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LETTER

Coupled model intercomparison project phase 6 (CMIP6) high resolution model intercomparison project (HighResMIP) bias in extreme rainfall drives underestimation of amazonian precipitation

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Abstract

Extreme rainfall events drive the amount and spatial distribution of rainfall in the Amazon and are a key driver of forest dynamics across the basin. This study investigates how the 3-hourly predictions in the High Resolution Model Intercomparison Project (HighResMIP, a component of the recent Coupled Model Intercomparison Project, CMIP6) represent extreme rainfall events at annual, seasonal, and sub-daily time scales. TRMM 3B42 (Tropical Rainfall Measuring Mission) 3 h data were used as observations. Our results showed that eleven out of seventeen HighResMIP models showed the observed association between rainfall and number of extreme events at the annual and seasonal scales. Two models captured the spatial pattern of number of extreme events at the seasonal and annual scales better (higher correlation) than the other models. None of the models captured the sub-daily timing of extreme rainfall, though some reproduced daily totals. Our results suggest that higher model resolution is a crucial factor for capturing extreme rainfall events in the Amazon, but it might not be the sole factor. Improving the representation of Amazon extreme rainfall events in HighResMIP models can help reduce model rainfall biases and uncertainties and enable more reliable assessments of the water cycle and forest dynamics in the Amazon.

1. Introduction

The Amazon is a key component of the Earth system by affecting climate regulation, carbon storage, and water recycling. The Amazon covers 5.65×10^6 km^2 (53%) of global tropical forest area (Negrón-Juárez *et al* 2018) and contains 25% of the world's terrestrial biomass (98 PgC), (Malhi *et al* 2011, Pan *et al* 2013). Regions within the Amazon receive between 1500 and 4000 mm of rain per year, and 32% of this rainfall is recycled water by evapotranspiration (Staal *et al* 2018).

Tropical convection is a key process producing large amounts of rainfall in the Amazon rainforest (Nobre *et al* 2009). The Amazon exhibits a gradient of rainfall from the southeast, which has a dry season of 5 to 6 months (consecutive months with rainfall $\leqslant$100 mm), to the rainy north (no dry season) (Sombroek 2001, Marengo *et al* 2012, Good *et al* 2016, Rasmussen *et al* 2016). Amazon rainfall is often characterized by extreme rainfall events produced by mesoscale convective systems (MCS), which significantly contribute to total annual rainfall (Silva Dias *et al* 2009, Pereira Filho *et al* 2015, Nunes *et al* 2016, Rehbein *et al* 2018). These systems are

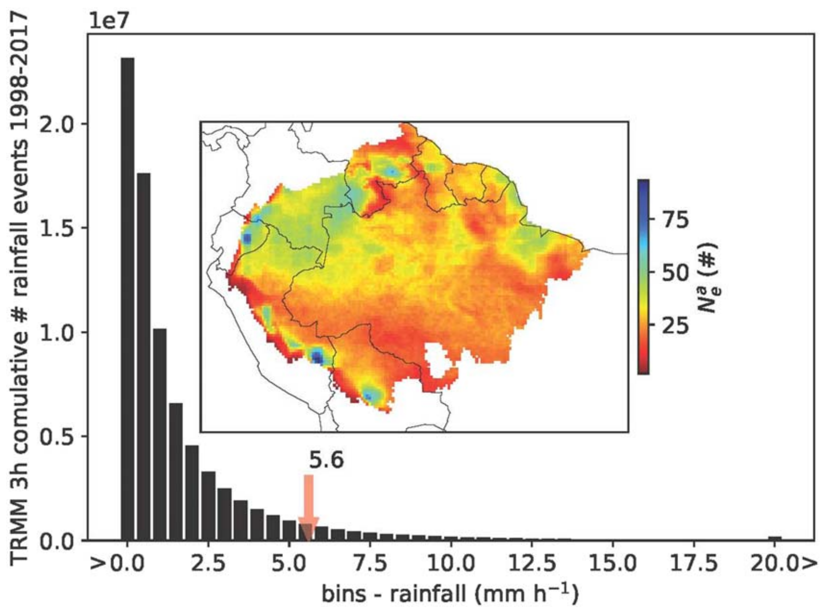

Figure 1. Cumulative number of 3 h rainfall events from 1998 to 2017 using TRMM 3 h (TRMM 3B42) data. The inset shows the mean annual number of extreme rainfall events (N_e^a) (rainfall events ⩾ 5.6 mm h^{-1}) over the Amazon. The red arrow shows the value of 5.6 mm h^{-1}.

regulated by the South American Monsoon System (SAMS) (Carvalho *et al* 2011, Marengo *et al* 2012) and the location of the Intertropical Convergence Zone (ITCZ) (Santos *et al* 2017). The MCS moves westward year-round, and some episodes can last longer than 3 days and cross the entire Amazon basin (Pereira Filho *et al* 2015, Rehbein *et al* 2018). Less frequent MCS moving from southwestern to northeastern in the Amazon also produce large amounts of rainfall (Negrón-Juárez *et al* 2017).

Extreme rainfall events in the Amazon represent ∼5% of all precipitation events (figure 1), contribute about 46% of total rainfall (Jaramillo *et al* 2017) and are a key component of forest dynamics and function. Associated with heavy rainfall from MCS are downbursts that can produce windthrows (uprooted and broken trees by wind), ranging from single trees to large areas of downed forest (Nelson *et al* 1994, Negrón-Juárez *et al* 2010, Negrón-Juárez *et al* 2011, Negrón-Juárez *et al* 2018, Negron-Juarez *et al* 2023). Windthrows can promote forest diversity by creating gaps in the canopy and increasing competition among species (Magnabosco Marra *et al* 2018, Negrón-Juárez *et al* 2018, Urquiza Muñoz *et al* 2021). A recent study showed that Amazon windthrows are expected to increase in frequency in a warming environment (Feng *et al* 2023a) and therefore could have significant implications for the functioning of the Amazon and its biodiversity.

The World Climate Research Programme (WCRP) initiated the Coupled Model Intercomparison Project Phase 6 (CMIP6) as a coordinated Earth System Models (ESM) experiment to improve understanding of the Earth System (Eyring *et al* 2016). Despite CMIP6's advancements in understanding the Earth system, accurately reproducing observed patterns of extreme rainfall in the Amazon remains a challenge (Hagos *et al* 2021). Included within CMIP6, the High Resolution Model Intercomparison Project (HighResMIP) seeks to quantify the benefits of increased horizontal model resolution for representing climatology and weather patterns with greater fidelity (Haarsma *et al* 2016). The hypothesis posits that higher spatial resolution improves the accuracy of rainfall patterns. Thus, this study aims to evaluate how the HighResMIP model represents Amazon rainfall focusing on: (a) observed associations between seasonal, annual and extreme rainfall events, (b) seasonal variability of extreme rainfall events, and (c) observed sub-daily patterns of extreme rainfall. This is the first study to examine how HighResMIP models represent Amazon rainfall across annual, seasonal, and sub-daily timescales.

2. Study area, data, and methods

2.1. Study area

The study area is the Amazon rainforest (figure 1). The Amazon has east-west gradients of rainfall, forest dynamics, and soil nutrient availability (Malhi and Davidson 2009). Deforestation has reduced the extent of the Amazon, and is more prevalent in the southern fringes, which also have the longest dry season. Deforestation in the Amazon is driven by a number of factors, including low productivity and unsustainable agricultural practices

(Nobre *et al* 2016). The Amazon area used in this study (figure 1) corresponds to the biogeographic limits of the Amazon from the Red Amazónica de Información Socioambiental Georreferenciada (https://.raisg.org).

2.2. Rainfall data

We used the 3-hour data from the Tropical Rainfall Measuring Mission (TRMM) Multi-Satellite Precipitation (TMPA) rainfall Level 3 V7 (3B42) (Huffman *et al* 2016). This data has a horizontal resolution of $0.25° \times 0.25°$ and the period used is from January 1, 1998 to December 31, 2017. This data is hereafter referred to as TRMM 3 h. TRMM 3 h data is available at https://disc.gsfc.nasa.gov/datasets/, and covers all longitudes and latitudes between $-50°$ and $50°$ on a $0.25°$ grid (1440×400). TRMM 3 h data are instantaneous rainfall (Huffman and Bolvin 2018, Huffman *et al* 2018). The TRMM satellite stopped collecting data in 2015, but TRMM-like data were processed using the successor satellite, the Global Precipitation Mission (Skofronick-Jackson *et al* 2017, Huffman *et al* 2018) until 2019. Previous studies have shown that TRMM 3 h accurately represents Amazon rainfall at the sub-daily (Machado *et al* 2002, Sapucci *et al* 2022), daily (Michot *et al* 2018), monthly (Zulkafli *et al* 2014), and annual (Michot *et al* 2018) time scales.

The mean annual rainfall (MAR) was calculated by adding all rainfall events per grid cell and dividing this total by the number of years in the observational record. An analogous approach was used for each season (DJF, MAM, JJA, SON). The number of extreme rainfall events (N_e) was calculated as the number of rainfall events $\geqslant$ 5.6 mm h^{-1}. This value reflects the average value of rainfall rates for MCSs across northwest, western, southern, central and eastern Amazon regions as reported in table 2 in Jaramillo *et al* (2017). The mean annual number of extreme rainfall events (N_e^a) per grid cell was calculated by adding the number of extreme rainfall events and dividing this total by the number of years in the observational record. An analogous approach was used to calculate the mean seasonal number of extreme events (N_e^{DJF}, N_e^{MAM}, N_e^{JJA}, N_e^{SON}). Figure 1 shows the rainfall events across the whole time series of TRMM 3 h data over the Amazon, and the spatial distribution of N_e^a.

2.3. HighResMIP models

We used model data from HighResMIP (available at https://esgf-node.llnl.gov), which investigates the impact of horizontal resolution in the model representation of the climate system (Haarsma *et al* 2016). HighResMIP is divided into experiments (tiers); for this study we used Tier1, HighResSST-Present. HighResSST-Present simulations are historically forced atmosphere-only (ForcedAtmos) runs from 1950 to 2014. The simulations are forced by observed sea surface temperature, sea ice cover, CO_2 concentration, solar variability, and ozone concentration with fixed land use according to the HighResMIP protocol (Haarsma *et al* 2016).

HighResSST allows for high resolution analysis of interannual variability of monsoons (Haarsma *et al* 2016) and is relevant for this study because an important fraction of the Amazon rainfall variability is related to the South American Monsoon (Robertson and Mechoso 2000, Marengo *et al* 2012, Wang *et al* 2018). In this study we used the last 20 years of HighResSST-Present data (1995 to 2014) to compare with TRMM 3 h.

Table 1 shows the models used, the model variants, and the reference for each model. For every model MAR and N_e was calculated with the same approach described for the TRMM 3 h data. We include in our analysis 17 HighResMIP models for a total of 18 simulations: (a) three models from the Institute Pierre-Simon Laplace (IPSL) in France: IPSL-CM6A-ATM-HR, IPSL-CM6A-ATM-ICO-HR, and IPSL-CM6A-ATM-ICO-VHR; (b) two models from the Model for Interdisciplinary Research on Climate (MIROC) in Japan: NICAM16-7S and NICAM16-8S; (c) two models from the European community Earth System Model (EC-Earth): EC-Earth3P-HR and EC-Earth3P; (d) two models from the Meteorological Research Institute (MRI) in Japan: MRI-AGCM3-2-H and MRI-AGCM3-2-S; (e) two models from the Chinese Academy of Sciences Flexible Global Ocean-Atmosphere-Land System Model (CAS FGOALS): CAS FGOALS-f3-H and CAS FGOALS-f3-L; (f) one model from the Beijing Climate Center-BCC in China: BCC-CSM2-HR; (g) one model from the Centre National de Recherches Météorologiques- CNRM in France: CNRM-CM6-1; (h) one model from the Met Office Hadley Centre (MOCH) in UK: HadGEM3-CG31-LM; (i) one model from the National Oceanic and Atmospheric Administration (NOAA Geophysical Fluid Dynamics Laboratory (GFDL) in USA: GFDL-CM4C192; (j) one model from the from the Research Center for Environmental Changes, Academia Sinica- AS-REC in Taiwan: HIRAM-SIT-LR and; (k) one model from the Chinese Academy of Meteorological Sciences - Climate Simulation Model - CAMS-CSM: CAMS-CSM1-0.

2.4. Regridding

To perform comparative analyses between TRMM 3 h and HighResMIP models, we used the TempestRemap remapping software (Ullrich and Taylor 2015, Ullrich *et al* 2016). We remapped the TRMM 3 h data grid to every HighResMIP model grid (Chen and Knutson 2008, Gervais *et al* 2014, Wehner *et al* 2021).

Table 1. List of HighResMIP models and variant used.

Institution	Model Name	Resolution lat° × lon°	Variant used	References
BCC	BCC-CSM2-HR	0.45 × 0.45	r1i1p1f1	Wu *et al* (2021)
CAS	FGOALS-f3-H	0.25 × 0.25	r1i1p1f1	An *et al* (2022)
CAS	FGOALS-f3-L	1 × 1.25	r1i1p1f1	He *et al* (2020)
MIROC	NICAM16-7S	0.56 × 0.56	r1i1p1f1	Kodama *et al* (2021)
MIROC	NICAM16-8S	0.28 × 0.28	r1i1p1f1	Kodama *et al* (2021)
MRI	MRI-AGCM3-2-H	0.56 × 0.56	r1i1p1f1	Mizuta *et al* (2019a)
MRI	MRI-AGCM3-2-S	0.187 × 0.187	r1i1p1f1	Mizuta *et al* (2019b)
CNRM	CNRM-CM6-1	1.4 × 1.4	r2i1p1f2	Voldoire *et al* (2019)
MOHC	HadGEM3-CG31-HM	0.23 × 0.35	r1i1p1f1	Roberts (2019)
GFDL	GFDL-CM4C192	0.5 × 0.625	r1i1p1f1	Zhao *et al* (2018)
AS-REC	HIRAM-SIT-LR	0.5 × 0.5	r1i1p1f1	Tu (2020)
CAMS	CAMS-CSM1-0	0.46 × 0.46	r1i1p1f1	Rong *et al* (2018)
EC-Earth-Consortium	EC-Earth3P-HR	0.35 × 0.35	r1i1p1f1	Haarsma *et al* (2020)
EC-Earth-Consortium	EC-Earth3P	0.7 × 0.7	r2i1p1f1, r3i1p1f1	Haarsma *et al* (2020)
IPSL	IPSL-CM6A-ATM-HR	0.50 × 0.70	r1i1p1f1	Boucher *et al* (2019)
IPSL	IPSL-CM6A-ATM-ICO-MR	1 × 1	r1i1p1f1	Boucher *et al* (2019)
IPSL	IPSL-CM6A-ATM-ICO-VHR	0.25 × 0.25	r1i1p1f1	Boucher *et al* (2022)

2.5. Analysis

To compare how HighResMIP models performed compared to regridded TRMM 3 h data, we used a relative error metric (100×(HighResMIP -TRMM 3 h)/TRMM 3 h) and Taylor diagrams (Taylor 2001) from SkillMetrics (Rochford 2016). To facilitate the comparison, we normalized the standard deviation of each model by the corresponding values of the observed (TRMM 3 h) extremes (Wehner *et al* 2021).

To calculate the seasonal 3 h diurnal cycle (00 h, 03 h, 06 h, 09 h, 12 h, 15 h, 18 h, 21 h UTC) areal mean number of extreme events, we first calculate the sum of the N_e values for all grid cells at each three-hour interval and then divide this sum by the number of grid cells.

3. Results

High correlation values (r) were found between MAR and N_e from TRMM 3 h across all four seasons, confirming the importance of observed extreme events for predicting rainfall (figure 2 and Supplementary figure S1). However, not all HighResMIP models captured the observed association between N_e and total rainfall at annual and seasonal scales (figure 2). Specifically, NICAM16-7S, NICAM16-8S, IPSL-CM6A-ATM-ICO-VHR, IPSL-CM6A-ATM-HR, HadGEM3-CG31-HM, GFDL-CM4C192, FGOALS-f3-H, BCC-CSM2-HR, and HIRAM-SIT-LR had the highest correlation values while MRI-AGCM3-2-H, MRI-AGCM3-2-S, IPSL-CM6A-ATM-ICO-MR, EC-Earth3P, and CNRM-CM6-1 had the lowest correlation values.

The relative error between the N_e from HighResMIP models and TRMM 3 h for annual and seasonal time scales varied widely among models (figure 3). Within model variants, consistent wet and dry seasonality patterns were found, but those patterns were very different between models from different institutions.

Some models exhibited strong skill in simulating N_e^a, N_e^{DJF}, N_e^{MAM}, N_e^{JJA}, and N_e^{SON} (figure 4). GFDL-CM4C192 and HadGEM3-CG31-HM consistently produced good results, while NICAM16-7S and NICAM16-8S also produce good results, except for N_e^{SON}. FGOALS-f3-H displayed particular strength across all seasons except for N_e^{JJA}. BCC-CSM2-HR produced good results for both N_e^{DJF} and N_e^{JJA}, and HiRAM-SIT produced good results for N_e^{MAM} and N_e^{JJA}. It is worth noticing that MRI-AGCM3-2-H, MRI-AGCM3-2-S, and EC-Earth3P-HR captured observed MAR (Figure S2), but their performance with N_e deviated from observations at annual and seasonal scales.

GFDL-CM4C192 and HadGEM3-CG31-HM reproduced the TRMM 3 h spatial pattern of N_e better than the other models. We also found that, even if a model reasonably represented the annual and seasonal association between rainfall and N_e (shown in figures 2 and 3), it might misrepresent the observed spatial patterns of N_e. For example, BCC-CSM2-HR showed a high correlation between MAR and N_e (figure 2) at the annual and seasonal scales, but its spatial patterns of N_e had large difference with TRMM 3h N_e. Specifically, this model showed a low N_e in the northeastern part of the Amazon (Figure S2). Similarly, IPSL-CM6A-ATM-ICO-VHR showed a lower N_e across the Amazon when compared to TRMM 3h N_e.

Analysis of TRMM 3 h data showed that the average maximum number of extreme rainfall events occurred at 18, and 21UTC across all seasons. However, all HighResMIP models predicted earlier average times of day for maximum rainfall values (figure 5). Further, the average temporal diurnal pattern of extreme rainfall events was

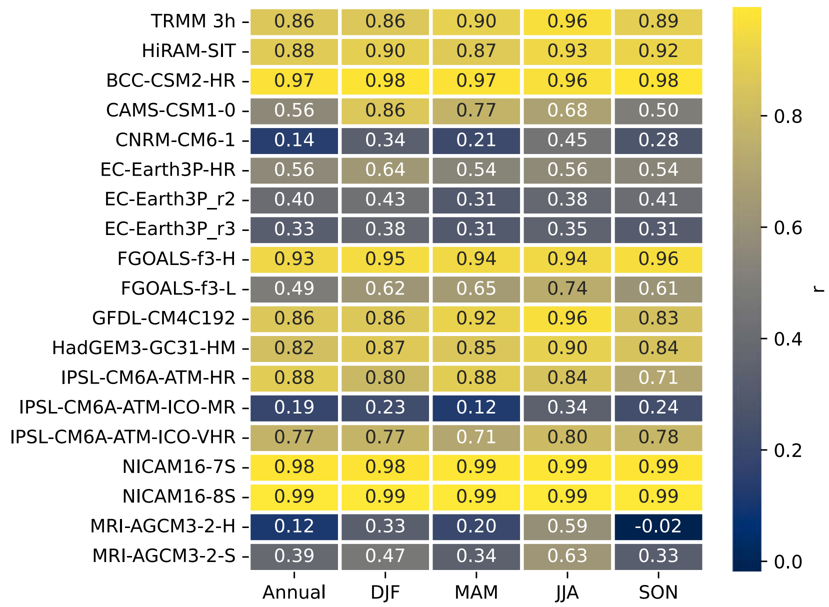

Figure 2. Correlation coefficient (r) between the number of extreme rainfall events (N_e) and rainfall using TRMM 3 h (observations) and HighResMIP models, for annual and seasonal mean periods. For this calculation each model uses its own resolution.

not reproduced by the models. We also observed that GFDL-CM4C192, HadGEM3-GC31-HM, NICAM16-7S and NICAM16-8S, HiRAM-SIT, and BCC-CSM2-HR, closely captured the average daily rainfall amounts for extreme events during each season (Figure S3).

4. Discussion and conclusions

Analysis of extreme rainfall events in the Amazon basin is highly dependent on the observational data used. Due to the lack of long-term rain gauge data over the Amazon, we used the TRMM 3 h data. The satellites used to develop the TRMM 3 h precipitation dataset do not view the Amazon (or any other region) continuously but only when the satellite's orbit places it over the region. By contrast, HighResMIP model outputs, aggregate precipitation continuously over each 3 h period. Hence, TRMM likely underestimates the actual number and magnitude of extreme rainfall events due to this incomplete sampling (Huffman *et al* 2016, Timmermans *et al* 2019). Rasmussen *et al* (2013) found that TRMM rainfall data can underestimate rainfall by up to 40% in areas with deep, intense thunderstorms. Despite the TRMM 3 h underestimation of extreme rainfall events, the HighResMIP models failed to reproduce either the frequency or spatial patterns of extreme rainfall events in the TRMM 3 h data. Furthermore, studies have shown that the spatial and temporal patterns from sub-daily to annual time scales of TRMM 3 h over the Amazon agree well with rainfall observations (Machado *et al* 2002, Zulkafli *et al* 2014, Michot *et al* 2018, Sapucci *et al* 2022). Specifically, a recent study found that TRMM 3 h data showed maximum precipitation occurring at the same time as ground-based observations (Sapucci *et al* 2022).

Regridding TRMM 3 h data to match different HighResMIP model grids could alter the threshold for defining extreme rainfall events. Nevertheless, comparing HighResMIP models and TRMM 3-hourly data remains valid because any threshold change would impact both datasets similarly. The biases we observed in HighResMIP models within the Amazon basin appear linked to limitations in representing regional relationships between total rainfall and extreme event frequency. Notably, HighResMIP models missed the observed correlation between higher rainfall and more frequent extreme events, especially in the northwestern Amazon. Over the Amazon, TRMM 3 h data showed a clear association between rainfall and extreme rainfall events. Eleven of the seventeen models showed this association (figure 2). Of these eleven, only five models performed well with the annual or seasonal number of extreme events, and only two models (GFDL-CM4C192, HadGEM3-CG31-HM) performed well in every season and throughout the year (figure 4 and figure S1). While most models underestimated the number of extreme events, NICAM16-7S and NICAM16-8S overestimated these events, producing the largest areas with positive relative errors. This result is consistent with previous studies that have shown that NICAM models overestimate the frequency of rainfall because the model's precipitation process scheme triggers rainfall very easily (Jing *et al* 2017, Na *et al* 2020). Unlike convection parameterization schemes, NICAM employs a cloud microphysics scheme to explicitly resolve convective circulations (Kodama *et al* 2021) that can lead to overestimates in rainfall (Na *et al* 2020). To address these biases,

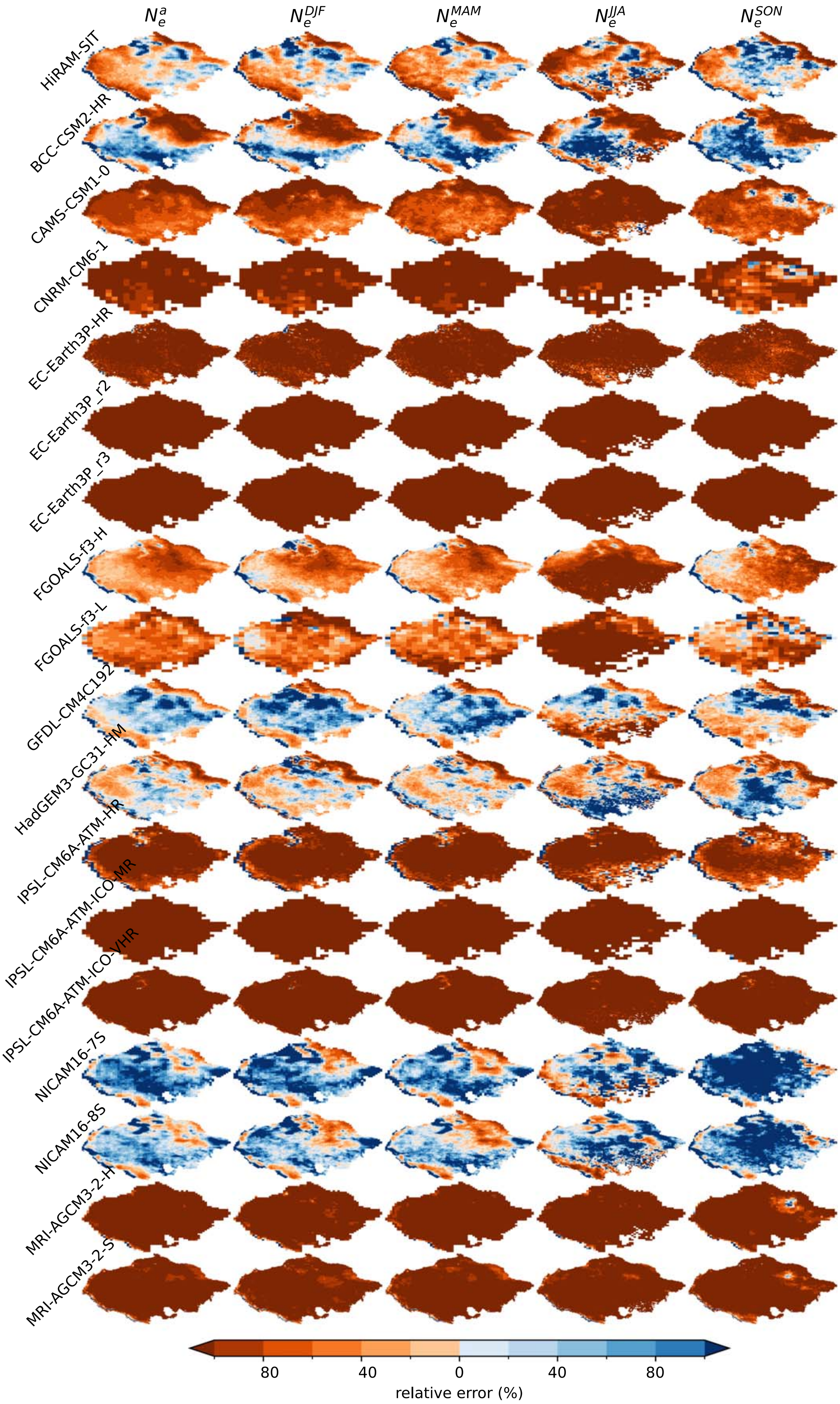

Figure 3. Relative error of number of extreme rainfall events N_e between HighResMIP and TRMM 3 h for the average year N_e^a (left hand column) and seasons, N_e^{DJF}, N_e^{MAM}, N_e^{JJA}, N_e^{SON}.

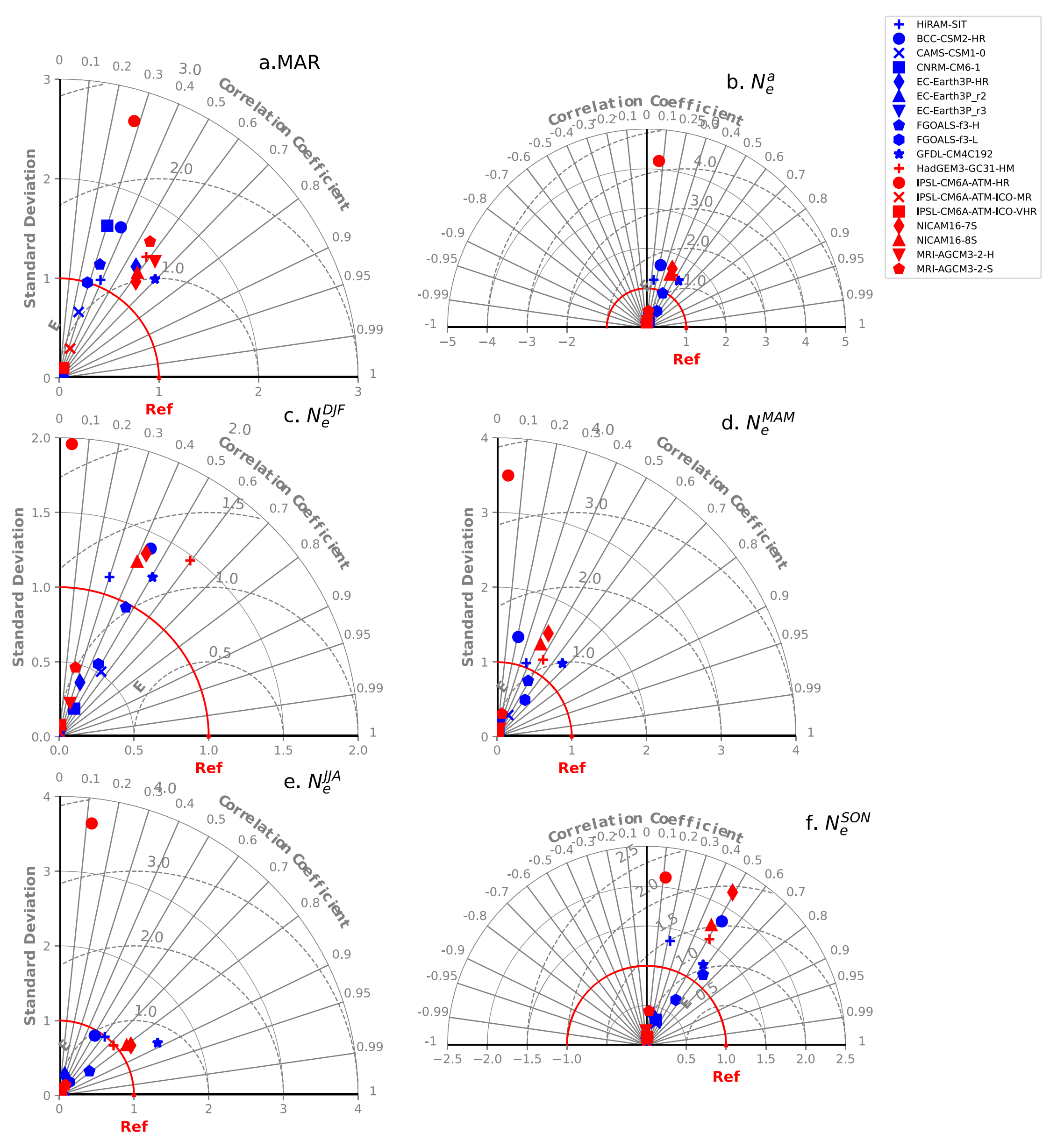

Figure 4. Taylor diagram comparing (a) MAR, and number of extreme events from HighResMIP models and TRMM 3 h for (b) mean annual N_e, and (c)—(f) seasonal N_e.

a new microphysics scheme has been developed for NICAM that improves agreement between modeled rainfall and observations (Seiki and Ohno 2023).

The HadGEM3-CG31-HM and GFDL-CM4C192 models performed better at simulating the average annual and seasonal rainfall over the Amazon basin. The HadGEM3-CG31-HM has one of the finest horizontal resolutions. It has been suggested that higher resolution can improve modeled rainfall in tropical regions (Monerie *et al* 2020). However, since GFDL-CM4C192 has nearly twice the horizontal resolution of HadGEM3-CG31-HM, yet performed similarly, we conckuded that resolution may be necessary but not sufficient to accurately reproduce extreme Amazon rainfall.

The fact that a model reproduced the annual and/or seasonal patterns of extreme rainfall events does not imply that it also reproduced the sub-daily patterns of extreme rainfall. TRMM 3 h showed a high number of observed N_e at 18 and 21 h UTC across the entire Amazon, and consistent with a previous study that analyzed regional Amazon hourly rainfall of the Amazon by regions (Nunes *et al* 2016). We found that while some models reproduce the daily seasonal total of N_e all models reproduced earlier in the day the time of observed N_e peak. This finding agrees with the earlier peak in the diurnal cycle of rainfall of CMIP6 models when compared with observations (Dong *et al* 2023). Recent studies suggested that grid spacing between 0.012° to 0.026° near the equator (1.56 to 3.25 km) is needed to capture the diurnal cycle of precipitation (Stevens *et al* 2020, Caldwell *et al* 2021). However, it is unclear whether tuning at high-resolution will improve these results, as many outstanding

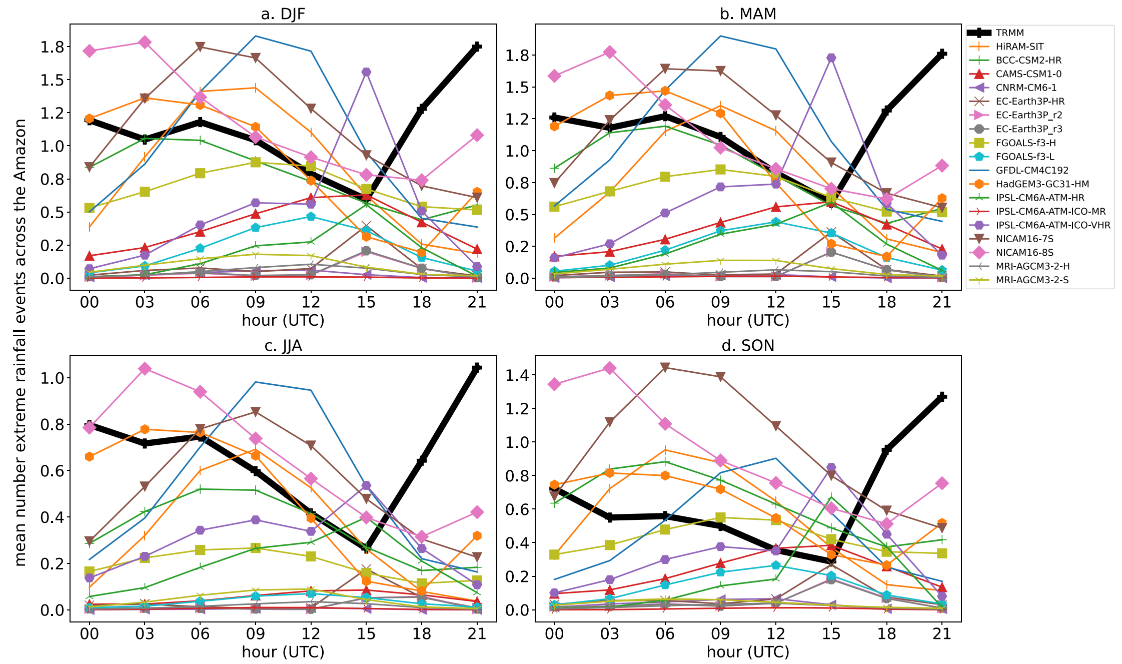

Figure 5. Seasonal 3 h mean of number of extreme events from TRMM 3 h (thick black line) and HighResMIP models used. (a) DJF, (b) MAM, (c) JJA, and (d), SON.

issues remain with parameterized precipitation processes. HighResMIP2 may offer some insight, since in this next phase of experiments modeling groups will be able to re-tune their models at high-resolution. Our results suggest that resolution is necessary but not sufficient to improve extreme precipitation. This is particularly true in cases where convective precipitation is the main contributor to extreme precipitation. It is important to also note that convective precipitation in HighResMIP is parameterized (Haarsma *et al* 2016) and these parameterizations are tuned to ensure that energy is balanced, but are not designed to capture precipitation extremes. The recent development of global convection permitting very high resolution models offers the prospect of directly simulating better extreme tropical precipitation statistics but much work remains to be done (Feng *et al* 2023b). Other factors affecting model performance include model resolution with higher resolution improving model performance of heavy rainfall (Seth *et al* 2004, Wehner *et al* 2010, Giorgi *et al* 2014), and biases in cloud microphysical properties (Jing *et al* 2017). Measurements and understanding of extreme rainfall events in tropical forests are research areas that deserves further attention. Future studies should also explore the interannual variability of Amazon rainfall at different spatial and temporal scales (Nunes *et al* 2016, Ramirez-Nina and Silva Dias 2024).

Extreme rainfall events play a key role in determining the pattern of rainfall in the Amazon. Although some HighResMIP models have good performance in representing the annual and seasonal patterns of N_e, none of the models reproduced the sub daily time of maximum extreme rainfall events in the Amazon. In general, HighResMIP models produced a low N_e in the northwestern Amazon, consistent with previous studies that CMIP6 models underestimate rainfall in this region (Hagos *et al* 2021). The persistent issue of ESMs underestimating rainfall in the northwestern Amazon has persisted for decades. Therefore, we suggest conducting observational studies in this region to enhance understanding of the underlying mechanisms driving rainfall. Our results are unlikely to change by using the lowest threshold for MCS rainfall reported in Jaramillo *et al* (2017) of 5.3 mm h^{-1}. Across the 20-years of 3-hourly data from HighResMIP models, the change in the number of grid cells is minimal, with an average increase of only 0.04% $\pm$ 0.03% (mean $\pm$ standard deviation), except NICAM that increased by 0.11%. However, this lower threshold represented an increase of 0.33% $\pm$ 0.1% in the number of grid cells identified in the TRMM 3-hourly data regridded to each model resolution.

The importance of accurately characterizing extreme rainfall events in ESMs extends beyond the water cycle. It also plays a crucial role in understanding the dynamics of Amazonian forests, particularly regarding windthrow-related disturbances. Negrón-Juárez *et al* 2018 employed a forest demographic model to simulate a doubling of windthrow mortality, resulting in a 30% decrease in aboveground biomass and a 7% decrease in aboveground net primary productivity (ANPP) in the northwestern Amazon forest. Notably, forest species composition remained largely unchanged. However, when the same mortality increase was applied to the Central Amazon, the model projected substantially higher reductions in biomass and ANPP, along with a significant shift in forest composition. While these findings represent initial estimates for specific locations, they highlight the potentially significant impact of extreme precipitation events on forest carbon cycling. Given the projected increase in extreme precipitation during the coming decades (Myhre *et al* 2019, Papalexiou and Montanari 2019) and windthrows (Feng *et al* 2023a), incorporating these mechanisms into ESMs becomes increasingly crucial.

Acknowledgments

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Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

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