

Reply to reviewer

Dear Dr. Sugata Narsey,

We sincerely thank you for your constructive comments and insightful suggestions, which have significantly enhanced the quality of this manuscript. Below, we have provided a detailed, point-by-point response to each of your comments in **blue font**. We have diligently incorporated all the suggestions and comments in the revised manuscript.

Title: Multiscale Assessment of Indian monsoon rainfall using ICON and CMIP6 model simulations

By: Pokhrel et al

Reviewer: Sugata Narsey, Australian Bureau of Meteorology

Recommendation: Accept with minor revisions

In this manuscript the authors systematically evaluate Indian monsoon rainfall at multiple time scales in the ICON non-hydrostatic model and 5 CMIP6 models under a prescribed SST set-up. They explore whether a non-hydrostatic model, and/or higher spatial resolution, improves the simulation of Indian monsoon rainfall across scales. Their findings are mixed – while ICON shows some improvements over the CMIP6 models it also has some larger deficiencies at some time scales and in geographic locations. Likewise, higher resolution alone was not a panacea for Indian monsoon rainfall, with relatively coarse models such as IITM-ESM outperforming or matching other models in some areas. The manuscript is well-written and presented, the analysis is of a high quality, the work is novel, and the conclusions are well-supported by evidence. I recommend that the manuscript is accepted with minor revisions.

Main comments:

1. While the multiscale error assessment is useful, I would find this manuscript to be more useful overall if there were a summary figure or analysis specifically showing the cross-scale relationships of errors, e.g. a heatmap of metrics for each model. I would cite this paper for that specifically! The abstract asks how scale-dependent biases shape monsoon variability, but I feel that this was not addressed clearly in the paper (but could be with one more figure).

Reply: We thank the reviewer for this valuable suggestion. Our existing Fig. 13 of the manuscript although quantified rainfall variance biases at individual timescales, however, it was unable to connect these biases in terms of cross-scale bias relationship. To address this, we have added two new summary figures consisting of complementary diagnostics.

The first figure (Fig-R1) quantifies the percentage contribution of each timescale (diurnal, synoptic, HF-MISO, LF-MISO, and seasonal) to the total variance bias over Central India (CI) and the Bay of Bengal (BoB) respectively. While Fig. 13 presents the magnitude of

variance bias at each timescale separately, this new diagnostic (Fig-R1) identifies the dominant source of error within each model. For example, over CI, the largest error contribution arises from the diurnal scale in MPI, the synoptic scale in GFDL, and the HF-MISO band in CNRM, ICON, IITM-ESM, and MIROC. Over the BoB, diurnal-scale errors dominate in ICON and GFDL, synoptic-scale errors in MPI, HF-MISO errors in MIROC, and LF-MISO errors in IITM-ESM. Seasonal-scale errors in general contribute the least across nearly all models and regions. Thus, the figure provides a compact summary of the dominant timescales governing the overall variance bias in each model.

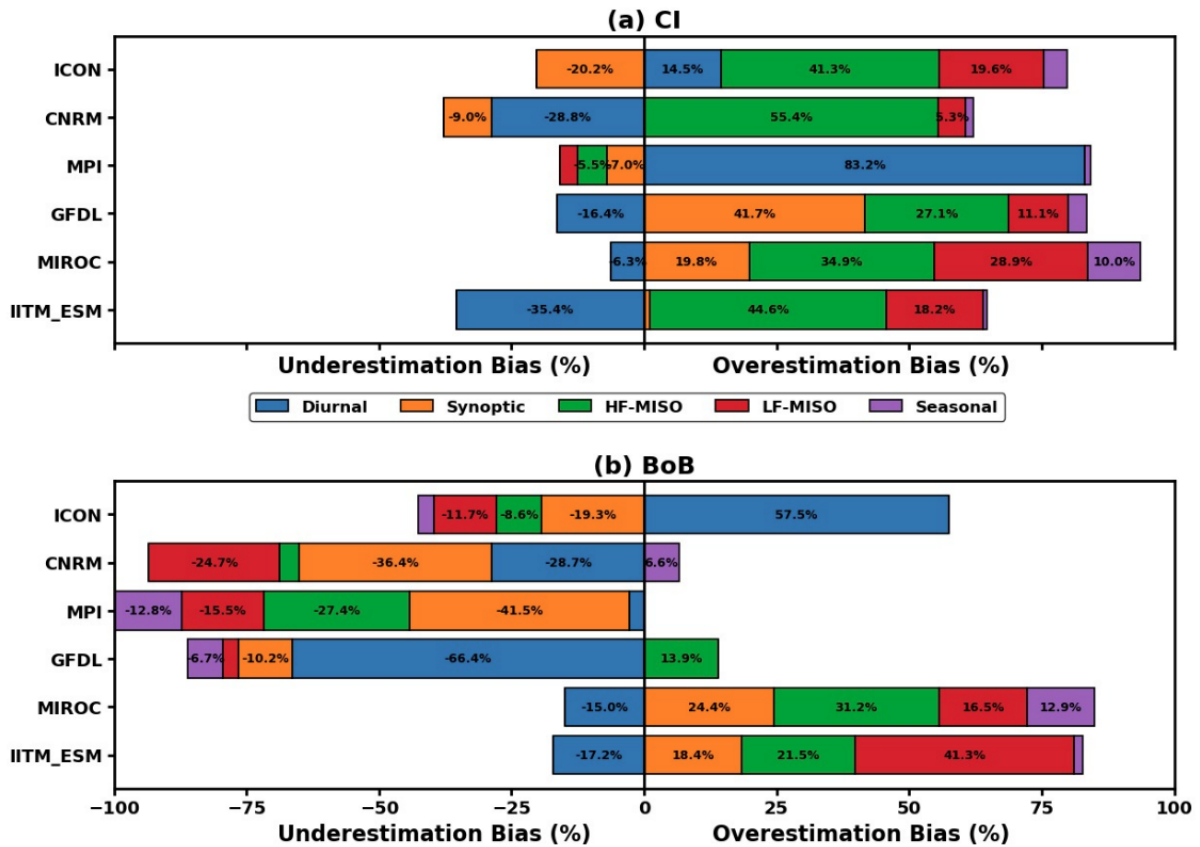


Figure R1: Percentage contribution of individual timescale variance biases relative to each model's total variance bias over (a) land (Central India) and (b) ocean (Bay of Bengal) domains.

The second figure (Fig-R2) presents a heatmap of spatial correlations between variance bias fields at different timescales. This heatmap explicitly examines whether bias patterns at one timescale are spatially related to those at another timescale. For physical interpretation, the heatmap is organized into three regimes: Convective Feedbacks, Synoptic Dynamics, and Intraseasonal Rectification.

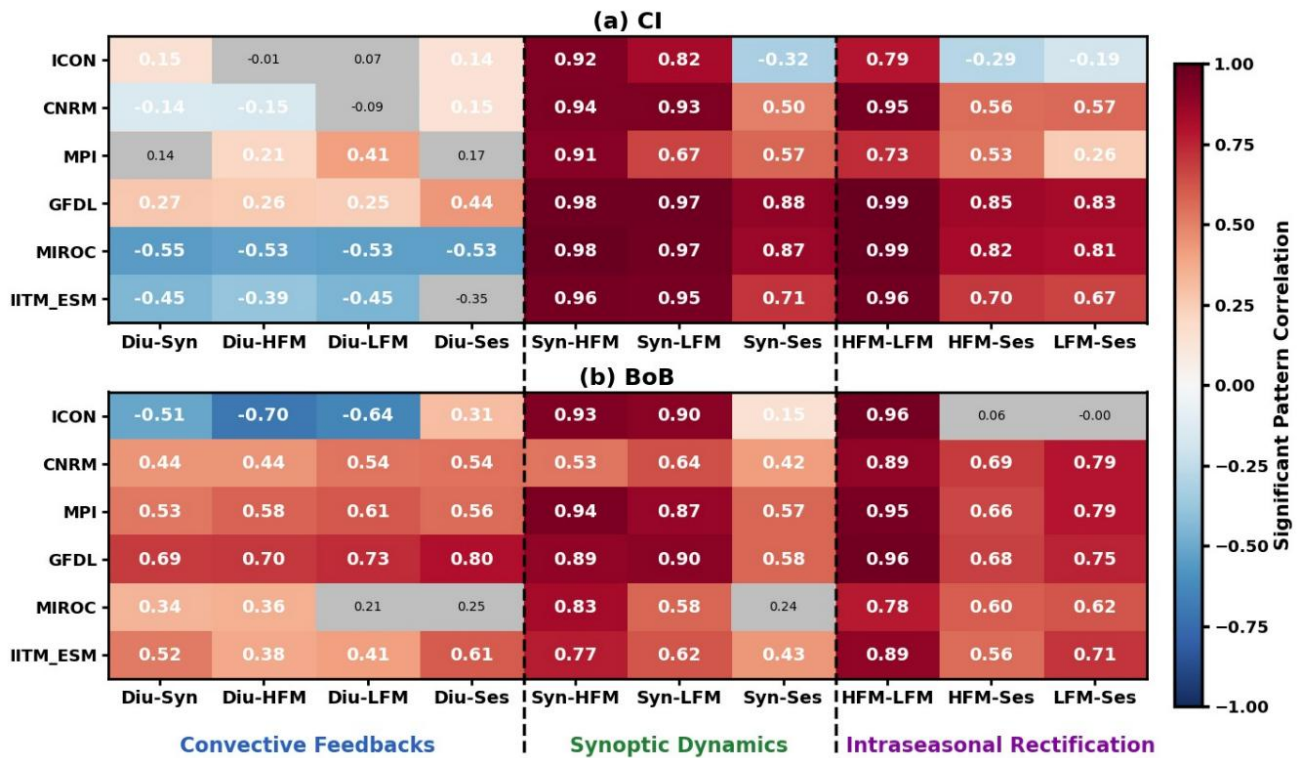


Figure R2. Heatmap of spatial pattern correlation coefficients among the relative bias fields of different scales. Correlations significant at the 95% confidence level are highlighted in bold white font, while non-significant cells are masked in gray (small black font). For clarity, the heatmap is divided into three scale-dependent regimes: convective, synoptic, and intraseasonal. The abbreviations Diu, Sys, HFM, LFM, and Ses represent the diurnal, synoptic, high-frequency MISO (10–20 days), low-frequency MISO (20–100 days), and seasonal scales, respectively.

In the **Convective Feedback regime**, the heat map connects sub-daily diurnal errors to macro-scales. Substantial inter-model differences emerge. Over the BoB, ICON exhibits negative correlations between diurnal and lower-frequency biases, indicating that regions with excessive diurnal variability tend to coincide with weaker synoptic and intraseasonal variability. This is consistent with the variance analysis in Fig. 13, where ICON shows a strong positive diurnal variance bias (~180%) but comparatively weaker biases at synoptic and intraseasonal scales. In contrast, both MIROC and IITM-ESM display the opposite tendency, with suppressed diurnal variability occurring alongside enhanced lower-frequency variance over BoB, reflecting their strong amplification of intraseasonal variability over the ocean. Over CI, ICON maintains a well-distributed error budget (+14.5% diurnal bias in Fig-R1) and shows statistically non-significant (greyed-out) correlations in Fig-R2, suggesting limited spatial correspondence between diurnal and lower-frequency error structures over land. These differences highlight the contrasting ways models partition rainfall variability between boundary-layer-driven diurnal convection and organized synoptic–intraseasonal disturbances.

The **Synoptic Dynamics regime** shows predominantly positive correlations across most models and regions. This indicates that locations with excessive (or deficient) synoptic variability generally exhibit similar intraseasonal and seasonal biases, suggesting coherent error structures across lower-frequency modes. A notable exception is ICON over CI, where correlations between synoptic, intraseasonal, and seasonal bias structures are weakly negative (e.g., Syn–Ses = -0.32). Likewise, over the BoB, ICON exhibits substantially weaker positive correlations than the CMIP6 models. These results suggest that lower-frequency errors in ICON are less spatially tied to seasonal rainfall errors than in the other models, contributing to its comparatively balanced multiscale bias structure

The **Intraseasonal Rectification regime** exhibits the strongest and most spatially coherent positive correlations. This suggests that intraseasonal variance biases and seasonal rainfall biases are often geographically co-located. Such behaviour is consistent with one of the central conclusions of this study: seasonal rainfall errors emerge as the cumulative imprint of variance redistribution across modes. Models such as IITM-ESM and MIROC, which exhibit amplified intraseasonal variability over the BoB, also show larger seasonal-scale deviations, whereas models with more balanced intraseasonal variability maintain better seasonal fidelity. A notable exception is ICON, particularly over CI, where weakly negative HFM–Ses and LFM–Ses correlations indicate a much weaker spatial correspondence between intraseasonal and seasonal bias structures than in the CMIP6 models.

Together, these diagnostics directly address the question raised in the abstract regarding how scale-dependent biases shape monsoon variability. Figure 13 quantifies the magnitude of variance redistribution at individual timescales, whereas the new figure identifies the dominant contributors to the total error budget and reveals whether errors at different timescales occur independently or as spatially coherent multiscale structures. The corresponding figure and discussion have been added to Section 3.3 of the revised manuscript.

2. A little more clarity on the model choices and methodological choices earlier in the manuscript would improve readability. Why ICON? Will it be used for some other purpose soon? Why these 5 CMIP models? Yes they vary across scales, but is this an ensemble of convenience (data availability) or is it a model subset choice? If the latter then justify it. Harmonic analysis is ubiquitous in math and physics, but less common in atmospheric science than perhaps it should be. Add a few references showing examples of how it has usefully been applied to gain insights.

Reply: We thank the reviewer for this helpful suggestion. As per the reviewer's suggestions, we have now incorporated the short discussion in the revised manuscript regarding the selection of ICON, the CMIP6 models, and the use of harmonic analysis.

ICON was selected for two primary reasons. First, most previous evaluations of Indian Summer Monsoon Rainfall (ISMR) have focused on hydrostatic climate models, while assessments using non-hydrostatic global models remain limited. ICON, therefore, provides an opportunity to examine whether next-generation non-hydrostatic dynamical cores offer improvements in simulating multiscale monsoon rainfall variability relative to conventional

CMIP6-class models. Second, ICON is increasingly being developed as a unified weather–climate modeling framework capable of kilometre-scale global simulations. Recent developments under projects such as EXCLAIM (Dipankar et al., 2026; Prein et al., 2026) highlight its growing role in future climate prediction systems, making a systematic baseline evaluation of its monsoon performance both timely and relevant.

The five CMIP6 models were chosen mainly based on the availability of 3-hourly AMIP simulations, which are necessary for resolving the diurnal cycle and are available for only a limited number of CMIP6 models through the ESGF archive. In addition, these models have been extensively evaluated in previous monsoon studies and collectively represent a broad range of horizontal resolutions (approximately 50–190 km), dynamical core formulations, and convection parameterization schemes (e.g., Chaudhari et al., 2019; Sperber et al., 2013; Rajendran et al., 2022). The selected set, therefore, provides a structurally diverse ensemble spanning major modeling centers across Europe, North America, Japan, and India, enabling a meaningful comparison of multiscale rainfall biases.

Regarding harmonic analysis, although it is more widely recognized in mathematics and physics, it has a long history of application in atmospheric science, particularly for diagnosing phase-locked variability such as the diurnal cycle of precipitation. Classical studies by Wallace (1975) and Dai et al. (1999) used harmonic decomposition to characterize large-scale diurnal rainfall patterns and the canonical land–ocean contrast. Over the Indian monsoon region, Sahany et al. (2010) and Johnson (2011) employed harmonic analysis to investigate diurnal rainfall propagation and coastal-orographic influences, while Utkarsh et al. (2026) recently applied the technique to examine the role of the low-level jet in modulating diurnal rainfall regimes over the Western Ghats. Tang et al. (2021, 2022) used harmonic decomposition to evaluate diurnal and semi-diurnal precipitation characteristics in CMIP6 models and demonstrated systematic timing biases in simulated rainfall. These studies illustrate the utility of harmonic analysis as a physically interpretable framework for quantifying rainfall amplitude and phase errors, which directly motivates its application in the present study.

References:

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- Prein, A. F., Pothapakula, P., Zeman, C., Lalonde, M., and Rixen, M.: From Single Storms to Global Waves: A Global 2.5 km ICON Simulation of Weather and Climate, *EGUsphere*, 2026, 1–34, <https://doi.org/10.5194/egusphere-2025-6414>, 2026.
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Role of cloud processes, *International Journal of Climatology*, 39, 901–920, <https://doi.org/https://doi.org/10.1002/joc.5851>, 2019.

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Dai, A., Giorgi, F., and Trenberth, K. E.: Observed and model-simulated diurnal cycles of precipitation over the contiguous United States, *Journal of Geophysical Research*, 104, 6377–6402, 1999.

Sahany, S., Venugopal, V., and Nanjundiah, R. S.: Diurnal-scale signatures of monsoon rainfall over the Indian region from TRMM satellite observations, *Journal of Geophysical Research: Atmospheres*, 115, <https://doi.org/https://doi.org/10.1029/2009JD012644>, 2010.

Johnson, R. H.: Diurnal Cycle of Monsoon Convection, pp. 257–276, https://doi.org/10.1142/9789814343411_0015, 2011.

Utkarsh, V., Pokhrel, S., Sahoo, P. K., Choudhury, B. A., Yashas, S., Chaudhari, H. S., ... & Saha, S. K. (2026). Low level jet controlled dynamical and thermodynamical regimes of the diurnal cycle of rainfall over the western ghats. *Environmental Research Communications*, 8(4), 045026.

Tang, S., Gleckler, P., Xie, S., Lee, J., Ahn, M.-S., Covey, C., and Zhang, C.: Evaluating the Diurnal and Semidiurnal Cycle of Precipitation in CMIP6 Models Using Satellite- and Ground-Based Observations, *Journal of Climate*, 34, 3189 – 3210, <https://doi.org/10.1175/JCLI-D-20-0639.1>, 2021.

Tang, S., Xie, S., Guo, Z., Hong, S.-Y., Khouider, B., Klocke, D., Köhler, M., Koo, M.-S., Krishna, P. M., Larson, V. E., Park, S., Vaillancourt, P. A., Wang, Y.-C., Yang, J., Daleu, C. L., Homeyer, C. R., Jones, T. R., Malap, N., Neggers, R., Prabhakaran, T., Ramirez, E., Schumacher, C., Tao, C., Bechtold, P., Ma, H.-Y., Neelin, J. D., and Zeng, X.: Long-term single-column model intercomparison of diurnal cycle of precipitation over midlatitude and tropical land, *Quarterly Journal of the Royal Meteorological Society*, 148, 641–669, <https://doi.org/https://doi.org/10.1002/qj.4222>, 2022.

3. Well done on a nice manuscript! I enjoyed reading it and learned some interesting things about Indian monsoon rainfall.

Reply: We sincerely thank the reviewer for their kind and encouraging comments. We are pleased that the manuscript was enjoyable to read and provided useful insights into Indian monsoon rainfall. We greatly appreciate this positive feedback and the constructive suggestions that helped to improve the manuscript.

Specific comments:

L27: what does block level mean?

Reply: Here, “block level” refers to a sub-district administrative unit or region in India, typically covering an area of a few hundred square kilometres. Previous studies (Mukhopadhyay et al. 2019; Deshpande et al., 2020) have also used this terminology. For clarity, we have now replaced “block level” with “sub-district level”.

Reference:

Mukhopadhyay, P., Prasad, V.S., Krishna, R.P.M. et al. Performance of a very high-resolution global forecast system model (GFS T1534) at 12.5 km over the Indian region during the 2016–2017 monsoon seasons. *J Earth Syst Sci* 128, 155 (2019). <https://doi.org/10.1007/s12040-019-1186-6>

M. Deshpande, C.J. Johny, R. Kanase, S. Tirkey, S. Sarkar, T. Goswami, K. Roy, M. Ganai, R.P.M. Krishna, V.S. Prasad, P. Mukhopadhyay, V.R. Durai, R.S. Nanjundiah, M. Rajeevan, Implementation of Global Ensemble Forecast System (GEFS) at 12 km Resolution, (2020), IITM Technical Report No.TR-06, ESSO/IITM/MM/TR/02(2020)/200

L31: N. 2005 is a strange way to reference.

Reply: The reference style “N. 2005” was a typographical error. This has been corrected in the revised manuscript and now appears as “(Goswami, 2005)”.

L45: There is some evidence that monsoon depressions are barotropic: Diaz, M., & Boos, W. R. (2021). The influence of surface heat fluxes on the growth of idealized monsoon. *Journal of the Atmospheric Sciences*. <https://doi.org/10.1175/JAS-D-20-0359.1>

Reply: We thank the reviewer for this important reference. We agree that attributing monsoon depression growth solely to moist baroclinic instability oversimplifies the current state of understanding. Diaz and Boos (2021) showed that barotropic mechanisms driven by horizontal wind shear within the monsoon trough play an important role in depression intensification, with surface heat fluxes providing additional energetic support. We have revised the text at L45 to acknowledge the potential roles of both baroclinic and barotropic processes and added the suggested reference.

L56: no need for etc

Reply: Now we have removed ‘etc’.

L75: This is a key point that I think could be made much earlier!! Forgot full stop.

Reply: The text in L75 basically introduces the vertical momentum equation and the contrasting treatment of vertical accelerations in hydrostatic and non-hydrostatic dynamical cores, which provides the specific physical motivation for including ICON in this study. Introducing this argument earlier, before the review of multiscale monsoon rainfall biases in existing models, would provide limited context for the reader. Its current placement,

immediately before the introduction of ICON, allows the need for a non-hydrostatic framework to emerge naturally from the preceding discussion of model limitations and therefore provides a more logical flow of ideas. Therefore, it is retained here.

We have added a full stop in the revised version of the manuscript.

L102: why these 5 models? And what is the motivation for ICON specifically?

Reply: The five CMIP6 models were selected based on availability of 3-hourly AMIP output as well as considering the broad range of horizontal resolutions (50-190 km), dynamical core formulations, and convection parameterization schemes across major modelling centres of the globe.

ICON was selected primarily because non-hydrostatic global models have received limited attention in Indian monsoon studies. ICON provides an opportunity to examine whether non-hydrostatic dynamical cores offer improvements in simulating multiscale monsoon variability, and its ongoing development toward kilometre-scale global simulation under the EXCLAIM project (Dipankar et al., 2026; Prein et al., 2026) makes a systematic baseline evaluation both timely and necessary.

We have also explained it in details in the 2nd major comment.

L170: can you provide some justification for using harmonic analysis? Some citations or examples of previous use. Pros and cons of this vs other potential methods.

Reply: As also discussed in our response to the Major comment-2 regarding harmonic analysis, here we provide additional justification for its use, together with representative applications from the atmospheric science literature.

Harmonic analysis was selected because it directly decomposes the diurnal rainfall cycle into physically interpretable amplitude and phase components, allowing straightforward quantification of timing and intensity biases across models and observations. This approach has been widely applied in studies of tropical and monsoon precipitation (e.g., Dai et al., 2001; Yang and Slingo, 2001; Nesbitt and Zipser, 2003; Sahany et al., 2010; Tang et al., 2021, 2022; Utkarsh et al., 2026).

Compared with alternative approaches such as EOF analysis, wavelet analysis, or empirical mode decomposition (EMD), harmonic analysis offers a simple and computationally efficient framework for diagnosing climatological diurnal variability. Its principal advantage is the direct estimation of the amplitude and phase of the dominant 24-hour cycle, which are the primary quantities of interest in the present study. We also acknowledge its limitations, including the assumption of stationarity and the inability to fully represent non-sinusoidal or transient variability. However, these limitations do not affect the objectives of the present work, which focuses on the climatological characteristics of the dominant diurnal harmonic and its representation across models.

The corresponding discussion and references have been added to the revised manuscript.

Reference:

Dai, A., 2001: Global Precipitation and Thunderstorm Frequencies. Part II: Diurnal Variations. *J. Climate*, 14, 1112–1128, [https://doi.org/10.1175/1520-0442\(2001\)014<1112:GPATFP>2.0.CO;2](https://doi.org/10.1175/1520-0442(2001)014<1112:GPATFP>2.0.CO;2).

Yang, G., and J. Slingo, 2001: The Diurnal Cycle in the Tropics. *Mon. Wea. Rev.*, 129, 784–801, [https://doi.org/10.1175/1520-0493\(2001\)129<0784:TDCITT>2.0.CO;2](https://doi.org/10.1175/1520-0493(2001)129<0784:TDCITT>2.0.CO;2).

Nesbitt, S. W., and E. J. Zipser, 2003: The Diurnal Cycle of Rainfall and Convective Intensity according to Three Years of TRMM Measurements. *J. Climate*, 16, 1456–1475, [https://doi.org/10.1175/1520-0442\(2003\)016<1456:TDCORA>2.0.CO;2](https://doi.org/10.1175/1520-0442(2003)016<1456:TDCORA>2.0.CO;2).

Zhou, T., R. Yu, H. Chen, A. Dai, and Y. Pan, 2008: Summer Precipitation Frequency, Intensity, and Diurnal Cycle over China: A Comparison of Satellite Data with Rain Gauge Observations. *J. Climate*, 21, 3997–4010, <https://doi.org/10.1175/2008JCLI2028.1>.

L173: throughout the manuscript, please use the acronyms from Table 1.

Reply: We thank the reviewer for pointing this out. We have revised the manuscript to ensure that the acronyms listed in Table 1 are used consistently throughout the text.

Fig 2: I wonder how these biases would look as a percentage... I suspect ICON would look better!

Reply: We thank the reviewer for this useful suggestion. Following the reviewer's recommendation, we calculated the mean rainfall biases as percentages relative to the observed climatology. The results indicate that the interpretation depends on the region considered. Over Central India (CI), ICON indeed exhibits the smallest positive percentage bias (~10%), whereas MPI shows the largest positive bias (~168%). However, over the Bay of Bengal (BoB), ICON exhibits the largest positive percentage bias (~66%), while several other models show smaller negative biases. Thus, expressing the biases as percentages does not consistently improve the relative ranking of ICON across all regions.

We have added the percentage bias values to Table 2 of the revised manuscript.

<u>Model</u>	<u>CI</u>	<u>BoB</u>
ICON	0.36 (10.10%)	3.91 (66.36%)
CNRM	-2.00 (-55.49%)	-1.32 (-22.48%)
MPI	6.16 (167.83%)	0.66 (10.90%)
GFDL	-1.52 (-42.76%)	-1.63 (-27.84%)
MIROC	-0.71 (-20.07%)	-1.54 (-25.12%)
IITM	-2.03 (-59.76%)	-2.54 (-42.89%)

L384: full stop.

Reply: Thanks for noticing this typo. We have added a full stop in the revised version of the manuscript.

L577: i can see how this is suggested by results, but its not clearly shown. here, and throughout the manuscript, the link between two or more evaluation metrics could be displayed through a figure (scatter plots for example).

Reply: We thank the reviewer for this suggestion. We agree that the original statement was primarily inferred from the collective results and was not explicitly demonstrated. This concern will be addressed by the already provided two new diagnostics (Fig-R1 and Fig-R2) as discussed in the main comments-1.

Fig-R1 quantifies the contribution of each temporal scale to the total variance bias, thereby identifying the dominant source of error in each model. Fig-R2 explicitly examines the spatial relationship between variance bias structures across timescales through a pattern correlation heatmap organized into Convective Feedback, Synoptic Dynamics, and Intraseasonal Rectification regimes.

Together, these diagnostics show that seasonal monsoon performance is not determined solely by the magnitude of errors at any individual timescale. While ICON exhibits higher standalone RMSE at some synoptic and intraseasonal scales (as shown in Supplementary Fig. S2 of the manuscript), its error does not propagate upscale. It maintains a comparatively balanced variance distribution across land and ocean regions (Fig-R1) and substantially weaker cross-scale error coherence than the CMIP6 models (Fig-R2). For example, over Central India, ICON shows weak or negative spatial correlations between its seasonal bias and higher-frequency structures (Syn–Ses = -0.32; HFM–Ses = -0.29; LFM–Ses = -0.19). Over the Bay of Bengal, these cross-scale correlations are even weaker (0.15, 0.06, and 0.00, respectively). In sharp contrast, CMIP6 models like IITM-ESM and MIROC exhibit strong, coherent positive correlations over CI (typically >0.67, with similarly high values over BoB). This proves that high-frequency errors in those models are structurally locked to and amplify the larger seasonal-scale biases. ICON successfully isolates its high-frequency errors within their respective bands, preventing an upscale cascade.

Now to address the reviewers concern we have integrated this cross-metric discussion into to the revised manuscript and the revised sentence at L577 is as following

“Models that maintain a balanced multiscale variance structure and weaker cross-scale error coupling tend to exhibit improved seasonal migration and annual-cycle fidelity. In contrast, models with strongly coupled synoptic and intraseasonal bias structures often show larger seasonal-scale deviations.

L640: what specifically do you mean by higher-frequency variance? these two statements seem circular, since higher amplitude surely means higher variance.

Reply: Thank you for this important observation. Our intention was not to relate diurnal amplitude to diurnal variance, but rather to discuss how biases at the phase-locked endpoints of the spectrum (diurnal and seasonal) are associated with the distribution of variance across

the intermediate synoptic and intraseasonal timescales. To avoid ambiguity, we have revised the text accordingly.

The revised sentence now reads:

"Taken together, the amplitude diagnostics confirm that errors at the phase-locked endpoints influence how variance is redistributed across intermediate timescales. Models with exaggerated diurnal amplitude often exhibit distorted synoptic and intraseasonal variance distributions, whereas amplified seasonal amplitude is generally associated with enhanced lower-frequency variability. Accurate simulation of these temporal endpoints is therefore important for maintaining physically consistent multiscale monsoon rainfall behaviour."

L645: this seems important. i would clarify this earlier, perhaps even in the methodology.

Reply: We thank the reviewer for this valuable observation. Following the reviewer's suggestion, we have now incorporated a brief discussion of the relationship between amplitude and variance in the Methodology section.

L671: is this shown somewhere? I guess this indicates a larger-scale e.g. circulation (or finer scale e.g. microphysics) control on precipitation?

Reply: We acknowledge that this statement was an assertion not directly demonstrated within the present manuscript. It is, however, well supported by existing literature: Hertwig et al. (2015) showed that increasing horizontal resolution primarily redistributes rainfall between convective and large-scale components without improving precipitation timing or intensity, as the convective parameterisation remains the dominant control at resolutions where deep convection is unresolved. Such resolution-insensitive biases can reflect both larger-scale thermodynamic controls, such as premature convective triggering driven by insufficient CAPE buildup in mass-flux schemes (Bechtold et al., 2004; Rio et al., 2009), and finer-scale microphysical deficiencies in cloud and precipitation processes (Stevens et al., 2013). Isolating the relative contributions of these two pathways would require targeted parameterisation sensitivity experiments beyond the scope of the present study.

Reference:

Bechtold, P., Chaboureaud, J.-P., Beljaars, A., Betts, A. K., Köhler, M., Miller, M., and Redelsperger, J.-L.: The simulation of the diurnal cycle of convective precipitation over land in a global model, *Quarterly Journal of the Royal Meteorological Society*, 130, 3119–3137, <https://doi.org/https://doi.org/10.1256/qj.03.103>, 2004.

Hertwig, E., von Storch, J.-S., Handorf, D., et al.: Effect of horizontal resolution on ECHAM6-AMIP performance, *Climate Dynamics*, 45, 185–211, <https://doi.org/10.1007/s00382-014-2396-x>, 2015.

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Stevens, B., Giorgetta, M., Esch, M., Mauritsen, T., Crueger, T., Rast, S., Salzmann, M., Schmidt, H., Bader, J., Block, K., Brokopf, R., Fast, I., Kinne, S., Kornbluh, L., Lohmann, U., Pincus, R., Reichler, T., and Roeckner, E.: Atmospheric component of the MPI-M Earth System Model: ECHAM6, *Journal of Advances in Modeling Earth Systems*, 5, 146–172, <https://doi.org/https://doi.org/10.1002/jame.20015>, 2013.

L677-681: this sentence is too long.

Reply: Following the reviewer's suggestion, the original sentence has been divided into shorter, logically distinct sentences to improve readability and clarity. The revised text now reads:

"The similar early land convection in GFDL is consistent with its strict quasi-equilibrium closure, which neglects non-equilibrium shallow convection. In addition, its nocturnal rainfall deficit points to missing cold-pool dynamics and mesoscale lifting processes that are important for sustaining nighttime convection (Zhang et al., 2024). Over the ocean, further biases may originate from deficiencies in boundary-layer and cloud microphysical processes, affecting the radiative balance and marine convection (Donner et al., 2011)."

L694: though here you have prescribed SST so not really well-investigated?

Reply: Yes, reviewer has rightly pointed out that, in the AMIP framework with prescribed monthly SSTs, two-way air–sea feedbacks are suppressed. Therefore, our results do not directly investigate the role of air–sea coupling in shaping diurnal biases. The original phrasing has been revised to avoid the confusion:

"Together, these results demonstrate that diurnal rainfall biases are not determined by parameterization framework alone, but also by its interaction with land–atmosphere processes. The potential role of air–sea coupling in modulating diurnal biases, particularly over oceanic regions such as the Bay of Bengal, cannot be fully assessed within the AMIP framework and warrants investigation using coupled simulations."

L718: credible for what purpose? No parameterised convection scheme will represent squall lines but may still be useful for other applications.

Reply: We thank the reviewer for this important clarification. We agree that the term "credible" was too broad in this context, as model suitability depends on the specific application being considered. Our intention was to emphasize that seasonal-mean rainfall alone does not fully characterize model performance across weather-to-climate timescales.

To clarify this point, we have revised the statement to emphasize the representation of monsoon variability rather than the general credibility of a model. The revised text now reads:

"This study demonstrates that accurate representation of monsoon variability across weather-to-seasonal timescales depends not only on seasonal-mean rainfall accuracy but also on maintaining physically consistent cross-scale organization."