i.e., PC timeseries) from the above EOF analysis of the 0.22° and 0.44° ensembles (Figures 4, 5, and Figures 6, 7). The solid black line represents the reference eigenvalues of the CPCU data set; normalized against itself. The normalization of the NA-CORDEX ensembles is based on the maximum eigenvalue from the 0.44° ensemble in order to best provide perspective for the evaluation of the 0.22° ensemble. The winter-summer and spring-fall modes of the 0.44° ensemble produced a phase in line with observations, although inconsistencies in the phase of the semi-annual modes are apparent. Two of the WRF members are lagged by 1 month (echoing NARCCAP’s WRF members; Wang09). Such seasonal differences might appear egregious, but are more likely an artefact of seasonal transitions straddling 2 months. Relative to the 0.44° ensemble, the 0.22° ensemble contains similar phase results, but with maximum amplitudes across the ensemble roughly double for the first and second PCs, respectively. The physical meaning behind the pronounced increase in the amplitude of the modes of variability can be explained by the slightly more intense daily precipitation in the 0.22° ensemble driving a more apparent transition between the wet/dry modes within the annual cycle.

Continuing to assess the impact RCM resolution has on the historical performance, the spatial patterns of the EOF analysis presented throughout Section 3.2 are distilled into a more concise comparison via Taylor diagrams (Taylor, 2001). Taylor diagrams summarize multiple aspects of statistical model performance in one visual framework. In this case, the reference data set for the statistical comparison are CPCU’s EOF pattern. Compared with these observation-based patterns, the ratio of each individual NA-CORDEX member’s normalized root mean square error (RMSE) score and weighted spatial pattern correlation was computed. Before computing these statistics, the CPCU fields and the 0.22° NA-CORDEX ensemble members were regridded to standardize all patterns onto the 0.44° domain.

Figure 9 provides the Taylor diagrams for the four modes of variability. Concentric rings emanating from the x-axis represent the ratio of the RMSE values while the weighted spatial correlation score is indicated by the outermost axis. The closer an individual ensemble member moves towards the ‘reference’ point listed on the centre of the x-axis the more statistically comparable that member was to the CPCU data set. A similar collection of Taylor diagrams showing the ERA-Interim driven ensembles is shown in Figure S3 and once again echo the performance evaluation findings shown for the GCM-driven ensembles discussed here.

Overall, the relationship between NA-CORDEX model performance and domain resolution is clear across all four modes of variability. Although the spread of each ensemble’s range of spatial correlations remains consistent between the 0.44° and 0.22° members, the spread of model performance tends to be far tighter for the 0.22° ensemble. These comparisons quantitatively corroborate
FIGURE 8  Normalized principal component variance of the annual and semi-annual modes of the 0.44° (a) and 0.22° (b) CORDEX members [Colour figure can be viewed at wileyonlinelibrary.com]
the spatial evidence of Figures 4–7 that show there is a noticeable improvement in the modes of precipitation variability throughout the western U.S. as resolution increases. For a more quantitative comparison between RCMs within the two ensembles, Table 2 supplies a matrix of the statistics included in Figure 9’s Taylor diagrams with colour coding based on the relative-ensemble skill (green = better than average, red = poorer than average). Based on NARCCAP (Wang09) and NA-CORDEX (Lucas-Picher et al., 2016) evaluations, an initial assumption going into this study was that RCMs employing spectral nudging would be more capable of simulating modes of variability. Spectral nudging constrains the RCM towards the atmospheric wave pattern dynamics present in the forcing data (Von Storch et al., 2000) and should better translate the synoptic waves dominating the annual- and to some degree the semi-annual modes. Lucas-Picher et al. (2016) found RCMs employing spectral nudging better reproduced the mean statistics of weather regimes and seasonal anomalies than RCMs without spectral nudging. Of the NA-CORDEX RCM’s employing spectral nudging (CanRCM4, CRCM5-OUR, and WRF), little cohesive signal demonstrating a linking in model performance with spectral nudging was found. Of course, the ability of spectral nudging to translate the parent GCM’s wave patterns means the mixed performance of the NA-CORDEX RCMs employing spectral nudging could very well be tied to the struggles of parent GCMs. As such, these mixed signals should not influence the future use of spectral

**FIGURE 9** Taylor diagrams comparing EOF patterns for the western U.S. region of CORDEX members and CPCU gridded precipitation. Before comparison, 0.22° CORDEX and CPCU domains were regridded to match the lower resolution 0.44° CORDEX domain. Red and blue markers represent the 0.44° and 0.22° ensembles, respectively [Colour figure can be viewed at wileyonlinelibrary.com]
nudging, as there are clear advantages when provided skilful boundary conditions. It is worth mentioning, however, that the top-performing NA-CORDEX member (CRCM5-UQAM) did not use spectral nudging while its sibling CRCM5-OUR did, with mixed performance results across the individual CRCM5-OUR members.

The intermountain west was a region of particular weakness in the NARCCAP ensemble (Wang09). Taylor diagrams focusing on this region (34°N to 46°N; −118°W to −104°W), are provided in Figure S4. Overall, similar gaps in performance between the two ensemble resolutions were found for both the full western U.S. and Intermountain West domains. It is important to note that these mountainous regions feature very little first-order observations and that gridded precipitation data sets are suspected to underestimate the observed precipitation and what appears as a model wet-bias in these regions are less dubious than what comparisons initially show (Cavazos et al., 2020; Cerezo-Mota et al., 2016).

| 0.44° Ensemble | 0.22° Ensemble |
|----------------|----------------|
| **RCM** | **GCM** | **Winter-Summer** | **Summer-Fall** | **Spring-Fall** | **Semi-Annual 1** | **Semi-Annual 2** |
| CanRCM4 | CanESM2 | 0.882 | 0.209 | 0.014 | 0.610 | 0.383 | 0.017 | 0.808 | 1.770 | 0.014 | 0.552 | 2.045 | 0.030 |
| CRCM5-UQAM | CanESM2 | 0.951 | 2.028 | 0.014 | 0.791 | 1.683 | 0.015 | 0.866 | 1.671 | 0.014 | 0.697 | 2.076 | 0.031 |
| CRCM5-UQAM | GeMmat-Can | 0.965 | 2.012 | 0.014 | 0.751 | 1.446 | 0.016 | 0.842 | 2.015 | 0.014 | 0.698 | 1.823 | 0.029 |
| CRCM5-UQAM | GeMmat-MPI | 0.963 | 2.046 | 0.013 | 0.795 | 1.538 | 0.016 | 0.830 | 1.880 | 0.014 | 0.512 | 1.876 | 0.028 |
| CRCM5-UQAM | MPI-ESM-LR | 0.910 | 2.038 | 0.013 | 0.704 | 1.650 | 0.016 | 0.862 | 2.150 | 0.011 | 0.719 | 1.983 | 0.030 |
| HIRHAM5 | EC-EARTH | 0.931 | 2.072 | 0.014 | 0.605 | 2.222 | 0.018 | 0.501 | 2.016 | 0.018 | 0.473 | 2.086 | 0.020 |
| RCA4 | CanESM2 | 0.930 | 2.071 | 0.013 | 0.708 | 1.933 | 0.016 | 0.815 | 1.966 | 0.014 | 0.706 | 2.105 | 0.031 |
| RCA4 | EC-EARTH | 0.931 | 2.039 | 0.014 | 0.604 | 1.792 | 0.017 | 0.852 | 1.810 | 0.014 | 0.741 | 2.109 | 0.016 |
| RegCM4 | FDSL-ESM2M | 0.829 | 2.046 | 0.013 | 0.419 | 1.849 | 0.019 | 0.665 | 1.360 | 0.017 | 0.404 | 2.100 | 0.029 |
| RegCM4 | HadGEM2-ES | 0.845 | 2.033 | 0.014 | 0.287 | 1.687 | 0.020 | 0.613 | 1.507 | 0.017 | 0.409 | 1.995 | 0.022 |
| RegCM4 | MPI-ESM-LR | 0.841 | 1.969 | 0.013 | 0.397 | 1.672 | 0.019 | 0.787 | 2.030 | 0.015 | 0.323 | 2.109 | 0.028 |
| WRF | FDSL-ESM2M | 0.904 | 2.010 | 0.014 | 0.795 | 1.984 | 0.015 | 0.693 | 1.793 | 0.012 | 0.460 | 2.107 | 0.020 |
| WRF | HadGEM2-ES | 0.925 | 1.962 | 0.014 | 0.567 | 2.056 | 0.018 | 0.838 | 1.954 | 0.014 | 0.769 | 2.066 | 0.016 |
| WRF | MPI-ESM-LR | 0.920 | 2.063 | 0.013 | 0.745 | 1.718 | 0.016 | 0.761 | 1.983 | 0.012 | 0.448 | 1.972 | 0.020 |

**Table 2**: Taylor diagram statistics for the annual and semi-annual models of variability simulated by the historical 0.44° (top) and 0.22° (bottom) CORDEX ensemble members [Colour table can be viewed at wileyonlinelibrary.com]

**Note**: Statistics shown are relative to the CPCU observations with pattern correlation (corr), ratio of standard deviation (ratio), and root-mean-square error (RMSE). Green to red colour shading indicates the ensemble-relative performance of each member with red (green) equating poor (good) performance.

**Table 2**: Taylor diagram statistics for the annual and semi-annual models of variability simulated by the historical 0.44° (top) and 0.22° (bottom) CORDEX ensemble members [Colour table can be viewed at wileyonlinelibrary.com]

**4 | Future Precipitation Projections**

Given the better historical performance demonstrated in the 0.22° ensemble for both the annual and semi-annual modes of variability, as well as summertime NAM precipitation, we narrow our focus for this section on just the high-resolution ensemble. However, both ensembles
were examined, and noteworthy differences (or similarities) between the 0.22° and 0.44° ensembles will be mentioned where necessary. Additionally, with only one NA-CORDEX member simulating the least aggressive future RCP2.6 scenario, we opted to only examine the ‘stabilization scenario’ RCP4.5 projection and the ‘high-emission’ RCP8.5 projection.

4.1 Changes to future seasonal cycle

With the perspective on historical model performance provided in Section 3, we look to examine the basic projected changes to the future seasonal cycle of precipitation. Analysis on future changes to the seasonal cycle is based on the relative difference between the 1950 and 2005 historical period and the end-of-the-century period (2070–2099).

Figure 10 illustrates the percent difference of precipitation relative to the historical normal across each of the four meteorological seasons in each of the six regions of interest. Except for the Desert Southwest’s spring season, the RCP4.5 scenario shows a consensus change towards an increase in winter and spring precipitation throughout all regions of interest. This springtime reduction in precipitation is a common projection for monsoon-
dominated regions due to a less favourable thermodynamic environment causing what has been coined a ‘springtime convective barrier’ delaying the onset of global monsoon systems (Seth et al., 2011; Ashfaq et al., 2020) and the NAM (Cook and Seager, 2013). The NAM-influenced regions (Desert Southwest and Colorado Rockies) show increasing summertime precipitation while the remaining regions feature a mixed signal. Fall precipitation tends to align with the spring trends, with the exception of the Sierra Nevada domain, which has a slightly increasing ensemble trend for the spring and a slightly decreasing ensemble trend for the fall season. The positive changes in the fall are consistent with numerous studies from CMIP3, CMIP5, and regional climate models that show a delay in the demise of the monsoon rains (e.g., Cavazos and Arriaga-Ramírez, 2012; Cook and Seager, 2013; Torres-Alavez et al., 2014; Colorado-Ruiz et al., 2018; Ashfaq et al., 2020).

A greater number of NA-CORDEX members simulated the more aggressive RCP8.5 projections allowing for a more robust assessment of ensemble spread. In the RCP8.5 scenario, wintertime precipitation is predicted to increase by a majority of members; the exception being once again in the Desert Southwest, which exhibits mixed trends and a near-zero ensemble trend average. Springtime precipitation trends appear split by geographic location, with the northern and western domains (Pacific NW, Northern Rockies, Intermountain West) exhibiting a greater propensity towards increasing precipitation, while the southern and eastern domains exhibit either ensemble-wide drying (Desert Southwest) or no ensemble consensus with members suggesting both increasing and decreasing precipitation (Colorado Rockies and Sierra Nevada). Both summer and fall seasons exhibit mixed signals for precipitation changes including the summertime Desert Southwest although the ensemble spread is far greater for the summertime than the fall months with some members predicted an almost doubling of monsoon intensity as well as a significant number of members predicting a modest reduction. Similar seasonal and ensemble patterns were found in the 0.44° members, although the 0.22° ensemble contained greater member variance and more extreme changes.

4.2 Changes to future modes of variability

Here we examine how the four modes of variability discussed in Section 3.2 are projected to change by the 0.22° ensemble. To include longer, decadal climate cycles in the analysis, a slightly longer future climatology spanning 2050–2099 was examined. Due to the mathematical nature of EOF analysis, where both the spatial covariance and temporal variance shape the resulting EOF spatial pattern, a simple difference between independently computed EOF patterns for the future and historical time periods creates a potential for mathematical artefacts to dominate the difference patterns instead of illustrating the actual changes to modes of variability. In order to show the true change in the modes of precipitation variability by the end of the 21st century, Fourier filtering, and subsequent EOF analysis needs to also factor in the historical (i.e., background) covariance. With that in mind, the annual cycle of a grid’s historical and future time periods was joined into a single 24-month timeseries, which was then subjected to the Fourier filtering and EOF analysis. Finally, similar to the historical EOF analysis in Section 3, all future EOF patterns were standardized to share a uniform phase of PC variance before the different patterns were computed.

The resulting difference plots showing the future changes to the four modes of variability is shown for the three members simulating the RCP4.5 scenario are shown in Figure 11. The 15 members simulating the RCP8.5 scenario are broken into Figures 12 and 13. We note that in each of these figures, the winter-summer mode of variability is scaled by approximately an order of magnitude relative to the other modes in order to visualize the comparably smaller changes in the primary annual mode. Because differences in these figures can come from either a shift in the epicentre of EOF variance or a change in the magnitude in the PC variability itself, we include the raw future EOF patterns in Figure S5 for the RCP4.5 0.22° ensemble and Figures S6 and S7 for the RCP8.5 0.22° ensemble to help guide the reader in their interpretation of the differences. The following sections will focus on changes to each individual mode of variability across both RCP scenarios. We note that while historical model performance appeared more a function of which RCM was used, future changes appear to be clustered around which GCM was downscaled.

4.2.1 Changes to future winter-summer mode of variability

Both RCP scenarios tended to group into one of two outcomes, with RCM acting as a strong predictor into which outcome was produced. Given the winter-summer mode of variability is predominantly an east–west process (Figure 4-7), the first outcome unsurprisingly highlights changes to this east–west seesaw pattern. This east–west magnitude change is dominant in the three RCP4.5 members as well as the RegCM4, WRF members, and the CRCM5-UQAM (CanESM2) member of the RCP8.5 scenario.
scenario. The second suggest a far more dramatic change to the winter-summer mode of variability punctuated by a striking split over roughly the Oregon-California border. This outcome seems most apparent in the RCP8.5 CRCM5-OUR and CRCM5-UQAM members but is a pattern found in the other RCM8.5 members to a lesser degree as well. Comparing the raw historical (Figure 4–7) and future (Figures S5–S7) EOF patterns, this West Coast split suggest a growing degree of variability to the northern West Coast states; possibly in response to changing the strength of the mid-latitude westerlies. One unified outcome across the NA-CORDEX ensembles is the elevated winter-summer variability as a function of elevation. Given the strength of orographic uplift in the region, the strength of the westerlies and the seasonality of atmospheric humidity are likely driving this trend. In fact, the elevation relationship is a common trait found across all four modes of variability in a significant number of members in each RCP scenario suggesting humidity and orographic effects will grow in importance for seasonal precipitation.

4.2.2 Changes to future spring–fall mode of variability

The Spring-Fall mode presents more of a north–south seesaw pattern as the subtropical jet migrates with the transition seasons. The future difference plots across both RCP scenarios and resolutions indicate a consensus enhancement of the dominant variability signal into the Great Plains and Desert Southwest. This might suggest an enhanced strength of the subtropical jet, but also an expanding influence of tropical moisture advection coupling with the NAM throughout the Desert Southwest and the low-level jet that spreads Gulf of Mexico moisture into the Great Plains.

4.2.3 Changes to future semi-annual modes of variability

Here, we combine the discussion on both semi-annual modes of variability given they are each shaped to a greater degree than the winter–summer or spring-fall modes by local effects interacting with the NAM circulation and the sub-tropical jet stream. One common trait among many members spanning both RCP scenarios and domain resolutions is the West Coast’s north–south bifurcation in variability. Unlike the winter-summer mode of variability, the West Coast’s semi-annual mode commonly features this north–south bifurcation in the raw EOF patterns (Figures 4–7). We note that the severity of these changes is less so in the 0.22° ensemble compared to the 045° ensemble with many of the members of the RCP8.5 0.22° ensemble barely, or not at all, presenting...
FIGURE 12  Same as Figure 11, but for eight of the fifteen 0.22° RCP8.5 ensemble [Colour figure can be viewed at wileyonlinelibrary.com]
this change. The general consensus in the coarser resolution ensemble's West Coast semi-annual modes suggests the NAM circulation has the potential to become more variable in the future while also interacting with the subtropical jet stream to shift precipitation events westward into California as it interacts with sub-tropical moisture plumes. However, the reduction in this feature across the higher resolution ensemble, which has been shown to produce a more accurate NAM (Figure 3), presents an interesting contrast in outcomes that should be studied in more detail.

5 | DISCUSSION AND CONCLUSION

Through an evaluation of the historical skill of the NA-CORDEX ensemble's ability to reproduce the annual precipitation cycles and modes of variability, this study provides useful context for applications employing NA-CORDEX RCMs for studying the hydroclimatic impact on the western U.S. Two principle questions were focused on throughout the evaluation: (a) Do the systematic biases found in the previous generations of RCM...
downscaling (e.g., the NARCCAP ensemble) persist in the NA-CORDEX ensemble? and (b) Do finer domain grid resolutions and state-of-the-art model configurations improve the ability of the NA-CORDEX RCMs to resolve precipitation patterns and modes of variability? It is our hope that through this evaluation, subsequent hydrologic climate impact studies can better, and more efficiently, leverage the NA-CORDEX ensembles as well as gaining useful context on the underlying precipitation patterns shaping the interpretation of their own results.

When compared to the previous generation of NARCCAP RCMs, the historical evaluation of the NA-CORDEX ensembles presented here highlights the consensus improvement to the fidelity of simulated western U.S. precipitation. However, this evaluation also underscores ongoing seasonal biases such as wintertime overestimation of precipitation also present in the NARCCAP ensemble (although the expected underestimation of observed precipitation and gridded precipitation data sets likely causes the bias to appear more egregious than it actually is). Summertime precipitation continued to show a consensus dry bias in the 0.44° ensemble (except for over the Colorado Rockies). Roughly half of the 0.22° ensemble transitioned towards an over-active monsoon; presumably, a response within the RCM’s convective parameterizations to better resolve mesoscale terrain-atmosphere interactions, remote moisture transport, and local thermodynamics. In general, model performance was a function of which RCM was used, while future trend scenarios seem to cluster around which GCM was downscaled.

If hydro-climate impact studies require more accurate seasonality and precipitation patterns, the higher resolution 0.22° ensemble outperformed the 0.44° ensemble; both of which demonstrated improved skill relative to the NARCCAP ensemble. For studies interested in summertime precipitation associated with the NAM, the set of WRF RCM members demonstrated top skill across the ensembles. We note that WRF and many of the others more capable RCMs did tend to over-simulate NAM precipitation amounts. Worst performers for the NAM seasonal cycle were most of the CRCM5-UQAM members while generally the CRCM5-OUR members had a slightly more apparent NAM signal, although still dry-biases. Despite this, based on Taylor diagram comparisons, the CRCM5 RCMs stood out in their ability to reproduce the modes of annual and semi-annual variability; this was true for both 0.44° and 0.22° resolutions. Poorest performing RCM’s tended to be the RegCM4 members.

EOF analysis of Fourier-filtered precipitation showed the higher resolution 0.22° NA-CORDEX ensemble produced decidedly improved annual and semi-annual modes of variability along with an improved signal of the NAM summertime precipitation. Also improved, was the poor representation of the less-dominant modes of seasonal variability within the intermountain west. However, the excessive amplitude in the annual cycle found in the NARCCAP ensemble persists in both the lower- and higher-resolution NA-CORDEX ensembles and is primarily attributed to excessive wintertime precipitation, even in the reanalysis-driven simulations. The use of linear wavelet analysis via Fourier filtering and EOF analysis, while a traditional approach, is just one of several techniques to study variability. Non-linear wavelet analysis would present an interesting approach towards continued assessment of the ability of RCMs to capture annual modes of variability and should be considered by future studies. We also note that while we have examined the historical skill and future changes to the NA-CORDEX ensemble’s modes of variability, we have not examined the underlying physical mechanisms controlling these modes of variability and associated changes. Future study into the role the sub-tropical jet plays on the spring-fall mode of variability would provide better context into the mechanism behind the changes presented here. At the time of this study, the limited availability of the necessary three-dimensional atmospheric variables across the full NA-CORDEX ensemble hindered such an in-depth evaluation.

Another interesting finding was the mixed performance of RCMs employing spectral nudging, which, based upon NARCCAP evaluations, was hypothesized to augment the capacity of the RCM to reproduce historical modes of variability. This was not the case for the NA-CORDEX ensemble whereas the top performing CRCM5-UQAM RCM opted out of spectral nudging and several RCMs employing spectral nudging performed below the ensemble average. The bifurcation in performance between the pair of CRCM5 RCMs presents an intriguing comparison given the similarity in their model configurations. Future evaluations could take advantage of the similarity in these RCM configurations to isolate and study the effects of spectral nudging while still accounting for parent GCM variations, which is still a controlling factor in the RCM’s ability to resolve modes of variability.

We also acknowledge that even the higher 0.22° grid resolution might not be sufficient to address some of the hydrologic community’s needs, where even finer resolution data is required. We hope that through this evaluation, such studies can more efficiently leverage the NA-CORDEX ensembles whether it be through further dynamical downscaling or other statistical downscaling techniques like weather generators.

Lastly, should the next phase of NA-CORDEX decide to continue with the theme of multiple-resolution
ensembles, we suggest a matching 0.22° domain be considered. This would allow a valuable inter-comparison between the CMIP5-based RCMs and the next generation CMIP6-based RCM configurations.

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