Simulation of ENSO Teleconnections to Precipitation Extremes over the United States in the High-Resolution Version of E3SM

SALIL MAHAJAN, a QI TANG, b NOEL D. KEEN, c JEAN-CHRISTOPHE GOLAZ, b AND LUKE P. VAN ROEKEL d

a Oak Ridge National Laboratory, Oak Ridge, Tennessee
b Lawrence Livermore National Laboratory, Livermore, California
c Lawrence Berkeley National Laboratory, Berkeley, California
d Los Alamos National Laboratory, Los Alamos, New Mexico

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ABSTRACT: We evaluate the simulated teleconnection of El Niño–Southern Oscillation (ENSO) to winter season precipitation extremes over the United States in a long (98 years) 1950 control high-resolution version (HR; 25-km nominal atmosphere model horizontal resolution) of the U.S. Department of Energy’s (DOE) Energy Exascale Earth System Model version 1 (E3SMv1). The model bias and spatial pattern of ENSO teleconnections to mean and extreme precipitation in HR overall are similar to the low-resolution model’s (LR; 110 km) historical simulation (four-member ensemble, 1925–59). However, over the southeastern United States (SE-U.S.), HR produces stronger El Niño–associated extremes, reducing LR’s model bias. Both LR and HR produce weaker than observed increase in storm track activity during El Niño events there, but HR improves the ENSO-associated variability of moisture transport over SE-U.S. During El Niño, stronger vertical velocities in HR produce stronger large-scale precipitation, causing larger latent heating of the troposphere that pulls in more moisture from the Gulf of Mexico into the SE-U.S. This positive feedback also contributes to the stronger mean and extreme precipitation response in HR. Over the Pacific Northwest, LR’s bias of stronger than observed La Niña associated extremes is amplified in HR. Both models simulate stronger than observed moisture transport from the Pacific Ocean into the region during La Niña years. The amplified HR bias there is due to stronger orographically driven vertical updrafts that create stronger large-scale precipitation, despite weaker La Niña–induced storm track activity.

SIGNIFICANCE STATEMENT: New high-resolution Earth system models (ESMs) solve mathematical equations of fluid flow at much smaller spatial scales than prevalent ESMs, and thus are prohibitively expensive to compute. However, they can be useful for simulating accurate details of regional climate extremes that are driven by naturally occurring climate oscillations like El Niño–Southern Oscillation (ENSO). Here, we evaluate the simulation of ENSO-driven precipitation extremes over the United States in the high-resolution version of the U.S. Department of Energy’s new Energy Exascale Earth System Model version 1. We find that the high-resolution model improves upon its low-resolution counterpart over the southeastern United States by producing a better transport of moisture into the region from the Gulf of Mexico during El Niño. Over the U.S. Pacific Northwest, the high-resolution model simulates the atmospheric flow in more detail over the complex mountainous terrain. However, it also brings in more moisture from the Pacific Ocean just like the low-resolution model. This causes it to produce precipitation extremes during La Niña years there that are stronger than that observed in the real world.

KEYWORDS: ENSO; Extratropical cyclones; Hydrologic cycle; Teleconnections; Extreme events; Climate models

1. Introduction

Systematic model biases of Earth system models (ESMs) can be attributed to structural uncertainties and errors originating from the misrepresented and underresolved (subgrid scale) dynamical and physical processes like clouds and precipitation. New global high-resolution ESMs explicitly resolve finer-scale processes and features of topography, coastlines, land use, and mesoscale eddies in the ocean offering the potential of improved realism in simulations, congruent to that achieved by the global numerical weather prediction (NWP) community. NWP models have clearly demonstrated improved forecast skills partly attributable to model resolution (e.g., Bauer et al. 2015; Wedi 2014; Rodwell et al. 2010); however, NWP models are not required to conserve energy and water mass. Correspondingly, studies show that high-resolution ESMs (<50-km atmosphere model horizontal resolution) improve upon numerous features of standard-resolution (>100 km) models including the simulation of long-term mean climatology (Shaffrey et al. 2009; Delworth et al. 2012; Caldwell et al. 2019), tropical cyclones (e.g., Roberts et al. 2020; Balaguru et al. 2020), extratropical storm tracks and jet streams (e.g., Jung et al. 2012; Lu et al. 2015; Roberts et al. 2018), Southeast Asian monsoons (e.g., Delworth et al. 2012; Johnson et al. 2016), and subdaily precipitation rate distributions particularly around topography (e.g., Johnson et al. 2016; Fosser et al. 2020), and so on.

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~ Corresponding author: Salil Mahajan, mahajans@ornl.gov

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High-resolution models also simulate more intense precipitation extremes and lower amounts of drizzle, generally improving upon their low-resolution counterparts (Bador et al. 2020; Mahajan et al. 2015, 2018; Wehner et al. 2014). However, the improvement in model skill at simulating precipitation extremes is not always clear, especially if the tuning of the low- and high-resolution model remains the same (e.g., Bador et al. 2020; Zhang et al. 2016). High-resolution models explicitly resolve finer-scale dynamical and physical processes, producing stronger grid-scale vertical velocities especially over complex topography, thus allowing these finer resolved scales of motion to produce large-scale precipitation by condensation. This becomes apparent as the large-scale fraction of precipitation increases with model resolution, including its contribution to precipitation extremes (Rauscher et al. 2016; O’Brien et al. 2016; Kooperman et al. 2018; Mahajan et al. 2018; Demory et al. 2014; Z. Li et al. 2011). However, these high resolutions (∼25 km) in models are still much larger than the convective length scales (<4 km) required to generate large vertical velocities associated with moist convection and its associated vertical redistribution of energy. Thus, moist convection, along with boundary layer processes and other cloud processes, still needs to be parameterized. Parameterization schemes for convection are widely known to be a major source of model bias in simulating precipitation, particularly over the tropics (e.g., Jakob 2010; Zadra et al. 2018). Substantial tropical convection biases exist even at convection-permitting model resolutions (<4 km), and the impact of uncertainty at convective scales remains to be fully assessed (e.g., Zadra et al. 2018; Kühnlein et al. 2014).

In the NH winter, precipitation in the midlatitudes is largely a result of large-scale flow and synoptic-scale phenomena such as extratropical cyclones that produce precipitation over weather fronts. Recent studies (e.g., Roberts et al. 2018; Jung et al. 2012) suggest that adequate resolution of both the atmosphere (<80 km) and the ocean (<20 km) model components is required to simulate realistic midlatitude storm track activity including the number and intensity of extratropical cyclones. High-resolution atmosphere models (<80 km) are capable of more accurately resolving frontal zones, steep frontal gradients, and orography, which interact with large-scale flows and extratropical cyclones to produce storms and extreme precipitation (Roberts et al. 2018). Recent studies (Chelton and Xie 2010; Small et al. 2008; Jung et al. 2012; Roberts et al. 2018) also show that climate models with eddy-resolving ocean models more realistically simulate air–sea coupling and their local and remote atmospheric response including storm track activity that impact the hydrological cycle.

While it is important to evaluate models for climate extremes statistics, their dependence on the large-scale environment and natural modes of climate variability also needs to be evaluated. High-resolution GCMs provide the benefit of investigating regional extremes coupled to and embedded in the large-scale environment driving them, augmenting studies with high-resolution regional climate models (RCMs) that by design are forced by large-scale lateral boundary conditions. A recent study suggests that a multimodel ensemble of coupled high-resolution GCMs (about 50 km) and a multimodel ensemble of GCM-driven RCM simulations of equivalent resolution exhibit similar characteristics of precipitation distribution over Europe (Demory et al. 2020).

RCMs simulate smaller domains at higher resolution, to limit computational expense, and generally simulate mean precipitation and extremes well with a tendency to overpredict (e.g., Rauscher et al. 2010; Caldwell 2009; Halmstad et al. 2013). For example, RCMs were found to simulate stronger than observed wintertime precipitation extremes over California (Caldwell 2009). Also, they often show poor teleconnection response to ENSO over the United States, sometimes with opposite signs than those noted in observational data (Whan and Zwiers 2017). Global high-resolution models (∼50 km) generally exhibit equivalent or better skill than their low-resolution (∼100 km) counterparts in the simulation of low-frequency modes of climate variability like the North Atlantic Oscillation (NAO) and El Niño–Southern Oscillation (ENSO) that often drive climate extremes (e.g., Delworth et al. 2012; Zadra et al. 2018). Some studies also suggest improvement in the simulation of their teleconnections with increase in resolution (Delworth et al. 2012; Zadra et al. 2018; Mahajan et al. 2018). However, a recent high-resolution multimodel study suggests that the resolution sensitivity of the fidelity of these teleconnections is not completely clear in atmosphere–land-only simulations with prescribed SSTs and sea ice conditions (Molteni et al. 2020).

Here, we focus on the simulation of ENSO teleconnections to precipitation extremes over the United States in the boreal winter season. Winter season precipitation over the NH midlatitudes is largely dominated by large-scale precipitation with little contribution from convective processes. This choice allows the study of model resolution sensitivity of resolved scale precipitation, somewhat in isolation from the error-prone convective parameterizations. Recent studies of global high-resolution model simulations of precipitation extremes have quantified the general characteristics of extreme precipitation and their nonstationarity associated with temporal trends (e.g., Mahajan et al. 2015; Zhang et al. 2016; Zadra et al. 2018; Wehner et al. 2020). A recent study also quantified NAO teleconnections (Mahajan et al. 2018). However, the assessment of the fidelity of the teleconnections of low-frequency modes of climate variability on climate extremes in global high-resolution models has been fairly limited.

ENSO’s atmospheric and oceanic teleconnections govern a large fraction of the interannual variability of the global climate system (e.g., Wallace and Gutzler 1981; Trenberth et al. 1998). Over North America, ENSO-induced large-scale Rossby waves excite the atmospheric Pacific–North American (PNA) pattern (Horel and Wallace 1981; Trenberth et al. 1998). This is associated with a southward shift and an eastward extension of the storm track activity and jet stream over the North Pacific and North America during El Niño events (Trenberth et al. 1998; Eichler and Higgins 2006; Kenyon and Hegler 2008; Zhang et al. 2010; L’Heureux et al. 2015; Seager et al. 2010), resulting in an increase in precipitation mean and extremes over the southwestern and southeastern United States, particularly over the winter and spring seasons (e.g.,
Over the Pacific Northwest and northern United States and Canada, La Niña is associated with an increase in precipitation mean and extremes (e.g., Schubert et al. 2008; Whan and Zwiers 2017). GCMs also tend to credibly simulate these ENSO-induced shifts in storm tracks and jet stream, yielding changes in climate mean and extremes over the United States (e.g., Bengtsson et al. 2006, 2009; Weare 2013), although there is a large variability in ENSO simulation and its teleconnections across models (Weare 2013; Langenbrunner and Neelin 2013).

The following section briefly describes the E3SMv1 simulations analyzed here and the observational data used for model evaluation. Our methodology for quantifying extremes and their ENSO dependence as well as approaches to establish statistical significance of our results are described in section 3. Section 4 discusses our findings including our analysis of associated dynamics to understand the exhibited resolution sensitivity in our results. Finally, our results are summarized in section 5 along with a discussion of some caveats of the study and future work.
2. Model, simulations, and data

We evaluate the Anthropocene-era control run of the fully coupled high-resolution model version of the Energy Exascale Earth System Model (E3SM; Caldwell et al. 2019), referred to herein as HR, for precipitation extremes over the continental United States and its teleconnections with ENSO. The nominal resolution of the atmosphere model component is about 25 km with 72 vertical layers, and the ocean model component’s resolution spans from 18 km over the tropics to 6 km near the poles with 80 vertical levels. This control run uses constant external forcings representative of the year 1950, following the HighResMIP protocol, and has been integrated for 123 years as of writing. We disregard the first 25 years as spinup for the analysis presented here. More details about the initialization of the run and other model details like tuning parameter choices are described in Caldwell et al. (2019).

We also evaluate 1925–59 segments of four members of the historical simulation ensemble of the fully coupled low-resolution version of E3SM (herein called LR) that was run for the period 1850–2014. This model and its historical simulation ensemble are documented in Golaz et al. (2019). The nominal resolution of the atmosphere model component is about 110 km with 72 vertical layers, whereas the ocean model has nominal resolution of 60 km in the midlatitudes and 30 km near the equator and poles with 60 vertical layers. LR is energy balanced at preindustrial radiative forcings (Golaz et al. 2019). The external radiative forcings during the 1925–59 period are small with weak trends and are largely comparable to the year 1950 forcings used for the control high-resolution simulation. The forcings induce a weak trend in the top of the atmosphere radiation fluxes and global average temperatures during that period in the LR historical simulations (Golaz et al. 2019, their Figs. 22, 23, and 25). The LR ensemble for the 1925–59 segment thus offers a low-resolution counterpart to the long 1950 control high-resolution simulation.

The high- and low-resolution model tuning parameters differ for the Zhang–McFarlane (ZM) deep convection scheme; the Cloud-Layers Unified by Binormals (CLUBB) scheme for macrophysics, turbulence, and shallow convection; and for the dust emission factor. The time steps for several processes were also altered in the HR model to maintain numerical stability; for example, the atmosphere physics and dynamics

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**FIG. 2.** ENSO teleconnections. Regression of mean monthly winter (November–February) season geopotential height at 500 hPa against the Niño-3.4 index for the (a) MERRA-2 data, (b) ERA5 data, (c) low-resolution simulation ensemble, and (d) high-resolution simulation. Hatching indicates regions where the regression coefficient is statistically distinguishable from zero (significant) at the 95% confidence level based on a two-tailed Student’s t test and using the false discovery rate (FDR) approach for determining significance when multiple hypothesis tests are conducted simultaneously. Also shown are the root-mean-square error and pattern correlation as compared to MERRA-2 data.
coupling time step in HR was reduced to 15 min from 30 min in LR (Caldwell et al. 2019, their Table 2). Thus, a comparison of LR and HR would yield differences that are not just a result of differences in horizontal resolution but also differences in magnitude of tuning parameters of physical parameterizations and model time steps. These comparisons in our results section should thus be considered as an evaluation of a high-resolution production model and its low-resolution production counterpart.

We also evaluate precipitation extremes of a short low-resolution simulation that uses the exact tunings and year 1950 representative external forcings as the HR model, but still uses the LR model’s time steps (Caldwell et al. 2019), thus allowing us to evaluate the impact of model tunings used by the HR model in the LR model. This simulation, referred to as LRtunedHR, was run for about 50 years, but the daily precipitation data were saved for only about 30 years of that period. The low duration of the simulation with high-frequency temporal data, however, precludes robust analysis of ENSO teleconnections to precipitation extremes in that simulation.

Overall, HR generally improves upon LR based on global root-mean-square error metrics, and significantly improves over the mean bias in the simulation of sea ice extent in both hemispheres, particularly over the Labrador Sea in the summer (Caldwell et al. 2019). LR and HR exhibit similar ENSO characteristics and statistics in terms of spatial pattern as well as frequency spectrum (Caldwell et al. 2019). The models exhibit a realistic spectrum of the modulation of ENSO variability over 2–7-yr periods, with a stronger than observed peak at 3 years and lower than observed power at longer time periods. The spatial pattern of ENSO variability in the models also matches well with observations with a larger westward extent, as diagnosed from empirical orthogonal function analysis and composite analysis of El Niño and La Niña events based on the Niño-3.4 index (Golaz et al. 2019; Caldwell et al. 2019).

We use a gauge-based precipitation analysis from the National Oceanic and Atmospheric Administration (NOAA) Climate Prediction Center’s (CPC) data (Xie et al. 2007) to evaluate the simulation of precipitation by the models. CPC provides daily precipitation at a resolution of 0.5° × 0.5° degrees over global land areas and we use the data for the period 1979–2018. We also use the Global Precipitation...
Climatology Project’s (GPCP) 1-degree daily (1DD) precipitation product (v1.3), which merges gauge based and satellite retrieved precipitation estimates globally (Huffman et al. 2001), for the period 1997–2018. Further, to evaluate the models’ simulation of large-scale dynamical features like storm track activity and moisture transport, we use the National Aeronautics and Space Administration’s (NASA) Modern-Era Retrospective Analysis for Research and Applications (MERRA-2) reanalysis product (Rienecker et al. 2011) and ERA5 reanalysis, also for the period 1979–2018. MERRA-2 is produced at a resolution of $0.5^\circ \times 0.675^\circ$ (Rienecker et al. 2011) and ERA5 at a resolution of $0.25^\circ \times 0.25^\circ$ (Hersbach et al. 2020). Also, the Niño-3.4 index does not exhibit a statistically significant linear trend over the analyzed segment of the observational data as well as LR simulations (1925–59), suggesting that the difference in external forcings in HR (1950 forcings) and LR (historical forcings) would generally have little impact on our results.

3. Methodology

*Generalized extreme value distribution*

We quantify precipitation by using the block maxima approach of generalized extreme value (GEV) distribution. GEV is a three-parameter distribution that estimates the probability distribution of the block maxima ($z$; maxima of a data block, e.g., annual or seasonal maximum) of a variable:

$$G(z) = \exp \left( -1 + \left( \frac{z - \mu}{\sigma} \right)^{-1/\xi} \right),$$

where $\mu$, $\sigma$, and $\xi$ represent the location, scale, and shape parameter respectively of the distribution for $\xi > 0$. If $\xi = 0$, $G(z)$ is interpreted as the limit of the equation as $\xi \to 0$ (Coles 2001). Here, we use daily precipitation and a block size of a month. These GEV parameters are estimated using the maximum log-likelihood method and we test the goodness of fit of the estimated distribution using the Kolmogorov–Smirnov test.

To quantify the impact of ENSO on precipitation extremes, we use the Niño-3.4 index as a linear covariate to the location parameter, $\mu = \mu_0 + \alpha_{\text{Niño-3.4}} r$, where $r$ is the Niño-3.4 index for the corresponding month. The linear dependence of $\mu$ to the Niño-3.4 index is represented by $\alpha_{\text{Niño-3.4}}$, which is also estimated along with the other parameters while fitting the GEV to the data using the maximum log-likelihood approach. GEV is widely used to quantify extremes as well as to understand their relationships with large-scale climate drivers using such linear covariate approaches (e.g., Brown et al. 2008; Whan and Zwiers 2017; Kharin and Zwiers 2005; Mahajan et al. 2015; Evans et al. 2014; Mahajan et al. 2018; Xu et al. 2019; Patricola et al. 2020). This generalized linear regression approach to estimate trends in extremes within GEV has been shown to exhibit more statistical power than other approaches like ordinary least squares method (Zhang et al. 2004). The GEV distributions can be used to compute

![Fig. 4: ENSO teleconnections to winter precipitation extremes on nominal resolution grid of the low-resolution model. As in Fig. 3, but with CPC data and high-resolution simulation data conservatively mapped to the $1^\circ \times 1^\circ$ grid.](image-url)
the familiar $\tau$-yr (say 20 yr) return period levels ($R$) of extreme events by inverting the GEV distribution as $R(\tau) = \mu + (\sigma/\xi) \left[ -\log(1 - 1/\tau)^{-\xi} - 1 \right]$ for $\xi \neq 0$ and its limit for $\xi = 0$ (Coles 2001). Thus, any modeled dependence of $\mu$ on a covariate would be reflected equivalently in $R$.

Here, we fit a GEV to maximum daily precipitation for the months of November to February at each grid point following Whan and Zwiers (2017). Using maximum daily precipitation over the season instead of each month yields qualitatively similar results and we do not discuss them further here. To establish the significance of the linear dependence of $\mu$ on covariates, we use a deviance statistic-based test (Coles 2001). Data are fit to the GEV with and without Niño-3.4 as a linear covariate. The test statistic is the difference in the maximum log-likelihood estimates of the two fits (deviance $D$). The null distribution of this deviance statistic is known (Coles 2001) and we use it to conduct statistical significance tests.

We also apply corrections for multiple testing. Since we are simultaneously applying statistical tests to each grid point, say at the 0.05 significance level, we can expect 5% of the grid points to fail even if the null hypothesis is true, on account of the prescribed false positive rate (significance level). To account for such discrepancies with multiple testing, we use the false discovery rate approach, which exhibits more statistical power (lower false negative rates) than other pertinent approaches. This approach has been used in field significance testing for climate studies (e.g., Wilks 2006; Renard et al. 2008; Ventura et al. 2004), including climate extremes (e.g., Whan and Zwiers 2017; Mahajan et al. 2018), and for statistical reproducibility tests of climate models (Mahajan 2021).

4. Results

a. Precipitation extremes

Figure 1 shows the location parameter of the GEV fit to maximum daily precipitation for the months of November to February for the CPC data, GPCP data, LR model ensemble (1925–59), LRtunedHR simulation, and HR simulation. For LR, data were pooled together from each run for the four winter months for the period 1925–59 to fit the GEV, with a total of $34 \times 4 = 560$ data points at each grid point. For the single 98-yr-long HR run segment, we used $98 \times 4 = 392$ data points, and we used $30 \times 4 = 120$ data points for the 30-yr segment of the LRtunedHR simulation. For the 1980–2018 CPC data, we used $39 \times 4 = 156$ data points and for 1997–2018 GPCP data we used $22 \times 4 = 96$ data points to fit GEVs at each grid point. GPCP, LR, and HR data were bilinearly interpolated to the CPC grid of $0.5^\circ \times 0.5^\circ$ before conducting GEV analysis. Figure 1 also shows the root-mean-square error (RMSE) and pattern correlation of GPCP, LR, LRtunedHR, and HR against the CPC data.

The CPC data exhibit strong extremes over the southeastern United States (SE-U.S.) and Pacific Northwest (P-NW) along with fine-scale features associated with topography. The
Fig. 6. Extratropical cyclones and ENSO impacts. Standard deviation of the 2–6 day band passed filtered geopotential height at 500 hPa (a metric for storm track activity over midlatitudes) in the winter season (November–February) for (a) MERRA-2, (b) ERA5, (c) low-resolution model ensemble, and (d) high-resolution model data. Also shown is regression of the same metric against the Niño-3.4 index for (e) MERRA-2 data, (f) ERA5, (g) the low-resolution simulation ensemble, and (h) the high-resolution simulation. Color indicates vector magnitude. Hatching in (e)–(h) indicates regions where the regression coefficient is statistically distinguishable from zero (significant) at the 95% confidence level based on a two-tailed Student’s t test and using the false discovery rate (FDR) approach for determining significance when multiple hypothesis tests are conducted simultaneously. Also shown are root-mean-square error and pattern correlation as compared to MERRA-2 data.
GPCP matches well with the CPC data with a pattern correlation of 0.87 (for the period 1997–2018 for both GPCP and CPC) but exhibits stronger extremes over the SE-U.S. and weaker extremes over the P-NW. LR simulates much weaker extremes over the SE-U.S. and stronger extremes over the P-NW, where the effect of topography is subdued in the model owing to spatial resolution, and shows larger RMSE than the GPCP data compared to CPC data. This result is broadly consistent with current generation of ESMs, at similar resolutions, that overestimate extreme precipitation over the western United States and underestimate it over the SE-U.S. (Srivastava et al. 2020). The LRTunedHR simulation is generally similar to the LR run. HR overall is similar to the LR, and exhibits a smaller RMSE and a slightly stronger pattern correlation against CPC data as compared to LR.

LR data represent precipitation aggregated over its nominal resolution, which is larger than CPC and HR data, and thus lack the spatial variability on smaller scales. When we aggregate CPC and HR daily data to LR’s nominal resolution of $1^\circ \times 1^\circ$ using conservative mapping, and recompute the GEV parameters on that grid, we find that the results are similar. LR (HR) exhibits an RMSE of 5.77 (5.03) mm day$^{-1}$ and pattern correlation of 0.78 (0.83) as compared to CPC data at the $1^\circ \times 1^\circ$ resolution, similar to that at the CPC grid (Fig. 1).

Over the SE-U.S., HR simulates stronger extremes over the SE-U.S. as compared to LR, but only marginally. This weak increase in extremes with resolution is inconsistent with previous studies that find significant increase in magnitude of precipitation extremes over SE-U.S. with a similar increase in model resolution (e.g., Wehner et al. 2010; Wehner 2013; Mahajan et al. 2015). It is perhaps due to the differing physical parameterizations and their tunings in E3SM as compared to other models. The LRTunedHR exhibits weaker extremes than LR over the region, with the RMSE over the boxed region in Fig. 1a (29$^\circ$–39$^\circ$N, 262$^\circ$–277$^\circ$E) of 7.03 mm day$^{-1}$ against CPC data as compared to 5.21 mm day$^{-1}$ for LR—an increase in RMSE of about 40%. HR over the domain exhibits an RMSE of 5.47 mm day$^{-1}$. The increase in the strength of extremes in HR due to the increase in resolution there, as seen in previous studies, is likely being offset by these tuning changes that appear to dampen extremes. We plan to investigate this further in the future with additional experiments, for example by conducting an HR simulation with LR tuning parameters.

Over the P-NW, HR simulates finer-scale features associated with topography similar to the CPC data, but still simulates stronger extremes across the region. Interpolating the CPC data and HR data to an LR equivalent grid using conservative mapping still yields stronger extremes than the LR there and largely maintains finer-scale features (not shown), consistent with previous studies that suggest the nonlinear impact of the increase in model resolution on precipitation (e.g., Kendon et al. 2012; Chan et al. 2014; Wehner et al. 2010; F. Li et al. 2011; Wehner 2013; Mahajan et al. 2015, 2018). Precipitation extremes in LRTunedHR are similar to the LR simulation ensemble over the region, suggesting that the differences noted above in the HR as compared to LR are likely a response to increase in resolution. Winter mean climate also shows a similar bias in both LR and HR runs, with a dry eastern and a wetter western United States (Caldwell et al. 2019). Over the surrounding oceans of continental United States, the strongest extremes are noted over the North Atlantic in GPCP data. LR and LRTunedHR produce weaker than observed extremes there while HR produces stronger extremes comparable to GPCP. GPCP also produces strong extremes over the North Pacific off the Pacific Northwest coast. LR, LRTunedHR, and HR underestimate extremes there.

b. ENSO teleconnections to precipitation extremes

Both LR and HR simulate a credible ENSO (Caldwell et al. 2019; Golaz et al. 2019) and its teleconnection patterns as represented by a regression of the geopotential height at 500 hPa against the Niño-3.4 index (Fig. 2). The models exhibit a PNA-like pattern response similar to MERRA-2 and ERA5 data but show a weaker North Pacific low pressure anomaly and a stronger North American high pressure anomaly with its center located westward than observed, resulting in a higher RMSE against MERRA-2 as compared to ERA5.

Figure 3 shows the impact of ENSO on precipitation extremes quantified by the ENSO-dependent component of the location parameter ($\alpha_{\text{Niño3.4}}$) for CPC data as well as GPCP data, LR, and HR—all interpolated to the CPC grid. The CPC data exhibit statistically significant ENSO dependence over wide swaths of SE-U.S. extending from eastern Texas to North Carolina, similar to that exhibited by other datasets (Whan and Zwiers 2017). The GPCP data with a shorter time period show a similar pattern to CPC data over all (RMSE: 0.86 mm day$^{-1}$, pattern correlation: 0.79 for the period 1997–2018 for both GPCP and CPC). Over SE-U.S., however, they show statistical significance over only a few points over Florida. While the overall spatial pattern of ENSO dependence of precipitation extremes exhibited by CPC data is generally consistent with previous observational studies (Whan and Zwiers 2017; Zhang et al. 2010; Patricola et al. 2020; Yeh et al. 2018), it demonstrates a weaker response over the P-NW, California, and the northern United States. Over the P-NW, the CPC data response is spatially incoherent. Some studies show an increase, albeit over a few grid points, in extremes during La Niña (Zhang et al. 2010; Whan and Zwiers 2017; Patricola et al. 2020). These differences may be due to the different methodologies used to create the datasets as well as different time period used for analysis. The GPCP data exhibit an increase in precipitation extremes with La Niña over the P-NW; however, the response is weak and statistically not significant. Recent studies show that precipitation extremes show wide differences in different observational data products (Bador et al. 2020). Likewise, ENSO teleconnections to precipitation extremes could also be expected to be data dependent, and we plan to investigate this in the future.

The models generally simulate a credible simulation of the ENSO dependence of precipitation extremes with a RMSE of 0.71 (0.81) mm day$^{-1}$ and a pattern correlation of 0.71 (0.68) for LR (HR). These metrics are similar when the GEV parameters are computed at the LR nominal resolution of $1^\circ \times 1^\circ$ (Fig. 4). However, the LR simulates much weaker
FIG. 7. Moisture transport and ENSO impacts. Winter season (November–February) mean moisture transport for (a) MERRA-2, (b) ERA5, (c) the low-resolution model ensemble, and (d) high-resolution model data. Regression of mean monthly winter season moisture transport against the NAO index for (e) MERRA-2, (f) ERA5, (g) the low-resolution simulation ensemble, and (h) high-resolution simulation. Color indicates vector magnitude. Hatching in (e)–(h) indicates regions where the regression coefficient is statistically distinguishable from zero (significant) at the 95% confidence level based on a two-tailed Student’s t-test and using the false discovery rate (FDR) approach for determining significance when multiple hypothesis tests are conducted simultaneously. Also shown are root-mean-square error and pattern correlation as compared to MERRA-2 data.
than observed ENSO dependence of precipitation extremes over SE-U.S. Also, it shows a strong statistically significant ENSO dependence over the U.S. P-NW region, not noted in the CPC data. The HR simulates comparable to observed magnitude of ENSO dependence over the SE-U.S. with a similar spatial pattern. Over the SE-U.S. domain, indicated by the boxed region in Fig. 3a (29°–35°N, 260°–280°E), the RMSE for LR (HR) is 1.21 (1.00) mm day\(^{-1}\) against CPC data, indicating a reduction in RMSE of about 17% in HR as compared to LR. This improvement is about 10% when compared against GPCP data. The RMSE of GPCP data against CPC data over the SE-U.S. domain is 1.53 mm day\(^{-1}\), indicative of the large discrepancy among different observational data. LR’s bias over SE-U.S. is only slightly reduced (RMSE of 1.17 mm day\(^{-1}\)) when GEV parameters are computed at the 1° × 1° grid (Fig. 4). HR’s RMSE is 0.85 mm day\(^{-1}\) against CPC data on the 1° × 1° grid—a 27% reduction compared to LR (Fig. 4). The RMSE in HR reduces by about 8% as compared to LR when evaluated against GPCP data at the 1° × 1° grid.

Over the P-NW, HR also exhibits a statistically significant ENSO dependence that is even stronger than the LR. The exaggerated response over the P-NW to ENSO has been noted in the variable-resolution version of the Community Earth System Model (Huang and Ullrich 2017). Other modeling studies also suggest that the SE-U.S. and P-NW response to ENSO is robust across a few models (Whan and Zwieiers 2017). Over California and the northerly central United States, models differ in their responses in terms of magnitude as well as sign (Whan and Zwieiers 2017). Over the oceans, GPCP data exhibit no regions with significant ENSO dependence, but show an increase in extremes with ENSO off the Atlantic coast and P-NW. LR and HR simulate statistically significant ENSO dependence over North Atlantic and are comparable to GPCP. Off the coast of P-NW both LR and HR simulate weaker than observed ENSO dependence.

The extremes response is very similar in pattern to the mean response in both the observations and model simulations, consistent with previous studies (e.g., Yeh et al. 2018) that suggest similar mechanisms underlie the mean and extreme response to ENSO. Figure 5 shows the regression of winter season mean precipitation against the winter season mean Niño-3.4 index. Similar to precipitation extremes response, CPC data exhibit a statistically significant relationship with ENSO only over the SE-U.S. The GPCP data show a similar relationship, and its spatial pattern is strongly correlated with the CPC data (RMSE: 0.11, pattern correlation 0.85). The LR simulates a weaker than observed response over the SE-U.S., and stronger relationship over the P-NW with a larger RMSE and smaller pattern correlation against CPC as compared to GPCP. The HR improves over the LR with stronger response over the SE-U.S. similar to CPC and GPCP data, but an even stronger response over the P-NW and a weaker response over California, also noted by Caldwell et al. (2019).

c. Extratropical cyclone activity and its ENSO dependence

We estimate the extratropical cyclone (storm track) activity as the standard deviation of the 2–6-day bandpass-filtered daily geopotential height at 500 hPa for the winter season (November–February). ERA5, LR and HR data were bilinearly interpolated to the MERRA-2 grid before conducting these analyses. Figures 6a–d show the storm track activity metric for MERRA-2, ERA5, LR, and HR for all the years of data analyzed over the Pacific Ocean and North America. Both the LR and HR simulate credible storm track activity over the midlatitude Pacific Ocean and North America as compared to MERRA-2 data with high pattern correlations, with the HR producing a little stronger activity over North America (Fig. 6).

Figures 6e–h show the regression of the storm track metric for each winter season against the Niño-3.4 index, as a measure of ENSO dependence of storm track activity. During El Niño years, MERRA-2 and ERA5 data indicate a southward shift in the storm track activity with reduced (increased) activity in the higher (lower) midlatitudes and are virtually identical to each other. El Niño-induced reduced storm track activity is stronger over North America than over the Pacific, consistent with previous studies (Seager et al. 2010; Eichler et al. 2015; Bengtsson et al. 2009). Over continental North America, there is a statistically significant reduction in storm track activity over parts of the P-NW and enhanced activity over parts of the SE-U.S., Mexico, and the Gulf of Mexico (Fig. 6). This increase in storm track activity over the SE-U.S. is associated with the enhanced precipitation mean and extremes there during El Niño years (Figs. 3 and 5). However, over the P-NW where there is a significant increase in storm track activity during La Niña years (reduced activity during El Niño years) there seems to be no significant impact on precipitation extremes in CPC data (Fig. 3) and a weak impact in the GPCP data.

LR also simulates a southward shift of storm track activity during El Niño years with large regions of P-NW and the northern central United States exhibiting weaker than observed reduction in activity (RMSE: 0.83 m, pattern correlation: 0.73). Despite this weaker response, there is a stronger than observed enhancement of precipitation extremes during La Niña years over the P-NW (Fig. 3). There is a weaker than observed enhancement of storm track activity over the lower midlatitudes though. This weaker response is associated with a reduced enhancement of precipitation mean and extremes over SE-U.S. during El Niño years (Fig. 3). HR shows a weaker than observed southward shift in storm track activity during El Niño years, but with a stronger than observed reduction in storm track activity over the northern central United States (RMSE: 0.75 m, pattern correlation: 0.79). There is an insignificant response over the P-NW as well as a weaker response over southeastern Texas and the Gulf of Mexico. Nonetheless, there is an intensification of precipitation extremes, stronger than LR, over the P-NW during La Niña years, and enhancement of precipitation extremes over the SE-U.S. during El Niño years (Figs. 5 and 3).

The above implies that the HR simulates stronger extremes compared to observations and LR despite weak storm track activities, suggesting a role for other mechanisms like moisture transport and vertical mass fluxes, which we explore.
FIG. 8. Moisture transport during extreme events over SE-U.S. Composite of vertically integrated moisture transport for all winter season precipitation extreme events (defined as monthly maximum) over a part of the Texas and Louisiana Gulf coast (boxed) for the (a) MERRA-2, (b) ERA5, (c) low-resolution model ensemble, and (d) high-resolution model simulation. Also shown is the difference in composite of vertically integrated moisture transport for all winter season precipitation extreme events during respective El Niño years and La Niña years (El Niño minus La Niña) for (e) MERRA-2, (f) ERA5, (g) the low-resolution model ensemble, and (h) high-resolution model simulation. Color represents vector magnitude. Hatching indicates regions that exhibit statistical significance at the 95% confidence level based on a two-tailed Student's t test (bootstrapping approach yields similar results). Also shown are the root-mean-square error and pattern correlation as compared to MERRA-2 data.
below. It should be noted that the bandpass filter approach we use here does not explicitly quantify individual storms and their intensities. Previous studies suggest that improvements in high-resolution models are clearly discerned by feature tracking metrics (Jung et al. 2012; Roberts et al. 2018). Since we are investigating the aggregate impact of ENSO on general circulation features associated with extratropical cyclone activity here, and not individual cyclones, we believe that a bulk metric like the bandpass filter-based metric is sufficient.

d. Moisture transport and its ENSO dependence

Figures 7a–d show the mean winter season moisture transport for MERRA-2, ERA5, LR, and HR respectively. MERRA-2 and ERA5 data exhibit virtually identical behavior. LR and HR simulations of moisture transport to the P-NW and SE-U.S. are generally similar to MERRA-2 and ERA5 data, with a little weaker transport to the western United States and a little stronger moisture transport to the SE-U.S. from the Gulf of Mexico. Figures 7e–h show the regression of winter season moisture transport against the Niño-3.4 index for MERRA-2, LR, and HR respectively. MERRA-2 and ERA5 data exhibit a strong north to northwest moisture transport along the P-NW coast during El Niño years. This is accompanied by a reduction in moisture transport into the P-NW and continental United States, although this response is not statistically significant. Over the SE-U.S., MERRA-2 and ERA5 show an increase in transport into the region from the Gulf of Mexico and the North Atlantic, with statistically significant response only over Florida. These responses in MERRA-2 and ERA5 data are broadly consistent with the large-scale atmospheric flow associated with the Z500 response (Fig. 2) and generally similar to results from previous studies analyzing other reanalyses datasets (e.g., Kim and Alexander 2015).

LR (HR) credibly simulates ENSO dependence of moisture transport with an RMSE of 4.19 (5.06) kg m⁻¹ s⁻¹ and a pattern correlation of 0.76 (0.65). LR simulates an increase in northwestern transport along and across the P-NW coast in Canada and Alaska. But, it is also accompanied with a strong statistically significant reduction (increase) in moisture transport into the U.S. P-NW and continental United States during El Niño (La Niña). This is also consistent with the Z500 response in the models (Fig. 2) with a weaker low pressure anomaly over the North Pacific and the westward North American high pressure anomaly that result in anomalous flow from the U.S. P-NW to the eastern North Pacific. This discrepancy in the simulation of moisture transport into the P-NW in the model appears to result in the stronger than observed simulated increase in mean and extreme precipitation over the P-NW in both LR and HR during La Niña years (Figs. 3 and 5).

Over the SE-U.S., LR simulates an increase in eastward moisture transport from the Gulf of Mexico across Florida, similar to MERRA-2 and ERA5 data, but produces little additional moisture transport into the SE-U.S. coastal areas from the Gulf of Mexico or the North Atlantic during El Niño. This is consistent with the anomalous Z500 response to ENSO (Fig. 2) with the stronger low pressure anomaly over the SE-U.S. and the North Atlantic in LR resulting in anomalous flow along the northern coast of the Gulf of Mexico in the SE-U.S. and over Florida. In addition to the weaker storm track activity (Fig. 6), this stronger than observed reduction in moisture transport into the SE-U.S. enhances the subdued response of precipitation extremes over the region during El Niño events compared to observations. HR’s simulation of the moisture transport to the SE-U.S. is also consistent with the Z500 response (Fig. 2) and comparable to MERRA-2 and ERA5 data, with transport into the SE-U.S. coastal area from the Gulf of Mexico, albeit a little stronger. The RMSE for HR over the SE-U.S. (boxed region, Fig. 7e; 29°–35°N, 260°–280°E) is reduced by about 8% against MERRA-2 as compared to LR. The pattern correlation of HR also improves to 0.98 against MERRA-2 as compared to 0.89 for LR. This improved moisture transport in HR (despite an overall weaker skill over the whole domain shown in the figure) appears to explain, at least partly, the improvement in precipitation extremes response to ENSO in HR as compared to the LR. The impact of improved moisture transport is however offset by the weaker than observed increase in storm track activity during El Niño (Fig. 6).

e. Moisture transport during extreme events

1) SOUTHEAST UNITED STATES

Figures 8a–d show the composite of vertically integrated moisture transport during extreme event days within the boxed region in southeast Texas and Louisiana for MERRA-2, ERA5, LR, and HR. Extreme event days are defined as the days with maximum daily precipitation in each winter season. For creating the composite, vertically integrated moisture data are collected for each such extreme event day for each grid point in the domain individually, for all years of data. MERRA-2 and ERA5 data show that extremes in the region are associated with large moisture transport from the Gulf of Mexico, and the LR and HR simulations compare well with MERRA-2 data. The statistical significance of the results is determined using a two-tailed Student’s t test conducted at the 95% significance level. The bootstrapping method of determining confidence intervals yielded similar results (not shown here).

Figures 8e–h show the difference in the composite of moisture transport during extreme events over the boxed region during El Niño years and La Niña years (El Niño minus La Niña) in MERRA-2, ERA5, LR, and HR respectively. El Niño (La Niña) years are defined as years when the standardized seasonal average Niño-3.4 index is greater (less) than one. MERRA-2 and ERA5 data indicate that moisture transport into the region during El Niño is significantly intensified as compared to La Niña years, thus contributing to precipitation extremes. The LR, on the other hand, simulates a statistically significant reduction in moisture transport during extreme events in the region during El Niño years, consistent with the mean response (Fig. 7), explaining the weaker than observed simulated precipitation extremes over SE-U.S. during El Niño years. The HR
FIG. 9. Moisture transport during extreme events over P-NW. Composite of vertically integrated moisture transport for all winter season precipitation extreme events (defined as monthly maximum) over a part of the U.S. Pacific Northwest (boxed) for (a) MERRA-2, (b) ERA5, (c) the low-resolution model ensemble, and (d) high-resolution model simulation. Also shown is the difference in composite of vertically integrated moisture transport for all winter season precipitation extreme events during respective La Niña years and El Niño years (La Niña — El Niño) for (e) MERRA-2, (f) ERA5, (g) the low-resolution model ensemble, and (h) high-resolution model simulation. Color represents vector magnitude. Hatch ing indicates statistical significance at the 95% significance level based on a two-tailed Student’s t test (bootstrapping approach yields similar results). Also shown are root-mean-square error and pattern correlation as compared to MERRA-2 data.
simulates an increase in moisture transport during extreme events in El Niño years but the response is weaker than MERRA-2 and ERA5 data, perhaps due to the weaker than observed storm track activity response in HR (Fig. 6). Nonetheless, this improvement in moisture transport during extreme events during El Niño years in HR appears to contribute to the improved precipitation extreme response as compared to LR, in addition to the improvement in mean moisture transport (Fig. 7).

2) PACIFIC NORTHWEST REGION

Figure 9 shows the composite of moisture transport over P-NW during precipitation extreme event days over a coastal part of the region (boxed), suggestive of atmospheric rivers making landfall into the region (e.g., Zhu and Newell 1998). Extreme events there are associated with increase in moisture transport from the Pacific Ocean in MERRA-2 and ERA5 reanalyses as well as both LR and HR, with the models simulating a stronger than observed influx in the region (Figs. 9a–c). Regional and variable modeling studies (Huang and Ullrich 2017; Huang et al. 2020) indicate that improvement in the simulation of extreme precipitation over the P-NW with resolution in response to atmospheric rivers, for example by 20%–30% in the 0.25° variable resolution model embedded in a 1° global model. These enhancements can be attributed to the improved representation of complex terrain by the high-resolution simulation (Huang and Ullrich 2017; Huang et al. 2020).

During La Niña, MERRA-2 and ERA5 composites (La Niña minus El Niño) show that there is significantly more moisture transport into the region (suggesting an intensification of atmospheric rivers) during extreme events as compared to El Niño events (Figs. 9e,f). LR simulates a stronger than observed increase in moisture transport during extreme events during La Niña years plausibly contributing to the stronger than observed extremes in the region. However, despite producing stronger than LR and observed extremes during La Niña years, HR fails to simulate that response, with the HR simulating a weakening of moisture transport into the region from the North Pacific during La Niña as compared to El Niño years (Figs. 9g,h).

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**FIG. 10.** ENSO impacts on vertical velocity. Regression of mean monthly winter (November–February) season vertical pressure velocity at the 500-hPa hybrid sigma model level against the Niño-3.4 index for (a) MERRA-2, (b) ERA5, (c) the low-resolution simulation ensemble, and (d) the high-resolution simulation. Negative pressure velocity implies updrafts. Hatching indicates regions where the regression coefficient is statistically distinguishable from zero (significant) at the 95% confidence level based on a two-tailed Student’s t test and using the false discovery rate (FDR) approach for determining significance when multiple hypothesis tests are conducted simultaneously. Also shown are root-mean-square error and pattern correlation as compared to MERRA-2 data.
FIG. 11. Vertical velocity during winter precipitation extremes over SE-U.S. Composite of vertically pressure velocity for all winter season precipitation extreme events (defined as monthly maximum) over a part of the Texas and Louisiana Gulf coast (boxed) for (a) MERRA-2, (b) ERA5, (c) the low-resolution model ensemble, and (d) high-resolution model simulation. Also shown is the difference in composite of vertically integrated moisture transport for all winter season precipitation extreme events during respective El Niño years and La Niña years (El Niño – La Niña) for (e) MERRA-2, (f) ERA5, (g) the low-resolution model ensemble, and (h) high-resolution model simulation. Negative values indicate upward velocity. Hatching indicates statistical significance at the 95% significance level based on a two-tailed Student’s t test (bootstrapping approach yields similar results). Also shown are root-mean-square error and pattern correlation as compared to MERRA-2 data.
Thus, it seems there is little role of moisture transport variability during ENSO events over P-NW in amplifying the HR model bias in precipitation extremes response to ENSO there.

\textit{f. Vertical updrafts and plausible mechanisms for resolution sensitivity}

1) \textbf{SOUTHEAST U.S. REGION}

The scale incognizance of subgrid-scale parameterizations of convective and large-scale precipitation processes results in stronger precipitation with increase in resolution (e.g., Yang et al. 2014; O’Brien et al. 2016; Rauscher et al. 2016). High-resolution models simulate stronger vertical velocities due to fluid continuity (e.g., Yang et al. 2014; O’Brien et al. 2016; Rauscher et al. 2016), which impacts large-scale precipitation, as large-scale precipitation is parameterized to be dependent on resolved scale upward mass and moisture fluxes via grid box saturation (Morrison and Gettelman 2008).

Figures 10a–d show the regression of mean winter season vertical pressure velocity at the 500-hPa model hybrid sigma level (negative values indicate upward direction) against the Niño-3.4 index for MERRA-2, ERA5, LR, and HR respectively. HR simulates stronger vertical updraft response to ENSO than LR over the SE-U.S., producing statistically significant increase in vertical velocities with increase in Niño-3.4 index along the SE-U.S. coastlines, similar to MERRA-2 and ERA5 (Fig. 10). LR does not exhibit a significant response over the SE-U.S. coastlines, except over Florida (Fig. 10). The increased vertical velocity in HR over the SE-U.S. results in a stronger large-scale (resolved scale) precipitation, which by a release of latent heat in the middle and upper troposphere could enhance the vertical updrafts bringing in more moisture from the surrounding ocean. This feedback mechanism is exhibited in our results with enhanced mean precipitation (Fig. 5), mean moisture transport (Fig. 7), and enhanced vertical uplifts in the HR model as compared to the LR model (Fig. 10).

Extreme precipitation also appears to be affected by this feedback with the simultaneous enhancement of moisture transport into the region during extreme events in the presence of ENSO forcing. Figures 11a–d show the composite of vertical velocity at 500 hPa during extreme events over the boxed region in southeastern Texas and Louisiana for the MERRA-2, ERA5, LR, and HR runs respectively. The model simulations exhibit similar responses to MERRA-2 and ERA5. Figures 11e–h show the difference in composite of vertical velocity during extreme events during El Niño and La Niña events (El Niño minus La Niña). During El Niño events, MERRA-2 exhibits strong uplifts during extremes as compared to La Niña events over the southern U.S. Gulf Coast. ERA5 exhibits a more widespread increase in vertical velocity along the Gulf Coast and north of it during extremes in El Niño events and MERRA-2 and ERA5 show large differences resulting in a poor pattern correlation.

During El Niño events, the increase in vertical updrafts is much stronger in the HR as compared to LR in the region (Figs. 11c,d) and compares well with MERRA-2 and ERA5 data over the Gulf Coast, yielding stronger precipitation extremes (Fig. 3) and stronger moisture transport into the region (Fig. 8). Previous studies show that latent heat associated with extratropical cyclones is important for simulating realistic winter storms. The above mentioned positive feedback between latent heating and storms has also been shown to be stronger in high-resolution models (Willison et al. 2013). High-resolution models simulate smaller scales of diabatic heating, which produce stronger eddies and intense extratropical cyclones and realistic winter storms that are not produced by low-resolution models (Willison et al. 2013).

2) \textbf{PACIFIC NORTHWEST REGION}

HR simulates a much stronger relationship of vertical uplifting with ENSO over the P-NW—stronger than MERRA-2 and ERA5—simulating strong and varied responses over topographically driven regions of the western United States (Fig. 10). The LR response over the region is more homogeneous than the HR given its smoother orography (Fig. 10). The spatial pattern of the vertical velocity response to ENSO over P-NW (uplift during La Niña) is similar to that of mean precipitation as well as extreme precipitation (Figs. 5 and 3) in both LR and HR. This stronger response in vertical velocity in HR occurs despite the weaker storm track activity in the HR model there, which induces vertical updrafts (Fig. 6). Extreme events in the region are associated with vertical uplifting in both the models, similar to MERRA-2 and ERA5, with the HR producing stronger vertical velocities associated with its stronger extremes, as is evident in composites (Figs. 12a–d). Orographic lifting over complex terrain is also found to be the key mechanism in the improvement of the simulation of extremes over the P-NW in high-resolution regional models (Huang and Ulbrich 2017; Huang et al. 2020). Orographic lifting was also found to be a factor in the improved response of precipitation extremes to NAO over Northwestern Europe in a recent study (Mahajan et al. 2018).

However, there is no coherent difference between vertical uplift during extreme events in La Niña and El Niño years in HR and LR (unlike in MERRA-2, which shows a coherent response), although the response is weak in ERA5 (Figs. 12e–h). This indicates the absence of the feedback mechanism between vertical uplifting, latent heating, and moisture transport (Fig. 9) in the models during extreme events associated with La Niña events over the region, unlike the SE-U.S. The above suggest that given similar amounts of mean moisture transport in the two models during La Niña years (Fig. 7), stronger orographic uplift from atmospheric flow over steep topography—even in the absence of strong extratropical cyclone activity—can generate stronger mean and extreme precipitation in HR over the P-NW during La Niña years.

While precipitation is an indicator of column-integrated latent heating, it does not provide any information about the vertical profile of diabatic heating. The vertical profile of latent heating has been shown to be a key influence on the evolution and structure of extratropical cyclones as well as that of associated storms through modulation of potential vorticity anomalies (e.g., Willison et al. 2013; Hawcroft et al. 2016).
Fig. 12. Vertical velocity during winter precipitation extremes over P-NW. Composite of vertically pressure velocity for all winter season precipitation extreme events (defined as monthly maximum) over a part of the U.S. Pacific Northwest (boxed) for (a) MERRA-2, (b) ERA5, (c) the low-resolution model ensemble, and (d) high-resolution model simulation. Also shown is the difference in composite of vertically integrated moisture transport for all winter season precipitation extreme events during respective La Niña years and El Niño years (La Niña – El Niño) for (e) MERRA-2, (f) ERA5, (g) the low-resolution model ensemble, and (h) high-resolution model simulation. Negative values indicate upward velocity. Hatching indicates statistical significance at the 95% significance level based on a two-tailed Student’s $t$ test (bootstrapping approach yields similar results). Also shown are root-mean-square error and pattern correlation as compared to MERRA-2 data.
5. Summary and discussion

We evaluate the simulated teleconnection of ENSO to winter season precipitation extremes over the United States in a control high-resolution version of the E3SMv1. HR improves both the spatial pattern and the magnitude of ENSO (quantified by the Niño-3.4 index) teleconnections to extreme (as well as mean) precipitation over the southeastern United States (SE-U.S.) as compared to the low-resolution model’s historical simulation ensemble, with stronger precipitation extremes, reducing the RMSE by 17% when compared against CPC data. But, the discrepancy between observational datasets over the region is also large, with the GPCP data exhibiting a stronger response to ENSO than the CPC data. However, HR also amplifies the stronger than observed ENSO impacts over the Pacific Northwest, with La Niña events associated with stronger extremes there. Both LR and HR simulate a weaker than observed increase in extratropical cyclone activity during El Niño events over SE-U.S. The bias over the P-NW region in LR and HR is associated with stronger than observed moisture transport in the region. The amplified bias in the HR model appears to be due to stronger than observed orographic lifting in HR as it resolves more fine-scale features around complex topography.

HR improves the ENSO impacts on mean moisture transport over the SE-U.S., contributing to the reduction in model biases there. Our results suggest the following mechanism could plausibly explain the reduced bias in HR: stronger vertical updrafts in HR during El Niño produce stronger stable condensation resulting in larger latent heating of the troposphere pulling in more moisture from the Gulf of Mexico into the SE-U.S. This positive feedback results in stronger mean precipitation—improving upon the LR—and is evident from a composite analysis of precipitation extreme events during ENSO events over the region. It should be noted however, that the HR and LR differ in their model tuning parameters in addition to spatial resolution. In a recent multimodel study with prescribed SST and sea ice conditions, where the low- and high-resolution model counterparts used the same low-resolution model tunings, Molteni et al. (2020) found the resolution sensitivity of ENSO teleconnections to mean precipitation unclear.

There are other mesoscale and synoptic processes that impact midlatitude winter precipitation extremes. For example, the western United States is significantly impacted by land-falling atmospheric rivers (e.g., Zhu and Newell 1998; Knippertz and Wernli 2010), which are known to be modulated by ENSO (Knippertz and Wernli 2010; Guan and Waliser 2015; Kim et al. 2019; Guirguis et al. 2019). Atmospheric blocking, also modulated by ENSO, impacts midlatitude precipitation extremes and its simulation tends to improve with increase in resolution (e.g., Kinter et al. 2013). Further, SST fronts and mesoscale eddies have been shown to drive winds, clouds, and precipitation and impact storm track activity and remote precipitation both in observational studies as well as high-resolution models (e.g., Chelton et al. 2004; Small et al. 2008; Jung et al. 2012; Roberts et al. 2018). We plan to investigate the explicit role of these phenomena in modulating ENSO-driven precipitation extremes in HR in the future.

The diverse forms of ENSO’s SST spatial pattern have different impacts on global climate variability (Capotondi et al. 2015; L’Heureux et al. 2015; Timmermann et al. 2018; Patricola et al. 2020). Our analysis of CPC data from 1979–2018 includes the 2015/16 strong central Pacific El Niño years, which did not influence the western United States as strongly as the other strong canonical El Niño years (1981–82 and 1997–98). The central Pacific El Niño, with the strongest warming around the date line, elicits a different wave train pattern as compared to the canonical eastern Pacific El Niño, yielding a more southward transition of the jet streams and storm tracks impacting precipitation mean and extremes over the United States (Kim and Alexander 2015; Okumura 2019; Yu and Zou 2013). A recent study (Patricola et al. 2020) demonstrates that a more physically based and flexible ENSO index better explains the variability of precipitation extremes than the rigid Niño-3.4 index over the United States. In the future we would use these other ENSO indices, like the convective threshold based index (Okumura 2019; Patricola et al. 2020; L’Heureux et al. 2015) that capture the diversity of ENSO, as covariates in our GEV analysis to fully capture ENSO impacts of precipitation extremes and evaluate HR in that context.

Also, North American climate is known to be impacted by other natural modes of climate variability like the NAO, MJO, Pacific decadal oscillation (PDO), and Atlantic multidecadal oscillation (AMO). The interaction of these modes with ENSO could either strengthen or weaken the impact of ENSO on climate mean and extremes (e.g., Moon et al. 2011; Roundy et al. 2010; Riddle et al. 2013; Enfield et al. 2001; Tootle et al. 2005). In the future, we plan to analyze the impact of multiple modes of climate variability including a GEV-based analysis with multiple covariates representing these different natural modes of climate variability. Also, previous studies (e.g., Gросман et al. 2004, 2005; Mahajan et al. 2009) suggest that precipitation should be averaged over spatially homogeneous regions to detect signals in precipitation extremes. In the future, we plan to conduct our analysis averaged over watershed scales and other homogeneous regions identified using regionalization approaches.
The benefit of high-resolution global models for future climate projections still remains to be clearly demonstrated, despite their documented benefits in reducing some model biases (e.g., Zadra et al. 2018). Given their formidable computational expense, it is critical to assess their advantages, particularly for simulating climate extremes, which have large societal impacts. Improved future projections by high-resolution models would also be necessary to provide better boundary conditions that capture large-scale circulation features accurately to force higher-resolution—possibly convection-permitting (<4 km)—regional models. It is thus important to understand if high-resolution models capture the circulation patterns induced by large-scale modes of climate variability (e.g., Roberts et al. 2018) and their impact on regional hydrological extremes. Our study is a step toward addressing this challenge by analyzing the simulation of ENSO-driven precipitation extremes in a nearly century-long high-resolution model run. We find that the high-resolution model does improve the simulation of the intensity and spatial distribution of ENSO-induced extremes over the SE-U.S. where different observational datasets are generally in agreement and exhibit significant ENSO impacts. This result supports an increased confidence in ENSO-induced extremes simulated in future projections with global high-resolution models. Similar results from other modeling centers would further boost it.

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Data availability statement. All the data used are listed in the references. The E3SM code that produced the analyzed simulations is open-source and can be accessed from https://e3sm.org/model. Simulation output is available through the Earth System Grid Federation (ESGF).

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