

1           **Advancing Organized Convection Representation in the Unified Model:**  
2           **Implementing and Enhancing Multiscale Coherent Structure Parameterization**

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14 **Key Points:**

- 15       • Organized convection scheme with realistic triggering and state-dependent partitioning  
16       between stratiform and convective heating is proposed
- 17       • Scheme leads to reduced storm area and shallower parameterized convection through  
18       lower-troposphere cooling from stratiform precipitation
- 19       • Scheme corrects systematic precipitation biases over India and the Indian Ocean through  
20       intensifying the Madden-Julian Oscillation

## 21 **Abstract**

22 To address the effect of stratiform latent heating on meso- to large scale circulations, an  
23 enhanced implementation of the Multiscale Coherent Structure Parameterization (MCSP) is  
24 developed for the Met Office Unified Model. MCSP represents the top-heavy stratiform latent  
25 heating from under-resolved organized convection in general circulation models. We couple the  
26 MCSP with a mass-flux convection scheme (CoMorph-A) to improve storm lifecycle continuity.  
27 The improved MCSP trigger is specifically designed for mixed-phase deep convective cloud,  
28 combined with a background vertical wind shear, both known to be crucial for stratiform  
29 development. We also test a cloud top temperature dependent convective-stratiform heating  
30 partitioning, in contrast to the earlier fixed partitioning. Assessments from ensemble weather  
31 forecasts and decadal simulations demonstrate that MCSP directly reduces cloud deepening and  
32 precipitation areas by moderating mesoscale circulations. Indirectly, it amends tropical  
33 precipitation biases, notably correcting dry and wet biases over India and the Indian Ocean,  
34 respectively. Remarkably, the scheme outperforms a climate model ensemble by improving  
35 seasonal precipitation cycle predictions in these regions. This enhancement is partly due to the  
36 scheme's refinement of Madden-Julian Oscillation (MJO) spectra, achieving better alignment  
37 with reanalysis data by intensifying MJO events and maintaining their eastward propagation after  
38 passing the Maritime Continent. However, the scheme also increases precipitation  
39 overestimation over the Western Pacific. Shifting from fixed to temperature-dependent  
40 convective-stratiform partitioning reduces the Pacific precipitation overestimation but also  
41 lessens the improvements of seasonal cycle in India. Spatially correlated biases highlight the  
42 necessity for advancements beyond deterministic approaches to align MCSP with environmental  
43 conditions.

## 44 **Plain Language Summary**

45 We improve a key component of the Met Office's climate model to better represent how  
46 widespread light rain in severe convective storms affects atmospheric patterns. We make the  
47 representation respond to different temperatures at the tops of clouds, which is a new approach  
48 compared to previous studies where the heavy-to-light rain partitioning was assumed constant.  
49 We find that the improved representation of the light rain associated with severe storms reduces  
50 the overall storm rainfall area and suppresses storm height. The changes are particularly effective  
51 in correcting rainfall forecasts in tropical regions like India and the Indian Ocean, outperforming  
52 other climate models. Notably, our model excels at predicting specific tropical climate patterns,  
53 enhancing wind and rainfall accuracy over the Maritime Continent. However, our model predicts  
54 too much rain over the Western Pacific. When we adjust how we calculate the heavy-to-light rain  
55 partitioning based on cloud top temperatures, it reduces this overestimation but also weakens our  
56 improvements elsewhere. This indicates that we need to keep exploring new approaches to  
57 consider the light rain probability in severe storms.

## 58 **1 Introduction**

59 Organized convection encompasses two distinct types of precipitation: intense convective  
60 precipitation, and quasi-steady, lighter stratiform precipitation, with this differentiation observed  
61 in both tropical (Cheng & Houze, 1979) and extratropical regions (Houze et al., 1990). The  
62 variation in organized convection, encompassing a spectral mix rather than a simple spatial  
63 separation between convective and stratiform precipitation, presents a significant challenge in  
64 weather and climate prediction (Schumacher & Rasmussen, 2020), as these precipitation types

65 differ substantially in redistributing moisture, momentum, and heat in the atmosphere (Houze,  
66 2004). One representative type of organized convection is a Mesoscale Convective System  
67 (MCS), which has a length scale exceeding 100 km in at least one direction (Houze 2004).

68 A fundamental distinction lies in the vertical profile of latent heating. In convective  
69 regions, intense updrafts induce rapid condensation, resulting in a bottom-heavy heating profile  
70 marked by a concentration of heating in the lower and middle troposphere (Houze, 1989).  
71 Conversely, in stratiform regions, the majority of latent heating occurs higher up, usually in the  
72 upper troposphere above the freezing level (Houze, 1989). This heating aloft is predominantly  
73 driven by the deposition of vapor into ice, a process facilitated by ice hydrometeors transported  
74 from convective regions (Han et al., 2019). Additionally, most stratiform regions exhibit net  
75 latent cooling below the freezing level, resulting from weaker updrafts and reduced local  
76 condensate production. This leads to insufficient condensational heating in the lower troposphere  
77 to counteract cooling from microphysical processes such as ice melting and raindrop evaporation  
78 (Leary & Houze, 1979). These dynamical and microphysical processes collectively lead to a top-  
79 heavy heating profile in stratiform regions (Houze, 1989; Schumacher et al., 2004).

80 A higher ratio of stratiform to convective partitioning leads to more top-heavy latent  
81 heating, crucially reshaping large-scale atmospheric circulations (Houze, 2018). For example,  
82 satellite observations show a sharp increase in stratiform precipitation and its associated top-  
83 heavy latent heating during the active stage of the Madden-Julian Oscillation (MJO) over the  
84 Western Pacific (Barnes et al., 2015). The spatial variability of the El Niño-Southern Oscillation  
85 (ENSO) is significantly influenced by the gradient of the stratiform fraction over the Pacific  
86 (Schumacher et al., 2004). Additionally, a greater stratiform fraction aids the propagation of  
87 large-scale waves from the tropics to extra-tropical regions, a phenomenon also highlighted in  
88 the same study. Incorporating stratiform latent heating in simulations notably elevates the center  
89 of the Walker cell, enhancing its alignment with observations (Hartmann et al., 1984). Overall,  
90 the more top-heavy the latent heating profile is, the stronger the upscaling feedback becomes  
91 from organized convection to large-scale atmospheric circulations (Houze, 2018).

92 However, it is difficult to represent top-heavy stratiform heating in weather and climate  
93 models due to its dependence on multiscale processes (Schumacher & Rasmussen, 2020),  
94 ranging from microphysics and convective drafts to mesoscale and large-scale circulations.  
95 Climate models with coarse resolution utilizing convection parameterizations often fail to  
96 represent mesoscale circulations within organized convection (Kooperman et al., 2015).  
97 Convection-permitting models with computational grids of a few kilometers partially represent  
98 mesoscale circulations yet tend to overestimate convective precipitation (e.g., Becker et al. 2021)  
99 and updraft intensity (Varble et al., 2014), and underestimate stratiform fractions (Prein et al.,  
100 2020). Specifically, overly-intense updrafts are too efficient in producing rimed ice and  
101 precipitating moisture in convective regions, resulting in fewer ice hydrometers aloft for feeding  
102 stratiform precipitation (Varble et al., 2014; Zhang et al., 2021). Even when model grid spacings  
103 reach large-eddy resolutions, the overestimation in the partitioning of convective and stratiform  
104 precipitation persists (Zhang et al., 2024). This indicates that improving stratiform precipitation  
105 representation requires more than just better resolved dynamics. Effective representation  
106 demands a coherent paradigm that spans multiple scales.

107 To mitigate such biases, a promising strategy developed in past studies (Chen et al.,  
108 2021; Moncrieff, 2019; Moncrieff et al., 2017; Moncrieff & Liu, 2006) is the Multiscale  
109 Coherent Structure Parameterization (MCSP). This scheme posits that the stratiform heating aloft

110 and lower-level cooling are directly proportional to the column-integrated convective heating  
111 estimated by a convection parameterization. The scheme is typically triggered in situations  
112 where the grid-scale winds promote slantwise layer overturning, which favors the partially-  
113 resolved organization of convection for generating stratiform latent heating (Moncrieff & Liu,  
114 2006). Incorporating top-heavy latent heating profiles associated with organized convection  
115 through the MCSP scheme enhances the capability of general circulation models to simulate the  
116 observed MJO, as evidenced by studies from Chen et al. (2021) and Moncrieff et al. (2017) for  
117 the E3SM and CAM models respectively. Moreover, the MCSP scheme contributes to an  
118 improvement in the representation of Kelvin wave spectra and a reduction in biases associated  
119 with tropical precipitation (Chen et al., 2021).

120 The coupling method between convection parameterization and the MCSP scheme  
121 presents opportunities for improvement. The recent implementation of MCSP by Moncrieff et al.  
122 (2017) employs the Zhang-McFarlane convection scheme (Zhang & McFarlane, 1995), using a  
123 rate of change of Convective Available Potential Energy (CAPE) threshold as the trigger for the  
124 convection scheme. However, this CAPE-based trigger can be disrupted by the introduction of  
125 stratiform aloft heating and lower-level cooling by MCSP. Such disruption may compromise the  
126 temporal continuity of both the convection and MCSP schemes, possibly leading to intermittent  
127 or on-off behavior for either or both schemes. In addition, shallower convective systems,  
128 especially those at or below the freezing level that do not efficiently produce ice hydrometeors  
129 for stratiform precipitation, might not be associated with MCS, such that the MCSP scheme is  
130 inappropriately triggered for those cases. An improvement is needed to specifically target those  
131 deep convective systems that efficiently produce stratiform components for coupling with the  
132 MCSP scheme.

133 A second limitation with previous implementations of MCSP is the partitioning between  
134 stratiform and convective heating. Past studies have assumed a fixed partitioning (e.g., 50%)  
135 between stratiform and convective heating. However, this does not necessarily reflect real-world  
136 conditions, where the influence of stratiform precipitation can vary significantly due to the  
137 melting of ice hydrometeors from convection regions. A suitably-varying stratiform to  
138 convective heating partitioning could offer a more realistic representation.

139 Aiming to progress beyond existing methods, this research is guided by the following  
140 objectives: 1) Couple the MCSP with advanced convection parameterization techniques to  
141 improve storm-lifecycle continuity and facilitate storm-track based assessment. 2) Tailor MCSP  
142 triggering conditions specifically for deep convection. 3) Develop an environmentally-  
143 conditioned partitioning to effectively relate stratiform and convective heating processes. 4)  
144 Understand the scheme's direct effect in weather simulations spanning several days as well as its  
145 indirect effect in decadal simulations.

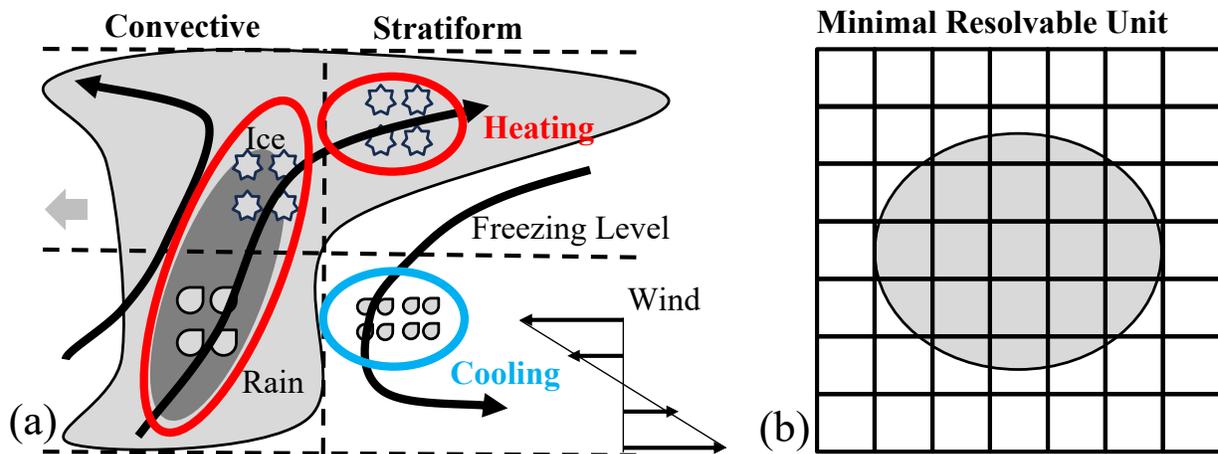
146 This study is carried out in the Met Office Unified Model, focusing on general circulation  
147 scales and is conducted as part of the Mesoscale Convective Systems: PRobabilistic forecasting  
148 and upscale IMPacts in the grey zonE (MCS: PRIME) project. The scheme, referred to as  
149 PRIME-MCSP, couples to a novel mass-flux convection scheme (CoMorph-A) that explicitly  
150 parameterizes convective detrainment and entrainment and smoothly transits between shallow  
151 and deep clouds (Whitall et al., 2022; Daleu et al., 2023; Lavender et al., 2024). A valuable  
152 feature of the CoMorph-A convection scheme for the current study is that it makes use of an  
153 implicit solver for its detrainment calculations. This contrasts with many other convection  
154 schemes, which can suffer from numerical overshoots and on-off behavior at the timestep level.

155 Moreover, CoMorph allows convection to be initiated from any layer in the vertical, depending  
 156 on the instability at each level. At least partly for these reasons, the CoMorph-A approach  
 157 enhances temporal-spatial continuity of precipitation clusters, capturing storm lifecycles in the  
 158 presence of the stratiform heating aloft and lower-level cooling introduced by PRIME-MCSP.  
 159 This improved continuity is crucial for enabling storm tracking, facilitating the lifecycle analysis  
 160 of PRIME-MCSP's effect on the internal cloud dynamics and the surrounding environments.

161 To evaluate the effectiveness of PRIME-MCSP, short-term weather ensemble simulations  
 162 and decadal climate simulations on a global scale are both conducted. The structure of the  
 163 remaining sections is as follows: Section 2 details the design of the PRIME-MCSP scheme;  
 164 Section 3 describes the simulations, observations, and methodology for storm tracking; Section 4  
 165 presents an analysis of the PRIME-MCSP impact throughout the lifecycle of MCSs using short-  
 166 term ensemble runs; Section 5 examines the long-term climatic impacts of the PRIME-MCSP on  
 167 large-scale precipitation patterns and the MJO in decadal simulations; and Section 6 summarizes  
 168 the conclusions drawn from these analyses.

## 169 2 Parameterization Scheme

170 The PRIME-MCSP parameterization is designed to represent the stratiform latent heating  
 171 profile associated with an MCS, which is otherwise missing in models. Drawing from Moncrieff  
 172 et al. (2017), Figure 1a depicts a schematic of a slantwise layer overturning pattern of wind,  
 173 highlighted by the black streamlines. Additionally, the schematic shows the vertical shear of  
 174 horizontal wind via straight vectors on the right, indicating a transition from westerly winds in  
 175 the lower troposphere to easterly winds in the mid-troposphere. Affected by this vertical wind  
 176 shear, an unstable atmospheric layer rises, culminating in a central slantwise updraft that reaches  
 177 the tropopause. This principal updraft then continues horizontally as an eastward flow, with the  
 178 subsequent subsidence manifesting as a mesoscale downdraft on the right, while a subsidiary  
 179 branch of the updraft diverges to the left at the top.



180

181 **Figure 1.** Schematic diagram for (a) stratiform and convective vertical cross sections in  
 182 slantwise layer overturning scenario. Streamlines indicate wind directions. Red and blue circles  
 183 represent the diabatic heating and cooling regions, respectively. The grey arrow represents the  
 184 MCS propagation direction. Adapted from Moncrieff et al. (2017). (b) Top view of a 7 by 7  
 185 model-grid domain capable of minimally resolving the MCS (grey shading).

186 Figure 1a presents the dynamical correspondence with microphysical processes occurring  
 187 within the convective and stratiform regions. The slantwise ascending layer in the center aligns  
 188 with the convective region, where condensational heating is driven by updrafts loaded with  
 189 raindrops below and ice condensates starting above the freezing level. The updrafts that curve  
 190 horizontally to the right carry ice condensates aloft, aiding in the horizontal growth of the  
 191 stratiform region. In the stratiform region, the ice condensates undergo depositional growth,  
 192 which releases latent heat in the upper atmosphere. As these particles fall below the freezing  
 193 level, they melt into raindrops. This melting process, followed by evaporation, induces cooling in  
 194 the stratiform region's lower levels.

195 Figure 1b illustrates the MCS previously described in Figure 1a, highlighting its nature as  
 196 an under-resolved phenomena for a given model resolution. Skamarock (2004) has shown that  
 197 models are capable of resolving features with a minimum length scale approximately seven times  
 198 the model's horizontal grid spacing. Thus, a climate model with a 100 km grid spacing could  
 199 theoretically resolve MCS with a length scale of at least 700 km. However, a significant number  
 200 of MCSs have at least one dimension shorter than this resolvable scale. For instance, Feng et al.  
 201 (2021) demonstrated that more than 90% of MCSs over the continental United States have  
 202 precipitation features shorter than 700 km, indicating a limitation in the model's ability to  
 203 capture the full spectrum of MCS sizes. This complexity necessitates the use of the MCSP  
 204 paradigm for multi-scale-coherent representation.

205 The potential temperature heating increment due to convective updrafts is parameterized  
 206 by the CoMorph-A convection scheme, and denoted as  $\Delta\theta_{CoMorph}$ . Figure 2a shows an example  
 207 temperature tendency profile from the CoMorph-A scheme: this is typically a net heating effect  
 208 at nearly all height levels, aligning with the conceptual model in Figure 1a.

209 In an advancement over previous MCSP triggers, we have formulated triggering  
 210 conditions that are designed to recognize slantwise layer overturning and mixed-phase deep  
 211 clouds:

$$212 \quad |\overline{V_{600}} - \overline{V_s}| > 3 \text{ m s}^{-1} \quad (1)$$

$$213 \quad T_{top} < 0 \text{ }^\circ\text{C} \quad (2)$$

$$214 \quad p_{base} > 600 \text{ hPa} \quad (3)$$

$$215 \quad p_{base} - p_{top} > 300 \text{ hPa} \quad (4)$$

216 Firstly, equation 1 identifies conditions suitable for slantwise layer overturning through  
 217 the absolute value of the difference in horizontal wind speed between the surface and the 600hPa  
 218 level. Note that Chen et al. (2021) computed only zonal wind shear when applying their  
 219 triggering threshold, while this study computes wind shear based on both zonal and meridional  
 220 wind components to depict the pattern of slantwise layer overturning. Secondly, the definition of  
 221 mixed-phase deep cloud involves meeting three criteria, detailed in equations 2–4: 1) The cloud  
 222 top temperature ( $T_{top}$ ) must be below 0 °C, a threshold crucial for the production of ice  
 223 condensates, which are key to generating stratiform precipitation. 2) The cloud base pressure  
 224 ( $p_{base}$ ) should be above 600 hPa, ensuring that there is adequate low-level moisture to support

225 and maintain deep convection. 3) The pressure difference between the cloud base and top ( $p_{base}$   
 226  $- p_{top}$ ) must exceed 300 hPa, confirming that the cloud has sufficient depth.

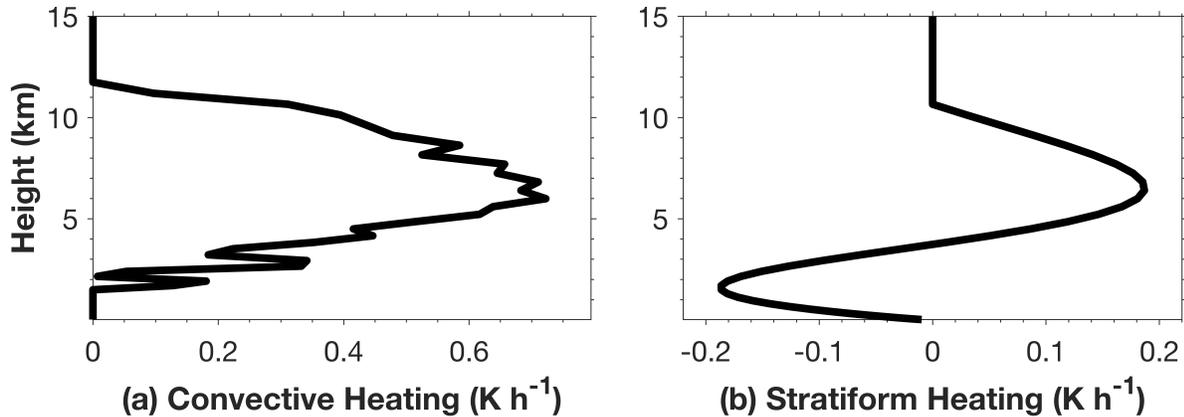
227 Building on Moncrieff (2017), the convective heating from CoMorph-A and the PRIME-  
 228 MCSP stratiform heating are related through equations 5–7:

$$229 \quad \overline{Q_{conv}} = \frac{1}{p_s - p_{top}} \sum_{p_s}^{p_{top}} \Delta\theta_{CoMorph}(p) dp \quad (5)$$

$$230 \quad Q_{strat}(p) = \alpha \sin\left(2\pi \frac{p_{top} - p}{p_s - p_{top}}\right) \overline{Q_{conv}} \quad (6)$$

$$231 \quad \alpha = 0.5 \text{ or } 0.5 \left(\frac{T_{freeze} - T_{top}}{T_{freeze} - T_{ref}}\right) \quad (7)$$

232 where  $p_s$  and  $p_{top}$  represent the surface and cloud top pressure levels, respectively, while  $dp$   
 233 denotes the pressure difference between adjacent model levels. Equation 5 calculates the  
 234 column-integrated convection scheme heating from the surface to the cloud top, normalized by  
 235 the total pressure difference. Equation 6 posits that the amplitude of the stratiform aloft heating is  
 236 proportional to the column-integrated convective heating and to a parameter  $\alpha$ . The sinusoidal  
 237 shape means that the column integral of stratiform heating aloft and low-level cooling balances  
 238 out to approximately zero. Figure 2b illustrates the vertical distribution of the emulated  
 239 stratiform latent heating that corresponds to the example CoMorph-A profile of Figure 2a.



241 **Figure 2.** (a) Example tendency profile obtained from the CoMorph-A convection scheme, and  
 242 (b) the corresponding stratiform tendency determined by PRIME-MCSP.

243 Previous studies (e.g., Chen et al. 2021) have used equation 6 with  $\alpha$  set to a fixed value  
 244 of 0.5. Here, we also consider a variable  $\alpha$  dependent on the temperature difference between the  
 245 freezing level  $T_{freeze}$  and the cloud top  $T_{top}$ , normalized by the temperature difference between  
 246  $T_{freeze}$  and a reference cloud top level  $T_{ref}$ , as shown in equation 7. The variable  $\alpha$  is designed  
 247 to reflect the idea that the growth of the stratiform region is proportional to the ice condensate  
 248 flux from the convective to the stratiform region and that ice condensate production correlates  
 249 with the temperature difference between the cloud top and the freezing level, indicated by Han et

250 al. (2019) and Zhang et al. (2024).  $T_{freeze}$  is set at  $0^{\circ}\text{C}$ , and  $T_{ref}$  to  $-80^{\circ}\text{C}$ , representing the  
 251 median value of the lifecycle-minimum cloud top temperature observed in global storm tracks  
 252 (Feng et al., 2021).

253 The stratiform latent heating profile in equation 6 is intended to have a vertical integral of  
 254 zero. However, due to the discrete nature of vertical levels in the model, a small residual may  
 255 exist in practice. The residual in dry static energy is computed, and used to calculate the  
 256 pressure-weighted residual error, denoted as  $\overline{Q_{err}}$ :

$$257 \quad \overline{Q_{err}} = \frac{1}{p_s - p_{top}} \sum_{p_s}^{p_{top}} Q_{strat}(p) dp \quad (8)$$

258 The final potential temperature tendency  $\Delta\theta_{org}(p)$  for a given grid at a specific level,  
 259 resulting from the organized convection, is computed as the sum of  $\Delta\theta_{CoMorph}(p)$  and  $Q_{strat}(p)$ ,  
 260 adjusted by subtracting  $\overline{Q_{err}}$ :

$$261 \quad \Delta\theta_{org}(p) = \Delta\theta_{CoMorph}(p) + Q_{strat}(p) - \overline{Q_{err}} \quad (9)$$

262 The PRIME-MCSP tendency as represented in equation 9 ensures the conservation of dry  
 263 static energy within a column, even after incorporating stratiform latent heating into the model.

### 264 3 Simulations, Observations, and Storm Tracking Methodology

265 The PRIME-MCSP scheme has been implemented into version 13.0 of the Unified  
 266 Model (UM13.0), developed by the United Kingdom Met Office. Its critical modules are  
 267 described in Davies et al. (2005). Both the weather ensemble and climate simulations utilize  
 268 UM13.0 over a global domain. The PRIME-MCSP scheme is evaluated by comparing against  
 269 control runs where PRIME-MCSP is deactivated.

270 **Table 1.** Weather Simulations Spanning from July 1st, 2020, 03Z to July 3rd, 2020, 03Z.

Name of Experiment	PRIME-MCSP Scheme	$\alpha$	Resolution	Ensemble Members
Control Run	N/A	N/A	~60 km	8
PRIME-MCSP Run	Activated	0.5	~60 km	8

271 The weather ensemble, as detailed in Table 1, is employed to evaluate the direct, short-  
 272 term effects of PRIME-MCSP on storm lifecycles and their surrounding environments from a  
 273 Lagrangian perspective. It has a horizontal grid spacing of approximately 60 km (N216) and 70  
 274 vertical levels. The model's integration time step is 7.5 minutes. The simulations are restarted  
 275 from 8 initial-condition perturbed ensemble members of the Met Office Global and Regional  
 276 Ensemble Prediction System–Global (Inverarity et al. 2023), on July 1st, 2020, at 0Z, and  
 277 undergo a 3-hour spin-up. The analyzed simulations span a duration of 48 hours, starting from  
 278 July 1st, 2020, at 3Z and ending on July 3rd, 2020, at 3Z. Two sets of simulations are produced:  
 279 a set of control runs and a set of PRIME-MCSP runs, with the latter implementing a fixed  $\alpha$   
 280 value of 0.5. Except for the CoMorph-A convection scheme, all other physical parameterizations  
 281 in these weather ensemble members align with those used in the Met Office's operational  
 282 weather forecasts, as described in Bush et al. (2022).

283 **Table 2.** Climate Simulations Spanning September 1988 to August 2008.

Name of Experiment	PRIME-MCSP Scheme	$\alpha$	Resolution
Control Run	N/A	N/A	~135 km
PRIME-MCSP Run	Activated	0.5	~135 km
PRIME-MCSP Variable $\alpha$ Run	Activated	Variable $\alpha$	~135 km

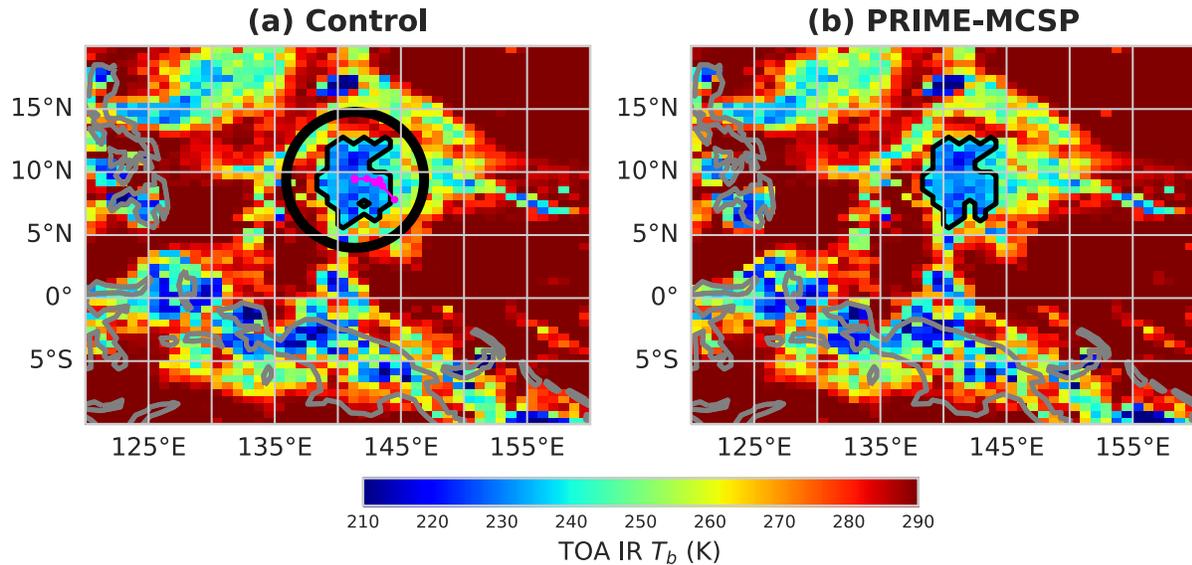
284 The climate simulations, as detailed in Table 2, aim to assess the long-term effects of  
 285 PRIME-MCSP on the large-scale precipitation patterns and MJO. This evaluation is based on  
 286 three model runs, each spanning 20 years from September 1988 to August 2008. The simulations  
 287 employ a horizontal grid spacing of approximately 135 km (N96) and have 85 vertical levels.  
 288 The model's integration time step is 20 minutes. The set includes a control run where the  
 289 PRIME-MCSP scheme is deactivated, a standard PRIME-MCSP run with a fixed  $\alpha$  value of 0.5,  
 290 and a PRIME-MCSP Variable  $\alpha$  run. In the Variable  $\alpha$  run, the stratiform-to-convective heating  
 291 fraction is dynamically adjusted based on the cloud top temperature, as described above. Except  
 292 for the adoption of the CoMorph-A convection scheme, the model setup adheres to the Met  
 293 Office Atmospheric Model Intercomparison Project Phase 6 (AMIP6) configuration, with the  
 294 atmospheric model being forced by climatological boundary conditions (Walters et al. 2019).

295 The reference dataset utilized for the global assessment comprises several key sources:  
 296 the Global Precipitation Climatology Project (GPCP; Pendergrass et al. (2022), is employed to  
 297 assess the accuracy of simulated monthly precipitation. Furthermore, we use 26 models from the  
 298 Coupled Model Intercomparison Project Phase 6 (CMIP6; Eyring et al. 2016a) to analyze the  
 299 seasonal cycle of precipitation. These 26 models were selected following the research of Lauer et  
 300 al. (2023) to include only the atmospheric components of the CMIP6 models and prescribed  
 301 observed SSTs. This selection, known as AMIP6, represents the state-of-the-art capability for  
 302 predicting the atmospheric climate state. The National Centers for Environmental Prediction  
 303 (NCEP) Reanalysis data (Kalnay et al. 1996) serves to evaluate the MJO. The observed global  
 304 MCS tracks, as identified by Feng et al. (2021), are applied to assess the frequency of PRIME-  
 305 MCSP scheme being called.

306 Customized MCS tracking in this project utilizes the PyFLEXTRKR software, as detailed  
 307 by Feng et al. (2023), employing hourly maps of Top-Of-Atmosphere (TOA) infrared brightness  
 308 temperatures (IR  $T_b$ ) alongside the surface rain rates. The conversion of simulated TOA  
 309 Outgoing Longwave Radiation (OLR) to IR  $T_b$  is achieved through the empirical correlation  
 310 established by Yang and Slingo (2001), enabling MCS identification as depicted in Figure 3a.  
 311 The MCS cold cloud shield mask is defined as its IR  $T_b$  falling below 241 K. This mask is  
 312 subsequently used to estimate the rainfall area and the mean rain rate underneath the MCS. The  
 313 criteria for selecting representative MCSs are a minimum cold cloud shield size of 60,000 km<sup>2</sup>  
 314 at the peak of its lifecycle, coupled with a duration exceeding 6 hours. Tracking an MCS requires a  
 315 minimum 50% overlap in its cold cloud shields for two consecutive model output time steps of  
 316 half an hour. Additional tracking configurations are elaborated in Feng et al. (2023).

317 MCS track matching between the MCS masks in the control (Figure 3a, black contours)  
 318 and the PRIME-MCSP (Figure 3b, black contours) runs is performed by requiring an areal  
 319 overlap ratio above 80% at the MCS initiation time. The magenta dots and lines in Figure 3a  
 320 illustrate the centroids and the path of the MCS at later times within the control run. The MCS

321 cloud region is delineated by the cold cloud shield mask, and the surrounding area of interest is  
 322 defined as a region within a 600 km radius around the centroid (marked by the black circle in  
 323 Figure 3a), excluding the areas under the cold cloud shield mask. The MCS cloud region and its  
 324 surrounding area in the control run serve as the spatial basis ranges for computing the difference  
 325 between fields in the control run and the PRIME-MCSP run. These differences are used to  
 326 evaluate the effect of the PRIME-MCSP scheme throughout the MCS lifecycle.



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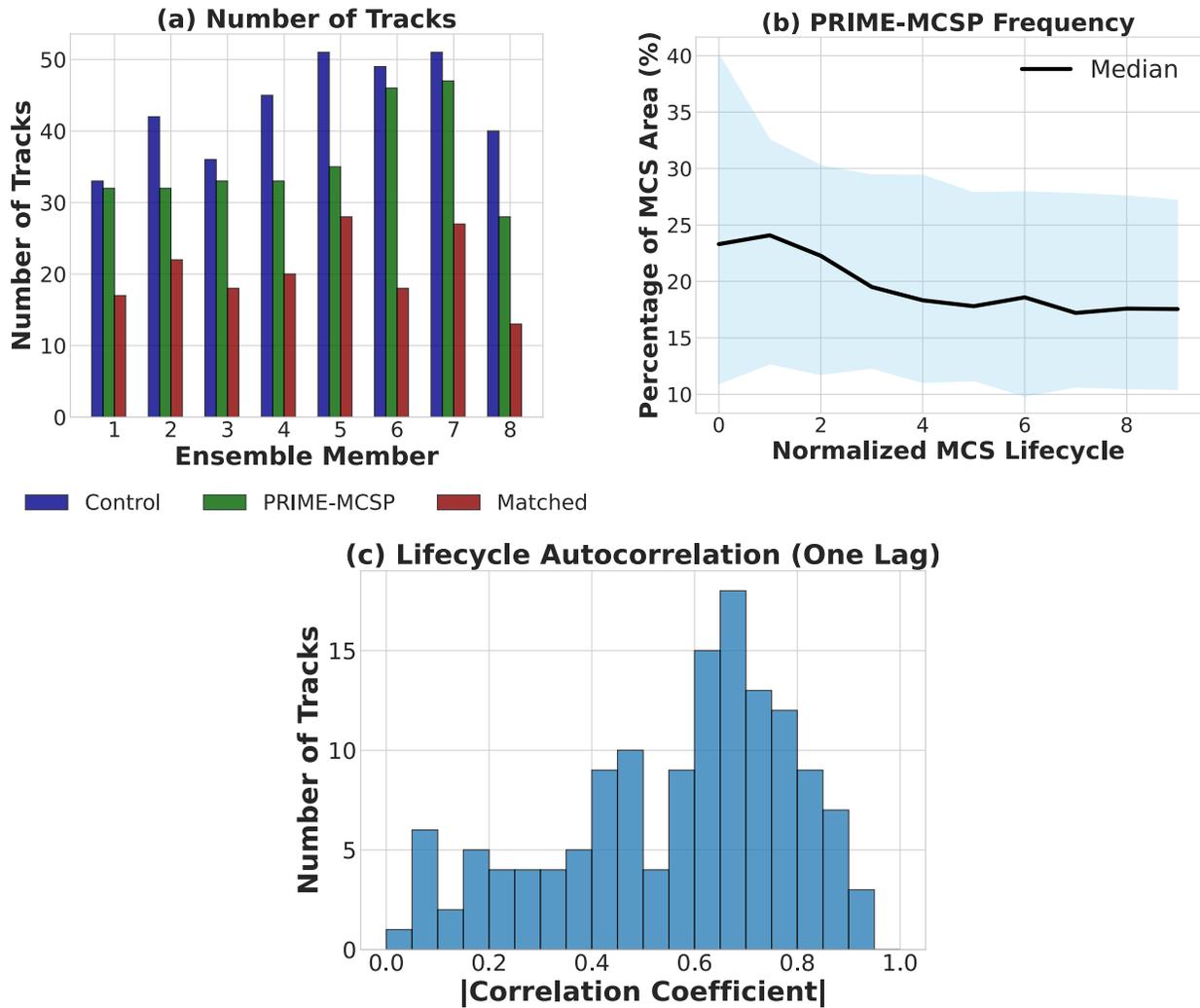
328 **Figure 3.** MCS track on July 1st, 2020, at 04:00 UTC. (a) The control run. The magenta dots and  
 329 lines trace the MCS centroids and trajectory, respectively; the circle delineates the MCS  
 330 surrounding environmental area of interest. (b) The PRIME-MCSP model run. The MCS  
 331 boundaries in (a) and (b) are delineated by black contours. The grey contours delineate the  
 332 coastlines over the Maritime Continent.

#### 333 4 Direct Effects of the Scheme in Weather Ensembles

334 Figure 4a shows the count of global MCS tracks in both control and PRIME-MCSP  
 335 ensemble runs across ensemble members 1 to 8, represented by blue and green bars, respectively.  
 336 The PRIME-MCSP runs show a general concurrence with the control, albeit with a slight  
 337 reduction in MCS track numbers. Approximately one-third to one-half of MCS tracks (indicated  
 338 by red bars in Figure 4a) are matchable between control and PRIME-MCSP runs, totaling 163  
 339 MCS tracks across 8 ensemble members. The detailed MCS track matching method has been  
 340 described in Section 3.

341 Figure 4b shows the frequency of PRIME-MCSP scheme activations throughout the  
 342 normalized MCS lifecycle. The lifecycle of the MCS is normalized into 10 timesteps, ranging  
 343 from 0 (initiation) to 9 (termination). The characteristics of the MCS are linearly interpolated  
 344 across these 10 normalized timesteps to facilitate the combination of lifecycle evolutions. The  
 345 calling frequency is defined as the ratio between grid points activating the PRIME-MCSP  
 346 scheme and the grid points within the MCS mask area. Data from all MCS tracks in ensemble  
 347 members is aggregated in Figure 4b. The median MCSP frequency exhibits a relatively stable  
 348 evolution throughout the lifecycle with variations from 18% to 24% of the MCS area. This is in

349 agreement with the prior MCSP approach (e.g., Moncrieff & Liu, 2006), wherein the scheme is  
 350 called in the convecting regions of the MCS, not the anvil. In addition to the combined statistics,  
 351 Figure 4c shows a histogram of autocorrelation at a one-time-step lag, based on the calling  
 352 frequency within each individual MCS lifecycle. The correlation coefficient is concentrated  
 353 around 0.7, indicating the consistency of the calling frequency throughout each MCS lifecycle.  
 354 This lifecycle continuity of calling frequency suggests effective coupling of the PRIME-MCSP  
 355 scheme with the CoMorph-A convection scheme, avoiding abrupt activations or deactivations.

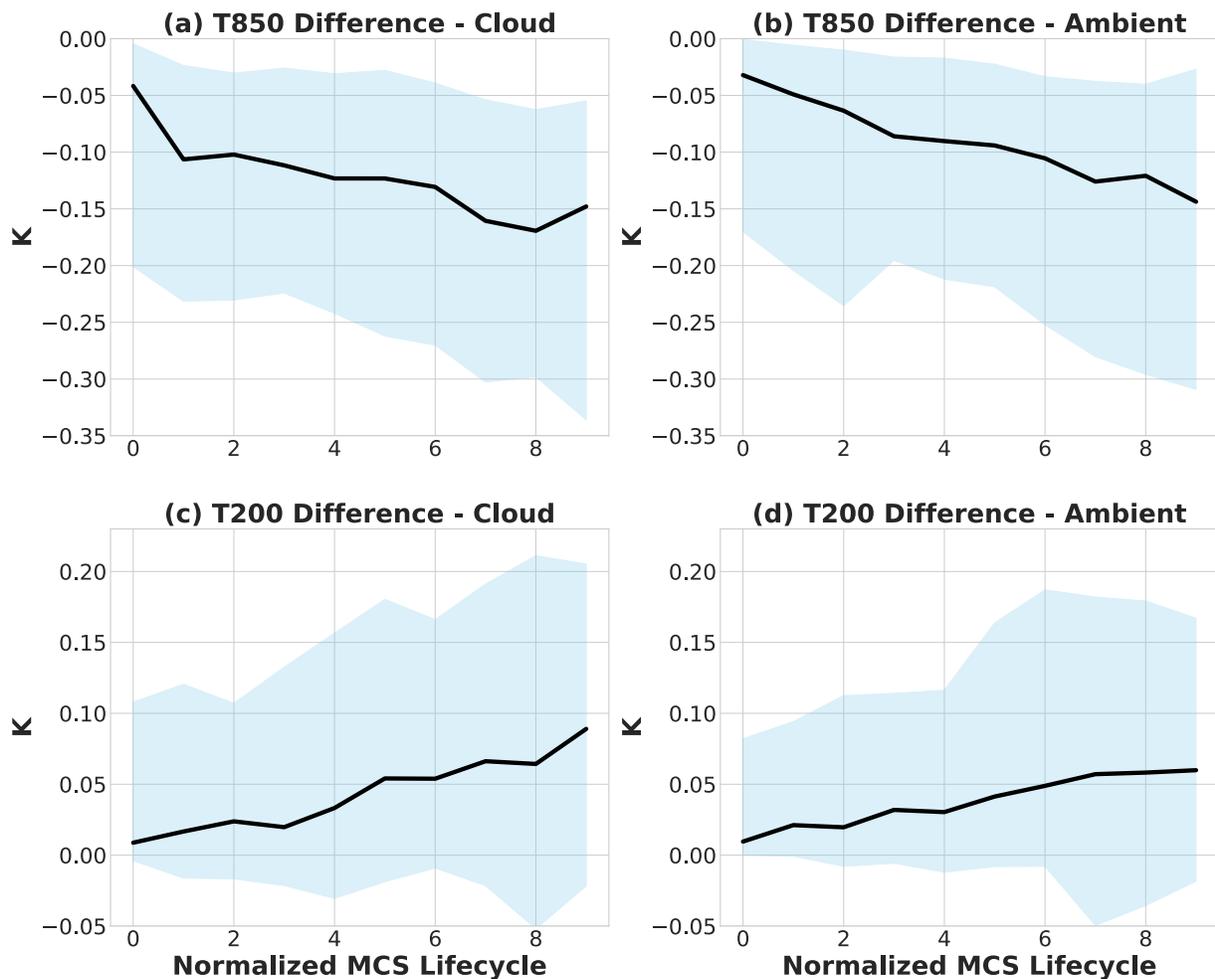


356

357 **Figure 4.** (a) MCS track counts, (b) invocation frequencies of the scheme across the MCS  
 358 lifecycles. The shaded areas represent the Interquartile Range (IQR) in all matched tracks from  
 359 all ensemble members, spanning the 25th to 75th percentiles, while the median value is depicted  
 360 by the solid black line, and (c) histogram of the absolute values of MCS lifecycle autocorrelation  
 361 with a one-time-step lag.

362 The PRIME-MCSP scheme primarily functions to transfer heat from the lower to the  
 363 upper troposphere. We examine the evolution of spatially averaged temperature throughout the  
 364 normalized lifecycles of the MCSs in both the cloud areas and surrounding environments. The  
 365 normalized lifecycles, cloud areas, and MCS surrounding environments are based on the MCS

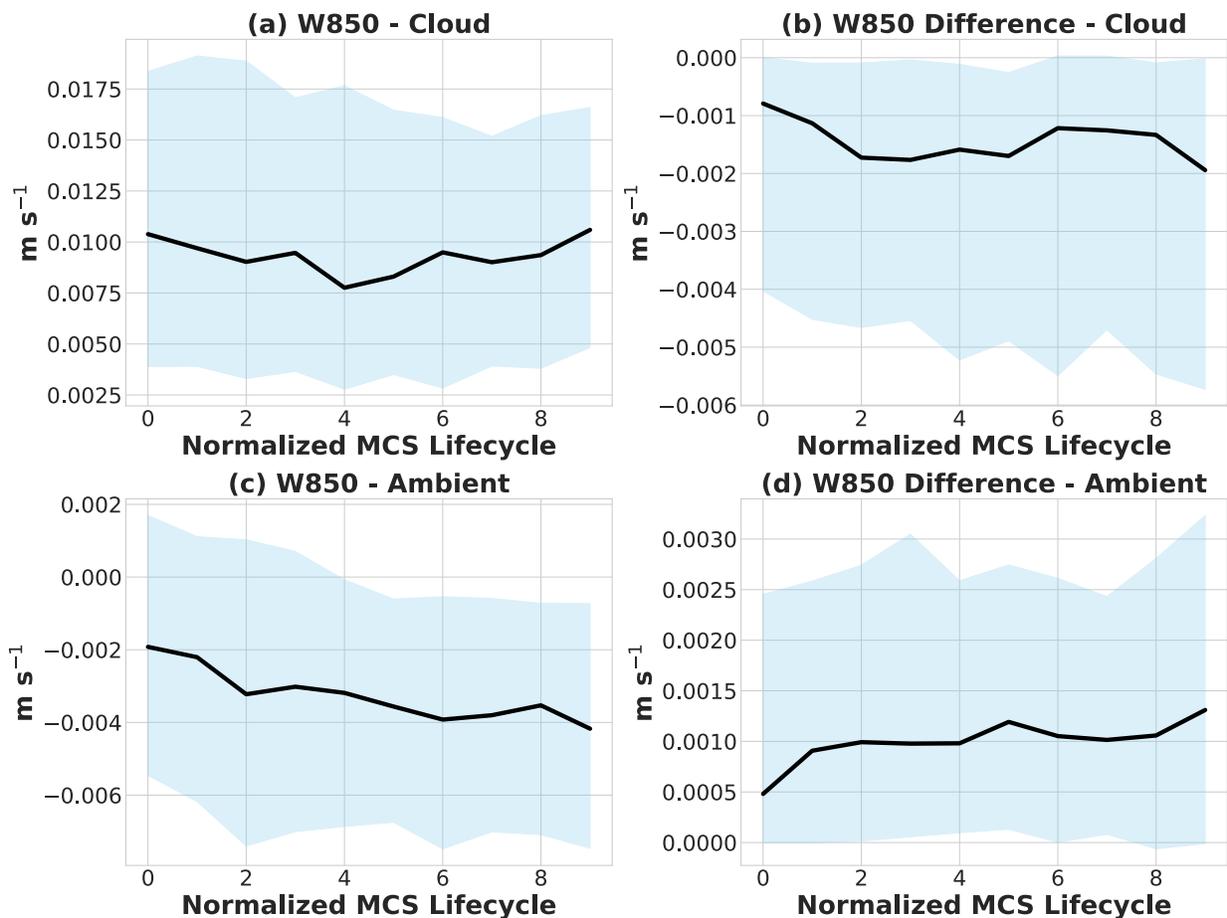
366 tracks in the control run that have corresponding matches in the PRIME-MCSP runs. It appears  
 367 that the temperature does not change much throughout the lifecycle. Therefore, our analysis  
 368 focuses on the temperature differences between the PRIME-MCSP run and the control run. In  
 369 Figure 5 a–b, we observe a decrease in temperature for both the MCS cloud and the surrounding  
 370 environment at 850 hPa as time progresses, with the rate of change in the MCS cloud being more  
 371 pronounced. This indicates that the PRIME-MCSP scheme effectively induces cooling in the  
 372 lower troposphere, as intended, and that over time, this cooling effect extends to the MCS’s  
 373 surrounding environment. Conversely, Figure 5 c–d shows an increase in temperature at 200 hPa  
 374 for both the MCS cloud and the environment, again with a faster rate of change within the cloud.  
 375 This demonstrates the scheme’s role in upper tropospheric warming, with the additional heating  
 376 in the cloud area gradually affecting the surrounding MCS environment over time.



377

378 **Figure 5.** Temperature differences between the PRIME-MCSP and the control runs within MCS  
 379 clouds and their surrounding environments at both 850 hPa (a–b) and 200 hPa (c–d) throughout  
 380 the normalized MCS lifecycle, using the MCS tracks in the control run that have matches in the  
 381 PRIME-MCSP runs. Shaded areas and lines follow the conventions from Figure 4b. Simulations  
 382 span July 1st, 2020, 03Z to July 3rd, 2020, 03Z.

383 Figure 6 shows the response of 850 hPa vertical velocity to the lower tropospheric  
 384 cooling induced by the PRIME-MCSP scheme. Within the MCS, a predominant positive vertical  
 385 velocity is associated with ongoing convective updrafts throughout the lifecycle (Figure 6a).  
 386 Conversely, in the surrounding environments of the MCS, a negative vertical velocity is also  
 387 persistent, indicating the presence of environmental subsidence air (Figure 6c). When the  
 388 PRIME-MCSP scheme is active, there is a weakening of convective updrafts (Figure 6b) and a  
 389 corresponding weakening of the surrounding air subsidence (Figure 6d). These alterations  
 390 highlight the PRIME-MCSP scheme's effect in moderating the explicit mesoscale circulations  
 391 associated with the MCS. Additionally, an examination of the 200 hPa vertical velocity response  
 392 (supplemental Figure S1) reveals no significant change, suggesting that the effects of the  
 393 PRIME-MCSP upper tropospheric heating are nuanced, likely influenced by cloud top height  
 394 and interactions with gravity waves.

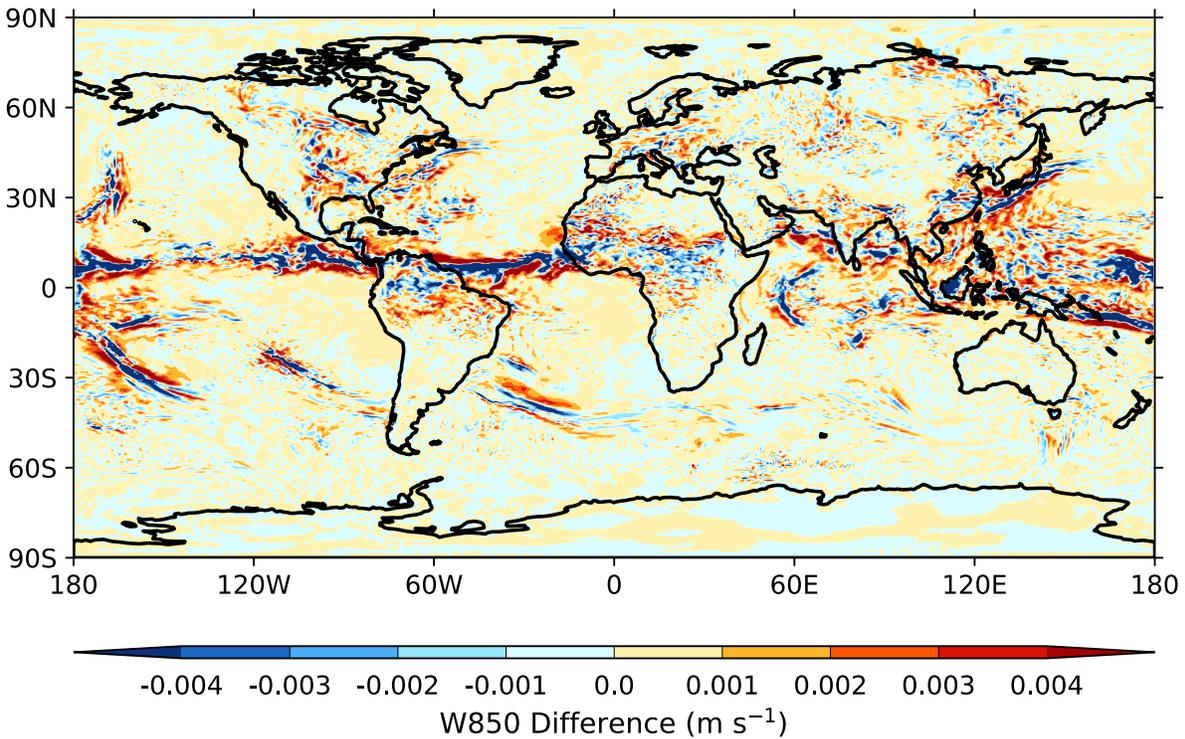


395

396 **Figure 6.** (a, c) 850 hPa vertical velocity in the control runs and (b, d) their changes following  
 397 PRIME-MCSP activation, where a positive velocity indicates upward motion. Shaded areas and  
 398 line conventions are as described in Figure 4b. Simulations span July 1st, 2020, 03Z to July 3rd,  
 399 2020, 03Z.

400 The impact of the PRIME-MCSP scheme on regional circulation is further demonstrated  
 401 in Figure 7, which presents a global map highlighting the differences in 850 hPa vertical velocity  
 402 between the MCSP run ensemble mean and the control run ensemble mean. Notably, over the

403 part of Intertropical Convergence Zone (ITCZ) between 10°–180°W, 0°–20°N and over various  
 404 extratropical low-level jet regions, the formation of three parallel bands—central blue shading  
 405 flanked by two red shading bands—mirrors the findings from Figure 6, indicating suppressed  
 406 regional upward motion and reduced surrounding subsidence following the PRIME-MCSP  
 407 scheme activation.

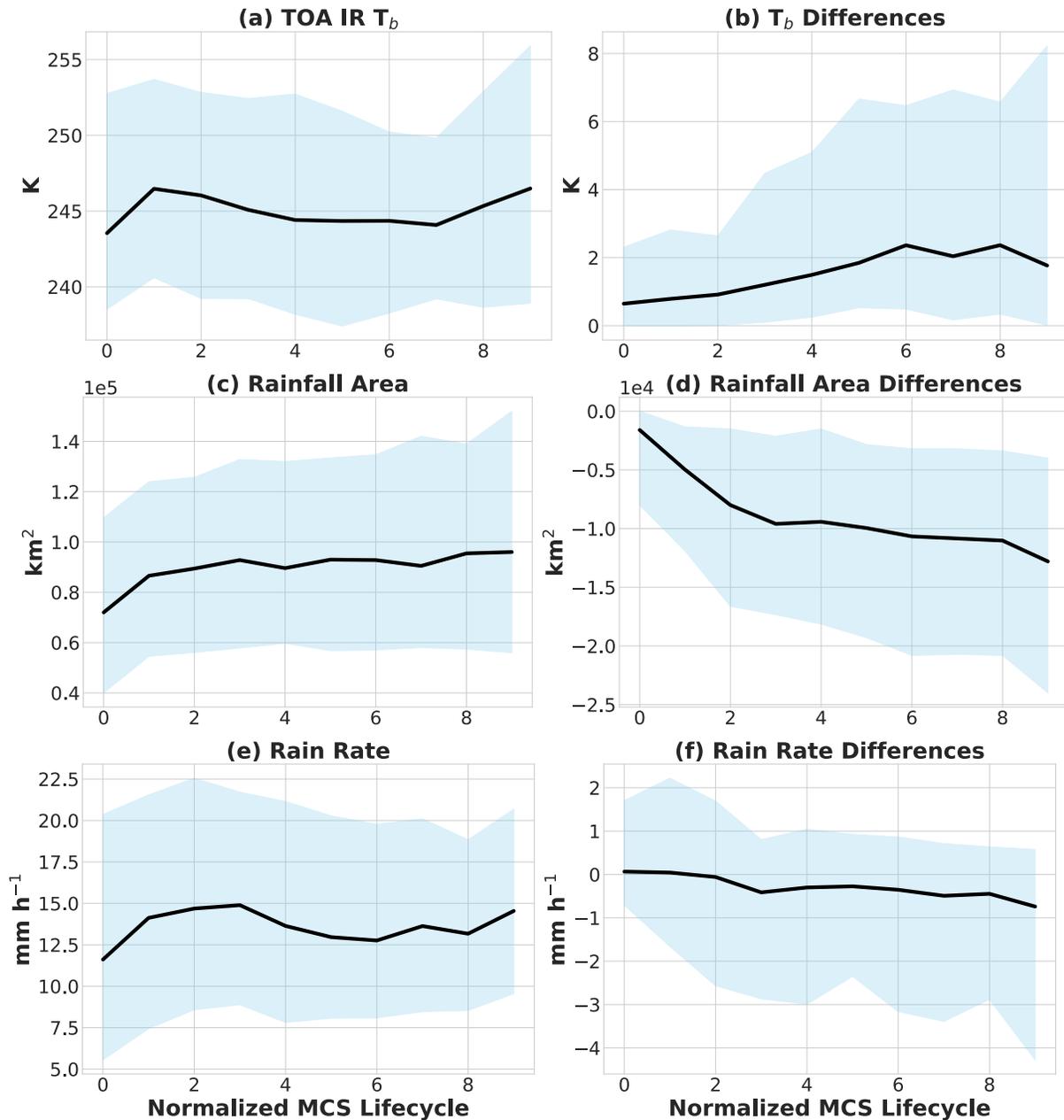


408

409 **Figure 7.** Ensemble mean difference in 850 hPa vertical velocity between the PRIME-MCSP  
 410 and control runs, with black contours delineating coastlines. The averaging period is based on the  
 411 entire 48 hours of the analyzed simulations.

412 The weakened circulations are linked to changes in MCS characteristics, including  
 413 convective depth, rainfall area, and rain rate. Convective depth is represented by the minimum  
 414 TOA IR  $T_b$  within the MCS's cold cloud shield, where colder TOA IR  $T_b$  values signify deeper  
 415 MCS convective systems (Figure 8a). The PRIME-MCSP scheme results in a consistently  
 416 positive TOA IR  $T_b$  difference throughout the MCS lifecycle (Figure 8b), suggesting a reduction  
 417 in convective depth. The area covered by rainfall expands as the MCS matures, stabilizing in the  
 418 latter part of the lifecycle (Figure 8c). The difference in rainfall area is consistently negative  
 419 (Figure 8d), indicating the PRIME-MCSP scheme's tendency to reduce the rainfall area beneath  
 420 the MCS's cold cloud shield. This explains the decrease in MCS track numbers as shown in  
 421 Figure 4a, since a reduced MCS area impacts the number of cases meeting the lifecycle-  
 422 maximum area threshold. Consistent with previous research indicating a positive correlation  
 423 between convective depth and MCS area (Zhang et al., 2021), the decrease in convective depth is  
 424 associated here with reduction in area. The PRIME-MCSP scheme's impact on rain rate is  
 425 minimal, likely because rain rate is more influenced by large-scale microphysics, and the scheme  
 426 primarily modifies heating tendencies without directly affecting rain rate. Combining reduced

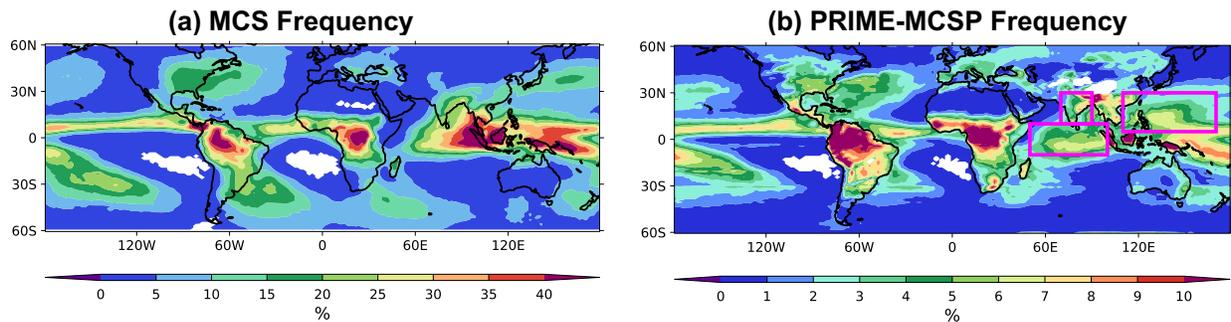
427 rainfall area with an unchanged rain rate suggests a decrease in rainfall volume within MCSs  
 428 following PRIME-MCSP activation. Accumulating these differences over time, along with  
 429 changes in large-scale circulations, the long-term indirect effect of PRIME-MCSP on rainfall is  
 430 assessed in Section 5.



431  
 432 **Figure 8.** The lifecycles of (a) TOA IR  $T_b$ , (c) rainfall area, and (e) rain rate in the control run,  
 433 and their changes (b, d, and f) following PRIME-MCSP activation. Simulations span July 1st,  
 434 2020, 03Z to July 3rd, 2020, 03Z.

## 435 5 Indirect Effects of the Scheme in Decadal Simulations

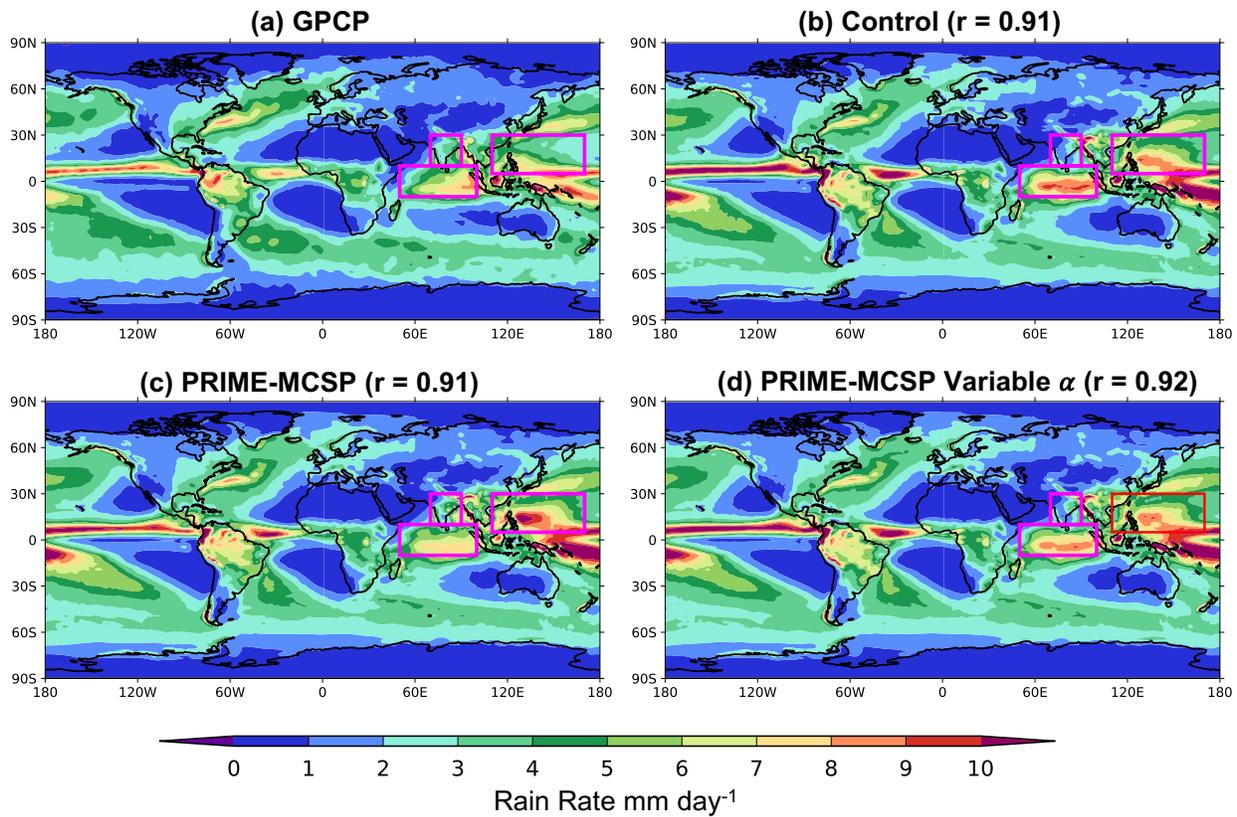
436 Before considering the indirect effects of the PRIME-MCSP scheme, we first compare  
 437 the calling frequency of the scheme with real-world MCS occurrence frequencies. The  
 438 comparison period spans from June 2000 to August 2008, coinciding with PRIME-MCSP runs  
 439 and observed MCS track data from Feng et al. (2021). Figure 9a shows the MCS occurrence  
 440 frequency using the observed global MCS track dataset, with color shading indicating the  
 441 percentage of time the MCS cold cloud shield is present. Figure 9b illustrates the frequency of  
 442 PRIME-MCSP scheme activation, defined by the percentage of timesteps on which the scheme is  
 443 called. MCS frequencies generally exceed PRIME-MCSP activation frequencies (compare the  
 444 color scales in Figures 9a and 9b). The relative spatial patterns show general agreement but with  
 445 some regional discrepancies. PRIME-MCSP activation frequencies are relatively low over the  
 446 Maritime Continent and slightly below those found in the ITCZ. Magenta rectangles in Figure 9  
 447 highlight areas where PRIME-MCSP frequencies strongly disagree with the MCS pattern,  
 448 particularly over India and the Indian Ocean, with an expanded strong center further north over  
 449 the Western Pacific.



450

451 **Figure 9.** (a) Observed MCS occurrence frequency and (b) frequency of calling the PRIME-  
 452 MCSP scheme in the decadal run. Magenta rectangles highlight regions of interest: India, the  
 453 Indian Ocean, and the Western Pacific. The comparison period spans June 2000 to August 2008.

454 Figure 10 presents a comparison of the averaged global rain rate distributions as derived  
 455 from satellite retrievals (GPCP), alongside those from the control, PRIME-MCSP, and PRIME-  
 456 MCSP variable  $\alpha$  runs over a 20-year period from September 1988 to August 2008. The Pearson  
 457 correlation coefficients between the GPCP and these three simulations are 0.91, 0.91, and 0.92,  
 458 respectively. These correlations indicate that the PRIME-MCSP scheme maintains the accuracy  
 459 of global rainfall distribution.



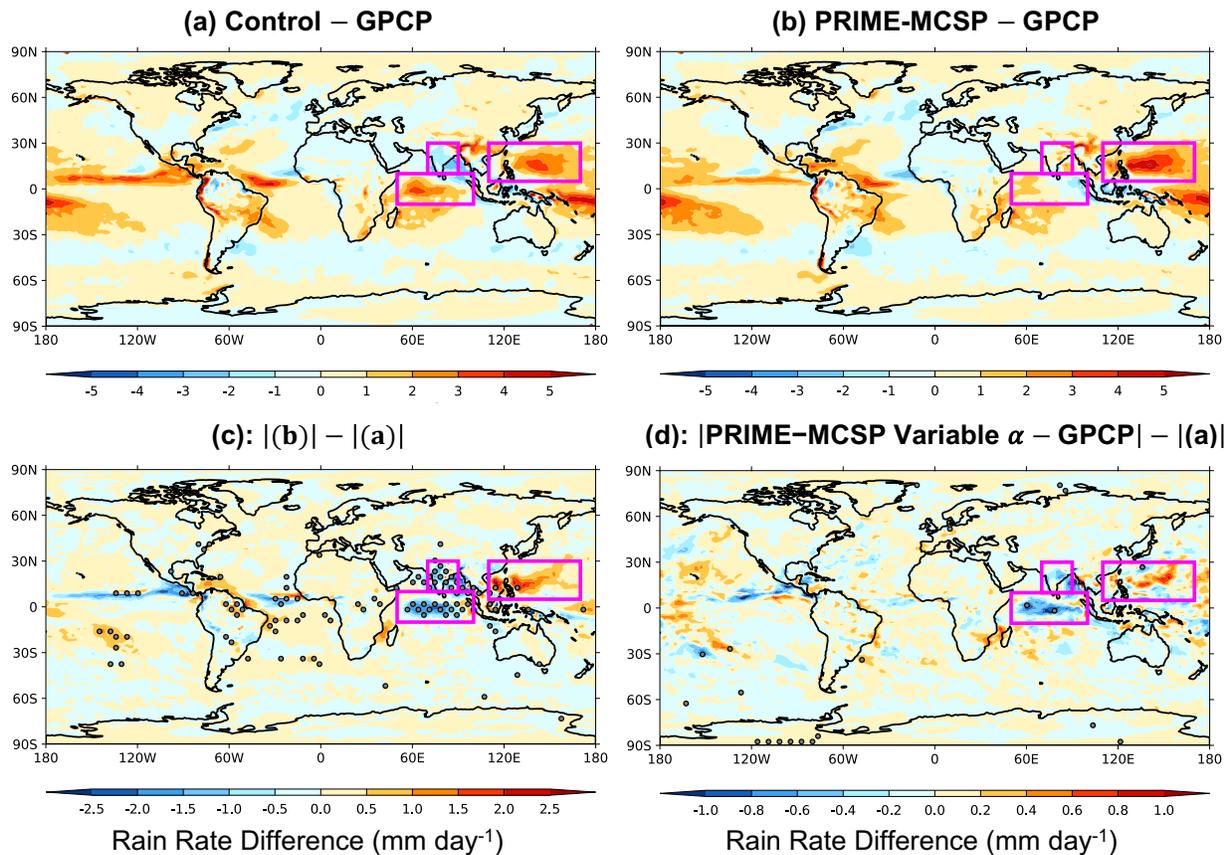
460

461 **Figure 10.** Average rain rate maps from (a) GPCP retrieval, (b) control, (c) PRIME-MCSP, and  
 462 (d) PRIME-MCSP variable  $\alpha$  runs. The Pearson correlation coefficient between the model runs  
 463 and the GPCP retrieval is quoted for panels (b–d) as “ $r$ ”. All simulations and observations span  
 464 September 1988 to August 2008.

465 Figure 11a presents the difference in rainfall between the control run and GPCP  
 466 retrievals, with warm and cold colors indicating precipitation overestimation and  
 467 underestimation, respectively. Predominantly, the control run overestimates rainfall across most  
 468 tropical regions, especially within the ITCZ. Specifically, it overestimates rainfall over the  
 469 Indian Ocean and Western Pacific, while underestimating it over India and the Bay of Bengal.  
 470 These control run biases are consistent with Bush et al. (2014). Figure 11b demonstrates how  
 471 PRIME-MCSP affects these biases, reducing the dry bias over India and mitigating the wet bias  
 472 over the Indian Ocean, albeit amplifying it over the Western Pacific. The PRIME-MCSP variable  
 473  $\alpha$  run generally mediates between the PRIME-MCSP and control runs, with a notable reduction  
 474 in the wet bias over the Western Pacific compared to the PRIME-MCSP run, as indicated in  
 475 supplemental Figure S2. However, improvements in rainfall accuracy over India and the Indian  
 476 Ocean are more pronounced in the PRIME-MCSP run than in the PRIME-MCSP variable  $\alpha$  run.

477 Figures 11c and 11d compare the absolute differences in rainfall biases (between the  
 478 GPCP and model runs) before and after activating the PRIME-MCSP scheme, using a  
 479 significance test based on 10,000 bootstrap resamples. Areas with significant changes ( $p$  values <  
 480 5%) in rainfall bias are marked with stipples, with cold and warm shadings indicating bias  
 481 mitigation and amplification, respectively. The results suggest that improvements over India and  
 482 the Indian Ocean are statistically significant. In contrast, the Western Pacific shows high internal

483 variability such that the apparent bias amplification in that region could be due to chance. The  
 484 PRIME-MCSP variable  $\alpha$  run shows a similar pattern to the PRIME-MCSP run but with a lesser  
 485 magnitude of bias change and fewer significance stipples, indicating a balance between bias  
 486 mitigation over the Indian Ocean and bias worsening over the Western Pacific, with a less  
 487 significant improvement over the Indian Ocean compared to the PRIME-MCSP run.



488

489 **Figure 11.** Rainfall difference between (a) the control run and GPCP, (b) the PRIME-MCSP run  
 490 and GPCP, (c) the difference between the absolute values of (b) and (a), and (d) the same  
 491 calculation as in (c) but for the PRIME-MCSP variable  $\alpha$  run. The stippling in (c) and (d)  
 492 indicates statistical significance, determined as described in the main text. Note the change of  
 493 color scale between (c) and (d). All simulations and observations span September 1988 to  
 494 August 2008.

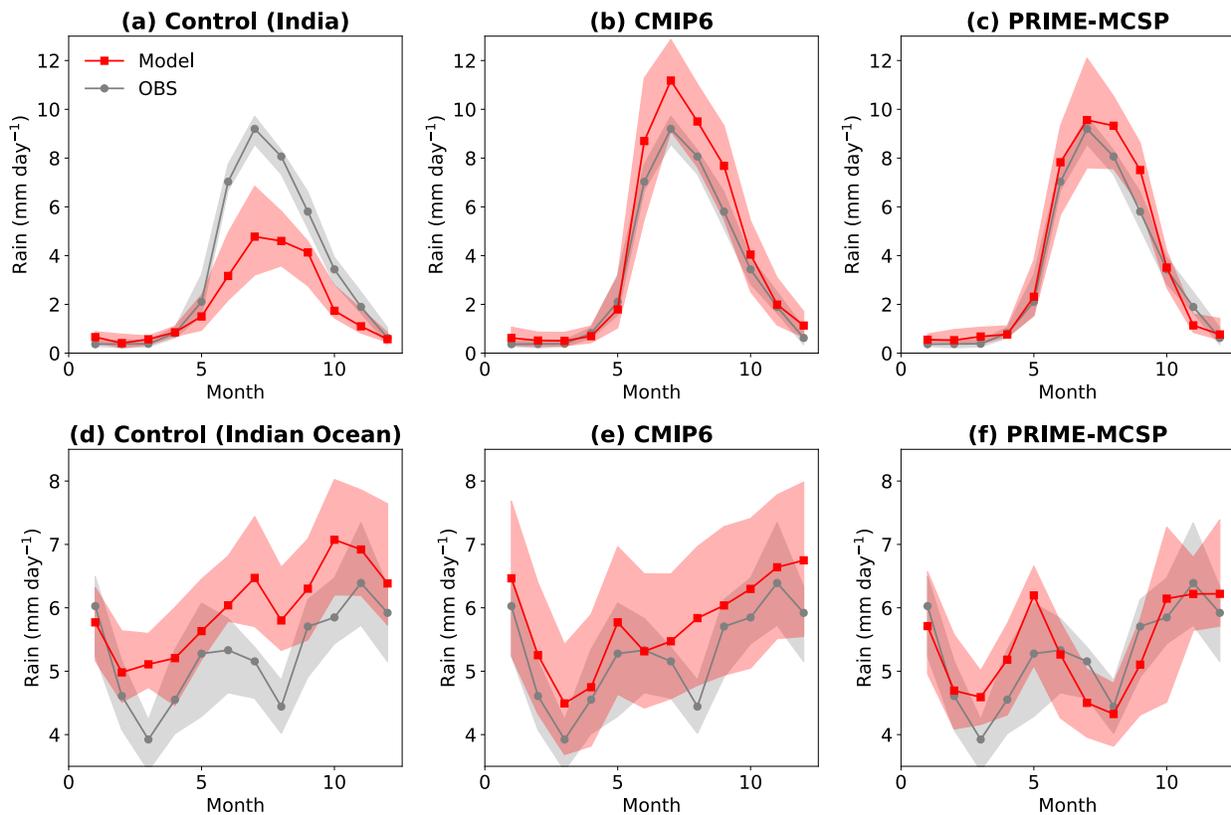
495 In Figure 12, the annual cycles of precipitation seasonal cycles are used to diagnose  
 496 further the rainfall changes over India and the Indian ocean in the PRIME-MCSP run and to  
 497 compare with the control run and the CMIP6 ensemble simulations.

498 Over India, the control run significantly underestimates the rainfall, especially during the  
 499 summer monsoon (Figure 12a). CMIP6 models agree better with the GPCP retrieval while  
 500 overestimating the median precipitation from May to October (Figure 12b). The PRIME-MCSP  
 501 run shows the closest agreement with the GPCP retrieval, outperforming both the control run and  
 502 CMIP6 simulations, especially in correcting the underestimation of rainfall, as shown in Figure

503 12c. However, the IQRs in all these simulations are greater than those observed, highlighting the  
504 persistent model uncertainties across all models.

505 Over the Indian Ocean, the control run fails to capture the phase of the seasonal cycle and  
506 overestimates rainfall during all months (Figure 12d). CMIP6 performs better to agree with the  
507 observations in both timing and rainfall amounts from January to June, but significantly  
508 overestimates the precipitation from July to December (Figure 12e). The PRIME-MCSP run  
509 simulates both the phase and amplitude of the seasonal precipitation cycle, aligning closely with  
510 GPCP retrievals and markedly deviating from CMIP6 predictions (Figure 12f).

511 The PRIME-MCSP run surpassing CMIP6 predictions to agree with GPCP over the  
512 Indian ocean is particularly noteworthy given the run's coarser grid spacing relative to most  
513 CMIP6 simulations, suggesting the PRIME-MCSP scheme's upscaling effect plays a crucial role  
514 in capturing large-scale circulation patterns in this region. Consistently, the PRIME-MCSP  
515 variable  $\alpha$  run also improves these seasonal cycles as for the PRIME-MCSP run, but with a  
516 muted amplitude alteration (shown in the supplemental Figure S3).



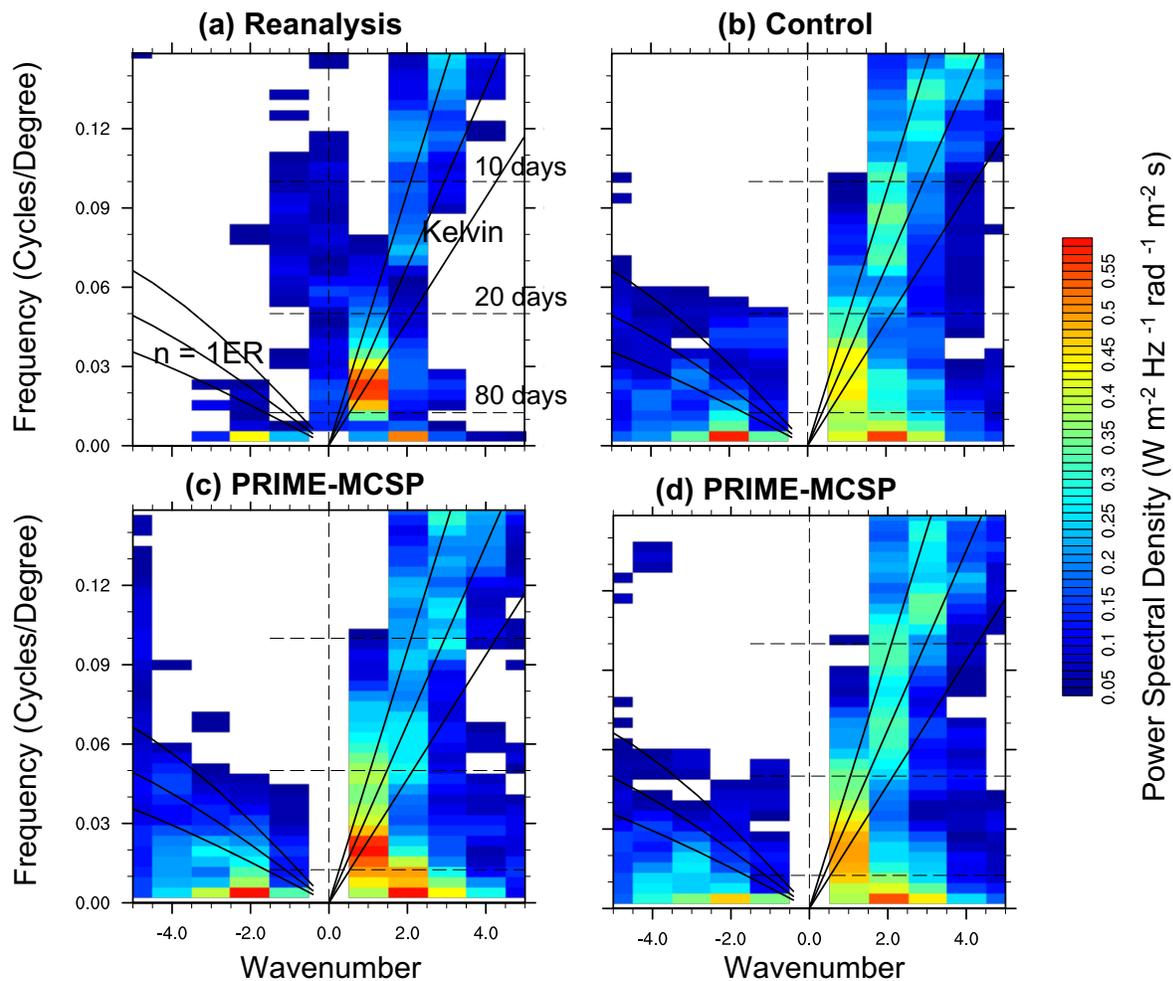
517

518 **Figure 12.** Simulated (red) and GPCP retrieved (grey) annual cycles of precipitation in the (a, d)  
519 control, (b, e) CMIP6, and (c, f) PRIME-MCSP run. The bands and lines indicate the IQR ranges  
520 and median values respectively. The India (a,b,c) and Indian ocean (d,e,f) regions are shown by  
521 the magenta boxes in Figure 10. All simulations and observations span September 1988 to  
522 August 2008.

523 The MJO plays a crucial role in influencing the annual precipitation cycle over India and  
524 the Indian Ocean, as proved in past studies (e.g., Hoell et al. 2018; Rushley et al. 2023). The

525 MJO's characteristics are analyzed for these climate runs in comparison with reanalysis, using  
 526 the community software ESMValTool (Eyring et al. 2016b).

527 Figure 13 shows the symmetric wave cross spectra, derived from OLR and zonal wind  
 528 data across the latitude range of 20°N to 20°S, following the methodology of Wheeler and  
 529 Kiladis (1999). The spectral power density, depicted through color shading, highlights the  
 530 presence of MJO signals. Specifically, Figure 13a identifies a peak at the MJO's characteristic  
 531 period (20 to 100 days) and spatial scale (wavenumbers 1–2) with an orange color shading,  
 532 indicating its typical spectral power density in reanalysis. The control run's spectra display a  
 533 much weaker signal in this region. Conversely, both the PRIME-MCSP and the PRIME-MCSP  
 534 variable  $\alpha$  runs more successfully capture this spectral feature, indicating a more accurate  
 535 representation of the MJO, with the PRIME-MCSP run exhibiting the closest match to  
 536 reanalysis. Additionally, the Kelvin wave intensity is overestimated in the control run with the  
 537 CoMorph-A convection scheme, but this overestimation is mitigated in the PRIME-MCSP run.  
 538 This suggests that PRIME-MCSP might be promising in mitigating the pre-existing spectral bias  
 539 inherited from the convection parameterization.



540

541 **Figure 13.** Symmetric wave cross spectra derived from OLR and zonal wind. The dashed lines,  
 542 from top to bottom, indicate wave periods of 10, 20, and 80 days, respectively. The three black

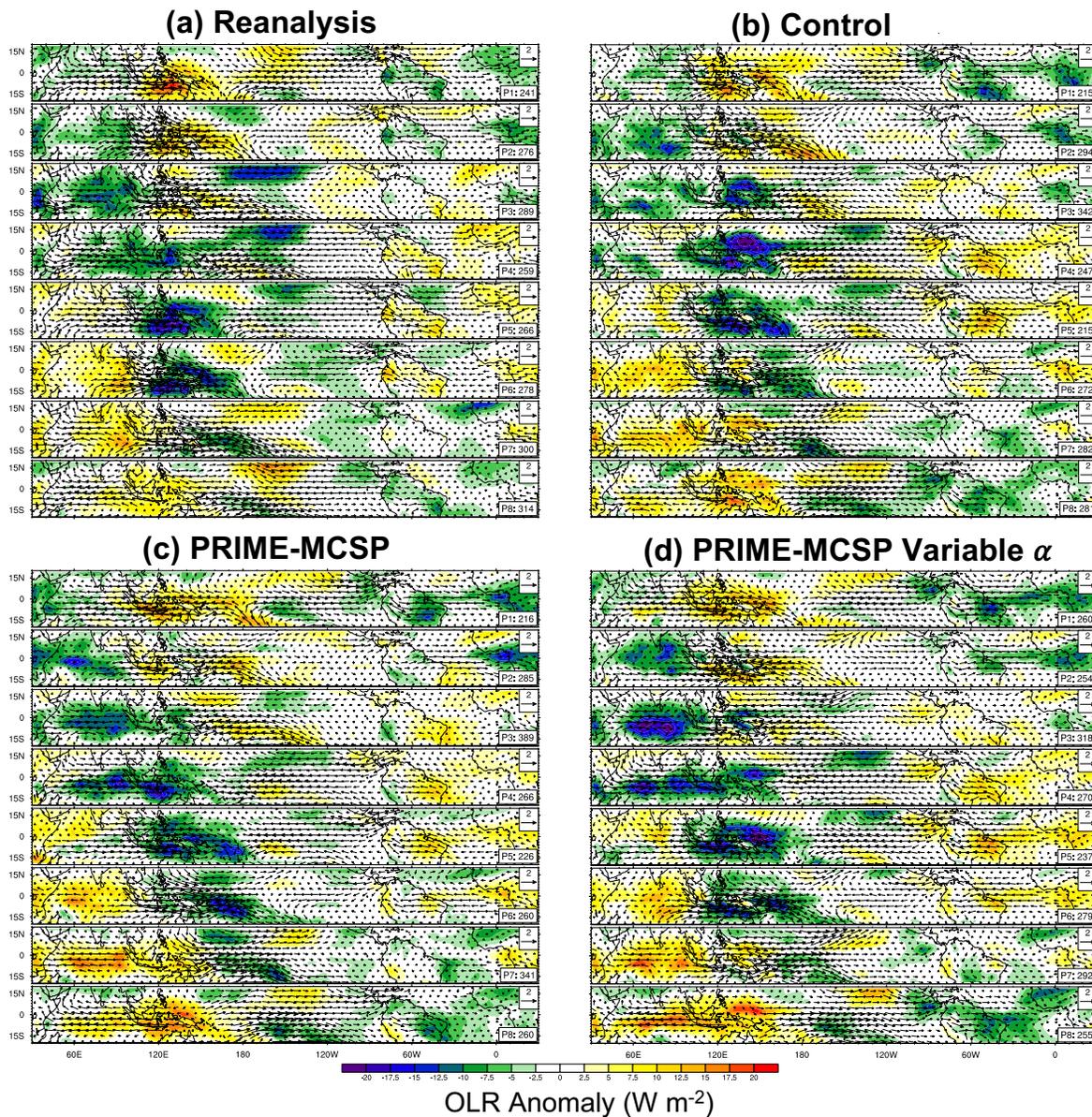
543 lines on the left and right sides denote Equatorial Rossby (ER) waves and Kelvin waves,  
544 respectively. a) Reanalysis, b) Control simulation, c) PRIME-MCSP simulation, d) PRIME-  
545 MCSP variable  $\alpha$  simulation. All simulations and observations span September 1988 to August  
546 2008.

547 The MJO index is calculated following Wheeler and Hendon (2004) approach, which  
548 uses 15°S to 15°N averaged 850-hPa zonal wind, 200-hPa zonal wind, and OLR at the TOA.  
549 These daily fields in the reanalysis, control, PRIME-MCSP, and PRIME-MCSP variable  $\alpha$  runs  
550 are filtered to leave the 20–100 days MJO components, before they are projected onto the same  
551 multiple-variable Empirical Orthogonal Functions computed from the reanalysis data. Two  
552 principal components are derived to depict the east-west and north-south progression of the  
553 MJO. The magnitude of the vector formed by these components serves as the MJO index,  
554 indicating the intensity of the MJO. When the MJO index exceeds a value of 1, these  
555 components are employed to categorize data into eight MJO phases, reflecting the spatial and  
556 temporal evolution of the MJO lifecycle.

557 Wintertime (November to April) MJO lifecycle composite maps are shown in Figure 14,  
558 again generated by ESMValTool. These maps use darker blue shading to indicate decreases in  
559 OLR, highlighting phases of enhanced rainfall and large-scale upward motion associated with  
560 the MJO. The sequence from Phase 1 (P1) to Phase 8 (P8) in Figure 14a illustrates the MJO's  
561 eastward propagation through its various phases in the reanalysis, with a consistent movement  
562 across the Maritime Continent. The control run (Figure 14b), however, shows discrepancies in  
563 capturing this propagation, particularly during Phase 6 (P6) when the anomaly dissipates too  
564 readily. The PRIME-MCSP and PRIME-MCSP variable  $\alpha$  runs (Figure 14 c–d) both improve  
565 upon the control run's performance, with the former better at representing OLR anomalies before  
566 the MJO reaches the Maritime Continent and the latter being more accurate afterwards. Notably,  
567 the PRIME-MCSP variable  $\alpha$  run depicts enhanced accuracy in P6, capturing the two strong  
568 centers of OLR anomalies over the Maritime Continent. This demonstrates the PRIME-MCSP  
569 scheme's effectiveness in improving MJO characteristics, aligning with findings from prior  
570 studies (e.g., Chen et al., 2021) and suggests sensitivity to variations of  $\alpha$  in capturing spectral  
571 density and MJO lifecycles.

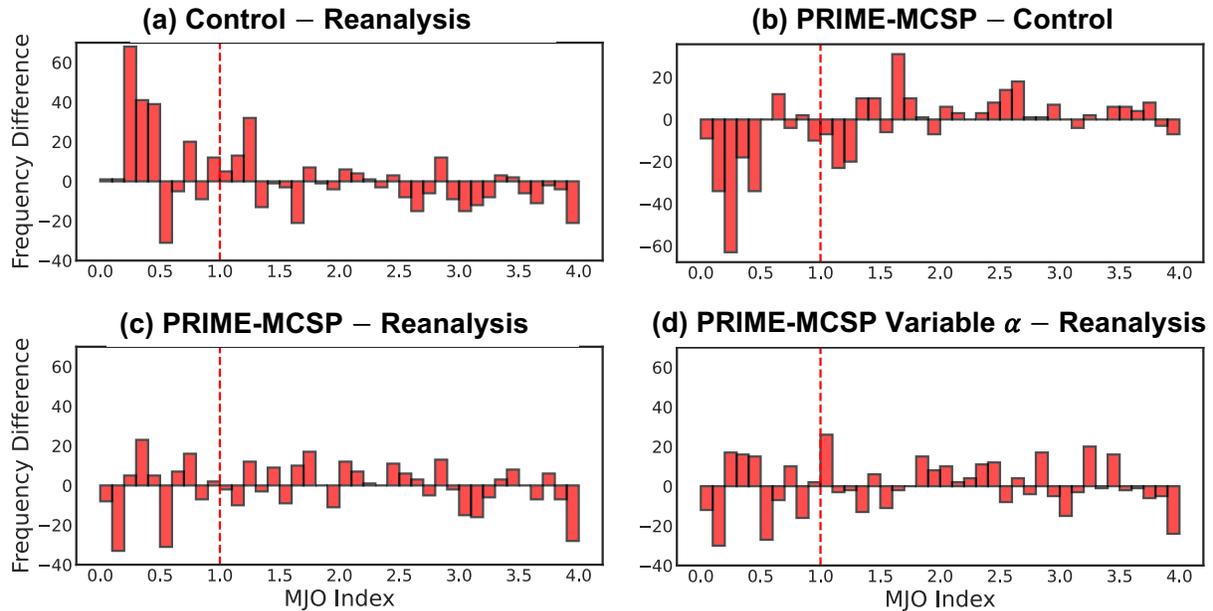
572 To quantify differences in wintertime MJO activity across the climate runs, histogram  
573 distributions of the MJO index are analyzed. A strong MJO event is defined as having an index  
574 greater than 1. According to this definition, the number of strong MJO events can vary between  
575 reanalysis and model runs. The control run exhibits too many weak MJO events (index less than  
576 one), as shown in Figure 15a. The PRIME-MCSP run reduces the occurrence of these weaker  
577 events (Figure 15b) while increasing the frequency of stronger events, indicating a mitigation of  
578 model biases in overestimating weak MJOs and underestimating strong MJOs. To assess the  
579 significance of Figure 15b, a Monte Carlo test was conducted, calculating the probability of  
580 changes in the 20-year total number of MJO occurrences between the control and the PRIME-  
581 MCSP run. This calculation was based on 100,000 resamplings using their respective annual  
582 counts of weak (index less than one) and strong (index greater than one) MJO occurrences. The  
583 significance test revealed that both the decrease in weak MJO occurrences and the increase in  
584 strong MJO occurrences are statistically significant, with p-values exceeding 94%. The  
585 comparison between the PRIME-MCSP run and reanalysis (Figure 15c) shows a closer  
586 alignment than that between the control run and reanalysis. The PRIME-MCSP variable  $\alpha$  run

587 similarly improves the MJO index histogram distribution, aligning closely with reanalysis data  
 588 (Figure 15d).



589

590 **Figure 14.** Wintertime (November–April) MJO lifecycle composites across different model  
 591 runs: (a) Reanalysis, (b) Control, (c) PRIME-MCSP, and (d) PRIME-MCSP Variable  $\alpha$ . The  
 592 color shading indicates the OLR anomalies. Wind vectors represent the 850 hPa wind field. The  
 593 subpanels, labeled P1 through P8, depict the sequential phases of the MJO lifecycle and the  
 594 number of days identified as that phase, used to create the composite. All simulations and  
 595 observations span September 1988 to August 2008.



596

597 **Figure 15.** Comparative histogram distributions of wintertime (November–April) MJO index  
 598 differences. (a) between the control run and reanalysis, (b) PRIME-MCSP run versus control run,  
 599 (c) PRIME-MCSP run against reanalysis, and (d) PRIME-MCSP variable  $\alpha$  against reanalysis.  
 600 The value in each bin represents the total number of MJOs that occur during the winter over the  
 601 20 years and fall within the index range.

## 602 6 Conclusions

603 This study implements the organized convection parameterization PRIME-MCSP in the  
 604 Unified Model in order to represent the stratiform heating associated with MCS. The scheme  
 605 incorporates several improvements over previous studies including:

606 1) Specialization of MCSP triggers: The PRIME-MCSP scheme features specialized  
 607 triggers for mixed-phase deep convection, incorporating ice condensate production into its  
 608 determination of whether the stratiform increment should be applied. This is achieved by only  
 609 triggering the scheme if the cloud top is above the freezing level. 2) Variable heating  
 610 partitioning: The study explores both a constant and a variable convective-to-stratiform heating  
 611 partitioning in the scheme, the latter being conditioned by cloud top temperature. 3) Leveraging  
 612 the mass-flux convection parameterization: The scheme's coupling with the Comorph-A scheme  
 613 is well suited to an MCS representation because CoMorph-A has a smooth numerical behavior in  
 614 time because of its allows convecting air parcels to ascend from any level, thereby promoting  
 615 continuity in the MCS evolution.

616 The scheme's evaluation is a comprehensive analysis of both its direct effects in weather  
 617 ensembles and its indirect effects in decadal simulations.

618 Direct effects: through an innovative use of MCS tracking, we showed that the scheme  
 619 acts to suppress MCS deepening and reduce MCS precipitation area. This is attributed to the  
 620 weakening of low-level mesoscale circulations associated with suppressed convective updrafts in  
 621 response to the stratiform lower-tropospheric cooling.

622 Indirect Effects: 20-year climate simulations assess the scheme's long-term impact,  
623 exhibiting a general agreement with global observed MCS frequencies, with regional variations  
624 over the tropical regions. Key results include 1) a reduction in precipitation bias across the  
625 Maritime time continent, effectively mitigating the dry bias over India and wet bias over the  
626 Indian Ocean; 2) The precipitation bias reduction is associated with a significant improvement in  
627 the representation of the precipitation seasonal cycle over the Indian and Indian Ocean,  
628 correcting a systematic bias observed across CMIP6 ensemble members; and 3) These  
629 precipitation improvements could be linked to the scheme's improvement on MJO spectra,  
630 aligning more closely with the reanalysis dataset by enhancing MJO intensity and continuing  
631 MJO eastward propagation during the post-Maritime Continent transit.

632 Despite these advances, the scheme's tendency to overestimate precipitation over the  
633 Western Pacific remains a challenge, echoing limitations in prior MCSP implementations (e.g.,  
634 Moncrieff et al. 2019). Over the Western Pacific, Liu & Moncrieff (2017) found that MCS  
635 ascending airflows are often parallel to the environmental wind shear, in contrast with MCSP's  
636 slantwise layer overturning assumption. This suggests that the MCSP slantwise layer overturning  
637 paradigm might not apply to all MCSs. Additionally, the exploration of variable convective and  
638 stratiform partitioning proved to be a successful bias mitigation strategy over the Western Pacific  
639 but inadvertently reduced the improved precipitation representation over India and the Indian  
640 Ocean, indicating a spatially correlated bias pattern. Notably, Khouider et al. (2023) suggested  
641 that stochastic parameterization could potentially improve the representation of convective  
642 organization by refining the predicted mass flux of convective updrafts. This presents intriguing  
643 possibilities for future investigations into the stochastic parameterization of MCSP triggering and  
644 convective-to-stratiform partitioning probabilities, conditioned by various environmental patterns  
645 (Muetzelfeldt et al, 2024), which might reduce the Western Pacific's wet bias while maintaining  
646 the desirable improvements to seasonal precipitation predictability over India and the Indian  
647 Ocean.

## 648 **Acknowledgments**

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657 UK Met Office for their invaluable support in providing the necessary setup to conduct the  
658 Unified Model runs.

## 659 **Open Research**

660 Monthly global precipitation data are provided by the Global Precipitation Climatology  
661 Project (GPCP) at the National Center for Atmospheric Research (NCAR), available at  
662 <https://climatedataguide.ucar.edu/climate-data/gpcp-monthly-global-precipitation-climatology->

663 [project](https://pcmdi.llnl.gov/CMIP6/). CMIP6 simulated precipitation datasets are accessible via <https://pcmdi.llnl.gov/CMIP6/>.  
 664 The observed global storm tracks dataset is available at <https://doi.org/10.5281/zenodo.4244985>.  
 665 MCS tracks are generated using the PyFLEXTRKR software, available at  
 666 <https://github.com/FlexTRKR/PyFLEXTRKR>. NCEP reanalysis data can be found at  
 667 <https://psl.noaa.gov/data/gridded/data.ncep.reanalysis.html>. Please contact the authors directly  
 668 for access to the PRIME-MCSP scheme and the model runs.

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