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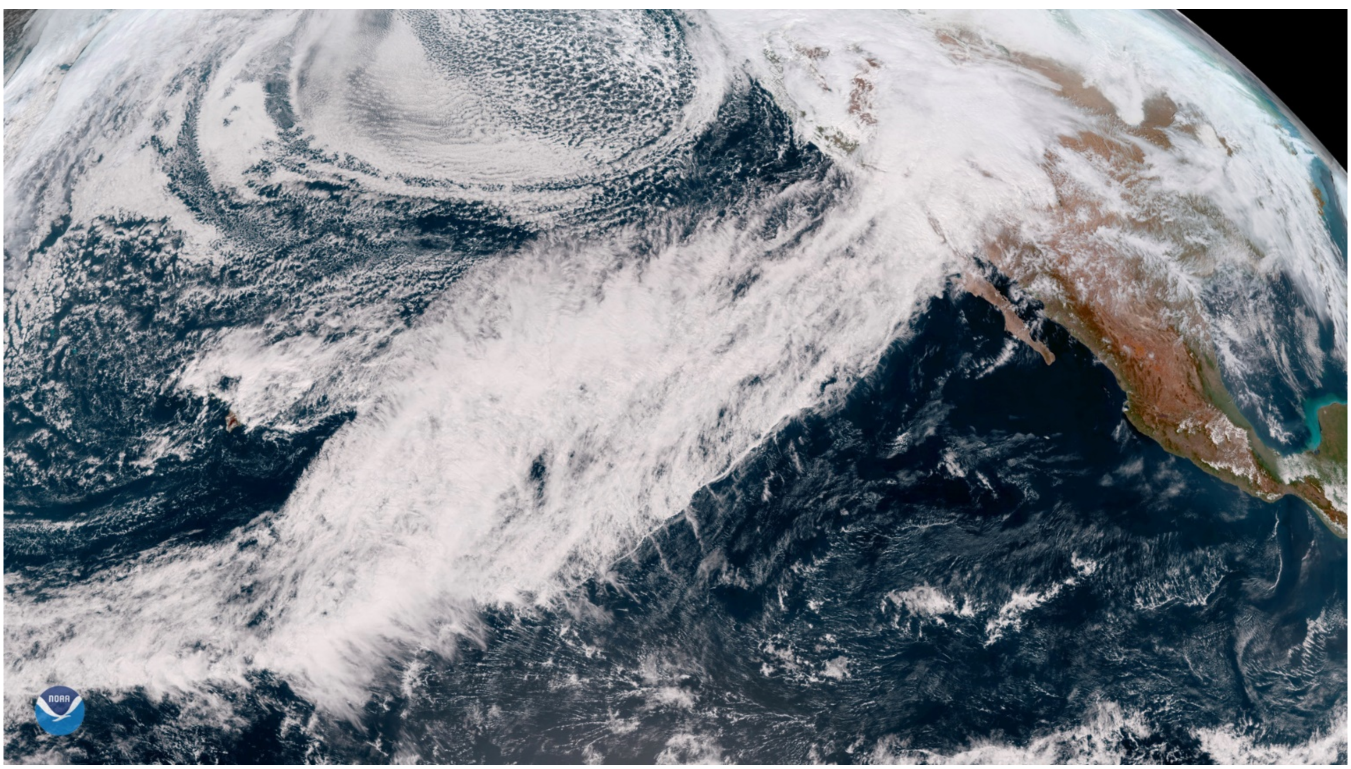

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14. ABSTRACT
Several of the NA-CORDEX RCMs project a decrease in cool season precipitation at high elevations across the west (e.g., across the Sierra Nevada) with a corresponding increase in the Great Basin. We explore the causes of this terrain-related precipitation change in a subset of the RCMs through an examination of integrated water vapor transport (IVT) events, since previous studies have shown that precipitation events in the western US are influenced by the timing, positioning, and duration of extreme integrated water vapor transport (IVT) events (e.g., atmospheric rivers) at the coast, and also by the pathways which this moisture-rich air takes through the complex terrain of the western U.S. Projected changes in frequency of IVT events depend on their intensity. By the end of the century extreme IVT events increase in frequency whereas moderate IVT events decrease in frequency. Projected precipitation changes during IVT events also depend on event intensity. In the future, precipitation across the Sierra Nevada generally increases during extreme IVT events and decreases during moderate IVT events. Thus, we argue that the mean cool season decrease at high elevation is largely determined by the response of moderate IVT events which are projected to be less frequent and bring less high elevation precipitation.

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Executive Summary

Understanding future precipitation changes is critical for water supply and flood risk applications in the western United States. The **N**orth **A**merican **CO**ordinated **R**egional **D**ownscaling **EX**periment (NA-CORDEX) matrix of global and regional climate models at multiple resolutions (~50-km and 25-km grid spacings) is used to evaluate mean monthly precipitation, extreme daily precipitation, and snow water equivalent (SWE) over the western United States, with a sub-regional focus on California.

Results indicate significant model spread in mean monthly precipitation in several key water-sensitive areas in both historical and future projections, but suggest model agreement on increasing daily extreme precipitation magnitudes, decreasing seasonal snowpack, and a shortening of the wet season in California in particular. While the beginning and end of the California cool season are projected to dry according to most models, the core of the cool season (December, January, February) shows an overall wetter projected change pattern. Daily cool- season precipitation extremes generally increase for most models, particularly in California in the mid-winter months. Finally, a marked projected decrease in future seasonal SWE is found across all models, accompanied by earlier dates of maximum seasonal SWE, and thus a shortening of the period of snow cover as well. Results are discussed in the context of how the NA-CORDEX ensemble can be used by stakeholders faced with future water planning challenges.

Several of the NA-CORDEX regional climate models (RCMs) project a decrease in cool season precipitation at high elevations across the west (e.g., across the Sierra Nevada) with a corresponding increase in the Great Basin of the U.S. We explore the causes of this terrain-related precipitation change in a subset of the NA-CORDEX RCMs through an examination of IVT events, since previous studies have shown that precipitation events in the western U.S. are influenced by the timing, positioning, and duration of extreme integrated water vapor transport (IVT) events (e.g., atmospheric rivers) at the coast, and also by the pathways which this moisture-rich air takes through the complex terrain of the western U.S.. Projected changes in frequency of IVT events depend on their intensity. By the end of the century extreme IVT events increase in frequency whereas moderate IVT events decrease in frequency. Projected precipitation changes during IVT events also depend on event intensity. In the future, precipitation across the Sierra Nevada generally increases during extreme IVT events and decreases during moderate IVT events. Thus we argue that the mean cool season decrease at high elevation is largely determined by the response of moderate IVT events which are projected to be less frequent and bring less high elevation precipitation.

1. Introduction

1.1 Project Background

The need for regional climate information from subseasonal to centennial time scales is critical for a wide range of applications including water management. Forecasts and projections of climate variability and change on these time scales can be implemented using dynamical downscaling, where large-scale circulation patterns simulated by global climate models (GCMs) are used to drive higher resolution dynamical regional climate models (RCMs) in areas of interest. The North American - Coordinated Regional Climate Downscaling Experiment (NA-CORDEX, https://na-cordex.org/) uses boundary conditions from CMIP5 climate models to drive regional models over North America. NA-CORDEX consists of pairs of GCMs-RCMs, with six different CMIP5 GCMs driving seven different regional models (where a subset of all the potential GCM-RCM combinations have been conducted). The regional models, with grid spacings of 25 and 50 km (with some additional simulations run at higher resolution) are able to better resolve topography and atmospheric processes than global climate models. NA-CORDEX simulations exist in three configurations: GCM-driven simulations for the "historical" period 1950-2005; observationally constrained simulations driven by the ECMWF Re-Analysis (ERA)-interim reanalysis from 1989-2008; and GCM-driven scenario runs from 2006-2100.

This project assesses how well processes critical to controlling western U.S. precipitation are simulated in NA-CORDEX, and whether the simulations are improved by resolution, by comparing the 25- and 50-km simulations to observed precipitation and to reanalysis datasets. The reasons for projected changes are then evaluated by investigating key processes that influence precipitation, including water vapor transport.

1.2 Previous Work

Climate change may alter many of the processes and phenomena that influence western U.S. precipitation, both in means and extremes. The effect of climate change on atmospheric rivers (ARs) in particular has been studied via a number of different approaches and datasets. GCM studies generally indicate that the impact of ARs on the western United States will increase both in frequency and intensity, which would accordingly lead to increased heavy precipitation (e.g., Dettinger 2011; Gao et al. 2015; Lavers et al. 2015; Warner et al. 2015; Hagos et al. 2016; Tan et al. 2020). While increased temperature and moisture (the so-called "thermodynamic effect") appears to dominate the climate change impact on AR intensity (e.g., Kossin et al. 2017), landfall location changes are also evident based on how GCMs represent shifts of the subtropical jet and associated storm tracks (e.g., Gao et al. 2015; Shields and Kiehl 2016; Payne et al. 2020). GCM projections for mean annual precipitation across the U. S. Intermountain West show less agreement (e.g., Lukas et al. 2014; USGCRP 2017), yet consistently indicate a likely increase in frequency and intensity of extreme precipitation for most regions (e.g., Kharin et al. 2013, Janssen et al. 2014, Janssen et al. 2016).

Increasing projection resolution through the use of RCM reveals qualitatively similar findings; that is, RCM studies largely corroborate the average changes indicated by global model studies, but impart additional spatial, temporal, and impact-relevant detail which is often desirable for water resources planning. For example, Rhoades et al. (2018) used regional climate simulation data from the North American Coordinated Regional Climate Downscaling Experiment (NA-CORDEX) to demonstrate how key hydrometeorological features controlling western U.S. hydrology, such as snowpack, peak timing, melt rate, and snow season length collectively indicate a nearly 80% reduction in peak snowpack water volume by the end of the 21st century. Similarly, Salathé et al. (2014) also employed a regional dynamical downscaling approach to show that the combination of more extreme storms and warming temperatures (causing precipitation type to shift from snow to rain) increases future flood risk in parts of the Pacific Northwest. A growing body of regional studies further demonstrate that increases in AR intensity and temperature may couple to produce winter precipitation that increasingly as rain rather than snow, thereby increasing high-elevation, complex terrain flood risk in particular (e.g., Leung et al. 2004; Leung and Qian 2009; Guan et al. 2016; Mahoney et al. 2018). Across the U. S. Intermountain West, regional climate studies suggest variable change signals. Alexander et al. (2013) examined warm season precipitation over Colorado and surrounding states using the North American Regional Climate Change Assessment Program (NARCCAP) dataset, and found overall drier summers despite an increase in the surface specific humidity, but no clear agreement on the sign of change for the most extreme precipitation. Studies focusing on the cool season across the Intermountain West highlight the northward shift in storm tracks as the main mechanism by which future precipitation climatologies change with latitude (e.g., USGCRP 2017). Finally, snow (and snow water equivalent, SWE), and the length of the season over which it falls and persists as snowpack, is generally projected to decline across the broader western U.S., partially due to more precipitation falling as rain than snow, as well as faster melting of snow on the ground (USGCRP 2017; Rhoades et al. 2018; McCrary and Mearns 2019).

1.2.1 The North American Coordinated Regional Climate Downscaling Experiment (NA-CORDEX)

The NA-CORDEX experiment aims to add value to the existing body of climate model projections by using multiple resolutions and a matrix of global and regional climate models to facilitate regional climate model intercomparison studies, and ultimately serve the impact and adaptation communities (Giorgi et al. 2009; na-cordex.org). As the spatial resolution of RCMs continues to increase, even to convection-permitting resolutions, balancing deterministic or very small ensemble collections with larger, more diverse ensembles remains key to exploring uncertainty; this is an important aspect of selecting the NA-CORDEX dataset for this study (Gutowski et al. 2020). Thus, while traditional GCM ensembles typically provide ~100-km grid spacing or more, and convection-permitting ensembles offer high-resolution but limited simulation membership, NA-CORDEX addresses an important need for stakeholders desiring uniform higher-resolution data than can resolve western U.S. terrain and AR phenomena, with enough multi-model diversity and sufficient ensemble membership to assess projection uncertainty. The larger (worldwide) CORDEX effort began as an initiative from the World Climate Research Program (WCRP), coordinating the regional climate modeling efforts to perform climate projections over large, predefined domains. The horizontal resolution of the simulations began with a relatively coarse grid mesh of 0.44° (~50-km grid spacing) in order to generate large ensembles of full 100+ year transient simulations; groups with larger computing resources could optionally perform finer resolution simulations to investigate the added value. In the NA-CORDEX framework, most simulations were performed at both 0.44°/50-km grid spacing and 0.22°/25-km grid spacing, with a few modeling centers also simulating at 0.11°/12.5-km grid spacing. In this study, we compare the 50-km and 25-km grid spacing simulations.

A small but growing number of NA-CORDEX studies have begun to examine precipitation and precipitation extremes. Gibson et al. (2019) examined NA-CORDEX historical daily precipitation indices against multiple gridded observational and reanalysis products, emphasizing the non-triviality of observational product differences across the contiguous United States (CONUS), while also summarizing where dynamical downscaling appears to add value, where it may degrade performance, and where model performance is most sensitive to model resolution. Diaconescu et al. (2016) and Whan and Zwiers (2017) focused on a small subset of RCMs driven by different reanalyses and historical GCMs, finding less sensitivity of model performance to the particular driving datasets, and more sensitivity to the region, season, precipitation characteristics, and climate mode indices examined. Lucas-Picher et al. (2017) examined the sensitivity of a single NA-CORDEX RCM to horizontal resolution, focusing on key simulated processes such as orographic precipitation and local and regional circulations. Rhoades et al. (2018) used NA-CORDEX simulations to evaluate snowpack over the headwaters of ten major California reservoirs.

The present study aims to complement these analyses and contribute to the larger body of work seeking to understand what can be learned – and specifically, what can be most effectively used by water management decision-makers – from this relatively new collection of RCM projections. Model datasets such as NA-CORDEX offer appeal to stakeholders because they can, in theory, provide an array of possible future climate states, derived from physically-consistent, spatially and temporally continuous gridded model output that can be used for secondary/application models. These data, by virtue of being produced by dynamical prognostic models as opposed to those based on statistical modeling using historical conditions, also provide physical process insight into how and why specific climate change impacts evolve in particular model projections.

1.3 The Problem the Study Addresses

While the NA-CORDEX matrix of model simulations may be but one cluster of relatively new data points in a growing sea of climate model guidance, its design and specific objectives render it an important potential resource in understanding the hydroclimate of this water-sensitive region. In this study we address: What does the NA-CORDEX model dataset reveal about western U.S. precipitation projections with respect to means, extremes, precipitation type, and its regional and seasonal distribution? Does the NA-CORDEX project offer unique advantages to stakeholders and end users?

1.4 Study Objectives and Approach

The objectives of this study are to (1) understand NA-CORDEX western U.S. precipitation projections with respect to means, extremes, precipitation type, and its regional and seasonal distribution, (2) evaluate the utility of the NA-CORDEX dataset to stakeholders and end users, (3) determine whether it increases or changes confidence in existing regional projections based on consistency with existing climate projections, and (4) investigate whether the dataset can help advance physical process-based insight with which to better understand the causes of projected changes?

By analyzing a large suite of diverse model projections over multiple resolutions and both historical and future periods, this study enhances understanding of projections of regional precipitation phenomena of interest across the western U.S. While we present most results for the entire western U.S., we also add an additional focus on California as a sub-region that has been both emphasized by a considerable volume of recent research (e.g., Rhoades et al. 2018; Swain et al., 2018; Gershunov et al. 2019), and is also of particular interest to key stakeholder groups with specific planning needs at critical water resource structures.

2. Methods

The NA-CORDEX model ensemble (Mearns et al. 2017) is composed of 6 RCMs: the CRCM5, RCA4, RegCM4, WRF, CanRCM4, and HIRHAM5 (see Table 1). The individual RCM simulations are driven by either reanalysis (ERA-INT) or one of six global climate models (GCMs): the HadGEM2-ES, CanESM2, MPI-ESM-LR, MPI-ESM-MR, EC-EARTH, and GFDL-ESM2M (Table 1). The RCMs examined in this study were run at resolutions of both 0.44° (~50-km grid spacing) or 0.22° (~25-km grid spacing). As the overarching purpose of this study is model evaluation, no post-processing (e.g., bias correcting, further statistical downscaling) has been applied, and only simulations having both spatial resolutions (50- or 25-km grid spacing) available are used in the analyses focused on identifying the potential added-value from increased resolution. While model domains are similar across the RCMs, regridding, when necessary, was performed using an inverse distance squared method to a 0.5 x 0.5 common grid. For a detailed description of the individual RCM configurations within the NA-CORDEX ensemble, see: https://na-cordex.org/rcm-characteristics.

For the historical period (1976 – 2005), precipitation values from the NA-CORDEX simulations are compared to values from two high-resolution precipitation datasets developed by Livneh et al. (2013) and Newman et al. (2015). The Livneh et al. (2013) data are available on a 1/16° latitude–longitude grid over the conterminous United States for the years 1915–2011, and provide an update of the Maurer et al. (2002) dataset derived using daily observations from approximately 20,000 National Oceanic and Atmospheric Administration (NOAA) Cooperative Observer stations. The Newman et al. (2015) daily precipitation dataset is a 100-member ensemble in which gauge data are probabilistically interpolated to a 0.125° resolution grid. Terrain impacts (e.g., elevation and slope) are included, and the ensemble approach is designed to account for uncertainties due to spatial undersampling, measurement projection irregularities, as well as random measurement errors. We also examine snow projections from NA-CORDEX using SWE, although we omit the RegCM4 simulations in our analysis of historical and future SWE due to unphysical snow accumulation values; this issue is discussed in more detail in Mahoney et al. (2020). While spatially and temporally continuous historical SWE datasets are limited, here we use the National Operational Hydrologic Remote Sensing Center (NOHRSC) Snow Data Assimilation System (SNODAS) data product for 2004 – 2018 (NOHRSC 2004; Barrett 2003). All future projection analyses are evaluated over the period 2070 - 2099.

For the investigation into physical reasons for projected changes in Sierra Nevada precipitation, we identify Integrated water Vapor Transport (IVT) 'events' in NA-CORDEX for three Weather Research and Forecast (WRF) RCMs: HadGEM.WRF, GFDL.WRF, and MPI.WRF, and then evaluate changes in frequency and duration of these 'IVT events' as well as changes in the event-associated precipitation. The technique we use for identifying IVT events is based on IVT intensity and duration as follows: Histograms of IVT from the historical simulations are constructed for every WRF grid point along the U.S. west coast, and used to identify historical IVT percentiles for each coastal location. These percentile values (e.g., 483 kg m-1 s-1 is the 99th percentile of IVT for the grid point at ~37 N) are then used to identify 'IVT events' with an additional criterion requiring IVT to exceed the threshold for at least 24 hours. Overlapping hours that are identified at adjacent grid points along the coast are combined, resulting in a 'catalog' of events that includes start and end times as well as start and end latitudes. Historical IVT thresholds are used to identify events for the future period. For IVT event composites, a 12-hour buffer is added after the coastal IVT event has ended to account for precipitation that is associated with the synoptic event that created the IVT event (e.g., as the associated precipitation moves inland, Dettinger et al. 2011). We examine two classes of IVT events: 'extreme' IVT events (IVT > 99th percentile) and 'moderate' events (IVT > 90th percentile but <99th percentile).

3. Results

3.1 Western U.S. Precipitation and Snowfall in NA-CORDEX

NA-CORDEX models generally reproduce the historical observed large-scale orographic precipitation enhancement features across the Western U.S., although they tend to overestimate mean seasonal precipitation relative to the observations used here (Figure 1). When evaluating historical mean monthly precipitation, sensitivity to the driving GCM is apparent from latitudinal shifts in monthly precipitation distributions, suggestive of a dependence on GCM-dictated storm track patterns. The higher resolution (25-km grid spacing) models generate more precipitation overall, particularly in complex, elevated terrain. Some particular RCM subsets (e.g., RegCM4) produce a notably wetter solution relative to other RCM subsets (e.g., WRF), but the large-scale spatial distribution of monthly mean precipitation is largely determined by the driving GCM.

Historical cool-season daily precipitation extremes maximize across regions of elevated, complex terrain along the U. S. West Coast, with greater intensities noted in the higher resolution 25-km simulations.

California is highlighted as a sub-region within the Western U.S. over which we assess the seasonal distribution of precipitation. The historical monthly precipitation climatology of the NA-CORDEX simulations has the correct annual shape relative to the observational datasets, although both the 50-km and 25-km ensemble mean values produce more precipitation relative to observations, in some months by as much as 50% (Figure 2). There is also considerable spread between individual model members, with no systematic difference clearly attributable to model resolution -- although this apparent result stems at least partially from cancelation effects due to spatial and temporal averaging. Historical daily extreme (99th percentile) precipitation over California also peaks in DJF, with the 25- and 50-km simulation 30-year ensemble mean daily values generally falling within or slightly above the envelope of observational spread (Figure 3); the impact of resolution does not systematically impact the seasonal cycle of California extrema, but sensitivity to resolution may increase for regions farther inland which are controlled more strongly by local processes and local terrain features.

Finally, snowfall-total precipitation ratios and SWE show vast model-to-model variability, with inter-simulation differences ranging upwards of 1000% over high-elevation terrain (Figure 4). As snow integrates the combined biases and uncertainties in both temperature and precipitation, the seasonal variability of SWE accumulation is quite large, with some models peaking in March-April, but others peaking as early as January-February. Model resolution appears to play a more significant role for SWE than for total precipitation; the 25-km simulations tend to have larger seasonal SWE values than their 50-km counterparts, and, in some cases, retain SWE later in the season. However, the evaluation of SWE projections is somewhat limited by a lack of reliable, spatially-distributed observations.

Projected future changes in monthly and seasonal mean precipitation are found to be generally consistent with other recent studies of western U.S. precipitation projections, that is, mixed, regionally-dependent results for seasonal mean changes, and more general agreement for an increase in precipitation associated with extreme events (Figure 5). However, we note sensitivity to a number of factors. First, inter-model variability of future projections can be considerable within the NA-CORDEX ensemble, with the largest and most spatially-sweeping changes again suggestive of storm track differences dictated by the driving GCM, and local-scale precipitation magnitudes and terrain-controlled mesoscale details differing considerably by RCM. Second, the definition of the cool season (e.g., focusing on OND vs. JFM) can completely reverse the apparent sign of projected mean precipitation change. Ensemble mean precipitation in OND increases across much of the Pacific Northwest, but sharply decreases over the California Sierra region (Figure 6). This signal is in stark contrast with that of JFM, in which the ensemble mean JFM precipitation increases over northern and central California, and relatively less so over the Pacific Northwest, although there is again considerable variability between individual models.

Regarding future projections of daily extreme precipitation, there is considerable ensemble agreement on the positive sign change (increase) in the intensity of future daily extreme precipitation across nearly the entire western U. S. domain. Seasonally, daily precipitation extremes over California increase most in the mid-winter months (DJF), but a general upward trend is present year-round, demonstrating that the upper bound on, and potential for, flood-inducing precipitation does not decrease even in areas of projected mean drying. NA-CORDEX ensemble agreement is also found for secondary flood risk factors such as more precipitation falling as rain rather than snow, and the changing character of snowmelt (lower totals and earlier spring meltout) in certain locations.

Finally, a marked projected decrease in future seasonal snowfall fraction and SWE is found across all models, accompanied by earlier dates of maximum seasonal SWE accumulation (Figure 7). The greatest losses in future projected SWE occur during the months of historically greatest accumulation (JFM), with near-zero SWE values projected in the later spring months (AMJ) for many historically snow-covered locations. Such a consistent change signal across the NA-CORDEX ensemble highlights one area of relatively high projection confidence, and prompts additional investigation of flood risk by region and by distinguishing flood-producing mechanisms (e.g, Kundzewicz et al., 2013; Berghuijs et al. 2016; Musselman et al. 2018).

We next briefly examine how precipitation and IVT are projected to change across the western U.S. in NA-CORDEX models through an examination of IVT events as a step towards understanding the physical reasons for the projected changes. We then frame these results with a discussion focused on the mechanisms potentially causing projected precipitation changes, follow with discussion of how these results fit into the existing literature on western U.S. precipitation and AR changes, and end with describing some implications and limitations of our study.

3.2 Change in IVT and Precipitation During IVT Events

The historical composite IVT for events that impact 37-39N (Figure 8, contours) has its maximum near San Francisco Bay in all three models for the extreme IVT events (top row), and a broader maximum shifted slightly farther to the north for the exclusive moderate IVT events (bottom row). The northward shifted, broader maximum in the moderate exclusive IVT event composite is likely a result of the much larger number of events in this composite combined with the Lagrangian component of the identification algorithm and fact that many of these events tend to sweep along the coast from north to south.

The composite IVT changes during both categories of IVT events (Figure 8, color fill) is positive everywhere in the domain. The spatial distribution of the changes varies considerably by model and event threshold, broadly indicating model-dependent projected changes in IVT event orientation. Composites of IVT event precipitation (Figure 9) also have changes that vary with model and threshold.

Focusing on IVT event precipitation changes across the Sierra Nevada (SN): HadGEM.WRF extreme events have increased precipitation southwest of the historical SN precipitation maximum and decreases to the northeast, whereas HadGEM.WRF moderate events have future decreases more centered on the historical maximum precipitation amounts. GFDL.WRF extreme IVT events have large increases across the SN, centered on historical maximum precipitation locations.

GFDL.WRF precipitation change for exclusive moderate IVT events has a consistent pattern of decreases to the south and increases to the north. MPI.WRF extreme IVT event precipitation changes generally change sign near Lake Tahoe, with increases to the north and decreases to the south. Precipitation changes during moderate IVT events in MPI.WRF generally decrease across the SN, with the largest decreases slightly to the northeast of the historical precipitation maximum.

3.3 Relating Precipitation Changes to Changes in IVT and Smaller Scale Factors

We frame our discussion with physical mechanisms controlling Sierra Nevada precipitation ordered from larger scale (e.g., relating to IVT event frequency, magnitude, and duration) to smaller scale. First, we discuss the IVT results and their relationship to precipitation amounts: We use a 'total days' metric that combines IVT event frequency and duration. For the three NA-CORDEX RCMs with IVT event information, we see somewhat consistent changes in IVT event characteristics intersecting CA and NV watersheds: more extreme IVT event total days, fewer moderate IVT event total days, and increased composite event intensity (i.e., larger composite IVT, with greater increases for extreme IVT events) (Table 2 and Figure 8). The more extreme IVT event total days and larger IVT would act to increase total precipitation amounts whereas fewer moderate IVT event total days would decrease total precipitation amounts, given unchanged precipitation efficiency (i.e., the amount of moisture in a storm that falls out as precipitation) during these events.

The composite IVT event precipitation maps (Figure 9) provide some insight into the net effect of mesoscale and microscale mechanisms combined with the impact of IVT event intensity changes on precipitation. IVT event precipitation changes for the CA watersheds are somewhat complex, but a few consistent patterns emerge. First, focusing on extreme IVT events: The southward-shifted, more zonal, more intense IVT distribution for the GFDL.WRF composite (Figure 8, top) likely explains the SN increases and northern CA decrease in precipitation during these events. Likewise, the more southwesterly orientation and large increase in IVT in HadGEM.WRF and MPI.WRF extreme IVT events seem consistent with the increases along the northwestern SN and northern CA, OR, and WA coasts; the decreases found downstream of the historical maximum along the SN could result from the shift in IVT orientation, or from shifts from snow to rain (since rain falls out faster than snow, less water would be lofted east; Pavelsky et al. 2012). Precipitation changes during the moderate IVT events appear less directly related to the changes in IVT for these cases, suggesting meso- and microscale processes are playing a larger role determining the precipitation change signal for these cases. Because the changes in IVT for these events are modest, it's possible that reduced orographic precipitation efficiency that comes with (presumably) somewhat warmer storms is not offset by increases in moisture, leading to the reductions in precipitation across the SN historical precipitation maxima, however more detailed analyses including investigations of microphysical processes (not available from NA-CORDEX simulations) would be necessary to confirm this mechanism.

Finally, we relate the changes in IVT events back to the cool season mean and seasonal changes presented in the first analysis of this report. In general, the cool season total precipitation change patterns more closely resemble the precipitation changes during moderate IVT events than those during extreme IVT events. Thus although extreme IVT events increase in frequency, and have increased precipitation amounts across the SN when they occur, the reduction in moderate IVT events and their reduced SN precipitation results in a net decreased cool season precipitation across the SN for the three RCMs investigated in detail.

3.4 Relationship to Previous Results

Several manuscripts have investigated projected changes in atmospheric rivers at the end of the 21st century in both CMIP3 and CMIP5; on the whole, these studies have found increases in either frequency and/or intensity of atmospheric rivers (with some differences based on how the events are defined, see review by Payne et al. 2020 for a summary of results from various manuscripts). Most existing definitions of ARs would exclude a large portion of the lower-end 'moderate' IVT events we identified using our definition, since they impose both a higher IVT threshold and/or object length and width requirements. Given this subtle difference, our results for the three RCMs are broadly consistent with these previous results: We find an increase in both frequency and intensity of the most extreme IVT events (analogous to extreme ARs). Most AR literature does not investigate changes in non-ARs (or with our definition, the lower-end of the 'moderate' IVT events).

Western U.S. cool season precipitation change has also been widely investigated in previous studies, and overall most GCMs project end-of-century precipitation increases for the northwestern U.S., decreases for at least a few southwestern states, with zero mean-change in between; the latitude of the change in sign in projected precipitation varies across GCMs. At lower elevations, the patterns of precipitation changes in the NA-CORDEX ensemble is broadly consistent with projected changes from GCMs. However, at higher elevations, NA-CORDEX models project cool season decreases at many locations across the western U.S., which here we've related to changes in the frequency, duration, intensity and precipitation efficiency of moderate IVT events.

While IVT events are likely reasonably well captured by GCMs, the meso- and microscale processes responsible for determining precipitation amounts at high elevation during IVT events are not well represented in GCMs, thus changes in these orographic precipitation processes might be totally absent (i.e., GCMs might miss the non-linearity of these changes, e.g., slight increases in event IVT but decreases in precipitation efficiency). Further, there's limited evidence that as GCMs move to higher resolution, similar features of reduced precipitation across higher western U.S. terrain might appear (IPCC chapter 14, their figure 14.18). This result suggests that further investment into higher resolution climate models, both global and regional in scale, that better resolve orographic precipitation processes, is warranted to better constrain projections of precipitation in areas of complex topography.

3.5 Limitations and Implications

End of century projections of western U.S. precipitation are quantitatively still very uncertain, due to several factors which ultimately conspire to confound our confidence in such projections, such as large natural variability, and model disagreement on the location of the boundary between midlatitude increases and subtropical decreases in precipitation (Neelin et al. 2013; Tebaldi et al. 2011). These issues are further complicated by the smaller GCM sample in NA-CORDEX than in CMIP5, and the regional variability introduced by the RCMs. In addition, we were able to test changes in IVT events in only three of the NA-CORDEX RCMs with high temporal-resolution 3D output available, limiting the models for which physical explanations of precipitation changes were available.

Nevertheless, our results are bolstered by a few factors. First is the relationship to previous work: Consistent with our finding of reduced moderate IVT events, Gershunov et al. (2019) found a decrease in 'non-AR' precipitation (along with an increase in 'AR' precipitation), although they do not relate it to a change in the frequency, intensity, duration or precipitation efficiency of 'non-AR' storms. Several manuscripts find increases in extreme ARs. Swain et al. (2018) found a tightening of the seasonality of CA precipitation in the CESM large ensemble, which appears to be consistent with our finding of reduced November and March IVT events (not shown). Second, even though IVT events could be investigated in only three RCMs, the cool season precipitation change patterns in those RCMs are similar to patterns seen in several other RCMs, suggesting this mechanism might be present in a substantial portion of NA-CORDEX simulations.

4. Discussion

The results of the NA-CORDEX analysis over the western United States share several common themes and findings with other recent, independent climate projection studies for this region. Placing this study's results in a broader context can help identify where agreement with other studies may increase confidence in certain aspects of western U.S. precipitation projections, while identifying outstanding areas of uncertainty helps prioritize future research directions.

The projected constriction of California's cool season precipitation whereby less precipitation is produced state-wide in October, November and early spring, and more precipitation becomes condensed into the mid-winter months aligns closely with Swain et al. (2018)'s analysis of independent climate model projections (i.e., using models distinct from those in NA-CORDEX) from the CESM Large Ensemble (LENS; Kay et al. 2015). Swain et al. (2018) demonstrate overall drying (in monthly mean precipitation) across most latitudes in California for the fall-early winter months, and a wetter shift in January and February by the end of the 21st century. Other studies such as Dong et al. (2019) also highlight an amplification of the precipitation seasonal cycle along the U.S. West Coast using CMIP5 GCMs. As witnessed by recent extreme wildfire events and periods of drought, decreasing "shoulder season" (fall and spring) precipitation, though lower in overall present-day climatological amounts, is a critical consideration in terms of ending the fall dry season and associated fire risk, and also extending the spring wet season to adequately support agriculture and water supply needs. Therefore, this is an important seasonal detail for planning purposes, and while corroboration across studies may increase confidence in a qualitative sense, significant variation within the NA-CORDEX dataset relative to the other aforementioned study datasets underscores that uncertainties remain. To address nuanced questions such as this, it also becomes key to understand the interplay between large ensembles generated by a single GCM versus multi-model RCM ensembles and the differences in the types of spread each approach generates (e.g., internal variability vs. internal variability combined with fundamental GCM-RCM differences). Comprehensively acknowledging and integrating these different approaches will be critical to designing the most useful future regional climate projections (e.g., Gutowski et al. 2020).

Additional findings with relatively robust stakeholder implications include the significant decrease in snowfall and SWE by 2100, along with the fairly systematic projected increase in western U.S. daily extreme precipitation intensity. That this latter effect occurs relative to more modest and mixed changes in seasonal mean precipitation also corroborate the results of Swain et al. 2018, reinforcing that uncertainty in mean seasonal precipitation changes does not necessarily decrease confidence in projected changes in precipitation extremes.

Finally, the sensitivity of the NA-CORDEX RCM projections to resolution also finds some common ground with recent related regional climate modeling studies. For the metrics examined here (mean monthly precipitation, daily extreme precipitation, and SWE), over the western U.S. during the cold season, the impact of increasing model resolution from ~50-km grid spacing to ~25-km grid spacing does not appear to drastically alter diagnostics such as monthly-scale precipitation climatology, but is relatively more important for daily precipitation extrema and snowfall. This is perhaps not terribly surprising given how a 50-km vs. a 25-km model grid box represents strong synoptically-forced precipitation [i.e., a blend of parameterized (approximated using environmental parameters to represent the effects of precipitation) and explicit (produced on the scale of a grid box using real equations of motion) precipitation], and how such processes average out over monthly and multi-year averages. However, for this particular western U. S. region, there are examples of terrain-controlled precipitation patterns, precipitation type (snow vs. rain) and moisture transport features which should be, and in some cases clearly are, impacted by model resolution. Related RCM studies have suggested resolutions around ~12.5-km grid spacing better reproduce mean and extreme precipitation for almost all regions and seasons, citing that this resolution is needed to most effectively capitalize on the improved representation of orography (e.g., Prein et al. 2016, Lucas-Pincher 2017), but that it may yet be insufficient for critical hydrologic applications (e.g., Castaneda-Gonzalez et al. 2019; He et al. 2019; Smiatek and Kunstmann 2019; Xu et al. 2019). The results of this study support the general notion that ~50-km grid spacing is sufficient for resolving regional-scale effects resulting from large-scale precipitation systems that characterize the climate of many locations in the western United States, but that smaller-scale physical processes critical for determining extreme precipitation, as well as land-surface processes controlling snow-dominated regions likely require finer grid spacing.

In closing, NA-CORDEX precipitation projections add confidence to certain aspects of the state of knowledge concerning the future of Western U.S. precipitation, and also highlight outstanding areas of uncertainty. How can end users harness both confidence and uncertainty information to optimally use NA-CORDEX to guide water resources management? We offer the following considerations for potential users and stakeholders:

- An increase in the magnitude of cool-season, western U.S. daily extreme (99th percentile) precipitation is a consistent finding that can be useful in both scenario planning and to inform inputs for secondary application models.

- Projected changes in seasonality (e.g., constriction of the wet season in California) provide a cautionary example of where broader-brush seasonal and/or ensemble averages might lead astray an end user. The significant intra-seasonal shifts in change projections underscore the sensitivity to the months chosen, and more broadly remind that choices such as the models, thresholds, and specific weather event types chosen over which to derive an average change signal can matter greatly (e.g., Prein et al. 2019).

- Ensemble spread can be wielded beneficially: though certain NA-CORDEX projection metrics possess a relatively large degree of spread, apparent model disagreement need not be interpreted as a lack of skill, particularly in regions where climate change signal-to-noise (e.g., internal variability) might be modest or difficult to discern (e.g., Tebaldi et al. 2011; Deser et al. 2012). For example, large ensembles of simulations with the same model and greenhouse gas forcing indicate wide ranges in the precipitation response over the western U.S., even for 30-year averages (e.g., Deser et al. 2014; NOAA PSL Climate Change Web Portal). In fact, studies such as Karmaklakar (2018) suggest that a lack of sufficient spread is more damaging to end user applications. Therefore, for particular objectives, stakeholders may find value in considering each model member as an internally-physically-consistent, plausible future climate state.

- The full potential of model datasets such as NA-CORDEX is not realized in a pursuit of identifying a "most skillful" model, and in this study we thus emphasize understanding and harnessing the ensemble spread versus emphasizing model skill relative to historical observational evaluations. The rationale for this is well supported by recent research, i.e., (1) large divergence in observational data can disproportionately determine what is deemed to be "skill," particularly in data-sparse regions such as the western U.S. (e.g., Gibson et al. 2019; Gampe et al. 2019); (2), the process of defining skill in RCM projections is a moving target, a function of the metrics and regions chosen, and possesses a strong potential to get the "right answers" for the wrong (physical process-based) reasons (e.g., Mahoney et al. 2013; Bukovsky et al. 2013; Thibeault and Seth 2015; Fan et al. 2015); and (3) the concept of weighting models within an ensemble to produce a superior regional climate "blended" projection has been demonstrated to come with many caveats and potential disadvantages, and in the end contributes yet another source of uncertainty (Christensen et al. 2010; Knutti et al. 2010; Weigel et al. 2010, Bukovsky et al. 2019).

- End users should plan for sufficient time and expertise to query the physical fidelity of model data and be prepared to investigate the possibility of model output curiosities. One example of an unphysical SWE feedback in the RegCM4 has been documented here, demonstrating that extracting data for use in sub-regional planning or secondary application models without first establishing bigger-picture context for the model output could easily lead one astray of using the best available data.

- It is a challenging but important undertaking to optimally combine models, methods, and diagnostics in ways that can produce a representative and relevant story for a specific application. Considering ensemble means alongside extreme member solutions while using ensemble spread in meaningful ways (e.g., Tebaldi et al. 2011) can provide value-added input to secondary application models, enabling so-called "storytelling" frameworks (e.g., Hazeleger et al. 2015; Shepherd 2016) that help define well-founded multiple futures for scenario planning (e.g., Star et al. 2016).

There remain many avenues of potential future work to better understand the NA-CORDEX model dataset in particular, and also the outstanding uncertainties in western U.S. precipitation projections. Future efforts to investigate other seasons and sub-regions in greater depth would benefit the research and regional climate modeling communities, as well as stakeholders and end users. As the enduring aphorism goes, "All models are wrong, but some are useful" (Box 1987). Great challenge and opportunity exists in both model advancement and optimizing the use potential of imperfect and inherently uncertain model guidance.

Results from this project suggest that approximately half of the NA-CORDEX simulations display a projected decrease in high-elevation precipitation across several Western U.S. mountain ranges, which we attribute to the response during moderate IVT events. However, NA-CORDEX WRF uses a rather simple microphysics parameterization, and also, with the highest-resolution simulations at 25km grid spacing, has a somewhat coarse representation of some of the fine-scale terrain processes that dictate the distribution of mountain precipitation. A follow-on S&T project will test the sensitivity of projected changes in precipitation (both rain and snow) to both microphysics representation and horizontal resolution through a series of experiments with both the Weather, Research, and Forecast (WRF) model and the Intermediate Complexity Atmospheric Research (ICAR) model. We will then prepare atmospheric forcing fields for reservoir level simulations with Cal Sim 3 by bias-correcting them and forcing a hydrologic model, the Variable Infiltration Capacity (VIC) model, with a subset of simulations that appropriately represent the uncertainty in atmospheric projections.

Figures and Tables

Table 1 Summary of daily NA-CORDEX data analyzed from historical and RCP8.5 (future scenario). Model combinations showing available Precipitation (P), Temperature (T), Snow (S) for 50-km and 25-km grid spacing simulations as indicated in parentheses. Columns: Regional Models. Rows: Large Scale GCM forcing.

	CanRCM4	**CRCM5**	**RCA4**	**RegCM4**	**WRF**	**HIRHAM5**
Can-ESM2	P,T,S (50+25km)	P,T,S (50km)	P,T (50km)			
EC-Earth			P,T (50km)			P,T,S (50km)
GFDL-ESM2M				P,T (50+25km)	P,T,S (50+25km)	
HadGEM2-ES				P,T (50+25km)	P,T,S (50+25km)	
MPI-ESM-LR				P,T (50+25km)	P,T,S (50+25km)	
MPI-ESM-MR		P,T,S (50km)				

Table 2 Number of 3-hour time slices during IVT events at 37-39N in each model for the historical and future periods.

		HadGEM.WRF	**GFDL.WRF**	**MPI.WRF**
Extreme	Historical	835	997	785
Extreme	Future	1025	1075	957
Extreme	Percent change (Future-Historical)	+23%	+8%	+22%
Moderate	Historical	10543	10841	9985
Moderate	Future	9133	10219	8666
Moderate	Percent change (Future-Historical)	-13%	-6%	-13%

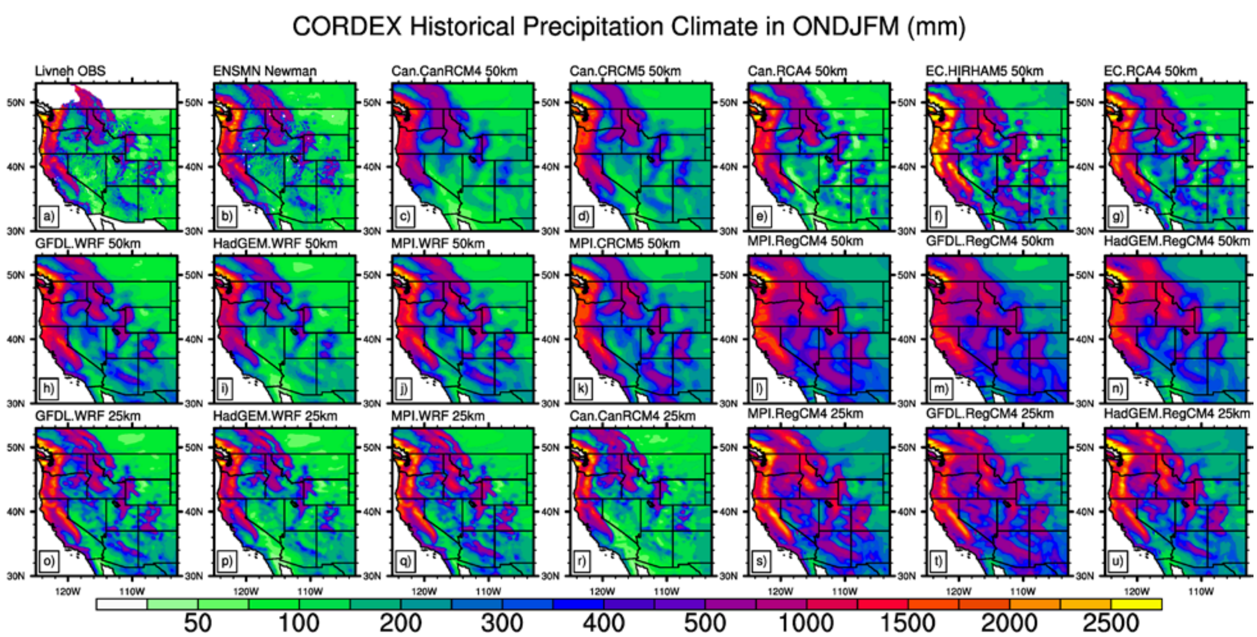

Figure 1 Mean historical (1976–2005) cool season (ONDJFM) precipitation (mm, as shaded) for each NA-CORDEX model listed in Table 1, as labeled. a) Livneh et al. (2013) reanalysis precipitation (mm); b) Newman et al. (2015) ensemble average reanalysis precipitation (mm) for same time period.

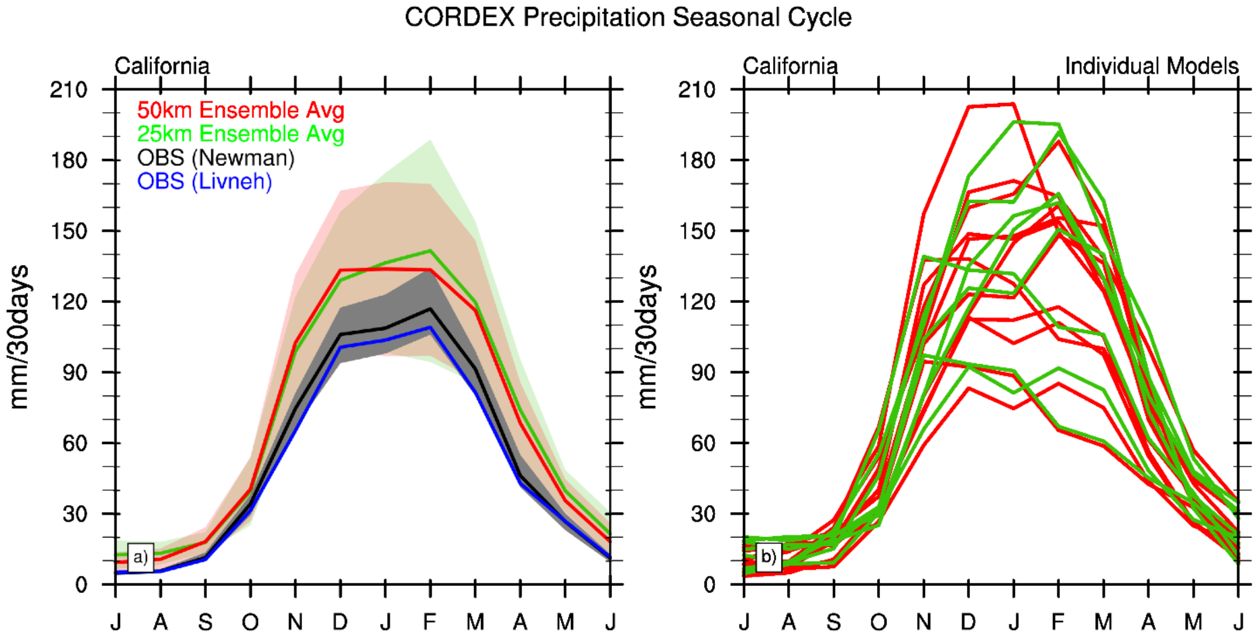

Figure 2 a) 50-km (red line) and 25-km (green line) simulation historical (1976 – 2005) ensemble mean precipitation versus reanalysis precipitation (Newman et al. (2015) in black and Livneh et al. (2013) in blue. Red (green) shaded area shows +/- 1 sigma of 50-km (25-km) grid spacing models, and gray shaded area shows Newman et al. (2015) uncertainty bounds containing the full range of the 100 ensemble members. b) Mean monthly historical (1976 – 2005) precipitation (mm/30 days) averaged over the state of California with 50-km (25-km) simulations shown in red (green).

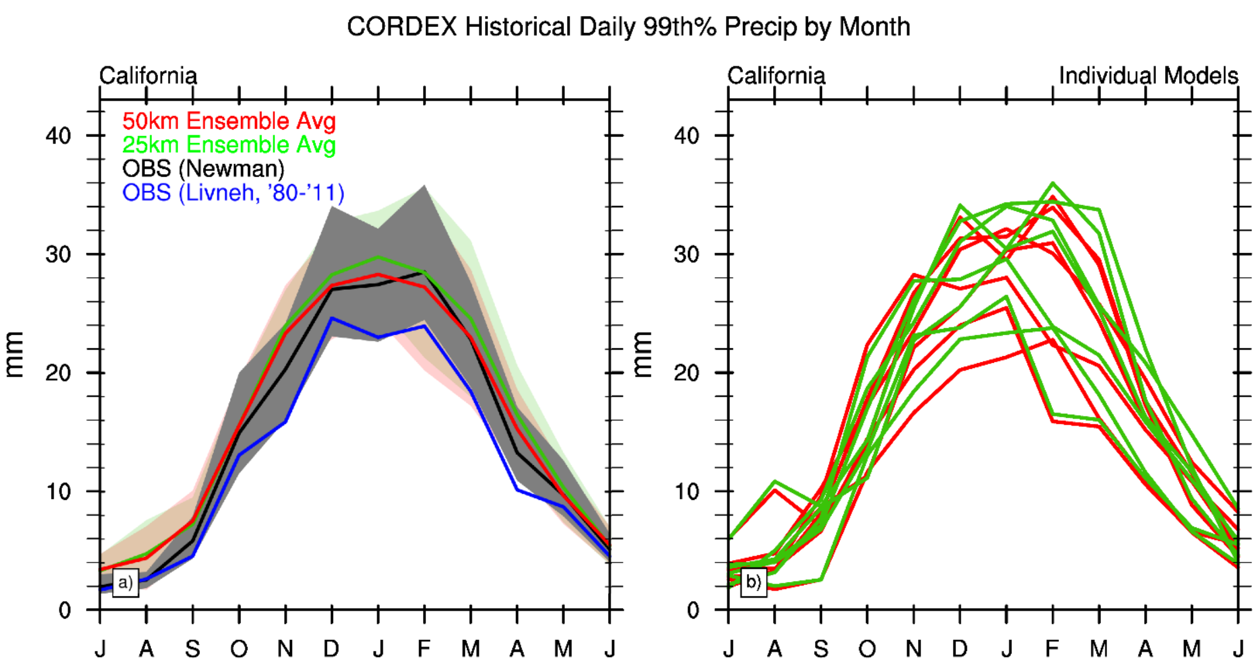

Figure 3 As in Figure 2 except for extreme daily (daily 99th percentile) precipitation.

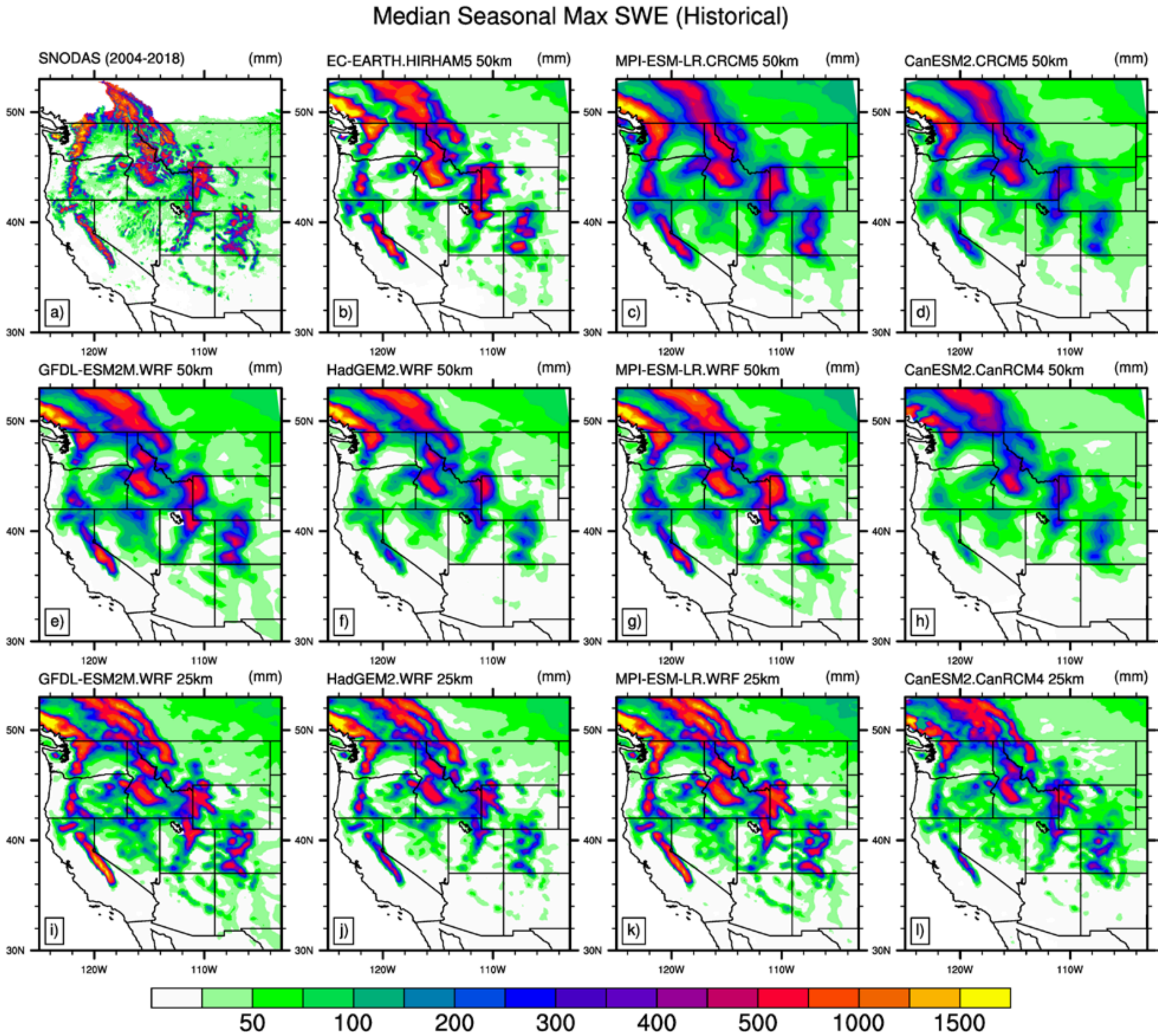

Figure 4 Historical (2004–2018) median seasonal maximum snow water equivalent (SWE, mm), where a) shows SNODAS SWE observational estimate, and b) – l) display all other available RCMs as labeled in upper left. RegCM4 simulations are omitted due to unphysical SWE values as discussed in the text.

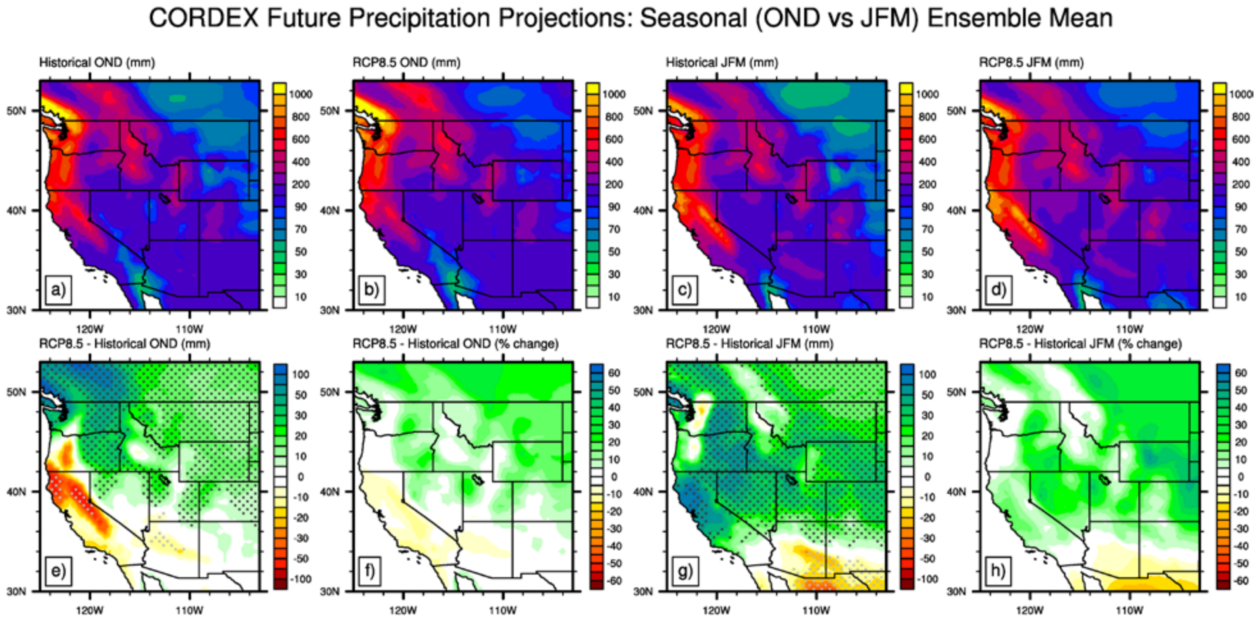

Figure 5 a) Historical mean OND precipitation (mm), b) future projected OND precipitation c), as in a) except for JFM, d) as in b) except for JFM. e) Future – historical projected change (mm) for OND, f) as in e) except as percent change, g) as in e) except for JFM, h) as in f) except for JFM. Black (grey) dot matrix stippling in panels e) and g) indicates >75% of the models agree that the anomalies are positive (negative).

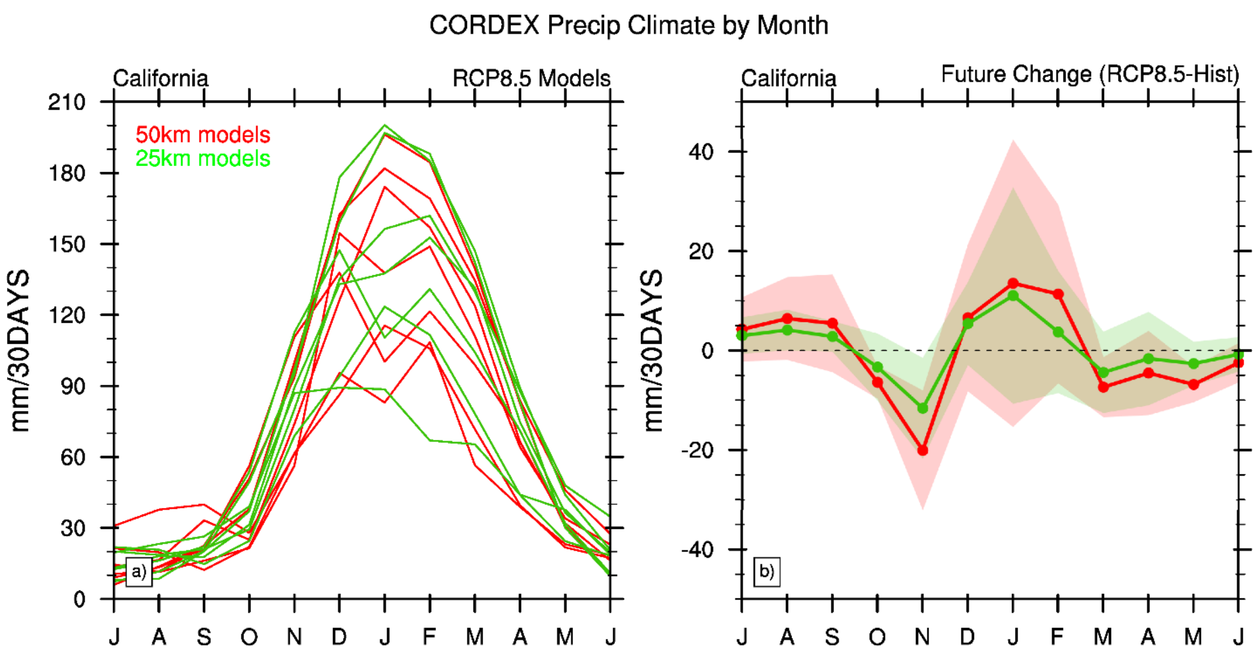

Figure 6 a) Seasonal mean monthly future precipitation (mm/30 days) averaged over the state of California for individual 50-km (25-km) simulations shown in red (green) lines; b) Future – historical projected changes in mean monthly precipitation (mm/30 days) for 50-km (red) and 25-km (green) simulations. Red (green) shaded area shows +/- 1 sigma of 50-km (25-km) grid spacing models for projected Future – Historical mean monthly change.

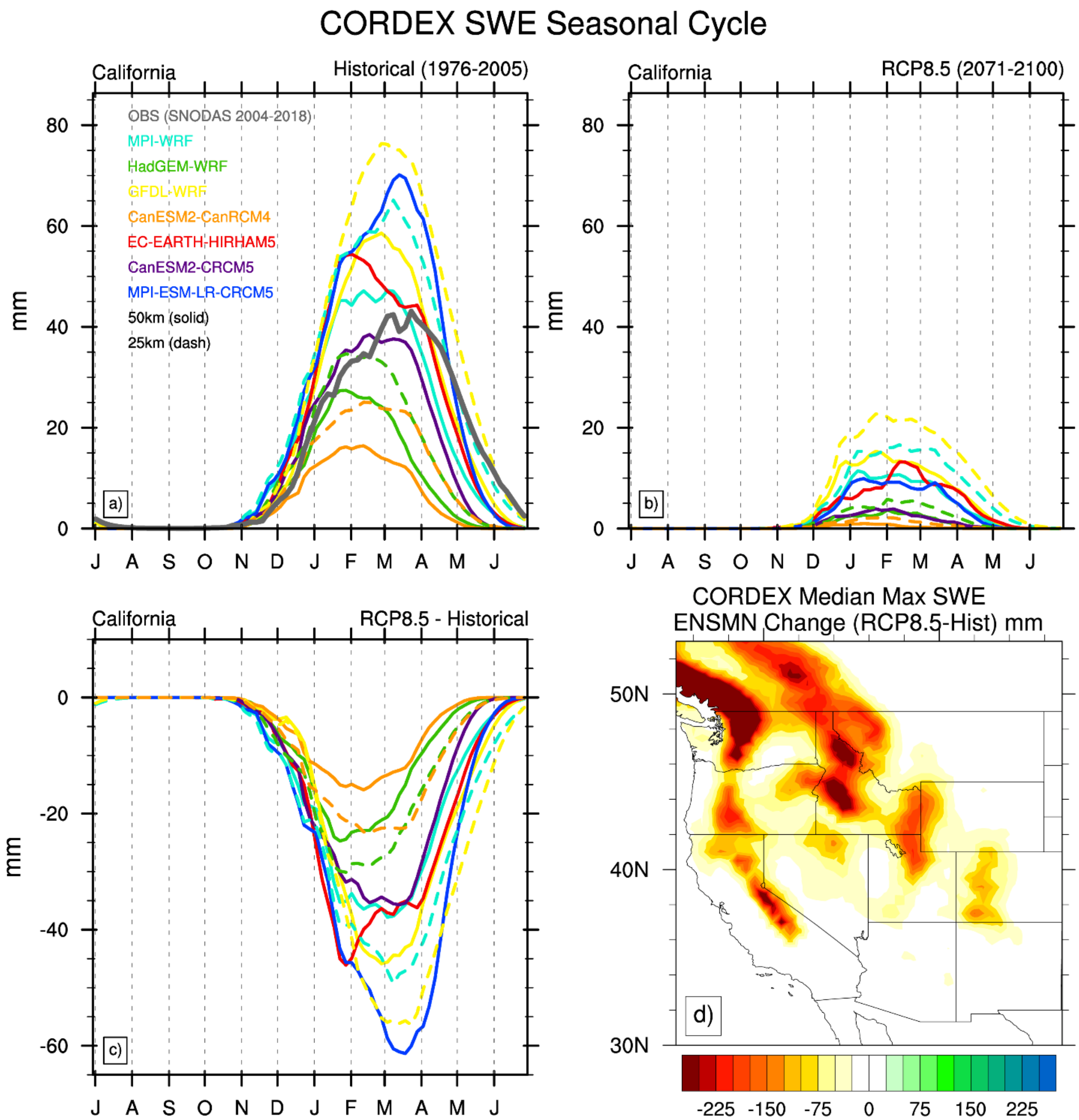

Figure 7 a) Historical (1976 – 2005) median max snow water equivalent (SWE, mm) annual evolution (months on x-axis) for each available NA-CORDEX member averaged over the state of California; grid spacing distinguished for 50-km (25-km) by solid (dashed) lines; b) as in a) except for future (2071 – 2100) period, c) as in a) except for Future – Historical projected change; d) ensemble mean change in median max SWE from historical to future period (mm, as shaded).

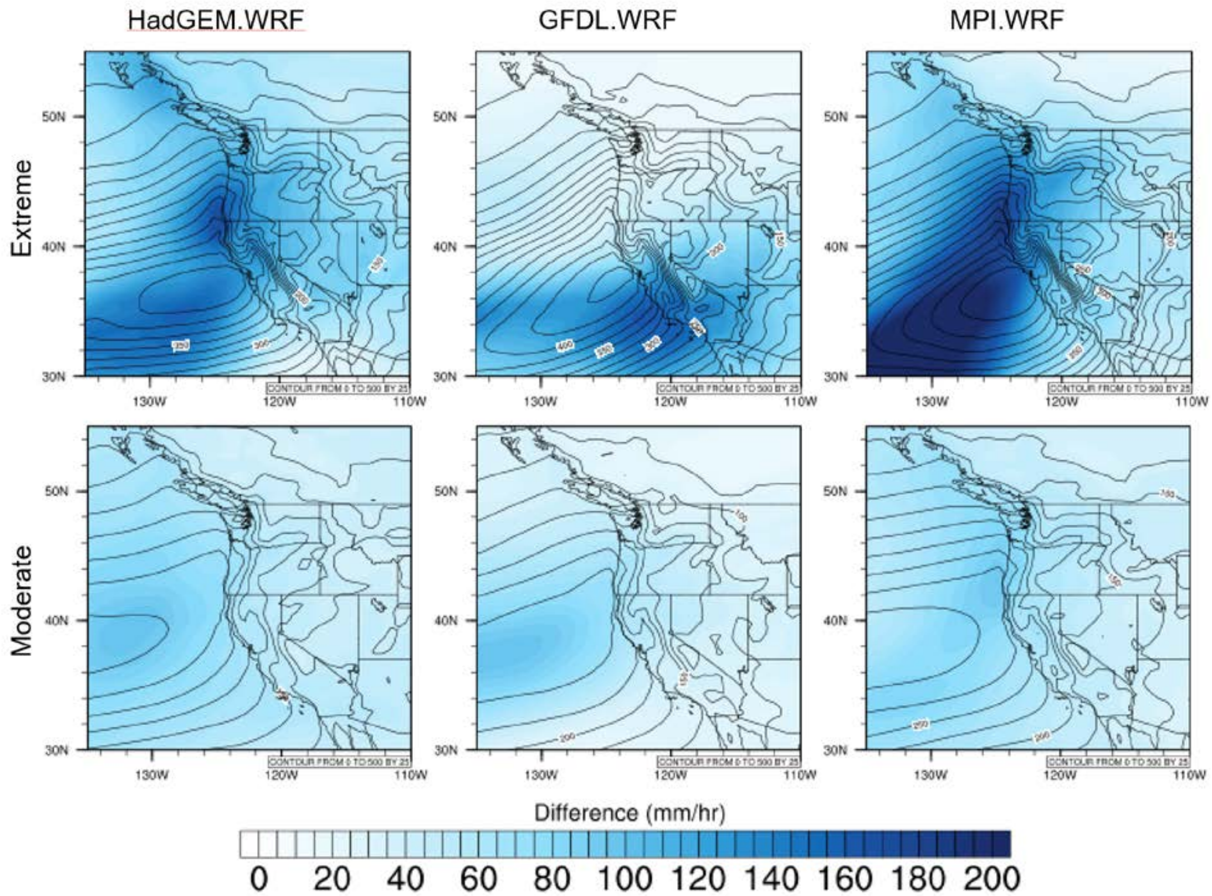

Figure 8 Composite IVT (black contours) and change in composite IVT (color fill) during (top) extreme IVT events and (bottom) moderate IVT events that impact the 37-39N latitude band. Black contours show historical values contoured every 25 kg m-1 s-1.

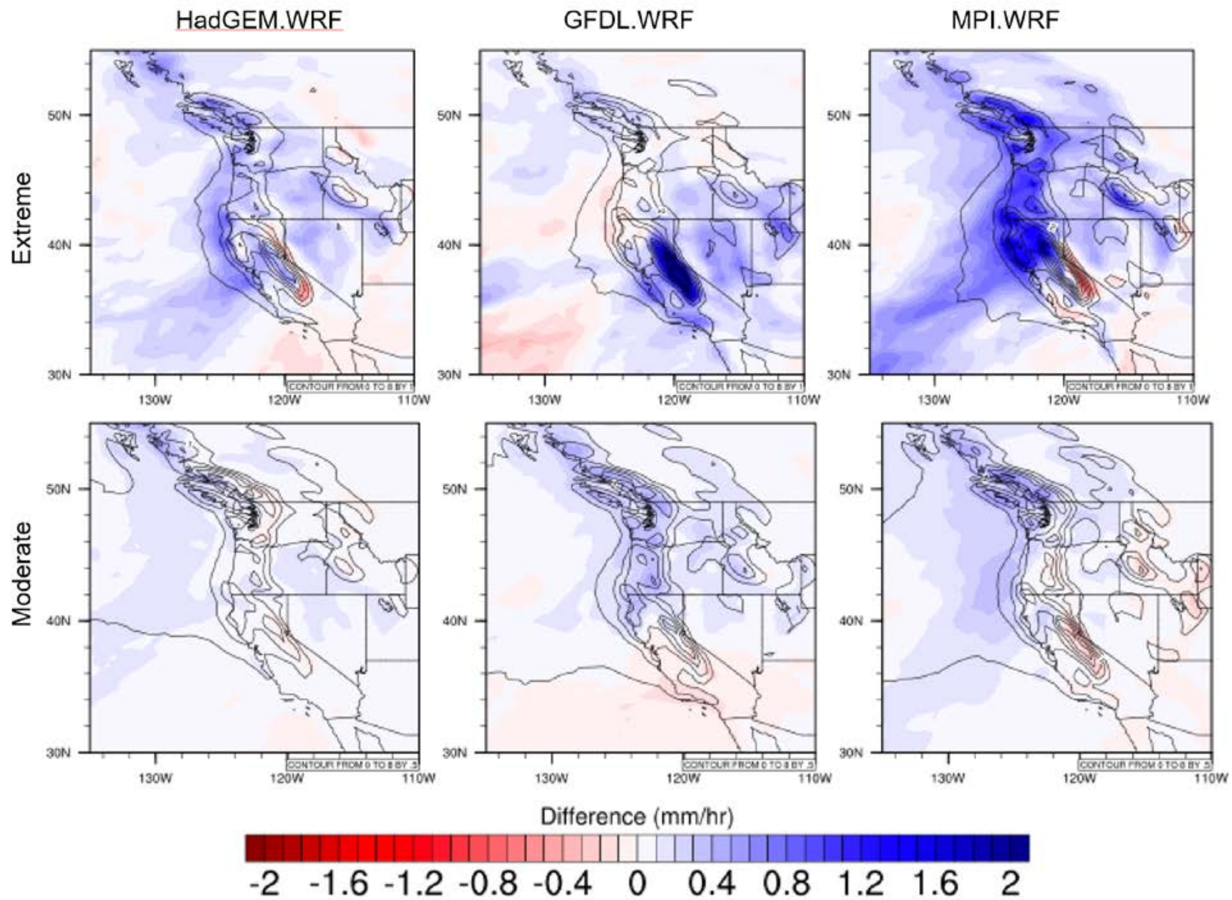

Figure 9 Composite precipitation rate (black contours) and change in composite precipitation rate (color fill) during (top) extreme IVT events and (bottom) moderate IVT events, for IVT events that impact the 37-39N latitude band. Black contours show historical values, contoured every (top) 1 mm/hr or (bottom) 0.5 mm/hr.

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