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Key Points:

- Characteristics of precipitation and mesoscale convective systems (MCSs) in the Peruvian Central Andes are investigated based on convection-permitting simulations
- WRF3km_MYNN outperforms in simulating mountain precipitation; both it and WRF4km_SAAG show superior performance in western Amazon
- Dynamic factors dominate precipitation and MCSs on the Andean east slope, while thermodynamic factors are dominant in western Amazon Basin

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Characteristics of Precipitation and Mesoscale Convective Systems Over the Peruvian Central Andes in Multi 5-Year Convection-Permitting Simulations

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Abstract Using the Weather Research and Forecasting model with two planetary boundary layer schemes, ACM2 and MYNN, convection-permitting model (CPM) regional climate simulations were conducted for a 6-year period, including a one-year spin-up period, at a 15-km grid spacing covering entire South America and a nested convection-permitting 3-km grid spacing covering the Peruvian central Andes region. These two CPM simulations along with a 4-km simulation covering South America produced by National Center for Atmospheric Research (NCAR), three gridded precipitation products, and rain gauge data in Peru and Brazil, are used to document the characteristics of precipitation and mesoscale convective systems (MCSs) in the Peruvian central Andes region. Results show that all km-scale simulations generally capture the spatiotemporal patterns of precipitation and MCSs at both seasonal and diurnal scales, although biases exist in aspects such as precipitation intensity and MCS frequency, size, propagation speed, and associated precipitation intensity. The 3-km simulation using MYNN scheme generally outperforms the other simulations in capturing seasonal and diurnal precipitation over the mountain, while both it and the 4-km simulation demonstrate superior performance in the western Amazon Basin, based on the comparison to the gridded precipitation products and gauge data. Dynamic factors, primarily low-level jet and terrain-induced uplift, are the key drivers for precipitation and MCS genesis along the east slope of the Andes, while thermodynamic factors control the precipitation and MCS activity in the western Amazon Basin and over elevated mountainous regions. The study suggests model improvements and better model configurations for future regional climate projections.

Plain Language Summary We ran high-resolution model simulations at a 3-km grid spacing with ACM2 and MYNN planetary boundary layer schemes for a 6-year period, including a 1-year spin-up, to investigate precipitation and storm patterns in the Peruvian central Andes region. Other data sets including a 4-km simulation produced by National Center for Atmospheric Research, three gridded precipitation products, and rain gauge data in Peru and Brazil were collected for comparison and evaluation. We found that all km-scale simulations capture overall patterns of precipitation and storms at both seasonal and sub-daily time scales, although some discrepancies exist in precipitation intensity and storm details. Compared to the gridded precipitation products and gauge data, the 3-km simulation using MYNN scheme generally outperforms the other simulations in capturing seasonal and diurnal precipitation over the mountain, while both it and the 4-km simulation demonstrate superior performance in the western Amazon Basin. Low-level wind and terrain-induced uplift are the key drivers for precipitation and storm genesis along the Andes' eastern slopes, while factors associated with vertical structures of temperature and humidity control the precipitation and storm activity in the western Amazon Basin and mountain regions. The study suggests model improvements and better model configurations for future regional climate projections.

1. Introduction

The Peruvian Central Andes, characterized by complex topography and unique climatological conditions such as the South American low-level jet (SALLJ), plays a vital role in influencing local and regional weather patterns and hydrological cycles (e.g., Arias et al., 2021; Drenkhan et al., 2015; Espinoza et al., 2015; Jones, 2019; Marengo et al., 2002; Poveda et al., 2020; Romatschke & Houze, 2010; Vera et al., 2006; Vernekar et al., 2003). The precipitation in the Peruvian Central Andes exhibits substantial spatial and temporal variability, driven by multi-scale atmospheric circulations and localized forcing such as topography (Anselmo et al., 2021; Chavez et al., 2020; Junquas et al., 2018; Mohr et al., 2014). Mesoscale convective systems (MCSs), which are organized clusters of thunderstorms, often accompany heavy precipitation, hail, and strong winds (Houze, 2004, 2018; R. Schumacher & Rasmussen, 2020). As a major source of precipitation in numerous regions (Anselmo et al., 2021; H. Hu et al., 2021; Kukulies et al., 2021; Li et al., 2020; Paccini & Stevens, 2023; Roca & Fiolleau, 2020; Salio et al., 2007; R. Schumacher & Rasmussen, 2020; M. Zhao, 2022), MCSs can cause severe flooding, landslides, and other natural disasters, thereby posing significant threats to human safety and infrastructure. As shown in Figure 10 of the study by Feng et al. (2021), MCSs can contribute to over 60% of the annual precipitation in the Peruvian Central Andes. Rapid urbanization further exacerbates the severity of flood extent in this region (Mazzoleni et al., 2022), intensifying the impacts on local communities and infrastructure (Son et al., 2020; T. Liu et al., 2022; Millán-Arancibia & Lavado-Casimiro, 2023). Understanding and accurately predicting the behaviors of precipitation and MCSs in the Peruvian Central Andes region are therefore crucial, and understanding the potential climate change impacts on MCSs is equally important (R. Schumacher & Rasmussen, 2020). Research findings in this area can significantly shape water management practices, disaster preparedness, climate change adaptation strategies, and enhance the resilience of local communities and economies to weather-related hazards in a changing climate (Drenkhan et al., 2015; Gonzalez et al., 2019; Martínez et al., 2008; Vergara et al., 2011).

The current understanding of precipitation and MCSs in the Andes and its surrounding regions, however, is limited by the scarcity of public observational databases, especially the scarcity of upper-air radiosonde observations in the region (Condom et al., 2020). State-of-the-art global climate models, such as those participating in the Coupled Model Intercomparison Project Phase 6 (CMIP6) program (Jukes et al., 2020), provide invaluable information on large-scale climate changes over South America. However, limited by available computing resources, the resolutions of these global climate models are too coarse (mostly at grid spacings of ~100 km) to resolve local orography and weather phenomena that are important for precipitation production (e.g., MCSs) (Giorgi, 2019; Jukes et al., 2020; Kendon et al., 2021). Numerous studies have highlighted the added value of convection-permitting models (CPMs, typically at a grid spacing of less than 4 km) for simulating precipitation and MCSs in different regions worldwide (Berthou et al., 2020; Fosser et al., 2015; Fumière et al., 2020; Gao et al., 2017; Guo et al., 2020; Halladay et al., 2023; Karki et al., 2017; Kouadio et al., 2020; Li et al., 2021; Lind et al., 2020; C. Liu et al., 2017; Paccini & Stevens, 2023; Prein et al., 2013, 2020; Stratton et al., 2018; Sun et al., 2016; Zhu et al., 2018). CPMs can significantly improve the representation of land surface conditions including complex topography as well as mesoscale and convective-scale dynamics. Most notably, deep convection can be represented explicitly in CPMs, rather than being parameterized using cumulus schemes which is a major source of uncertainty in quantitative precipitation forecasting.

For example, Sun et al. (2016) found that a 4-km regional climate simulation for the U.S. Great Plains more successfully reproduced the extreme precipitation magnitude and the precipitation diurnal cycle than a corresponding 25-km simulation. The 4-km grid also more realistically simulated the low-level jets and related atmospheric circulations important for low-level moisture transport. Prein et al. (2020) presented a CPM climate simulation over North America at a 4-km grid spacing that was able to capture key characteristics of observed MCSs such as their size, propagation speed, lifetime, and precipitation rate, though an underestimate of MCS frequency in the central US during late summer was noted. Paccini and Stevens (2023) demonstrated that simulations at convection-permitting grid spacings (2.5–5.0 km) improved the distribution of precipitation intensity as well as the representation of rainfall diurnal cycle over the Amazon Basin. Better representation of organized convective systems played a key role in improving the precipitation simulations. Halladay et al. (2023) presented a CPM regional climate simulation using the Met Office Unified Model at a 4.5-km resolution for South America covering the period of 1998–2007. They found significant improvements in the representation of precipitation in terms of its frequency, diurnal cycle, and sub-daily intensity distribution. To date, CPM regional climate simulations targeting South America remain limited in number (e.g., Bettolli et al., 2021; Dominguez et al., 2023; Halladay et al., 2023; Junquas et al., 2022; Lavin-Gullon et al., 2021; Paccini & Stevens, 2023; V. Schumacher

et al., 2020). Among these, Halladay et al. (2023) and Paccini and Stevens (2023) are the two recent studies over South America covering part of the Peruvian Central Andes region, however, their research is primarily focused on weather phenomena specific to the Amazon Basin region. Hence, CPM regional climate simulations and associated research for the Peruvian Central Andes region are still needed.

In light of the lack of long-term reliable observations and insufficient understanding of the role of climate change in precipitation and MCSs in the Peruvian Central Andes region, the present study employs convection-permitting simulations and available precipitation products to probe into the characteristics and mechanisms of precipitation and MCSs in this region. Before conducting a long-term CPM regional climate simulation over the Peruvian central Andes, Huang et al. (2023) conducted a series of 2-month CPM simulations during the austral summer. These simulations used various physics parameterization schemes to optimize the configuration of the regional climate models for this region. The configuration demonstrating better performance is then selected for the long-term CPM regional climate simulations in this study. We will evaluate whether the CPM simulations maintain similar performance in simulating precipitation and MCSs as observed in the short-term sensitivity study by Huang et al. (2023). This study will also provide information on the feasibility of using CPM simulations for climate change assessments, particularly in terms of precipitation and MCSs in the Peruvian Central Andes region.

The subsequent sections of this paper are structured as follows: Section 2 describes the data sets employed in this study, along with the model configuration of CPM simulations. In Section 3, the characteristics of precipitation and MCSs are presented and discussed. A summary is offered in Section 4.

2. Data and Method

2.1. Observational Data

For the evaluation of simulated precipitation, three global gridded precipitation data sets are utilized: the 30-min Integrated Multi-satellite Retrievals for GPM (IMERG) at $0.1^\circ \times 0.1^\circ$ resolution (Huffman et al., 2019), the 30-min NOAA Climate Prediction Center MORPHing Technique (CMORPH) with a grid spacing of approximately 8 km (Joyce et al., 2004), and the 3-hourly Multi-Source Weighted-Ensemble Precipitation (MSWEP) version 2, also at $0.1^\circ \times 0.1^\circ$ resolution (Beck et al., 2019). Both IMERG and MSWEP incorporate gauge stations in their precipitation estimates while gauge stations are very sparse in the examined region of this study (Beck et al., 2019; Huffman et al., 2019), and CMORPH does not integrate rain gauge data into its precipitation estimates (Joyce et al., 2004). Monthly precipitation from 329 rain gauge stations in Peru (red dots in Figure 1, Aybar et al., 2020) are utilized for the evaluation of monthly precipitation. These data sets have been employed in previous simulation evaluations by this research team (Chen et al., 2022; Huang et al., 2023). Huang et al. (2023) found that among the three gridded precipitation products, MSWEP has the smallest bias in monthly precipitation during February 2019 when compared to rain gauge data. It should be noted that the National Service of Meteorology and Hydrology of Peru (SENAMHI) also released a gridded rainfall data set incorporating the aforementioned rain gauge data (Aybar et al., 2020). However, the coverage of this product is smaller than the study region in our analysis. Thus, the data set is not included in this study. Additionally, hourly precipitation data from 10 rain gauge stations within the study region, mainly in the western Amazon Basin of Brazil (magenta dots in Figure 1, accessible at <https://bdmep.inmet.gov.br>), have been collected for the specific evaluation of precipitation diurnal cycle. Due to the coarse temporal resolution of the Peruvian rain gauge data and the limited spatial coverage of Brazilian rain gauge data in the study region, the evaluations of spatial distribution, seasonal and sub-daily scales of precipitation, and analyses of MCSs primarily rely on the higher-spatiotemporal-resolution global gridded precipitation data sets. The rain gauge data primarily serve as auxiliary data to evaluate the gridded precipitation data sets and simulations.

2.2. Model Configuration

The simulations conducted in this study utilize the Weather Research and Forecasting (WRF) model with two one-way nested domains, and their configurations are similar to those described by Huang et al. (2023), which are summarized in Table 1. The outer domain (d01) covers the entirety of South America with a horizontal grid spacing of 15 km, and the inner domain (d02) specifically targets the Peruvian central Andes region with a 3-km horizontal grid spacing (Figure 1). The hourly, 0.25° European Centre for Medium-Range Weather Forecasts (ECMWF) atmospheric reanalysis version 5 (ERA5) data (Hersbach et al., 2020) are used for initial and boundary conditions. Our previous short-term sensitivity tests (Huang et al., 2023) revealed a pronounced sensitivity of simulated precipitation in the Peruvian central Andes region to the choice of planetary boundary layer (PBL) schemes, which

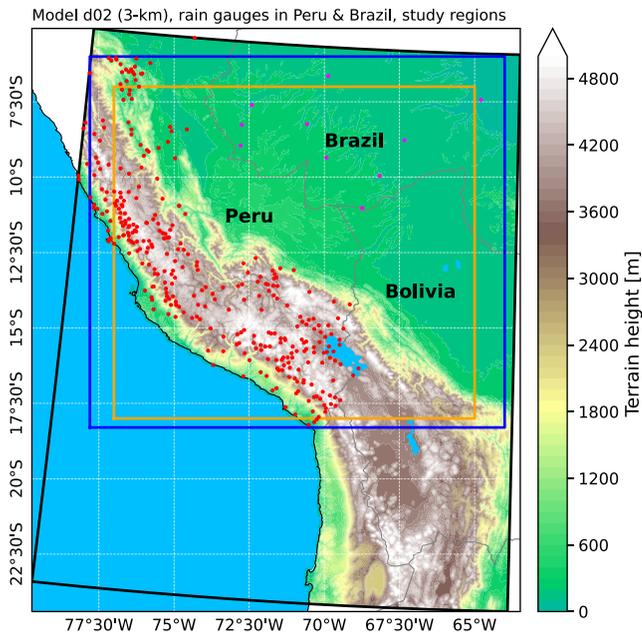


Figure 1. Terrain height (shaded, m) in the 3-km domain with the locations of rain gauges in Peru (red dots) and Brazil (magenta dots). The blue rectangle indicates the region of Figures 2 and 4. The orange rectangle indicates the region of Figures 7, 9, 12, and 13.

can be attributed to differences in the treatment of free-troposphere mixing (X.-M. Hu et al., 2023). We will evaluate whether the CPM simulations have a similar performance in simulating precipitation and MCSs compared to our short-term sensitivity study (Huang et al., 2023). Consequently, this study includes two simulations, each employing a different PBL scheme: ACM2 and MYNN level 2.5 based on our previous sensitivity tests (Huang et al., 2023) (Table 1). Limited by computational resources, the simulations cover the period of 2014–2019 with the initial year (2014) serving as the spin-up period, primarily for the land surface model. Hereafter, the two simulations are referred to as WRF3km_ACM2 and WRF3km_MYNN, respectively.

Additionally, a simulation using one domain with a grid spacing of 4 km, covering the entire South America (Dominguez et al., 2023), produced by the South America Affinity Group (SAAG) led by National Center for Atmospheric Research (NCAR), is also collected, and the simulation data set is available at <https://ral.ucar.edu/projects/south-america-affinity-group-saag/model-output>. Hereafter, this data set is referred to as WRF4km_SAAG. The WRF4km_SAAG simulation covers a 22-year period (Jan 2000–Dec 2021) and also uses 0.25°ERA5 reanalysis data for boundary conditions (Dominguez et al., 2023). The main physics parameterizations used are: YSU PBL scheme (Hong & Lim, 2006), Thompson microphysics scheme (Thompson et al., 2008), RRTMG radiation scheme (Iacono et al., 2008), and the Noah-MP land surface model (Niu et al., 2011) with an activated Miguez-Macho-Fan groundwater scheme (Barlage et al., 2021; Miguez-Macho et al., 2007). Spectral nudging is not used in WRF4km_SAAG.

To facilitate comparison among the observational and simulated data sets at various resolutions, the data sets including CMORPH, MSWEP, and the CPM simulations are regridded to match the IMERG grid ($0.1^\circ \times 0.1^\circ$) utilizing the “patch recovery” technique, a method previously employed by Sun et al. (2016) and Huang et al. (2023). The time period analyzed in this study spans 2015 through 2019, encompassing a total of five years.

2.3. MCS Identification

Python package Tracking and Object-Based Analysis of Clouds (TOBAC, Heikenfeld et al., 2019) is adopted to identify and track MCSs based on the observed and simulated hourly precipitation data sets. In this study, MCSs

Table 1
Summary of WRF3km_ACM2 and WRF3km_MYNN^a

	Domain 1 (d01)	Domain 2 (d02)
Model	WRF V4.2.1 (Skamarock et al., 2019)	
Initial and boundary conditions	ERA5 hourly reanalysis (Hersbach et al., 2020)	
Simulation period	2014–2019 with 2014 as the spin-up period	
Grid spacing	15 km	3 km
Time step	45 s	9 s
Spectral nudging	On (Huang et al., 2023)	Off
Cumulus	Tiedtke (Tiedtke, 1989)	Off
Planetary boundary layer	MYNN level 2.5 (Nakanishi & Niino, 2009) or ACM2 (Pleim, 2007)	
Microphysics	Thompson (Thompson et al., 2008)	
Land surface model	Unified Noah (Ek et al., 2003)	
Surface layer scheme	revised MM5 Monin-Obukhov (Jiménez et al., 2012)	
Longwave and shortwave radiation	RRTMG (Iacono et al., 2008)	

^aMore details can be referred to Huang et al. (2023).

are identified using a precipitation threshold of 5 mm hr^{-1} , which is commonly used in previous studies (Hwang et al., 2023; Prein et al., 2017, 2020; Schwartz et al., 2017). A precipitation region is defined as an object if it exhibits spatial and temporal contiguity and encompasses a minimum area of $1,000 \text{ km}^2$, approximating a horizontal scale on the order of 100 km (https://glossary.ametsoc.org/wiki/Mesoscale_convective_system). By tracking these objects, we can obtain MCS properties throughout their lifetimes. Since hourly precipitation data are used to identify MCSs, the minimum duration for an MCS is set to 1 hr . Utilizing the TOBAC output, various MCS characteristics are calculated, including hourly mean precipitation, hourly peak precipitation, hourly precipitation volume, MCS size, duration, and propagation speed.

3. Results

3.1. Precipitation Characteristics

Prior to the investigation of MCS characteristics, the simulation of average precipitation features such as seasonal and diurnal distributions are evaluated using the three gridded precipitation products in conjunction with rain gauge data.

3.1.1. Seasonal Precipitation

In terms of the spatial distribution of seasonally averaged precipitation (Figure 2), the gridded precipitation products IMERG, CMORPH, and MSWEP show consistent seasonal variations in precipitation distribution, as well as the four notable hotspots (marked by numbers 1–4 in white) along the east slope of the Andes where precipitation can exceed 16 mm day^{-1} in austral summer (December–January–February, DJF). These precipitation hotspots were also identified by previous studies using Tropical Rainfall Measuring Mission precipitation products (e.g., Chavez & Takahashi, 2017; Espinoza et al., 2015; Gutierrez et al., 2023; Junquas et al., 2018; Mohr et al., 2014). From northeast to southwest, the precipitation exhibits a distinct “strong-weak-strong-weak” spatial pattern. Specifically, it is high over the western Amazon Basin, weakens over the transition between the basin and the foothills of the Andes, increases again along the east slope of the Andes, and then weakens once more over the mountains. The three simulations (Figures 2d1–2f4) successfully reproduce the spatial distributions and seasonal variations of precipitation. The WRF3km_ACM2 simulation, which demonstrated superior performance in precipitation amount in our previous short-term sensitivity experiments (Huang et al., 2023), yields lower precipitation in comparison to the three gridded precipitation products and the other two simulations. This discrepancy is particularly noticeable in the southeastern region of the domain, where the precipitation is less than 6 mm day^{-1} during the summer season (DJF) and less than 3 mm day^{-1} in other seasons (Figures 2d1–2d4). The WRF4km_SAAG simulation exhibits more precipitation compared to the other simulations particularly over the mountainous region, where the precipitation exceeds 6 mm day^{-1} during the summer season (DJF) and is over 3 mm day^{-1} in other seasons (Figures 2f1–2f4). A comparison between the gridded precipitation products, the simulations, and the rain gauge data (primarily located over the mountainous region) confirms the overestimate by WRF4km_SAAG (Figure 3). Among the three gridded precipitation products compared to the rain gauge data, IMERG has the lowest absolute value of bias (0.16 mm day^{-1}) and root mean square error (RMSE = 1.60 mm day^{-1}), and the highest correlation coefficient (0.85 and 0.83 before and after removing seasonal cycles, respectively) (Figure 3). Regarding the three simulations, although WRF4km_SAAG has a relatively high correlation with the rain gauge data, with a correlation coefficient of 0.80 after removing seasonal cycles, it also exhibits the largest bias (1.19 mm day^{-1}) and RMSE (2.53 mm day^{-1}) among all gridded and simulated precipitation data (Figure 3). Huang et al. (2023) showed that WRF3km_ACM2 simulates monthly precipitation that is the closest to that of the rain gauges in February 2019, which is also seen in Figure 3. However, WRF3km_ACM2 underestimates the peaks of monthly precipitation in 2016 and 2017. The monthly precipitation amount of the WRF3km_MYNN simulation falls between WRF4km_SAAG and WRF3km_ACM2, and the correlation coefficient after removing seasonal cycles of WRF3km_MYNN with the rain gauge data is 0.76, which is also between those of WRF4km_SAAG (0.80) and WRF3km_ACM2 (0.71) (Figure 3).

Overall, the three simulations broadly capture the spatiotemporal pattern of precipitation at a seasonal scale, but biases in precipitation do exist. Among the simulations of precipitation, WRF3km_MYNN generally outperforms the other two simulations in the Peruvian Central Andes in a combined consideration of bias, RMSE, and correlation coefficient compared with the rain gauge data.

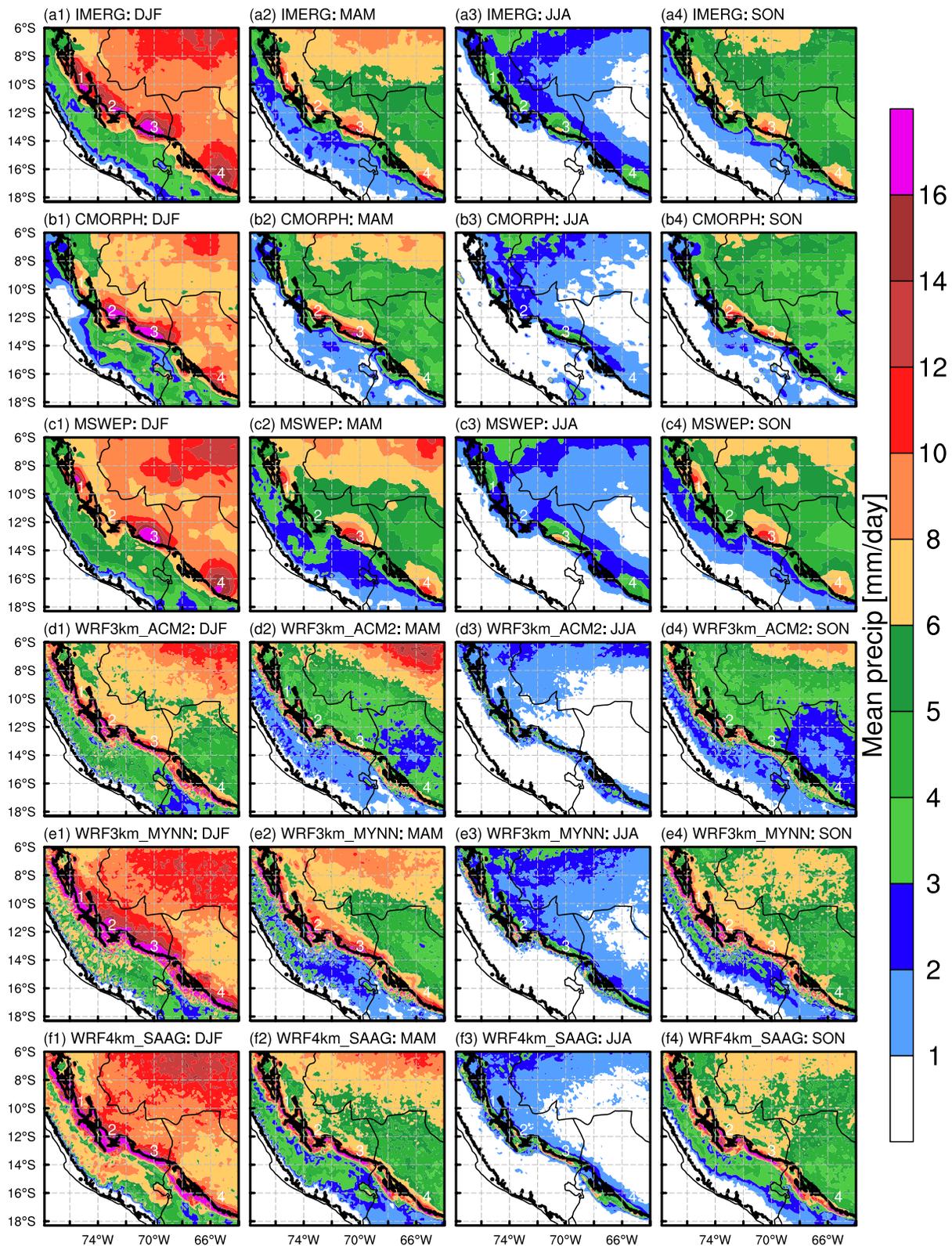


Figure 2. Seasonally averaged precipitation (shaded, mm day^{-1}) for the period of 2015–2019 of (a1–a4) IMERG, (b1–b4) CMORPH, (c1–c4) MSWEP, (d1–d4) WRF3km_ACM2, (e1–e4) WRF3km_MYNN, and (f1–f4) WRF4km_SAAG. (a1–f1) DJF: December–January–February, (a2–f2) MAM: March–April–May, (a3–f3) JJA: June–July–August, and (a4–f4) SON: September–October–November. The 1-km terrain elevation is depicted by the black contour in each panel. The numbers 1–4 in white denote the precipitation hotspots along the eastern slope of the Andes.

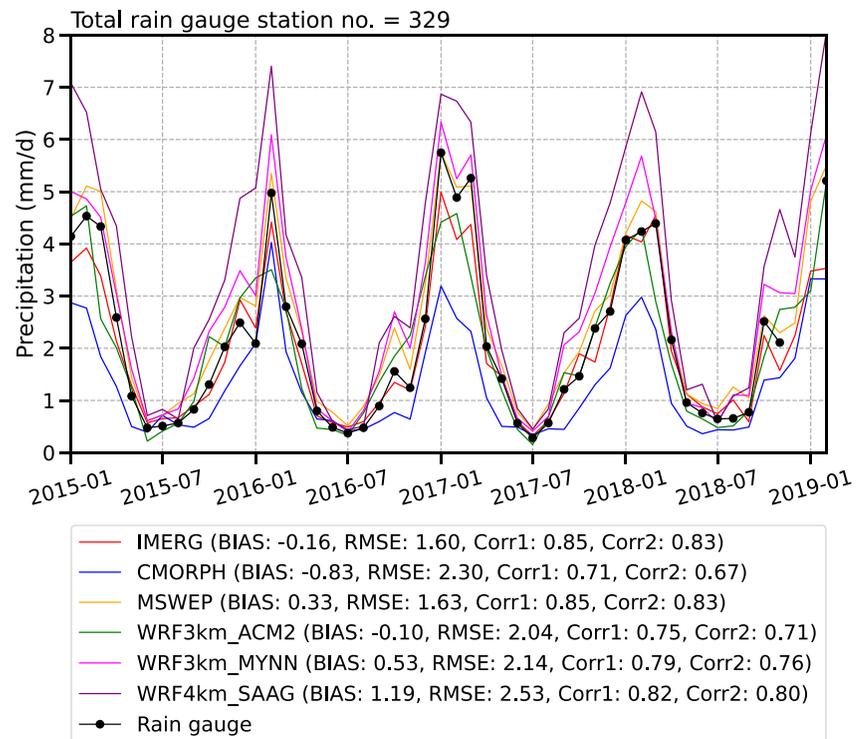


Figure 3. Time series of monthly precipitation (in mm day^{-1}) averaged from rain gauges in Peru within the 3-km domain (Figure 1), and corresponding data from IMERG, CMORPH, MSWEP, WRF3km_ACM2, WRF3km_MYNN, and WRF4km_SAAG at rain gauge locations. The legend includes the averaged bias (BIAS), root mean square error (RMSE), correlation coefficient (Corr1) between the gridded precipitation products or simulations and the rain gauge data, and the correlation coefficient (Corr2) for data with seasonal cycles removed.

3.1.2. Diurnal Cycle of Precipitation

The diurnal precipitation peak times of IMERG, CMORPH, and the three simulations are shown in Figure 4. The MSWEP is not included due to its coarser temporal resolution (three-hourly). As for IMERG and CMORPH, the diurnal precipitation peak time exhibits three distinct belts from the western Amazon Basin to the Andes mountains with a northwest-to-southeast orientation, and this is consistent across all seasons (Figures 4a1–4b4). All three simulations generally reproduce this pattern (Figures 4c1–4e4). While the gridded precipitation products IMERG and CMORPH may have certain biases in precipitation intensity, their diurnal precipitation peak time should be reliable. Using the diurnal precipitation peak time in IMERG as a reference, the seasonal average pattern correlation coefficients with it are 0.900 for CMORPH, 0.856 for WRF3km_ACM2, 0.877 for WRF3km_MYNN, and 0.896 for WRF4km_SAAG. The higher correlation coefficient in WRF4km_SAAG is probably due to its larger model domain at a 4-km grid spacing, while the 3-km WRF runs have a much smaller domain nested within a 15-km grid.

To gain a clearer view of the diurnal precipitation, three regions (represented by blue polygons in Figure 4) are selected to compute the mean diurnal cycle of precipitation over the western Amazon Basin, the Andes foothills, and the mountains, respectively (Figure 5). Because the spatial distributions of diurnal precipitation peak time are similar across all seasons, only the annual-averaged hourly precipitation as a function of local time is shown in Figure 5. The precipitation peak time over the western Amazon Basin primarily occurs between ~ 12 – 17 Local Standard Time (LST) with the maximum average precipitation of ~ 0.40 and $\sim 0.34 \text{ mm hr}^{-1}$ in IMERG and CMORPH, respectively (Figure 5c). The three simulations are able to capture the peak time period in this region. However, in comparison to IMERG, the simulation WRF3km_ACM2 underestimates the average precipitation with a maximum of $\sim 0.28 \text{ mm hr}^{-1}$, while WRF3km_MYNN and WRF4km_SAAG overestimate it with the maximum values of ~ 0.54 and $\sim 0.49 \text{ mm hr}^{-1}$, respectively (Figure 5c). When compared to the rain gauge data in Brazil (primarily in the western Amazon Basin region, Figures 1 and 4a), the magnitudes of precipitation in WRF3km_MYNN and WRF4km_SAAG are closer to the rain gauge data than to IMERG (Figure 6). IMERG

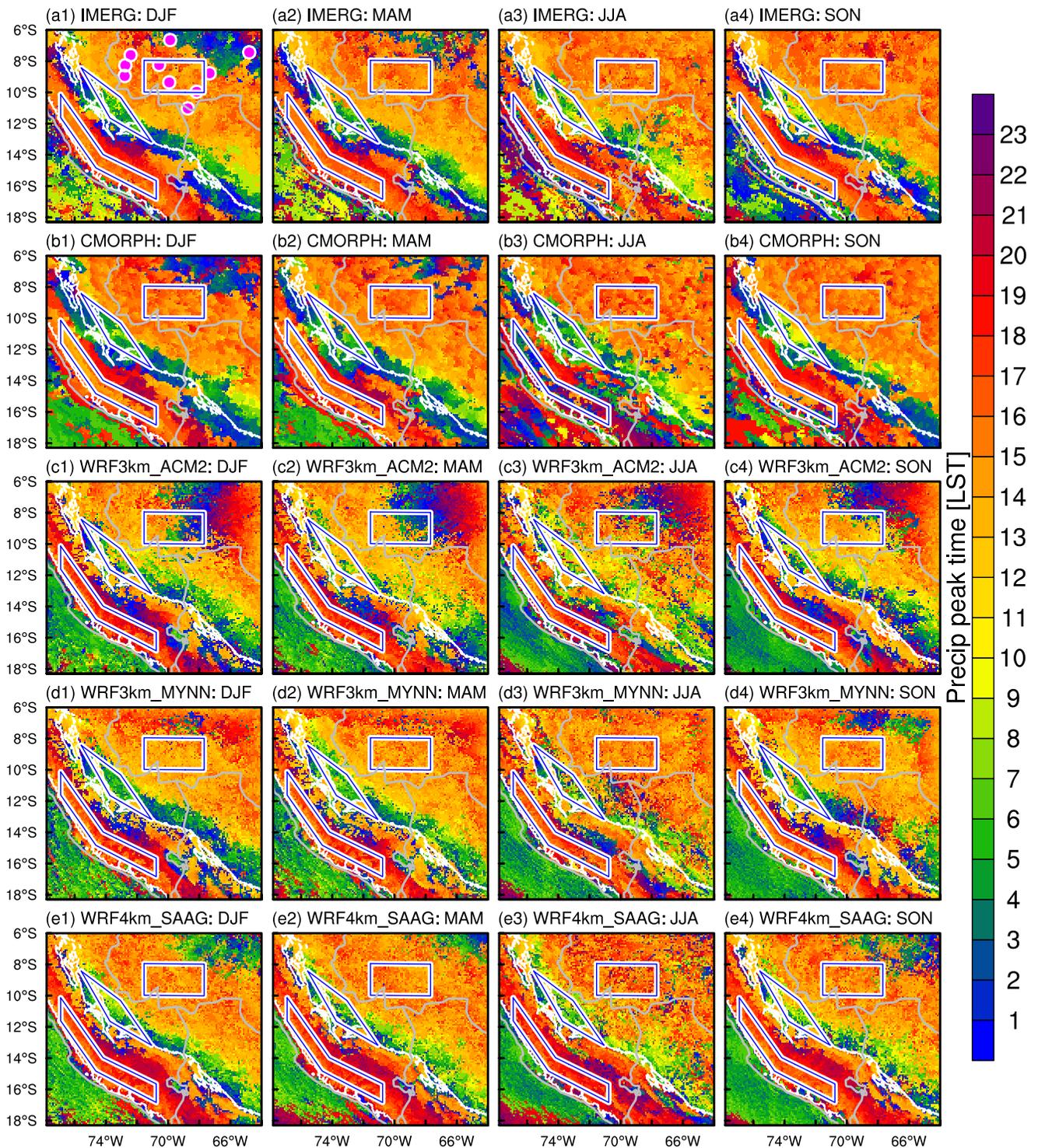


Figure 4. Precipitation peak time (shaded areas in Local Standard Time in each season in panels (a1–a4) IMERG, (b1–b4) CMORPH, (c1–c4) WRF3km_ACM2, (d1–d4) WRF3km_MYNN, and (e1–e4) WRF4km_SAAG. The 1-km terrain elevation is depicted by a white contour in each panel. The blue polygons represent the regions utilized for the calculation of precipitation diurnal cycle shown in Figure 5. The magenta dots in panel (a1) mark the locations of the hourly rain gauge data in Brazil.

actually underestimates the maximum average precipitation by $\sim 20\%$ when compared to the rain gauge data (Figure 6). Taking the rain gauge data as a reference, the RMSEs for the annual average diurnal precipitation are about 0.054, 0.074, 0.094, 0.051, and 0.037 mm hr^{-1} and their corresponding correlation coefficients are around 0.932, 0.891, 0.861, 0.893, and 0.950 for IMERG, CMORPH, WRF3km_ACM2, WRF3km_MYNN, and

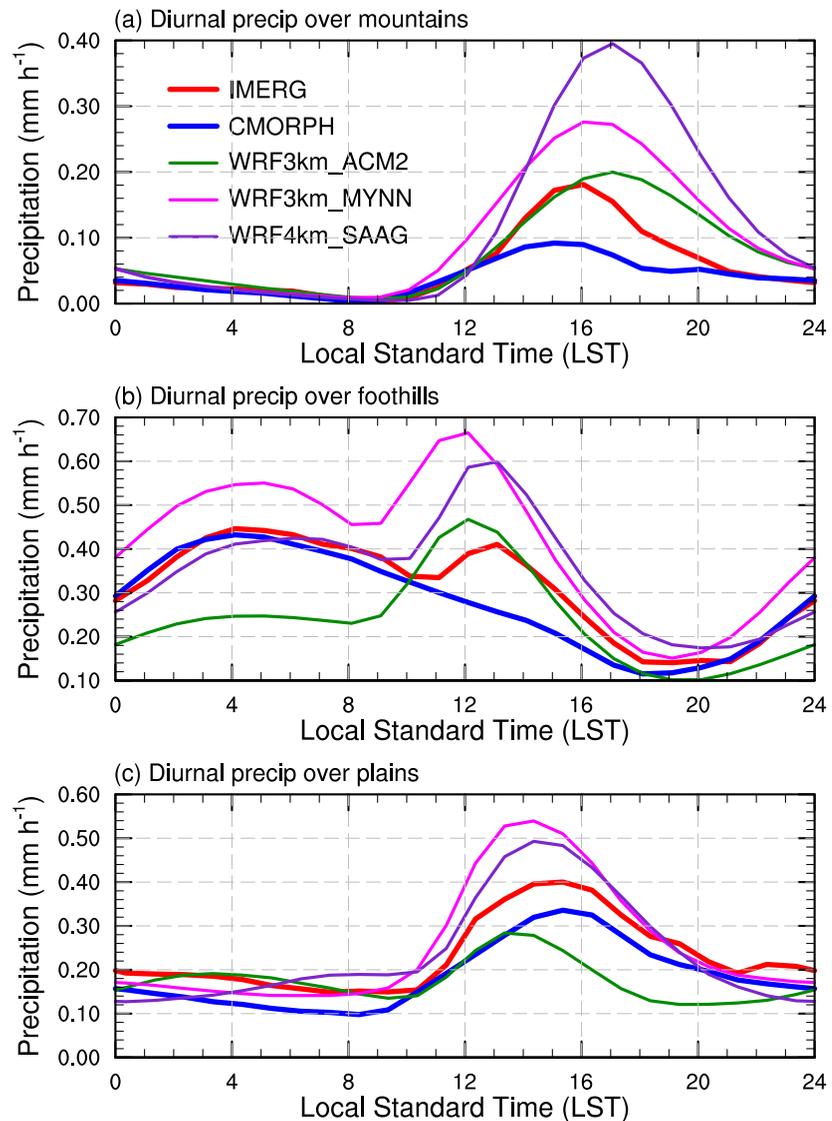


Figure 5. Averaged diurnal cycle of precipitation (mm h^{-1}) in the (a) Andes mountains, (b) Andes foothills, and (c) the western Amazon Basin regions shown in Figure 4 from IMERG, CMORPH, WRF3km_ACM2, WRF3km_MYNN, and WRF4km_SAAG.

WRF4km_SAAG, respectively. This suggests that WRF3km_MYNN and especially WRF4km_SAAG perform well in simulating the diurnal cycle of precipitation over the western Amazon Basin with smaller RMSEs and higher correlations. Similarly, the three simulations reproduce the precipitation peak time periods in the foothill and mountain regions, which occur approximately during 0–7 and 13–19 LST, respectively (Figure 4). Both WRF3km_MYNN and WRF4km_SAAG generally have larger average precipitation in these two regions compared to IMERG, CMORPH, and WRF3km_ACM2 (Figures 5a and 5b). Given the lower RMSE for monthly precipitation in WRF3km_MYNN compared to rain gauge data in Peru (Figure 3), the intensity bias of diurnal precipitation in WRF3km_MYNN should be smaller than that in WRF4km_SAAG over the mountain region. It should be noted that two distinct precipitation peaks are shown in the foothill region (Figure 5b). The dual-peak pattern is consistently observed across all seasons, with slight variations in the relative peak values (not shown). This consistency indicates that the dual-peak pattern is primarily associated with the specific region selected for analysis, which includes the transition zone of precipitation from the Andean foothills to the western Amazon Basin. This regional influence highlights the need for a more detailed examination of the underlying mechanisms driving this pattern in future studies.

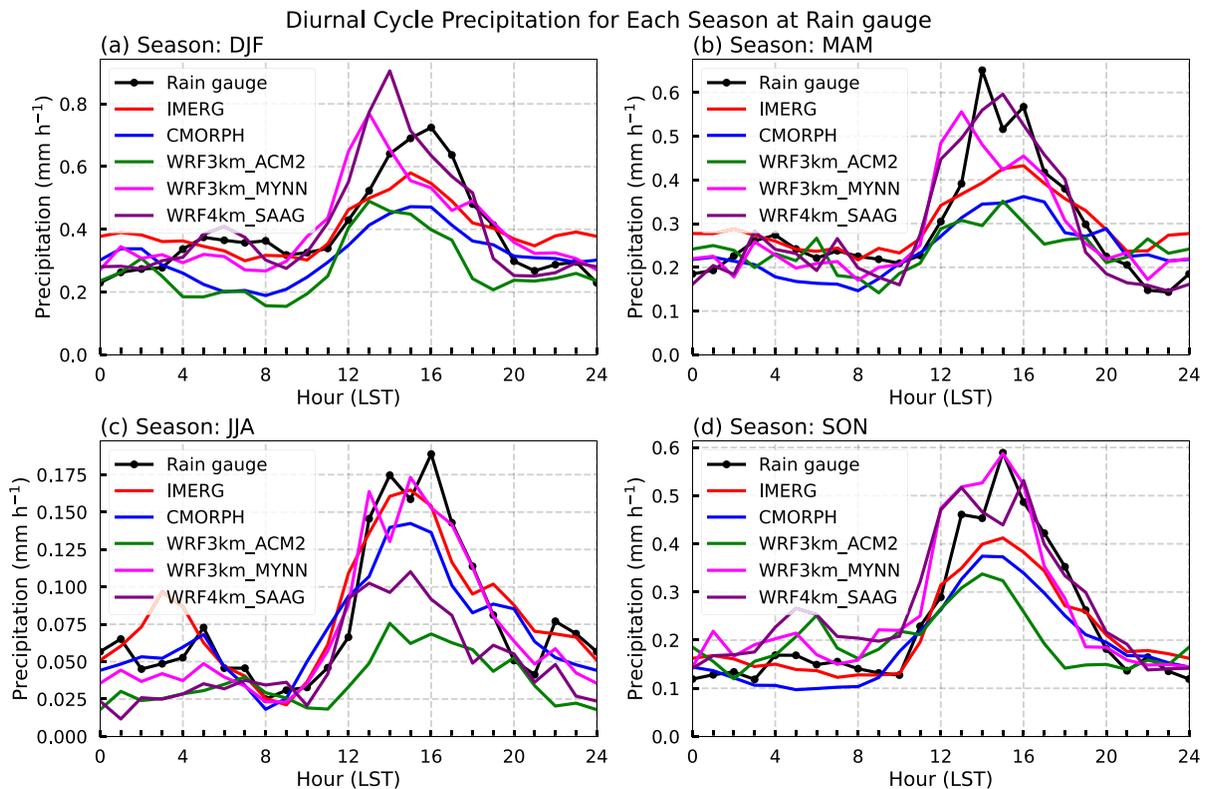


Figure 6. Averaged diurnal cycle of precipitation (mm h^{-1}) of 10 rain gauges in Brazil shown in Figure 4a1 for each season from IMERG, CMORPH, WRF3km_ACM2, WRF3km_MYNN, and WRF4km_SAAG.

Overall, the three simulations successfully capture the spatiotemporal patterns of precipitation at a sub-daily scale, but biases in precipitation amounts are evident. When taking into account both the spatial distribution and intensity of diurnal precipitation, WRF3km_MYNN generally outperforms the other two simulations in the mountain region. Both WRF3km_MYNN and particularly WRF4km_SAAG demonstrate superior performance in the western Amazon region. X.-M. Hu et al. (2023) found that during the morning, the free atmosphere cloud decks dissipate much faster in the simulation using the YSU PBL scheme than the simulation using the ACM2 PBL scheme, leading to more surface radiative heating and convective instability therefore more precipitation in the simulation using the YSU PBL scheme. The cloud cover results in less precipitation in the simulation using the ACM2 PBL scheme.

3.2. MCS Characteristics

The earlier evaluations show that the three WRF simulations effectively reproduce the main features of precipitation at both seasonal and sub-daily time scales in the Peruvian Central Andes region. In the following section, the characteristics of MCSs in this region are examined.

3.2.1. Spatiotemporal Distribution and Propagation

Only the MCSs generated within the region depicted by the orange rectangle in Figure 1 are considered. This specified region is smaller than the 3-km simulation domain to reduce the influence of domain boundaries on the analysis. The spatial distributions of seasonal MCS genesis frequency in Figure 7 reveal that the genesis hotspots for MCSs are along the east slope of the Andes and over the western Amazon Basin. These MCS genesis hotspots were also identified in previous studies (e.g., Feng et al., 2021; Rehbein & Ambrizzi, 2023; Rehbein et al., 2018). These locations coincide with the precipitation hotspots (Figure 2), and MCSs can account for up to 50% of annual precipitation in some of these hotspots (not shown), which is also revealed in Feng et al. (2021). All three simulations produce spatiotemporal evolutions of MCSs that are consistent with IMERG and CMORPH, but WRF3km_ACM2 notably underestimates the MCS genesis frequency (Figure 7). The lower frequency is linked

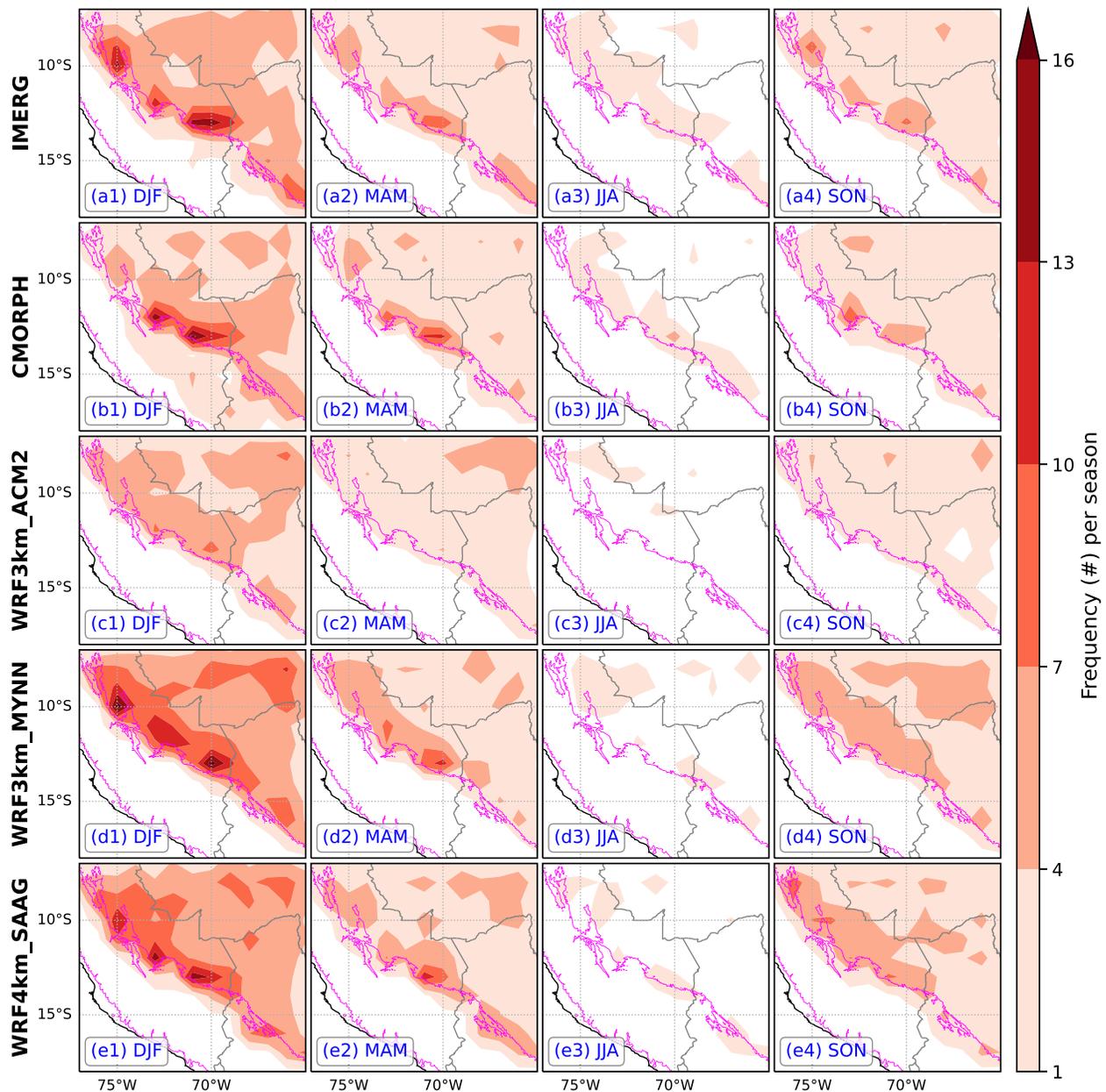


Figure 7. Spatial distribution of mesoscale convective system genesis frequency (in counts) in $1^\circ \times 1^\circ$ bin in each season for (a1–a4) IMERG, (b1–b4) CMORPH, (c1–c4) WRF3km_ACM2, (d1–d4) WRF3km_MYNN, and (e1–e4) WRF4km_SAAG. The 1-km terrain elevation is represented by a magenta contour in each panel.

to the underestimate of precipitation in WRF3km_ACM2 (Figures 2, 3, 5, and 6) and the use of a fixed threshold of 5 mm hr^{-1} for MCS identification. The differences in MCS frequency are more apparent in the time series in Figure 8. Specifically, the MCS frequency in WRF3km_ACM2 is generally lower than in the other data sets, especially during the warm seasons of 2016 and 2019 (Figure 8a). Conversely, WRF3km_MYNN and WRF4km_SAAG display 5-year average MCS frequencies of about 200 in January and February (Figure 8b) and the frequency peaks at around 250 in 2019 (Figure 8a). These two simulations generally exhibit higher MCS frequencies than IMERG and CMORPH during the warm season, exceeding their frequencies by about 20 and 50 ($\sim 10\%$ and $\sim 33\%$) in January and February, respectively (Figure 8b). However, during the cold season (June and July), WRF3km_MYNN and WRF4km_SAAG simulate about 10 fewer MCSs per month compared to IMERG and CMORPH (Figure 8b).

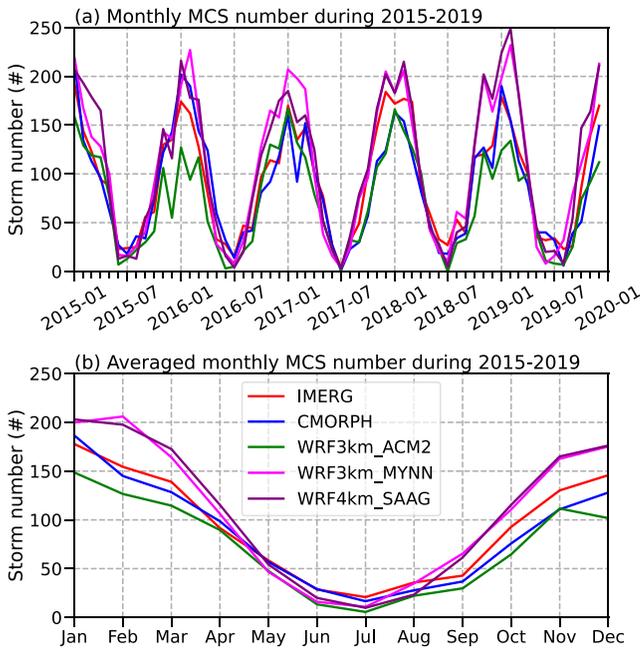


Figure 8. Frequency (in counts) of mesoscale convective system genesis for (a) each individual month from 2015 to 2019 and (b) the average for each month over the 5-year period for IMERG, CMORPH, WRF3km_ACM2, WRF3km_MYNN, and WRF4km_SAAG.

Based on the IMERG and CMORPH data, MCSs along the east slope of the Andes start to initiate during nighttime hours (18–00 LST, see Figures 9a4 and 9b4) and reach a peak in genesis frequency in the early morning (00–06 LST, see Figures 9a1 and 9b1). In contrast, the western Amazon Basin sees a concentration of MCS genesis in the afternoon (12–18 LST, Figures 9a3 and 9b3). All three simulations successfully replicate these diurnal MCS genesis hotspots at terrain notches and over the Amazon Basin. However, WRF3km_ACM2 noticeably underestimates the frequency of MCSs in both the east slope of the Andes and the western Amazon Basin regions (Figures 9c1–9e4).

To examine MCS propagation patterns in the Peruvian Central Andes, MCS propagation direction and speed in the three notable hotspots along the east slope of the Andes and one over the western Amazon Basin are calculated and displayed in the form of wind roses (Figure 10). It should be noted that the spokes in each wind rose plot indicate the direction toward which MCSs move. The concentric circles in each wind rose plot are divided into 16 sectors at intervals of 22.5°, and each sector would represent a probability of 6.25% if the distribution of MCS propagation were uniform. In observational data sets IMERG and CMORPH, MCSs originating along the Andean east slope mainly propagate parallel to the mountain range (Figures 10a and 10b), and the probability of southeastward propagation exceeds 10% in both the northern and southern hotspots in IMERG (Figure 10a). This behavior likely arises from the natural barrier posed by the high, steep Andean slopes. Over the western Amazon Basin, westward propagation dominates with a probability close to 10% in IMERG data (Figure 10a), which is close to the motion

of downwind-developing MCSs estimated by the method proposed by Corfidi (2003) considering the influence of cold-pool factors (not shown). All three simulations can replicate these dominant MCS propagation characteristics, although discrepancies in specific directional angles, probabilities, and speeds exist (Figure 10). For instance, WRF3km_ACM2 shows a notably higher northwestward propagation probability both along the east slope of the Andes and over the western Amazon Basin, peaking at probabilities above 15%, a higher value than observed in IMERG (Figures 10a and 10c). Northwestward propagation is also prevalent along the east slope of the Andes, as seen in WRF4km_SAAG (Figure 10e). Compared to WRF3km_ACM2, the WRF4km_SAAG simulation, similar to IMERG (Figure 10a), exhibits a broader directional spread over the western Amazon Basin, ranging from southward to northwestward, with the highest probability of ~10% in the west-northwestward direction (Figure 10e). WRF3km_MYNN closely aligns with IMERG for MCS propagation along the Andean slope but veers more southwestward over the Amazon Basin (Figure 10d). Additionally, all three simulations simulate higher probabilities for MCS propagation speeds exceeding 65 km hr⁻¹ compared to IMERG and CMORPH, implying an overestimate of MCS propagation speed in the simulations. However, it should be noted that IMERG and CMORPH also have uncertainties, especially in CMORPH, whose MCS propagation direction has a large difference from IMERG and all simulations (Figure 10).

Overall, although specific discrepancies exist in the MCS genesis frequency and propagation speed, the WRF simulations generally replicate the observed spatiotemporal patterns at both seasonal and diurnal scales and the propagation of MCSs in the Peruvian Central Andes and western Amazon.

3.2.2. Statistics of MCS Properties

In this section, MCS properties are statistically examined to identify main differences in MCSs among IMERG, CMORPH and all simulations. Properties of MCSs, such as hourly mean precipitation, peak hourly precipitation, size, duration, hourly precipitation volume (equals hourly mean precipitation × area), and moving speed, are displayed for IMERG, CMORPH, WRF3km_ACM2, WRF3km_MYNN, and WRF4km_SAAG using violin plots (Figure 11). The MCS properties are generally consistent between IMERG and CMORPH, as well as among the three simulations themselves, as shown in Figure 11. However, a significant discrepancy exists between the gridded precipitation products, IMERG and CMORPH, and the simulations, WRF3km_ACM2, WRF3km_MYNN, and WRF4km_SAAG, particularly in MCS precipitation intensity, including both mean and

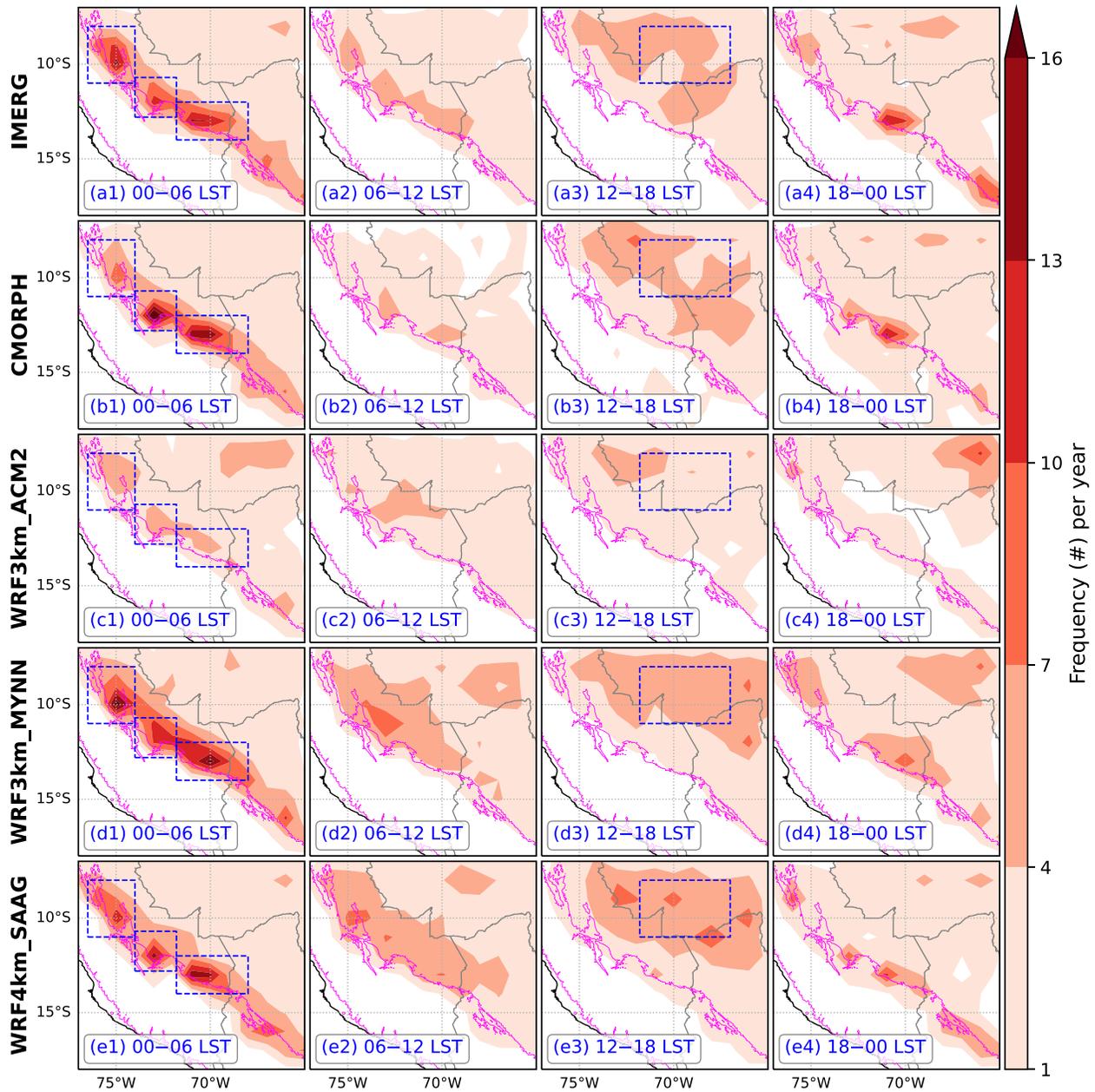


Figure 9. Spatial distribution of the diurnal mesoscale convective system genesis frequency (in counts) in $1^\circ \times 1^\circ$ bin for (a1–a4) IMERG, (b1–b4) CMORPH, (c1–c4) WRF3km_ACM2, (d1–d4) WRF3km_MYNN, and (e1–e4) WRF4km_SAAG. The 1-km terrain elevation is represented by a magenta contour in each panel. The Local Standard Time (LST = UTC – 5 hr) here is based on the longitude of 75°W. The blue rectangles in panels (a1–c1) and (a3–e3) indicate the regions to create wind roses shown in Figure 10.

peak hourly precipitation (Figures 11a and 11b). The interquartile range (25th to 75th percentiles) for the mean hourly precipitation in IMERG and CMORPH spans $\sim 8\text{--}11 \text{ mm hr}^{-1}$, centering around a median value of $\sim 9 \text{ mm hr}^{-1}$. In contrast, all simulations exhibit a higher interquartile range, covering $\sim 13\text{--}19 \text{ mm hr}^{-1}$, and center around median values of about 16 mm hr^{-1} (Figure 11a). The differences between the gridded precipitation products and simulations are also evident in peak hourly precipitation rates. Specifically, the 25th, 50th (median), and 75th percentiles for IMERG are approximately 14, 20, and 28 mm hr^{-1} , respectively, and for CMORPH, they are around 14, 18, and 24 mm hr^{-1} . In contrast, these percentiles are notably higher in the simulations: for WRF3km_ACM2, they are about 35, 46, and 59 mm hr^{-1} ; for WRF3km_MYNN, they are approximately 38, 48, and 60 mm hr^{-1} ; and for WRF4km_SAAG, the values are around 40, 51, and 64 mm hr^{-1} (Figure 11b). This

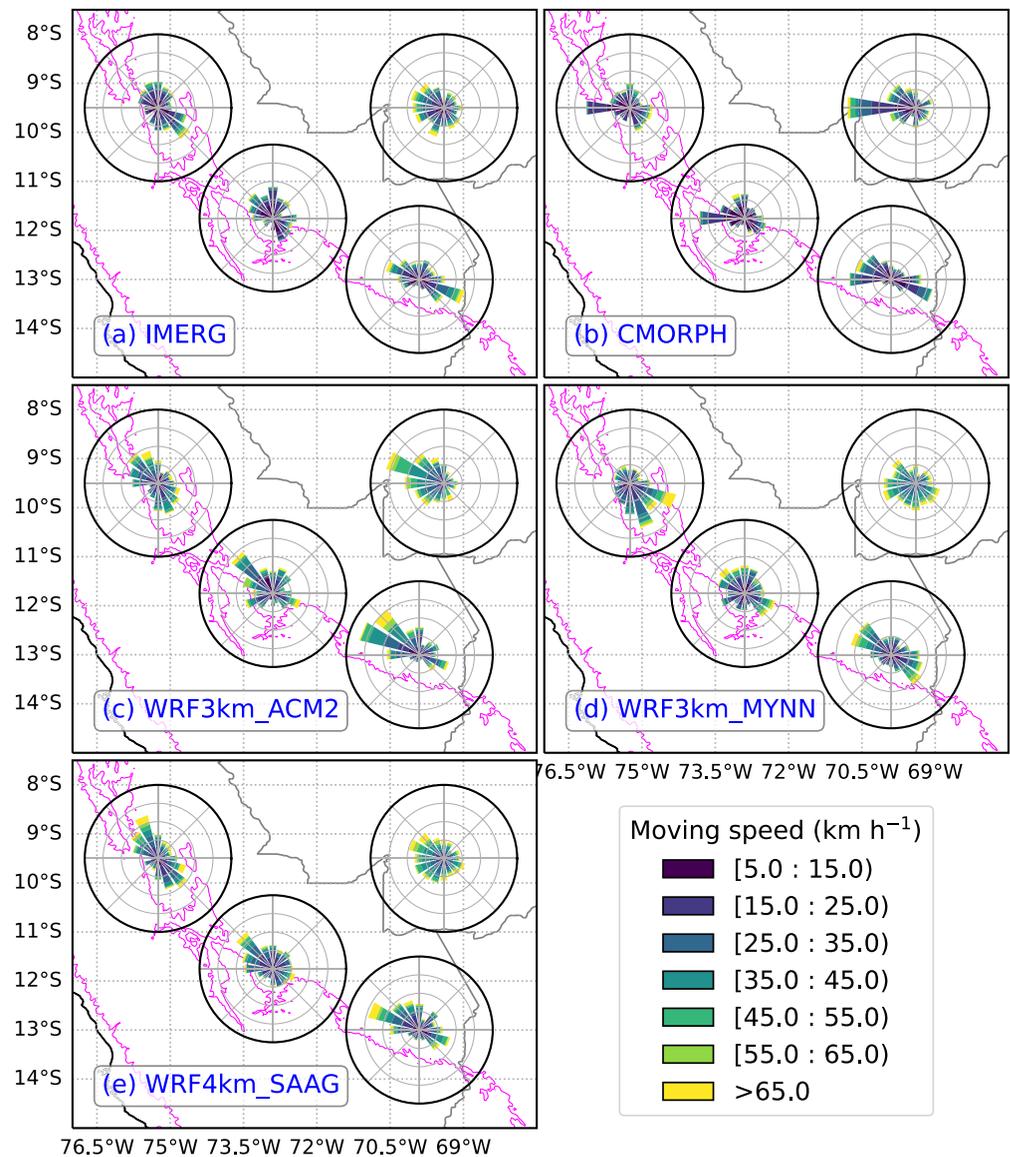


Figure 10. Wind roses for mesoscale convective system (MCS) propagation in the hotspots along the east slope of the Andes and in the western Amazon Basin shown in Figure 9 for (a) IMERG, (b) CMORPH, (c) WRF3km_ACM2, (d) WRF3km_MYNN, and (e) WRF4km_SAAG. The concentric circles in each panel indicate the probability (5%, 10%, 15%, and 20%) of MCS propagation direction, divided into 16 sectors at intervals of 22.5°. The colors within the circles represent the MCS moving speed classes, segmented into intervals of 10 km hr⁻¹. The 1-km terrain elevation is represented by a magenta contour in each panel.

suggests that the simulations tend to overestimate the median of peak hourly precipitation by more than 130% compared to the IMERG. Regarding MCS size, IMERG and CMORPH show 25th to 75th percentile ranges of approximately 4,700–12,000 km², with median sizes close to 7,000 km² (Figure 11c). However, the simulations generally produce smaller MCS sizes, with 25th to 75th percentile ranges spanning about 3,000–7,000 km² and median sizes around 4,000 km². Despite the smaller sizes, the simulations exhibit higher precipitation intensity (Figure 11a). Consequently, the simulated and observed hourly precipitation volumes are relatively similar (Figure 11e). Specifically, the 25th to 75th percentile ranges in the simulated and observed hourly precipitation volumes are approximately 0.04–0.11 km³ hr⁻¹, with median volumes of around 0.065 km³ hr⁻¹ (Figure 11e). Meanwhile, all data sets exhibit a median MCS duration of 3 hr (Figure 11d). However, the simulations generally produce higher MCS movement speeds, with a median of ~36 km hr⁻¹, compared to the observed median speeds of ~20 km hr⁻¹ in IMERG and CMORPH (Figure 11f), which aligns with the findings presented in Figure 10.

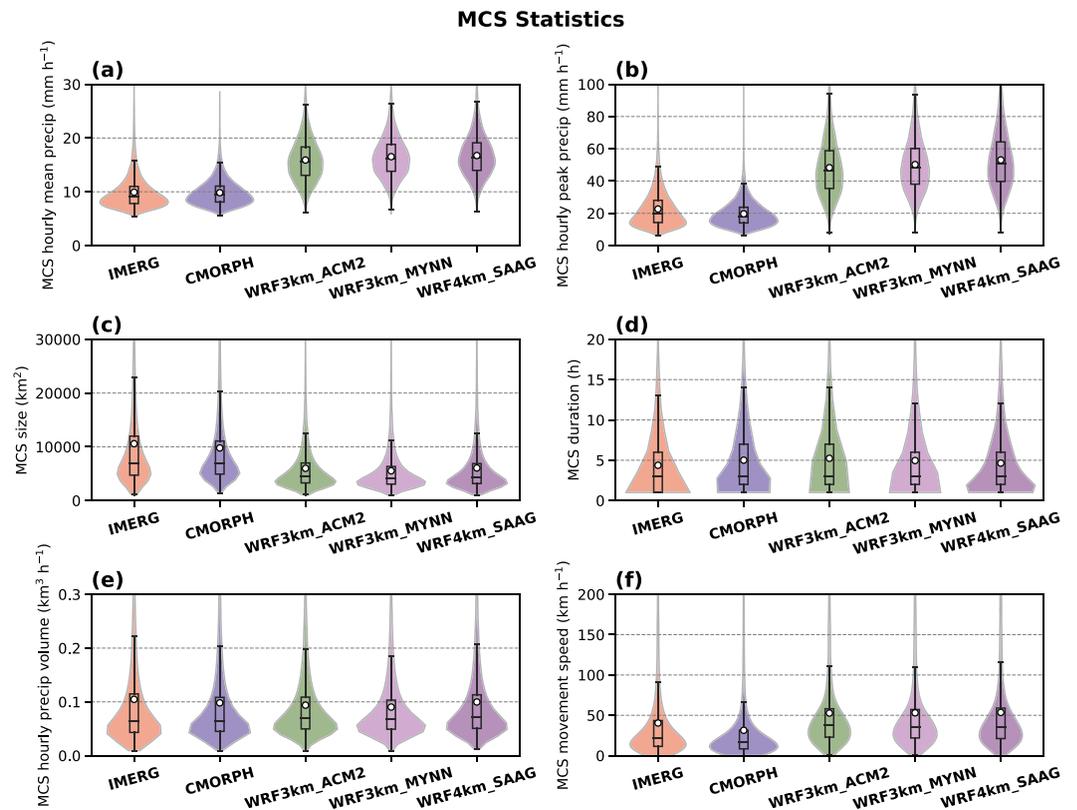


Figure 11. Violin plot of mesoscale convective system (MCS) properties including MCS (a) hourly mean precipitation, (b) hourly peak precipitation, (c) size, (d) duration, (e) hourly precipitation volume, and (f) moving speed for IMERG, CMORPH, WRF3km_ACM2, WRF3km_MYNN, and WRF4km_SAAG. The white circles in box-and-whisker plots represent the average value of samples. The distributions and medians of the gridded precipitation products and simulations are significantly different at the 0.05 level, except for MCS duration comparisons between CMORPH and WRF3km_ACM2 or WRF3km_MYNN.

Overall, statistical analyses of MCS properties reveal that the simulations generally overestimate both mean and peak hourly precipitation rates associated with MCSs, and simulate smaller MCS sizes but similar hourly precipitation volumes compared to gridded precipitation products. All data sets agree on a median MCS duration of 3 hr, though simulated MCSs tend to move faster. It should be noted that the discrepancies between the simulations and the gridded precipitation products may also arise from the uncertainties and low effective resolutions of the gridded precipitation products (Guilloteau & Foufoula-Georgiou, 2020), thereby emphasizing the need for more reliable observational products.

3.2.3. Diurnal Dynamic and Thermodynamic Factors

Despite noted differences in MCS precipitation intensity, frequency, and movement speed, all three simulations, particularly WRF3km_MYNN, successfully replicate key spatiotemporal distributions and evolution of MCSs across multiple scales. In the subsequent section, diurnal variations of dynamic and thermodynamic fields from the 3-km simulations WRF3km_MYNN and WRF3km_ACM2 are used to understand the mechanisms underlying MCS genesis in this region.

From the DJF-seasonal mean hourly horizontal wind fields at 850 hPa in WRF3km_MYNN and WRF3km_ACM2 shown in Figures 12 and 13, we can see that the mean winds in the examined region on the east of the Andes are predominantly northwesterly, influenced mainly by the steep high Andean terrain that blocks the northeasterly SALLJ and turns the flows into northwesterly. However, the mean wind speed in WRF3km_MYNN ($\sim 3.9 \text{ m s}^{-1}$) is closer to that in ERA5 ($\sim 4.6 \text{ m s}^{-1}$, not shown) than that in WRF3km_ACM2 ($\sim 2.6 \text{ m s}^{-1}$). In WRF3km_MYNN, wind convergence (divergence $< -1 \times 10^{-6} \text{ s}^{-1}$, orange dot-filled areas) is primarily found along the east slope of the Andes and over the western Amazon Basin between 00 and 06 LST (Figures 12a–12g). Such enhancement of

convergence and precipitation in the early morning hours near the LLJ terminus (Figure 14a) can be mostly explained by the theory of boundary layer inertial oscillation (Blackadar, 1957; Xue et al., 2018).

Starting from 07 LST, the convergence zones (divergence $< -1 \times 10^{-6} \text{ s}^{-1}$, orange dot-filled areas) begin to contract and become concentrated within the basin area around the latitude of 10°S between 12 and 15 LST (Figures 12h–12p). From 16 LST, the convergence region gradually expands and eventually covers both the Andean slope and the basin regions again (Figures 12q–12x). Such distribution and evolution of wind convergence in WRF3km_MYNN are consistent with those in ERA5 (not shown). The diurnal variations in wind convergence and horizontal wind speeds along the east slope of the Andes (Figures 12 and 14a) are consistent with the diurnal variation of MCS genesis in the region, where the frequency of MCSs begins to increase between 18 and 00 LST and peaks between 00 and 06 LST (Figure 9). This suggests that MCS activity and precipitation along the eastern Andean slope are mainly driven by dynamical forcings, such as the uplift of moist air by SALLJ and by the mountain-range-parallel northwesterly flows when they encounter the terrain notches near the precipitation hotspots. In WRF3km_ACM2 (Figure 13), the area of the wind convergence (divergence $< -1 \times 10^{-6} \text{ s}^{-1}$, orange dot-filled areas) first decreases and then increases from 00 to 23 LST, which is consistent with that in WRF3km_MYNN. However, in WRF3km_ACM2 (Figure 13), the wind convergence (divergence $< -1 \times 10^{-6} \text{ s}^{-1}$, orange dot-filled areas) primarily covers the east slope of the Andes and part of the western Amazon Basin between 00 and 06 LST (Figures 13a–13g). The horizontal wind speeds associated with LLJ are also weaker in WRF3km_ACM2 than in WRF3km_MYNN (Figure 14). There are few convergence zones in the study region between 12 and 15 LST (Figures 13h–13p). It is consistent with the weaker precipitation (Figures 2, 5, and 6) and fewer MCS geneses (Figure 9) over the western Amazon Basin in WRF3km_ACM2. It should be noted that although there are differences in the magnitudes of the horizontal wind speeds in the three MCS genesis hotspots along the east slope of the Andes (marked in Figures 9c1 and 9d1), the diurnal variations of wind speeds in the three hotspots are similar in both WRF3km_MYNN and WRF3km_ACM2 (not shown). Notably, the horizontal wind speeds are consistently larger in WRF3km_MYNN compared to WRF3km_ACM2.

For the western Amazon Basin, convergence is consistently present throughout the day in WRF3km_MYNN (Figure 12) and ERA5 (not shown). Despite this, MCSs predominantly form between 12 and 18 LST (Figure 9), indicating that dynamic convergence associated with low-level flows is not the most dominant driver of MCS activity in this region. Thermodynamic forcing likely plays even more important roles in triggering and supporting a majority of MCSs. To further understand the underlying mechanisms, vertical cross-sections of diurnal vertical velocity at the latitude of 10°S are examined, along with maximum convective available potential energy (CAPE) and maximum convective inhibition (CIN) (Figures 15 and 16).

In WRF3km_MYNN, during the early morning hours (00–06 LST), strong updrafts are observed on the Andean east slope, mainly attributed to enhanced low-level flows (Figure 14a) and associated terrain lifting, although the CAPE values are moderate, ranging from approximately 500 to 1000 J kg^{-1} (Figures 15a–15g). In the western Amazon Basin, CAPE is comparable, but CIN is noticeably higher (up to $\sim 160 \text{ J kg}^{-1}$) (Figures 15a–15g), inhibiting the triggering of significant convection despite the convergence. Starting at 07 LST, both CAPE and CIN undergo diurnal changes in the basin due to solar radiative heating. CAPE rises to $1,200$ – 1600 J kg^{-1} , while CIN approaches zero between 10 and 15 LST (Figures 15h–15p). Consequently, updraft frequency in the basin increases during this period. During 11–13 LST (Figures 15l–15n), updrafts shift from the Andean slope to the smaller mountains to the east (around 74°W) with a low CAPE between 400 and 800 J kg^{-1} , showing the importance of even small terrains here. In contrast, despite maximum CAPE values on the Andean slopes up to 1600 J kg^{-1} (Figures 15n–15p), updrafts in this region decline, which is largely attributed to divergence in this region associated with enhanced convection upstream over the basin (Figures 12k–12p). Although CAPE starts to decrease and CIN begins to rise after 16 LST, updrafts can persist for a while due to the presence of existing convection and relatively high prior CAPE ($>800 \text{ J kg}^{-1}$, Figures 15q–15u) and previous convection trigger effect. Hence, MCSs in the western Amazon Basin are predominantly influenced by thermodynamic factors. Additionally, updrafts are observed at elevations around 4 km during 12–18 LST over the mountains, aligning with the evolution of CAPE and precipitation in the regions (Figures 5a, 15m–15s). It suggests that thermodynamic factors also have a significant influence on precipitation over these elevated terrains. In fact, over major mountain ranges, afternoon convection is often prevalent, such as over the Rocky Mountains (e.g., Carbone & Tuttle, 2008; Sun et al., 2016; Y. Zhao et al., 2023).

For the WRF3km_ACM2 simulation (Figure 16), the diurnal evolution of updrafts, CAPE and CIN are basically consistent with those in WRF3km_MYNN (Figure 15). However, there exist obvious differences in their

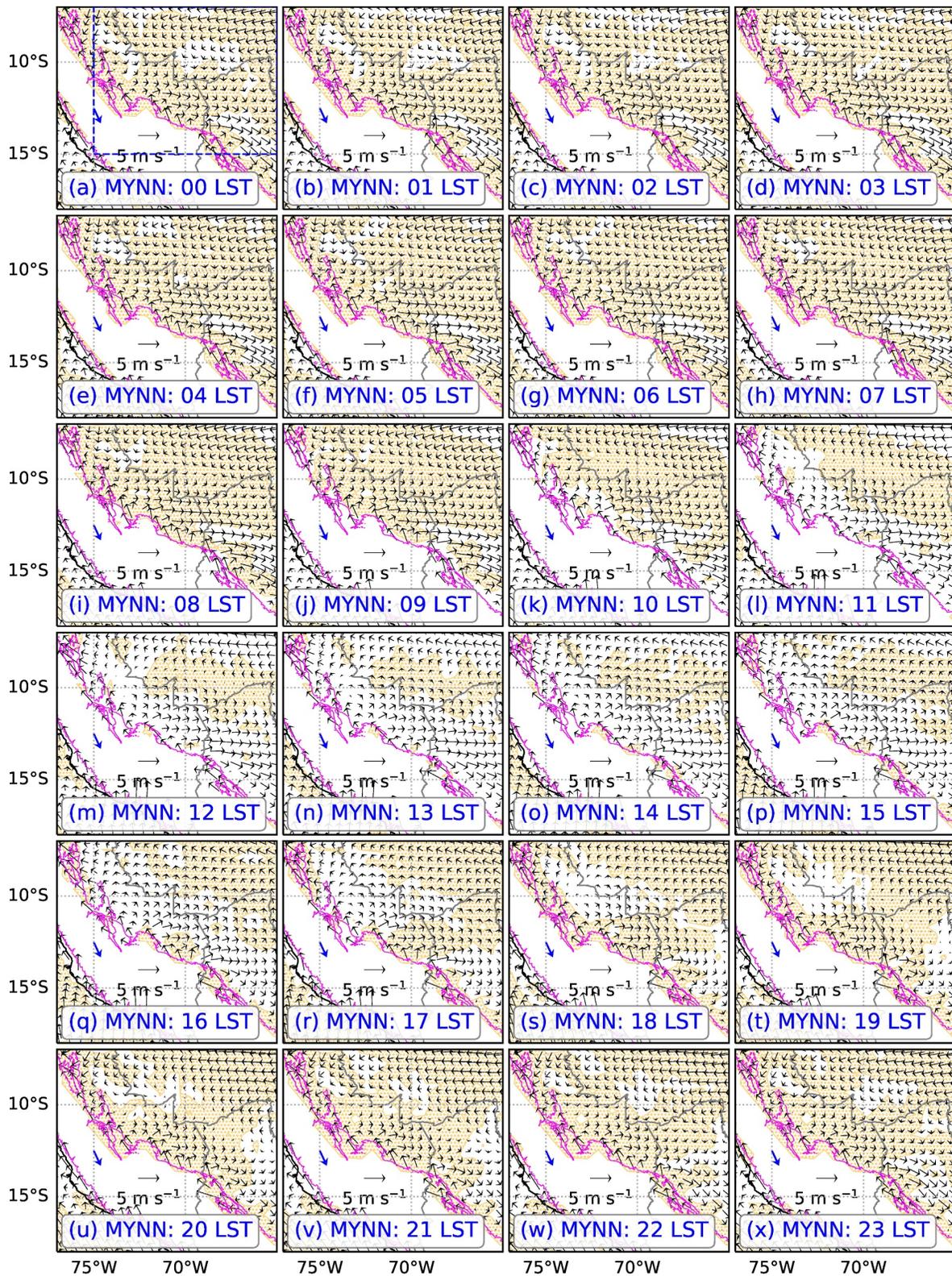


Figure 12.

magnitudes. From 00 to 07 LST, CAPE in WRF3km_ACM2 is around 400 J kg^{-1} (Figures 16a–16h), which is $\sim 100\text{--}500 \text{ J kg}^{-1}$ smaller than that of WRF3km_MYNN (Figures 15a–15h). In the meanwhile, CIN in WRF3km_ACM2 is mostly between 80 and 160 J kg^{-1} and can be up to 200 J kg^{-1} over the western Amazon Basin, which is about 40 J kg^{-1} higher than that of WRF3km_MYNN (Figures 15a–15h and 16a–16h). Therefore, the triggering of updrafts is more inhibited in WRF3km_ACM2, which is consistent with the weaker updrafts in WRF3km_ACM2. Between 08 and 15 LST, CAPE in WRF3km_ACM2 starts to increase, but it is lower than 1200 J kg^{-1} and mostly around 800 J kg^{-1} over the western Amazon Basin (Figures 16i–16p), about 400 J kg^{-1} smaller than that in WRF3km_MYNN (Figures 15i–15p). Moreover, CIN is also generally higher in WRF3km_ACM2 than in WRF3km_MYNN in this period. Thus, there are much fewer updrafts over the western Amazon Basin in WRF3km_ACM2 (Figures 16i–16p). Therefore, the lower CAPE and higher CIN along with the weaker LLJ and fewer convergence zones in WRF3km_ACM2 result in weaker precipitation and fewer MCSs than WRF3km_MYNN. These differences were also found in our previous short-term simulation study (Huang et al., 2023), and analyses in X.-M. Hu et al. (2023) show that the differences in the strength of vertical mixing within the PBL and entrainment flux at the PBL top in different PBL schemes impact the vertical transportation of moisture and momentum. This affects cloud formation and cloud fraction, ultimately influencing surface radiative heating, CAPE and precipitation (X.-M. Hu et al., 2023; Huang et al., 2023). Sensitivity experiments in X.-M. Hu et al. (2023) suggest that the stronger free-troposphere mixing in ACM2 scheme is the primary factor responsible for the discrepancies in the vertical thermodynamic structure and simulated precipitation between the simulations using different PBL schemes.

4. Summary

To investigate the precipitation and MCSs in the Peruvian Central Andes, a region with very complex terrain, two CPM regional climate simulations are run using the WRF model and two PBL schemes, namely ACM2 and MYNN, over a 6-year period (2014–2019) with the first year treated as a spin-up period. These simulations are at a grid spacing of 15 km covering the entire South America and a nested convection-permitting grid spacing of 3 km covering the Peruvian central Andes region. The ERA5 reanalysis data are used to provide the lateral boundary conditions for the 15-km grid. These two CPM simulations combined with the SAAG 4-km simulation covering the entire South America and using the YSU PBL scheme, rain gauge data in Peru and Brazil, and three gridded global precipitation data sets, are used to study the characteristics of precipitation and MCSs in the Peruvian central Andes region and evaluate the capability of models in replicating key observed characteristics. This study provides the evidence on the feasibility of CPM simulations thus configured for projecting the potential climate change impacts on precipitation and MCSs in this region while pointing out certain deficiencies. The key findings are summarized as follows.

- (1) All three simulations, the two 3-km simulations (WRF3km_ACM2 and WRF3km_MYNN) and the 4-km simulation (WRF4km_SAAG), broadly capture the seasonal spatiotemporal patterns of precipitation, particularly the hotspots associated with the prevailing wind patterns and topographical characteristics along the eastern slopes of the Peruvian Central Andes, although some biases in specific precipitation values are present. Among the simulations, WRF3km_MYNN generally outperforms the other two simulations over the mountain regions compared to the gridded precipitation products and available rain gauge data. Meanwhile, WRF3km_MYNN and WRF4km_SAAG display comparable performance in the western Amazon Basin region.
- (2) The three simulations also effectively replicate the sub-daily spatiotemporal patterns of precipitation, but biases in precipitation intensity are evident. When taking into account both the spatial distribution and intensity of diurnal precipitation, WRF3km MYNN generally outperforms the other two simulations in the mountain region. Both WRF3km MYNN and particularly WRF4km SAAG demonstrate superior performance in the western Amazon region when compared to gridded precipitation products and available rain gauge data in Brazil.

Figure 12. Diurnal horizontal winds at 850 hPa averaged over the DJF months from 2015 to 2019 in WRF3km_MYNN. In order to see the convergence region clearly, the full wind field is decomposed into two components: Thick blue vectors represent the time-area-averaged wind in the blue dashed box shown in panel (a), and thin black vectors represent the deviation of the full wind field from the time-area-averaged wind. Regions with wind divergence less than $-1 \times 10^{-6} \text{ s}^{-1}$ are indicated by the orange dot-filled areas. The 1-km terrain elevation is represented by a magenta contour in each panel. The Local Standard Time (LST = UTC – 5 hr) here is based on the longitude of 75°W .

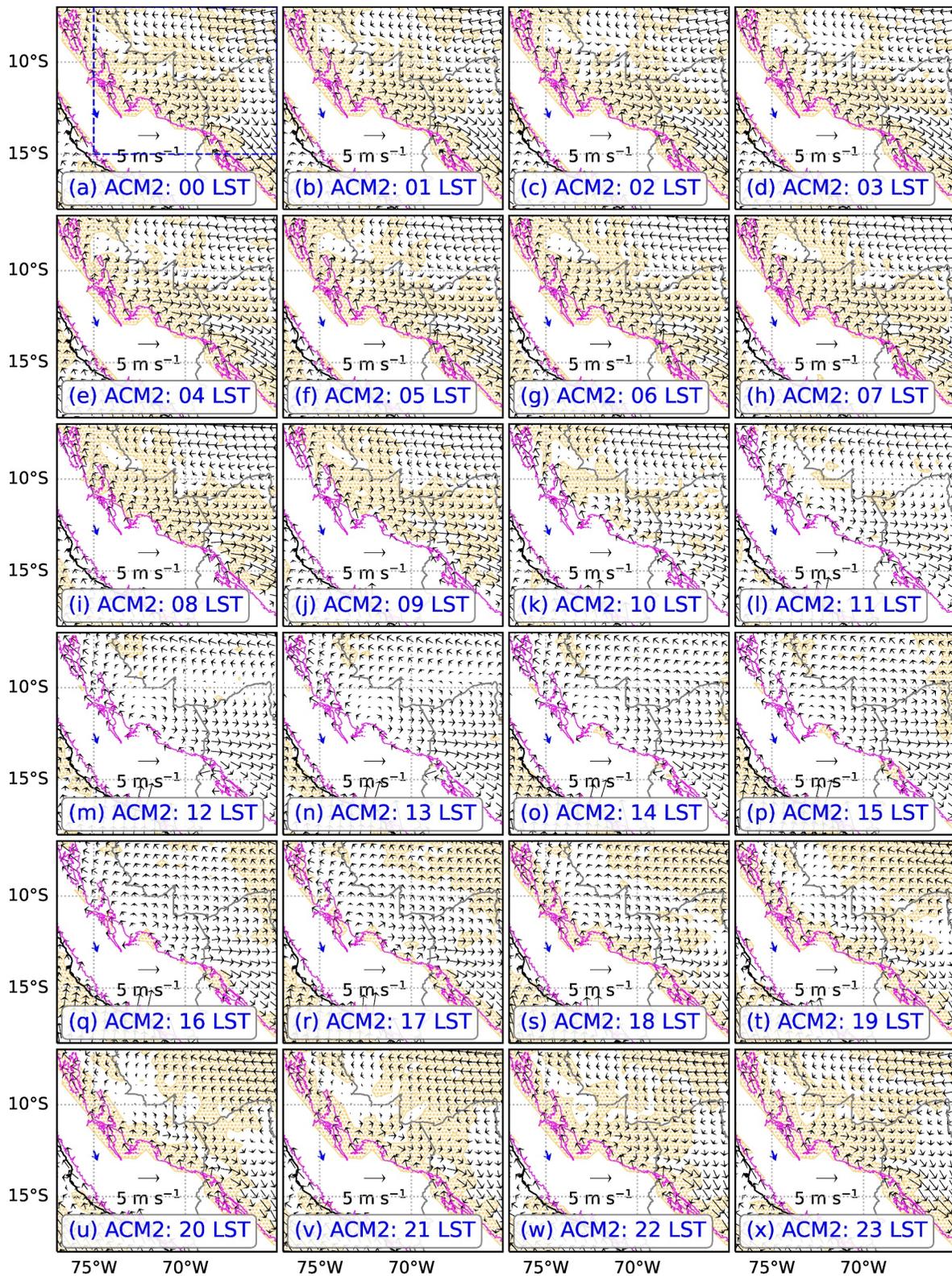


Figure 13. As in Figure 12, but for WRF3km_ACM2.

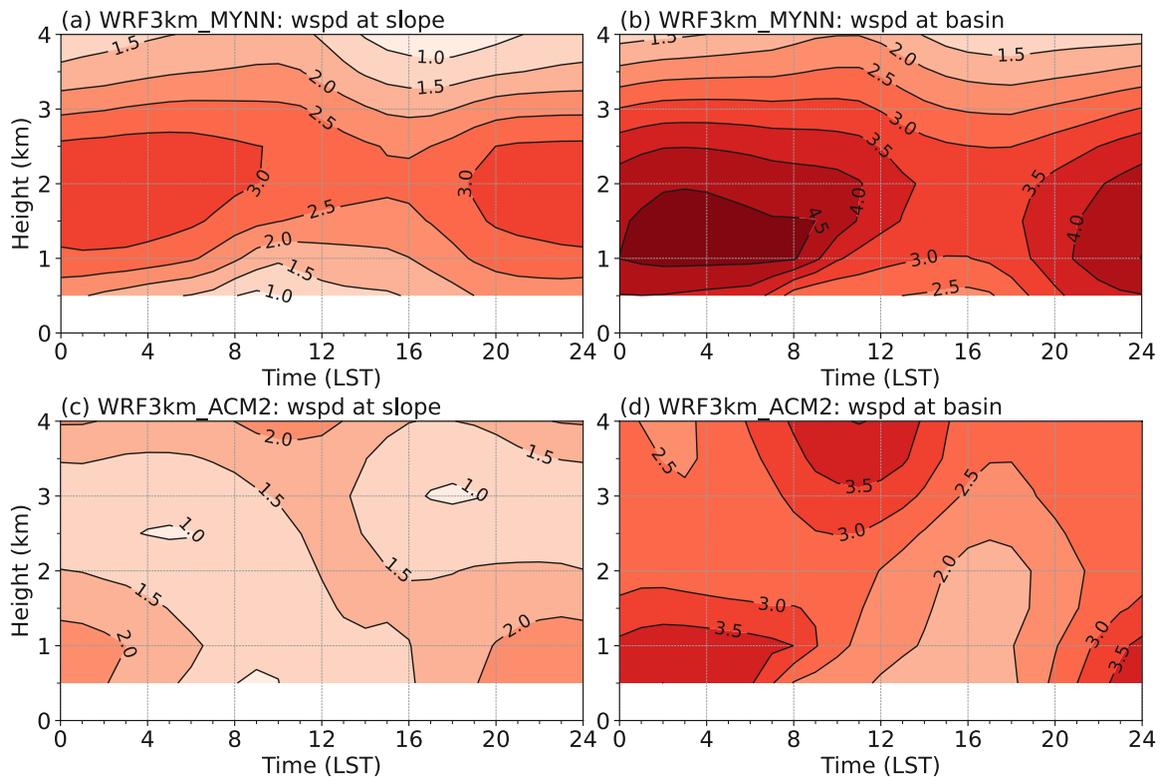


Figure 14. Height-time cross-section of area-averaged horizontal wind speeds (m s^{-1}) in the regions of (a) and (c) northern mesoscale convective system genesis hotspot along the east slope of the Andes and (b) and (d) the hotspot over the western Amazon Basin (blue rectangles shown in Figure 9) in panels (a) and (b) WRF3km_MYNN and (c) and (d) WRF3km_ACM2, respectively.

- (3) The simulations generally replicate the observed spatiotemporal patterns and propagation of MCSs, particularly along the eastern slopes of the Peruvian Central Andes and over the western Amazon Basin, across both seasonal and diurnal time scales. However, specific discrepancies exist in MCS genesis frequency and movement speed. For instance, WRF3km_ACM2 notably underestimates the frequency of MCSs, particularly during the warm seasons of 2016 and 2019. Conversely, WRF3km_MYNN and WRF4km_SAAG tend to overestimate MCS frequency during the warm season. Additionally, all three simulations consistently depict higher frequencies of MCSs with higher moving speeds than those observed in IMERG and CMORPH, highlighting areas for model improvement. Nonetheless, uncertainties do exist with the IMERG and CMORPH precipitation estimate products, and more robust precipitation observations are needed to obtain more reliable evaluations.
- (4) Statistical analyses of MCS properties reveal that the simulations generally overestimate both mean and peak hourly precipitation intensity associated with the MCSs, and produce smaller MCS sizes but similar total hourly precipitation volumes compared to the gridded precipitation products. Moreover, all data sets agree on a median MCS duration of ~ 3 hr within the study area, and the simulations generally produce faster MCS moving speeds compared to the gridded precipitation products.
- (5) Analyses of the diurnal variations in dynamic and thermodynamic parameters indicate that dynamic factors, mainly LLJ-terrain-induced uplift of moisture and energy, are the principal drivers for MCS genesis along the east slopes of the Andes. While in the western Amazon Basin, MCSs predominantly form in the afternoon and are largely governed by thermodynamic factors, specifically solar radiation-induced diurnal changes in CAPE and CIN. The lower CAPE and higher CIN along with weaker convergence in WRF3km_ACM2 result in weaker precipitation and fewer MCSs than in WRF3km_MYNN. These differences are attributed to the differences in vertical mixing within the PBL and especially entrainment flux at the PBL top in different PBL schemes. They impact the vertical transportation of moisture and momentum, then cloud formation and cloud fraction, and ultimately surface radiative heating, CAPE, and precipitation, analyzed previously based on shorter-term simulations (Huang et al., 2023; X.-M. Hu et al., 2023). Besides, similar thermodynamic effects are observed to be the dominant influence on precipitation over elevated mountains.

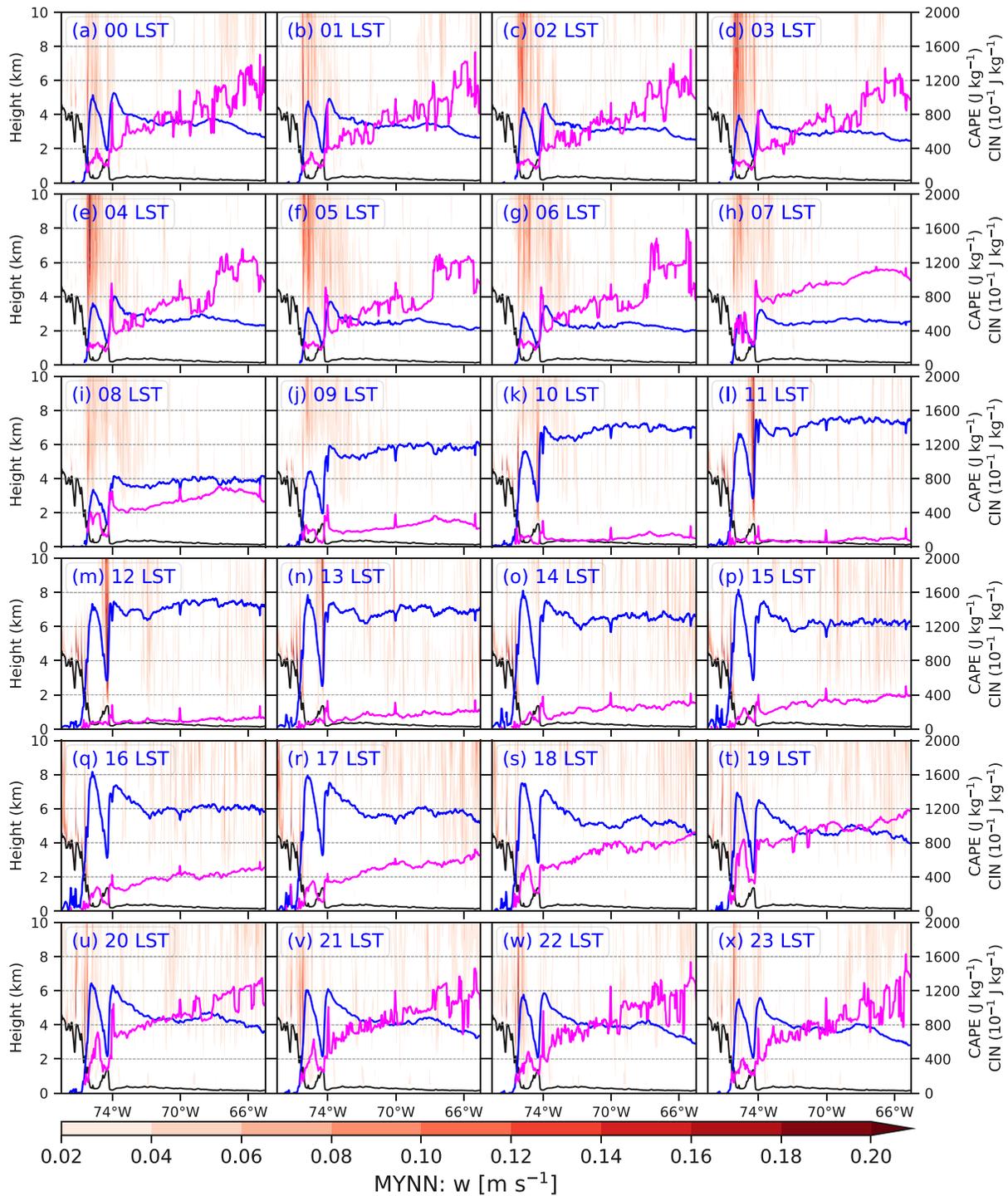


Figure 15. Vertical cross-section of vertical velocity (shaded, in units of m s^{-1}) along the latitude of 10°S in WRF3km_MYNN. The black curves represent the terrain height (km), and the blue and magenta curves represent convective available potential energy (CAPE) (J kg^{-1}) and convective inhibition (CIN) (10^{-1}J kg^{-1}), respectively. The unit of CIN in 10^{-1}J kg^{-1} is used here to make CIN more visible. The Local Standard Time (LST = UTC - 5 hr) here is based on the longitude of 75°W .

In summary, the investigation of precipitation and MCS characteristics in the Peruvian Central Andes in this study offers valuable insights into both observed patterns and convection-permitting regional climate simulation performances. The findings not only enhance our understanding of the specific precipitation and MCS characteristics within this region, but also document the differences between observations and the WRF simulations, which can inform future model improvements. It should be noted that the discrepancies between the gridded

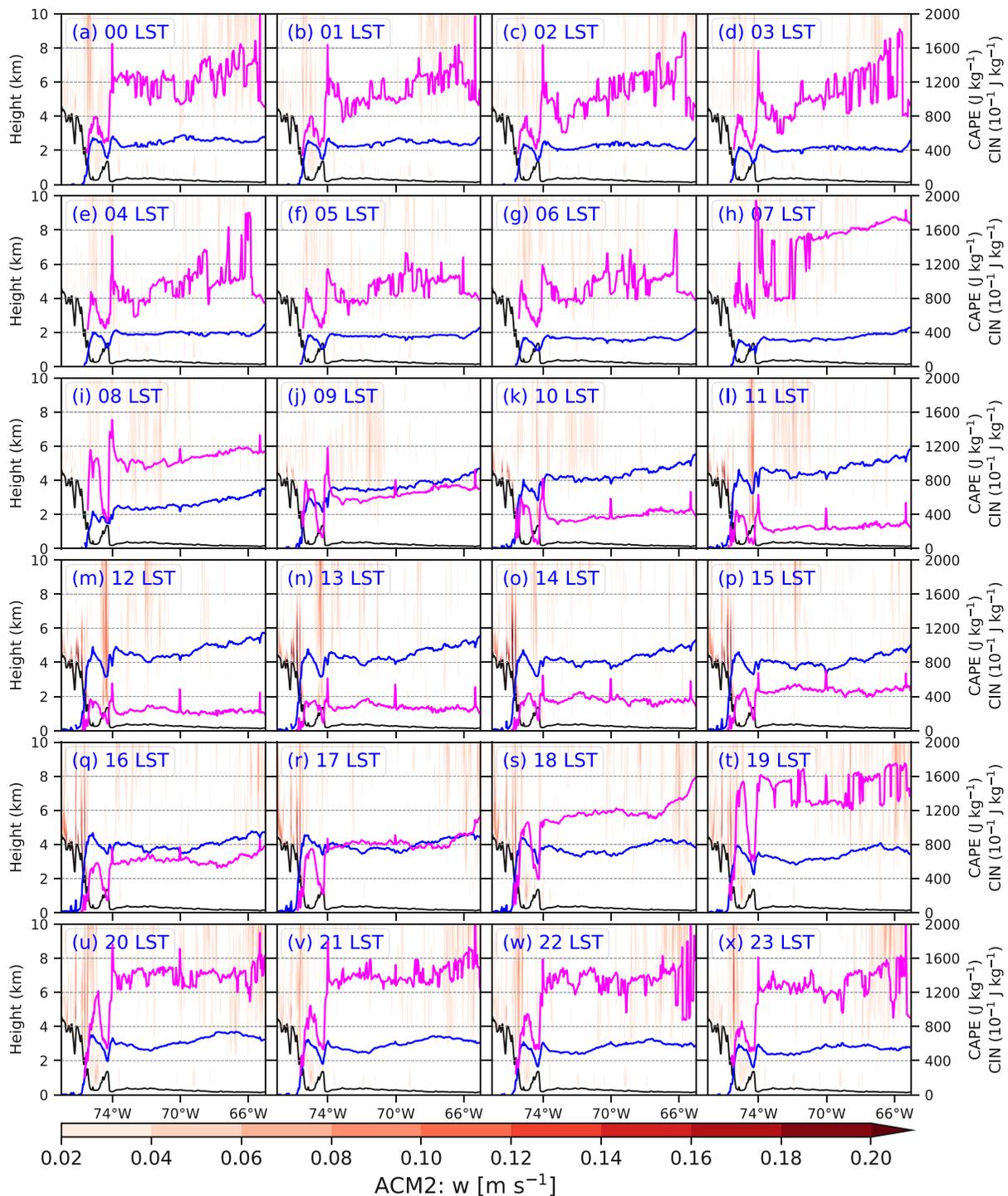


Figure 16. As in Figure 15, but for WRF3km_ACM2.

precipitation products and the simulations may also arise from the uncertainties and low effective resolutions of the gridded precipitation products (Guilloteau & Foufoula-Georgiou, 2020), thereby emphasizing the need for more reliable observational products. Despite the presence of biases, the CPM simulations effectively capture the fundamental mechanisms that govern precipitation and convective systems in the Peruvian Central Andes region. It suggests the feasibility of CPM simulations for projecting the potential climate change impacts on precipitation and MCSs in the region, thereby providing critical input for tailored climate adaptation strategies

in this region, especially after bias correction/calibration of the model projections. Two future climate simulations have been conducted using the same model configuration as WRF3km_MYNN, focusing on two shared socioeconomic pathway scenarios, SSP2-4.5 and SSP5-8.5, that represent the medium and high emission scenarios, respectively. The choice of the WRF3km_MYNN configuration was based on the evaluations of the historical simulations reported in Huang et al. (2023), X.-M. Hu et al. (2023), and this study. These simulations are driven by a bias-corrected global data set, derived from a CMIP6 multi-model ensemble (Xu et al., 2021). The SAAG future simulation is running as well using a pseudo global warming approach and targeting a warming level of $\sim 2.5^{\circ}\text{C}$ in the period of 2060–2080 over South America (Dominguez et al., 2023). Projected changes in precipitation and MCSs in the Peruvian Central Andes region, based on these CPM simulations, are analyzed and reported in Huang et al. (2024).

Data Availability Statement

The ERA5 reanalysis data used for model initial and boundary conditions in the study are available at the U.S. National Science Foundation's NCAR (NSF NCAR) Research Data Archive (European Centre for Medium-Range Weather Forecasts, 2019). GPM IMERG Final Precipitation data set is available at the NASA GESDISC Data Archive (Huffman et al., 2019). CMORPH data set is available at NOAA National Centers for Environmental Information Data Archive (Xie et al., 2019). Multi-Source Weighted-Ensemble Precipitation data set is available online (Beck et al., 2019). The rain gauge data in Peru and Brazil are available at Zenodo (Huang, 2024). The SAAG 4-km simulation data set is available at NSF NCAR Research Data Archive (Rasmussen et al., 2022).

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