Prof. Axel Lauer, Handling topic editor

Geoscientific Model Development

May 26, 2026

Re: Decision on Manuscript ID egusphere-2025-5847 | Model evaluation paper

Dear Prof. Axel Lauer,

We sincerely appreciate the opportunity to revise our manuscript, *“Spectral Nudging Impacts on Precipitation Downscaling in the Conformal Cubic Atmospheric Model, version CCAM-2504: Insights from Summer 2011”* (egusphere-2025-5847). We thank you, the reviewers, and the community commenter for the constructive feedback, which has helped us substantially improve the manuscript.

We have submitted a revised manuscript with tracked changes, together with a detailed point-by-point response. The major revisions include:

1. Clarifying the novelty and positioning of the study by better distinguishing spectral nudging in CCAM’s variable-resolution global stretched-grid framework from previous limited-area RCM studies.
2. Strengthening the physical interpretation of the results, including added discussion of low-level circulation, moisture convergence, MJO-related precipitation peaks, moisture nudging limitations, ERA5 moisture uncertainty, and the role of model physics.
3. Expanding and clarifying the methods, including the experiment design, sub-region selection, nudging wavelengths, vertical nudging levels, control simulation, and the rationale for using ERA5.
4. Improving the evaluation and presentation by adding supplementary heatmaps and spatial evaluation maps, reducing redundant figure panels, revising figure captions, adding domain-average annotations, and improving figure readability.
5. Expanding the discussion of limitations, particularly clarifying that spectral nudging improves large-scale circulation and moisture transport but is not a complete solution for precipitation biases, which also depend on model physical parameterizations, resolution, and observational/reanalysis uncertainty.

We believe these revisions have strengthened the manuscript and addressed the reviewers’ concerns. We hope the revised version is now suitable for further consideration in Geoscientific Model Development.

Sincerely,

Son Cong Hoang Truong

Community comment

Review of '*Spectral Nudging Impacts on Precipitation Downscaling in the Conformal Cubic Atmospheric Model, version CCAM-2504: Insights from Summer 2011*'

General comments

Study provides a very comprehensive analysis of how different aspects of nudging impact the representation of precipitation in CCAM in the context of downscaling ERA5. Overall, I found the analysis to be thorough, and the experiment design is systematic and well planned out in advance. The paper is well written and easy to follow, and the research aligns directly with the scope of the journal. The research makes an important contribution to the literature and will no doubt provide important technical guidance for users of the model in future downscaling work.

My comments below are relatively minor (mostly seeking clarification on methods/results), and I strongly support this important work being published.

Specific comments

-In the introduction section, when talking about nudging wavelength results (e.g. line 45-50), it would help to add detail around what model was being used in these studies. And note in the introduction what other regional models (e.g. WRF) have implemented spectral nudging approaches alongside CCAM.

> Thank you for pointing out the potential value of including some information along these lines. A relevant sentence has been added at lines 54-80.

-For the studies debating moisture nudging versus not (Line 51 onwards), were these in the context of downscaling reanalysis, or GCMs? Perhaps add some detail there, as that seems relevant to how well it performs?

> We appreciate this point. We have updated the introduction to clarify that the studies on moisture nudging were conducted in the context of downscaling reanalysis, rather than GCMs. Additionally, we have added a line to mention the potential biases in ERA5 moisture fields, which could influence the performance of moisture nudging in precipitation simulations. A relevant sentence has been added through the introduction and at lines 54-56.

-Table 1 is very helpful and well planned. However, I wasn't quite sure of the 'level' description in the caption and text earlier. Does level = 0.85 mean nudging from 850 hPa and higher? If that is the case, wouldn't it be simpler to just say "lowest nudging level" and then include pressure level/units? Apologies if I have misunderstood.

> The reviewer is correct. We have revised Table 1 and the caption to clarify the description of the 'level'. We have now specified that level = 0.85 refers to nudging from 850 hPa. To simplify, we have also updated the description to "lowest nudging level" and included the corresponding pressure level/units.

-Section 2.4. For the 'ctrl,' what does ‘no nudging’ mean exactly? Clarify what ‘no nudging’ entails for the control simulation, e.g., whether it is a raw ERA5 field or an SST-forced CCAM run, and reiterate this when interpreting results.”

> We apologize for the ambiguity. We have updated Section 2.4 to provide a clearer explanation of what ‘no nudging’ entails for the control simulation at lines 178-180. This clarification has been included in the revised section, and we have reiterated it when interpreting the results.

-Figure 2 caption, instead of ‘bias between simulations’ would be more clear to say ‘bias relative to IMERG for each of the 16 simulations’. Caption should also specify what the different header colors mean.

> Thanks for suggesting this clarification. We have revised the Figure 2 caption to clarify that it represents ‘bias relative to IMERG for each of the 16 simulations’, as this more accurately describes the content of the figure. Additionally, we have specified what the different header colors represent in the revised caption.

-Figure 5, when referring to specific events (i.e. TCs) it would help to mark these out on the figure for readability.

> Figure 5 has been revised to mark out these events.

-When interpreting Figure 5, I wonder if at times the peak of the precipitation in individual simulations for individual events may be missed more due to intrinsic internal variability (as we often see with deterministic weather forecasts vs ensemble forecasts for extremes). Sometimes this clearly isn’t the case (i.e. if all simulations show clear underestimation), but other times the results might be more mixed. Suggest just adding a sentence or two when interpreting results related to individual events here.

> We very much appreciate the spirit of this comment, and we have added discussions on it at lines 318-320.

-In Figure 8, the R3 specific humidity results are most notable, where for all experiments the correlation at around 900 to 850-hPa drops to between 0.15-0.4. Worth commenting on this a bit more in the context of physical processes, and possibly even adding the maps of this (i.e. selecting a certain specific humidity level) to supplementary material, for this specific case/domain. And, when interpreting what this means, how much trust do we put in ERA5 (e.g. how constrained to obs is it for this region/level/variable).

> Thank you for your thoughtful comment. In response, we have added a more detailed explanation in the manuscript regarding the R3 specific humidity results at 900hPa. A relevant discussion has been added at lines 408-411.

-Lines 365 onwards, good to see that the limitations of IMERG are acknowledged. I think this can matter quite a bit, when interpreting small differences between the simulations relative to the likely uncertainty in IMERG. To this end, it would be helpful to expand on this in the discussion a bit more. Comparisons between IMERG and AGCD are helpful to estimate this uncertainty, and it would be useful to use these numbers a bit more directly in the text when interpreting apparent model biases vs observational uncertainty.

Thank you for your helpful suggestion.

A relevant discussion has been added at lines 247-251 and Figure 2.

Minor

-L33 – "A central challenge for RCMs is ensuring that RCMs efficiently assimilate ...."

Revised accordingly.

-Figure 6, include y-axis details/units in caption.

Agreed. The y-axis and detail units have been added to Figure 6.

-Figure 8, these vertical profiles of correlation coefficients are a very nice way to present the evaluation, and the results very insightful. Caption should say "against ERA5".

Thank you.

Reviewer 1's comment

General Comments (Recommendation: Reject)

This manuscript investigates the sensitivity of precipitation simulations to different spectral nudging configurations using the CCAM model for summer 2011. While the topic is relevant to regional climate modeling, the study offers limited novelty and insufficient scientific advancement beyond what has already been extensively documented in the literature.

The primary conclusions that optimal nudging involves intermediate wavelengths (~500-1500 km), inclusion of wind and temperature, and higher-frequency updates are well established in previous studies, many of which are cited by the authors. The manuscript does not offer new physical understanding, methodological innovation, or conceptual development. Instead, it simply reproduces expected results using a different model configuration, which does not constitute a sufficient contribution for publication.

Although the study is reasonably structured, it does not adequately engage with or build upon recent developments in the field. Notably, there is a lack of discussion of more recent literature, and few (if any) references on spectral nudging from the past 6 years are included. This weakens the positioning of the work within the current state of research.

Moreover, the experimental design is overly simplistic and incremental, essentially consisting of turning nudging parameters on and off (e.g., variables, wavelength, frequency) without a clear scientific hypothesis or attempt to address unresolved questions in the field. This type of sensitivity testing has been performed extensively over the past decade, and the outcomes reported here are entirely predictable. As such, the study lacks both originality and intellectual depth.

In its current form, the manuscript does not meet the level of originality and impact required for publication.

Major Comments

1. Lack of Novelty and Originality

The main findings, such as the benefits of nudging wind and temperature, the optimal wavelength (~500-1500 km), and the use of high-frequency (1-hour) nudging, have been extensively documented in prior studies (e.g., Omrani et al. 2015; Alexandru et al. 2009; Gómez and Miguez-Macho 2017; Tang et al. 2017).

The manuscript does not introduce new theory, methodology, diagnostics, or coupling strategies, but instead presents a largely incremental parameter sensitivity analysis with expected outcomes. The experimental design, testing combinations of variables (p, u, v, t, q), wavelengths (500-3000 km), and nudging frequencies (1h vs 3h), follows well-established frameworks and does not reflect a new scientific hypothesis or conceptual advance.

Previous studies have already explored a wide range of spectral nudging configurations, with general consensus on key aspects, including:

- The need for weaker nudging coefficients for moisture compared to dynamical variables (Spero et al., 2014, 2018; Hu et al., 2018);
- Applying temperature nudging above the boundary layer and below the tropopause, and moisture nudging below the tropopause (Gómez and Miguez-Macho, 2017; Spero et al., 2014, 2018; Huang et al., 2021);
- Avoiding nudging within the boundary layer to preserve surface and turbulence processes.
- Combination of wind and moisture nudging can outperform wind-temperature nudging in simulating cloud fraction and precipitation (Lai and Gan, 2025).

Given this context, the manuscript requires a much clearer articulation of its novel contribution and how it advances beyond existing knowledge. In its current form, the study largely reaffirms established findings.

> We respect this comment. We acknowledge that many aspects of spectral nudging, including wind and temperature nudging, optimal wavelengths (~500–1500 km), and high-frequency nudging (1 h), have been explored in previous studies (e.g., Alexandru et al., 2009; Omrani et al., 2015; Gómez and Miguez-Macho, 2017; Tang et al., 2017). However, most of these studies focused on limited-area RCMs such as WRF, whereas spectral nudging in variable-resolution global models remains comparatively underexplored. Our study extends the work of Thatcher and McGregor (2008) by systematically evaluating spectral nudging configurations in the stretched-grid global model such as the Conformal Cubic Atmospheric Model (CCAM) during the extreme 2010–11 La Niña event, providing insights into how nudging affects precipitation downscaling, moisture transport, and large-scale circulation in a variable-resolution global modelling framework.
>
> Furthermore, the novelty of spectral nudging in CCAM lies in its unique grid configuration and the use of convolution-based filters, as introduced by Thatcher and McGregor (2008). Using a variable resolution grid allows us to apply wavelengths larger than the high-resolution region, which enables more efficient use of computational resources while maintaining accurate large-scale circulation. We also employ a convolution approach which has been optimised for the cubic grid, reducing computational complexity from $O(N^4)$ to $O(N^3)$. These aspects of spectral nudging in CCAM make it an innovative contribution to the field and offer insights into how global models can better simulate regional climate features.
>
> We have clarified the novel contributions of our study in the introduction, model configuration and discussion sections, explicitly highlighting how our work builds upon existing knowledge while addressing the specific challenges and configurations unique to CCAM.

2. Limited Scope (Single Case Study)

The analysis is based on a single extreme event (2010-2011 La Niña), which the authors acknowledge as a limitation. Consequently, the conclusions regarding "optimal" nudging configurations are not robust or generalizable.

To strengthen the findings, I suggest multi-year simulations and the inclusion of multiple climate regimes (e.g., El Niño, neutral years) to ensure statistical robustness and broader applicability.

> We very much appreciate the spirit of this comment. We agree that multi-year simulations and the inclusion of multiple climate regimes (e.g., El Niño, neutral years) would provide a more robust and generalizable understanding of the impact of spectral nudging on precipitation downscaling. However, due to computational limitations, conducting such extensive simulations, particularly at a 12 km resolution over the Australasia domain, would be highly resource intensive.
>
> In our study, we focused on the 2010-2011 La Niña event as a case study, which provided an extreme and significant climatic scenario for evaluating the performance of CCAM. While the findings are limited to this specific extreme case study, we recognize the need for future research to expand the time frame of simulations and assess variability across different climate conditions. This expansion will be considered in future work, as computational resources allow.
>
> A relevant sentence has been modified at lines 528-531.

3. Insufficient Mechanistic Insight

Although the results show that spectral nudging improves precipitation simulation, the manuscript lacks in-depth physical interpretation. The analysis remains largely descriptive, without sufficiently explaining why certain configurations perform better.

In particular, the analysis of vertically integrated MFC instead of single pressure level or a discussion on the relative contributions of thermodynamic vs. dynamic processes in precipitation.

Although several process-level variables are examined, the physical understanding behind the results from different nudging experiments remains limited. More detailed process-level analysis is needed. Please analyze in more depth the reasons for the overestimation or underestimation of precipitation, particularly focusing on the physical processes involved. This analysis is crucial to understanding the limitations and sensitivities of the nudging approach.

> Thank you for your thoughtful comment. Our findings indicate that pressure and wind nudging significantly enhance moisture convergence by improving the representation of low- and high-pressure systems, particularly over regions like the Gulf of Carpentaria and New Guinea. By constraining the large-scale circulation, pressure nudging helps to more accurately position and intensify the low-pressure system over northwest Australia, thereby improving the alignment of moisture flux divergence with observed precipitation patterns, especially at shorter wavelengths (e.g., PUVT_0500_1h_L0.85

and PUVT_1500_1h_L0.85). Wind nudging in the PUV simulations also improves monsoonal wind flow, MJO phases, which contributes to better moisture convergence, MJO-related precipitation peak, and tropical cyclones in these regions. On the other hand, the Ctrl simulation, where no nudging is applied, fails to capture the low-level circulation, leading to misrepresented moisture convergence and underestimated precipitation, particularly in the Gulf of Carpentaria. This highlights the critical role of wind and pressure nudging in capturing the dynamics of monsoonal winds and large-scale atmospheric processes. We found moisture nudging introduced additional convergence regions emerge, particularly over northern Australia, leading to overestimated rainfall. This underperformance may be partly due to biases in ERA5 moisture fields, especially in regions with sparse observations, which introduce uncertainties and limit the effectiveness of nudging in improving precipitation simulations.

We have also added a discussion in the revised manuscript to explicitly acknowledge that the results obtained in this study are conditional on the selected model physics, which were kept unchanged across all simulations. However, the model's physical parameterizations (e.g., cloud microphysics and convection schemes) remain imperfect, as many are based on empirical formulations. Therefore, further improvements in precipitation and extreme event simulations will likely require continued refinement of these parameterizations, particularly for convection and cloud microphysics, especially in higher-resolution simulations (e.g., 4 km).

We have revised Section 3.1.3, "Low-level circulation and vertical correlation", to better illustrate the potential dynamical and physical mechanisms influencing the simulation results. We also revised Section 4, "Discussion and Conclusion", to explicitly acknowledge the need for further refinement of physical parameterizations to improve precipitation simulations, and to clarify that spectral nudging can improve large-scale circulation and moisture transport but is not itself a complete solution for improving precipitation simulation.

4. Evaluation Metrics

The evaluation relies primarily on standard metrics (MAPE, correlation, RMSE), which provide limited insight into model performance for extremes. It is recommended to include additional metrics commonly used in precipitation verification, such as: Threat Score (TS), Probability of Detection (POD), False Alarm Rate (FAR) for each grid point.

Furthermore, the validation relies heavily on satellite-based products, despite acknowledged uncertainties (particularly in R1 and R3). The study lacks validation against in situ observations (e.g., rain gauges or station data), which is critical for assessing precipitation biases, especially in regions with high observational uncertainty.

Lastly, while the manuscript evaluates region-averaged outcomes, it does not examine finer-scale variability. Incorporating comparisons with weather station data would help assess the model's ability to capture local-scale features and improve the robustness of conclusions.

Thank you for your valuable feedback. We acknowledge that metrics such as TS, POD, and FAR are widely used for grid-point precipitation verification. However, our study focuses on the impact of spectral nudging on large-scale circulation and regional precipitation patterns during the 2010–11 La Niña event, rather than point-scale precipitation skill. Since spectral nudging primarily constrains large-scale dynamics while allowing smaller-scale processes to evolve freely, grid-point metrics, whether indicating better or worse agreement with observations, may not fully reflect the large-scale impact of spectral nudging examined in this study.

To evaluate model performance, particularly for extremes, we included Taylor diagrams to assess spatial skill and quantile-quantile plots to evaluate extreme precipitation distributions, together with correlation, bias maps, and time-series analysis. We believe these metrics provide a more suitable assessment of spectral nudging performance in the context of large-scale simulations.

We appreciate the concern regarding weather station data and acknowledge that in situ observations (e.g., rain gauges and station data) would provide a valuable reference for assessing precipitation biases. However, several challenges limit their use in this study, not least that they are irregularly spaced and very limited in e.g. central and Western Australia and the Maritime Continent and are often not continuously available for the full study period. Therefore, satellite- and reanalysis-based products such as IMERG and ERA5 were considered more suitable for this large-scale regional analysis. However, for this reason we already included a comparison with the in situ-based gridded product AGCD to test some of these potential biases.

To further address your comment, we have added an additional correction map and RMSE between IMERG and AGCD for daily precipitation at each grid point across the Australian continent (Figure S3) and Heatmap of evaluation metrics for 16 CCAM Simulations compared to IMERG daily precipitation in six subregions (R1–R6), averaged over December 2010 to March 2011 (Figure S4) in the appendix.

Here are some additional and specific comments:

L50 As noted by the authors, moisture nudging is a debated technique. It would be valuable to explore in more depth the effects of moisture nudging, particularly in relation to precipitation simulations.

We appreciate this comment. We have added a line to mention the potential biases in the moisture fields from reanalysis such as ERA5, which could influence the performance of moisture nudging in precipitation simulations.

A relevant sentence has been added at lines 54-56.

L66 Needs to be supported by appropriate references.

Thank you for pointing to the need to provide some additional evidence here. The related references have been added.

L85 add (GPM) and “GES DISC” needs clarification.

The terms have been clarified in the revised manuscript

L110-111 CABLE and UCLEM need clarification.

The definition of CABLE and UCLEM have been updated in the revised manuscript

L115 Model configuration section. The authors should more thoroughly acknowledge and engage with prior work before presenting their experimental design. A comprehensive review of relevant studies is essential. In addition, the rationale behind the model experiment design should be clearly justified.

We very much appreciate the spirit of this comment. In response to your suggestion, we have updated the Model Configuration section to more thoroughly engage with and acknowledge prior work on spectral nudging. We have included a comprehensive review of relevant studies to provide context and clearly position our experimental design within the existing literature. Additionally, we have provided a more detailed justification for the rationale behind the model experiment design, explaining why specific configurations were chosen and how they align with previous findings. These updates can be found in the Section 2.4 "Model configuration" of the revised manuscript.

L116 The choice of wavelengths (3000, 1500, and 500 km) requires clearer justification. Previous studies generally suggest that a range of ~1000-2000 km is more appropriate. The authors should explain the rationale behind their selected values and clarify how these choices align with the goal of minimizing nudging while still achieving improved simulation performance.

Thank you for pointing to the need to provide some additional evidence to clarify the choice of wavelength. In response, we have addressed the justification for the choice of wavelengths (3000, 1500, and 500 km) in the Section 2.4 "Model configuration" at lines 160-175.

L124 Justify the choice of vertical levels for nudging. Many studies suggest nudging above the PBL to avoid disturbing surface layer physics. Why use 0.5 and 1 levels? Also, the PBL height is variable during the simulation, so the nudging should ideally follow the PBL rather than be fixed at a single level.

Thank you for this comment. While varying boundary layer heights can improve model performance in scenarios like tropical cyclones (Cha et al., 2009), moisture transport (Tang et al., 2017), and precipitation (Menut et al., 2024; Lai and Gan, 2025), its effectiveness depends on the model and physical processes involved. Varying PBL heights requires more computational resources, making it computationally expensive for high-resolution models like CCAM. For this study, we opted for a fixed nudging level to balance model performance with computational feasibility, though future work could explore more dynamic nudging strategies. A relevant sentence has been added at lines 193-198.

L124 The choice of 3000 km wavelength for the PUVTQ configuration is questionable. As identified in the literature, this wavelength may not be optimal and combining temperature and moisture could lead to overestimated rainfall due to thermodynamic inconsistencies. Further investigation is needed for experiments using PUVT and PUVQ with better parameter configurations.

We appreciate this comment and agree that previous studies, such as Lai and Gan (2025), have shown that limited-area models like WRF can overestimate precipitation when both temperature and moisture are nudged, partly due to overstimulated convection.

In our study, the overestimated rainfall likely results from a combination of factors, including model physics, horizontal resolution, study region characteristics, and potential biases in ERA5 moisture fields, particularly in regions with sparse observations. To the best of our knowledge, previous studies have not quantitatively partitioned the relative contribution of these factors, and this remains an open question for future work.

Our analysis shows that pressure and wind nudging substantially improve monsoonal flow and moisture convergence over regions such as the Gulf of Carpentaria and New Guinea, leading to more realistic precipitation patterns. However, when moisture nudging is included, additional convergence regions emerge, particularly over northern Australia, resulting in overestimated rainfall (Fig. 7). Under the current CCAM physics configuration, forcing data (ERA5), and model resolution, we therefore do not find moisture nudging to improve precipitation simulation for this extreme La Niña case study.

L138 A more thorough time-series validation is needed to assess model performance over time.

Thank you for this suggestion. A correlation heat map has been added to the appendix (Figure S4).

L144 Justify the choice of 700 hPa for validation. But Figure 7 shows 875hPa? Consider using depth-integrated values for a more comprehensive analysis.

Thank you for pointing out the discrepancy regarding the use of 700 hPa for validation. We apologize for the confusion; this was a typo. We have corrected the text to refer to 875 hPa, which is the correct level used in our analysis.

Regarding your suggestion to use depth-integrated values for a more comprehensive analysis, we have found that the conclusions regarding the improvement in moisture transport and moisture convergence are consistent whether we calculate water vapor flux divergence at different lower or upper-level layers such as 875 hPa and 700 hPa.

Figure 7 is used to emphasize the key findings:

- The Ctrl simulation shows a weaker, displaced low-pressure system over northwest Australia, leading to underestimated precipitation, particularly over the Gulf of Carpentaria.
- Pressure nudging improves the representation of low- and high-pressure systems, while wind nudging in the PUV simulations enhances monsoonal wind

flow and moisture convergence in regions like New Guinea and the Gulf of Carpentaria.

- Moisture nudging introduces additional convergence regions, leading to overestimated rainfall in northern Australia.

Additionally, we believe some parts of the figure were redundant and scattered the main findings. We have refined the figure and the corresponding text to focus on the key results.

L151 Justify the domain selections for the simulations. Why was this specific region chosen? Why southwest Australia exclude?

Thank you for your comment. Ideally, we would have included additional regions around Australia for a broader analysis. However, for the extreme 2010–11 La Niña case study, the region most affected by strong tropical cyclones and major flooding occurred in the northwest, northeast, and southeast of Australia (Karoly and Boulter, 2013). Therefore, we focused on these key regions to ensure the most relevant climatic events were represented. A relevant sentence has been added at lines 219-220.

L166 The maximum precipitation in IMERG is around 20–25 mm/day, but the bias in Figure 2 reaches -9 mm/day. Suggest showing both simulated rainfall and bias side by side for clearer interpretation.

We apologize for the confusion. The panels from (b) to (q) were intended to show the bias relative to IMERG for each of the 16 simulations, but we acknowledge that the caption was unclear. In response, we have revised the figure caption to clarify this point. Additionally, we have added domain averages in the black box at the lower left of each panel to further improve clarity and provide a more straightforward interpretation of the data.

L177 Figure S3 should present the spatial distribution of correlation and RMSE for daily precipitation at each grid point across the Australian continent (December 2010-March 2011). The current domain-averaged view does not adequately capture the model's spatial accuracy in rainfall representation.

We appreciate this point. We have revised the manuscript (Please refer lines 249-253) to more fully describe the spatial distribution of correlation and RMSE for daily precipitation at each grid point across the Australian continent (December 2010-March 2011).

L185 This suggests a potential model physics issue. The convective parameterization might be suited for continental regions but not for tropical ones. Have different convective parameterization schemes been tested? Please provide evidence and further exploration.

Thank you for your insightful comment. We agree that the observed behaviour may reflect limitations in the model physics. The parameterization scheme has been developed particularly for monsoon regions. However, convective parameterization remains a challenging task. In our study, spectral nudging primarily aims to preserve large-scale circulation and atmospheric features, rather than compensate for deficiencies in model physics.

We acknowledge that the choice of convection and cloud microphysics schemes can substantially influence simulation outcomes in both limited-area and variable-resolution models such as CCAM. However, the primary objective of this study was to investigate the impact of spectral nudging on precipitation downscaling during an extreme event, and therefore the model physics were kept unchanged across all simulations. Exploring alternative physical parameterizations, particularly convection schemes, is an important direction for future work and may help reduce the discrepancies identified over tropical regions.

A relevant discussion has been added at lines 513-524.

L203: To strengthen the conclusions, compare the model results with weather station data, particularly in regions where GPM data uncertainties are high.

Please refer to our response in the major comment number 4.

Section 3.1.1: Including a table that summarizes performance metrics and time-series comparisons for each region, along with extreme rainfall statistics (e.g., TH), and highlighting the best values would provide clearer and more comprehensive insights.

Thank you for your valuable comment. In response, we have added a summary table in the appendix, which includes performance metrics for each region. We have also highlighted the best values to provide clearer and more comprehensive insights.

L220 Figure 4 is difficult to interpret due to excessive clutter. Simplify the figure or highlight the key differences to make it more readable.

Thank you for this suggestion. We have simplified Figure 4 by adding blue and red boxes to clearly highlight the areas where the model underestimates and overestimates precipitation.

L275 Consider using depth-integrated MFC for a more comprehensive analysis. And also compare the domain-average.

Please refer to our response in L144. The domain-average values have been added to Figure 7.

L309 Figure 8 compares nudged simulations with ERA5. It would be more informative to compare against independent observational data or other reanalysis products, since nudging toward ERA5 variables naturally leads to higher correlation with ERA5 itself. While moisture nudging improves moisture simulation, it does not improve precipitation. The authors should provide a more detailed analysis to explain the reasons behind this discrepancy.

We appreciate your concern regarding the comparison of nudged simulations with ERA5. While nudging toward ERA5 can often increase agreement with ERA5 fields, this is not always the case and depends on the nudging configuration and region. For example, Figure 8 shows relatively low correlations between all model configurations and ERA5 at 900 hPa in region R3. We have added further discussion of this point in Lines 408–411 of the revised manuscript.

Regarding moisture nudging, we agree that improved moisture fields do not necessarily translate into improved precipitation simulations. This discrepancy may partly reflect uncertainties and biases in ERA5 moisture fields, particularly over tropical regions and areas with sparse observations (Virman et al., 2021; Truong et al., 2022). This remains an important topic for future investigation. A relevant discussion has been added at lines 54-56.

The figures are cluttered and some are difficult to read due to poor visibility or excessive similarity. Figures 2, 6, 7, and 10 are too similar to clearly differentiate the results. Additionally, some colored lines in Figures 4, 5, and 8 have poor visibility. These should be adjusted for better clarity. Furthermore, there is no need to present all experiment results. For instance, it is well known that nudging P produces the worst results, so repeating the experiment across all wavelengths (3000, 1500, 500 km) is unnecessary, especially since 500 km is clearly the most effective. Reducing redundant figures and focusing on the most significant results will improve the clarity and impact of the presentation.

We have thought carefully as to how we might accommodate yours and other reviewers' comments. Specifically, we have reduced the redundant panels in Figure 7 to better illustrate the key findings, modified Figure 2 and Figure 10's caption to better explain the meaning of each panel and added a dashed blue box to Figure 6 to highlight the regions of MJO-related precipitation peak. Finally, we also added boxes in Figure 4, 5, and 8 to better communicate the results.

Include key and latest references on spectral nudging to strengthen the context and scientific grounding of the study. Suggested references are provided above:

Spero TL, Nolte CG, Mallard MS, Bowden JH (2018) A maieutic exploration of nudging strategies for regional climate applications using the WRF model.

Mai X, Qiu X, Yang Y, Ma Y (2020) Impacts of spectral nudging parameters on dynamical downscaling in summer over Mainland China. Front Earth Sci 8.

Huang Z, Zhong L, Ma Y, Fu Y (2021) Development and evaluation of spectral nudging strategy for the simulation of summer precipitation over the Tibetan plateau using WRF (v4.0). Geosci Model Dev 14:2827–2841.

Hutson, A., Fujisaki-Manome, A., & Lofgren, B. (2024). Testing the sensitivity of a WRF-based great lakes regional climate model to cumulus parameterization and spectral nudging. Journal of Hydrometeorology, 25(7), 1007-1025.

Lai, W., & Gan, J. (2025). On spectral nudging and dynamics to improve representation of marine cloud and precipitation over the China sea in summer. Theoretical and Applied Climatology, 156(8), 444.

Citation: https://doi.org/10.5194/egusphere-2025-5847-RC1

Reviewer 2's comment

General comments

I read the discussion paper entitled "*Spectral Nudging Impacts on Precipitation Downscaling in the Conformal Cubic Atmospheric Model, version CCAM-2504: Insights from Summer 2011*", submitted to *GMD* by Truong and colleagues. The Conformal Cubic Atmospheric Model (CCAM) is a reputable regional modelling platform developed by this group and widely used in Australia and globally for downscaling global climate models. Several meaningful recent scientific contributions have featured CCAM and evaluated its runs, demonstrating added value as well as systematic biases. Therefore, this group effort to enhance and further develop the model is very important for the regional model scientific community, climate adaptation and resilience building. For instance, CCAM simulations have been submitted to the CORDEX archive of CMIP6 downscaled projections for the Australasian domain by distinct modelling groups using varying experiment designs and their outcomes are featured in a range of climate services portal providing application-ready data.

A key characteristic of CCAM is that it runs over a stretched grid with maximum spatial resolution over the target region, which enables to reconcile global and regional climate processes – such as the influence of large-scale SST patterns, global circulation processes, as well as local and regional topography on precipitation. To impose boundary conditions and forcings, a technique named spectral nudging is used as opposed to lateral nudging traditionally used in other modelling platforms for data assimilation at their boundaries. This allows the regional model to develop its own high-resolution details, such as local storms or terrain-influenced winds, without drifting away from the overarching global weather patterns. An advantage of spectral nudging is that it prevents internal model variability from causing the regional simulation to deviate unrealistically from the global state it is meant to represent. However, spectral nudging needs to be tuned to optimise its performance. The paper undertakes an assessment of how systematically varying nudging wavelength, vertical extent, frequency, and variable choice influence the performance of precipitation simulations during an extreme 2010 – 11 La Niña. GPM-IMERG precipitation and ERA5 reanalysis datasets are used as ground truth. It shows that configurations at short nudging wavelengths (~500 – 1500 km), with high-frequency updates (1 h), and including pressure, wind and temperature delivered the most robust performance.

I believe the paper suits the journal scope well and will be of interest of the climate modellers community. My recommendation is for it to be published after minor revisions.

Specific comments

Title: "version CCAM-2504" does not need to be listed in the title. Suggest move it to abstract. Title will be more concise

> We appreciate this comment. As per the journal's policy, we are required to include the model version "CCAM-2504" in the title to ensure clarity and precision regarding the specific model used in this study.

L31: Chapman et al (2023) Earth's Future - would be a more suitable citation for this statement. https://agupubs.onlinelibrary.wiley.com/doi/full/10.1029/2023EF003548

Thank you for your suggestion. We have added Chapman et al. (2023) as the reference in the introduction. A relevant sentence has been added at line 31.

L31: Sugata et al., 2025 should by Narsey et al (2025) instead, as Sugata is his first name. Another suitable citation to be included for the BARPA model and to back the statement would be Howard et al (2024) GMD - https://gmd.copernicus.org/articles/17/731/2024/

The reviewer is correct. We apologize for using the wrong last name here. We have revised the text and added the reference in the updated manuscript.

L38: add Huang et al (2021) GMD as it demonstrates more recent development in spectral nudging published in the same journal - https://gmd.copernicus.org/articles/14/2827/2021/

Thanks for the suggestion. We have added Huang et al (2021) as the reference in line 38.

L56-57: "While RCM performance has been evaluated in Australasia (Liu et al., 2024; Ma et al., 2025; Truong and Thatcher, 2025)" – I would see value in expanding this as a paragraph outlining the recent CCAM evaluation papers by Chapman, Gibson, Ma, Shoereter and others to better showcase what has already been evaluated in CCAM, its advantages (e.g., added value), limitations (e.g. systematic biases) and what is still outstanding, such as the systematic evaluation of spectral nudging configuration and sensitivity which may enhance advantages and constrain limitations. Consider also adding a quick description on the extent to which CCAM has been used in CORDEX CMIP6 with some examples to set the scene on why there's a need to keep improving it.

Regarding the use of ERA5 reanalysis – it would be worthy to add a sentence or two justifying its usage against BARRA2 – i.e., need for global coverage as CCAM runs globally. Many readers may not grasp that and may think BARRA2 might be more suitable given the higher horizontal/spatial resolution closer to the 12 km CCAM runs that are being assessed.

We very much appreciate the spirit of this comment. We have modified the introduction and added the discussion on BARRA2 in Section 2.1 of the revised manuscript.

L97: "(Imran and Eván 2025)" should be (Imran and Evans 2025)

Thank you. We have revised the text in the updated manuscript.

L103: Sugata et al (2025) should be Narsey et al (2025). Suggest inclusion of Chapman et al (2023) Earth's Future.

We have revised the text and added the reference in the updated manuscript.

L103-105: suggest inclusion of a Queensland's study that uses this CCAM experiment design – i.e., driven by SSTs and ice sheets

We have added the relevant reference in the updated manuscript.

L112: "Thatcher and McGregor (2008) introduced a scale-selective filtering approach (e.g., spectral nudging)" – this statement may confuse the readers as the main topic for the paper is spectral nudging, which now appears as “scale-selective filtering”. Needs further explanation for clarity.

We apologize for the confusion. We have followed your suggestion and modified the text for better clarity in the Section 2.3 and 2.4 of the revised manuscript.

L142: “, where n is the number” – remove “,”

Typo corrected.

L150: 3.1.1 Spatial variability of precipitation – please introduce the figure in the text before inserting them for context and guidance of figure interpretation. This applies to all other figures.

Thank you for the excellent suggestions for enhancing the paper. We have followed your advice and introduced the figures in the text before presenting them to provide better context and guidance for their interpretation. This has been applied to all relevant figures in the manuscript.

L158-159: “R1 and R3 belong to the CORDEX – SEA domain” – they are also part of the CORDEX Australasian domain, right? At least partially.

We have modified the text in the Section Data and methods of the updated manuscript.

Methods – after reading the results, methods seem incomplete. Authors need to better explain the experiment design, sub-regions selection, and assessment metrics presented in their results and figures.

We appreciate this comment. We do appreciate the need to better explain the experiment design, sub-regions selection, and assessment metrics. We have revised and addressed these issues in the Section 2 Data and methods of the updated manuscript.

Figure 1 and its description :155-162 should be presented in methods instead as no result is presented about spatial variability of precipitation. It’s clearly about experiment design, variable horizontal resolution, and sub-regions – which are all methods.

Thanks for suggesting these improvements. We have followed your recommendation and moved Figure 1 and its description to the Data and Methods section (Nice suggestions)

Fig 2 – as stated above, please move figure to after its description (L166-187) otherwise no context and guidance is provided for interpretation.

Thanks, and modified accordingly.

Fig 2 subpanels – consider plotting average bias over the entire domain as annotation per sub-panel as a quantitative indicator of model configuration performance, should be useful for interpretation along with spatial patterns. This could be included after sub-panel config name separate by colon or dash. The annotations could be placed over the map on the bottom left corner of each subpanel. Alternatively, a table could be added with additional parameters, such as average bias, absolute bias, correlation, etc.

Thank you for your suggestion. We have calculated the domain average for each bias map and inserted the values in the black box at the lower left of each panel for clearer interpretation.

Fig 3 – suggest adding axis names for the three dimensions: x-axis, y-axis and radial components. And don't forget to move the Taylor diagrams to after the description paragraph.

Thanks, and modified accordingly.

L196: A sentence introducing the analytical strategy would be useful to guide the reader – e.g., "Next, we assess the performance of the spectral nudging configuration over the six regions presented in Fig 1 using Taylor diagrams…"

Thanks, and modified accordingly.

L203-204: "in convective (R1) and orographic (R3) regions," – it would be nice to have mentioned this as an analytical strategy for the selection of regions in the methods. Please insert this information when moving Fig 1 and description to the methods.

Thanks, and modified accordingly.

L200-205: Maybe consider a supplementary information table (or heatmap) with all metrics for the entire domain and sub-domains summarising the results for the 16 spectral nudging configurations.

Thank you for your excellent suggestion. In response, we have created a heatmap summarizing the results for the 16 spectral nudging configurations across all domains. This heatmap has been included in the appendix for further clarification.

Fig 5 is insightful, but I could not find the ground truth that should be used as reference to compare simulations against as IMERG has no colour / line attributed to it in the legend. By looking closer, it looks like it is the black line that is not attributed to anything else. Just need to add it to IMERG I the legend and maybe consider making it thicker to stand out amongst the other 16 time-series.

Thank you for your helpful comment. We apologize for the mistake in Figure 5. There was no black line to represent IMERG, as indicated in the legend. We have now fixed this issue and added the IMERG line to the legend for clarity.

I like the consistency of colours over the figures subpanels tittles, symbols in the Taylor diagrams and plot/time-series lines – these show authors are committed to present a quality material with substantial attention to detail.

Thank you.

L282: this is the first time a figure is referred in the text before its appearance. This makes the material more intelligible, and this style should be adopted as standard.

Thank you.

Fig 7: this is very nice visualization of circulation patterns and how wind field influences moisture fluxes. Well done!

Thank you.

Fig 8: row numbers and axis titles are disproportionately large, please reduce font size.

Thanks, and modified accordingly.

Fig 10 is insightful as it shows large biases in extreme rainfall for all spectral nudging configurations. This shows that the technique has limitations and is not supposed to resolve a much bigger issue which is, for instance, the underestimation of monsoonal rainfall in northern Australia regardless of the configuration used. This point could be added to the discussion.

Thanks for pointing out the potential value of including some information along these lines. We have modified our discussion and conclusion and addressed this concern at line 513-524.

I like the concluding remarks with explicit recommendation of spectral nudging configuration based on the results of this experiment and the clear outlining of limitations – there are overarching issues in regional climate modelling that spectral nudging will not be able to fix and readers should lower their expectations.

Thank you.

References format is not fully consistent – refer to L533-539 for an example – sometimes two authors references have "&", sometimes not. Sometimes year appears after authors, sometimes in the end, sometimes in brackets. Sometimes colon is used too - see below highlighted in bold

Thank you. We have modified the reference accordingly.

"Hong, S. Y., **&** Chang, E. C. **(2012)**. Spectral nudging sensitivity simulations in a regional climate model. Asia-Pacific Journal of Atmospheric Sciences, 48(4), 345–355. https://doi.org/10.1007/s13143-012-0033-3

Imran, H.M., Evans, J.P. Observational uncertainty in the added value of regional climate modelling over Australia. Clim Dyn 63, 73 **(2025)**.https://doi.org/10.1007/s00382-024-07562-y

Isphording, R. N., Alexander, L. V., Bador, M., Green, D., Evans, J. P., and Wales, S.: A Standardized Benchmarking Framework to Assess Downscaled Precipitation Simulations, J. Climate, 37, 1089–1110, https://doi.org/10.1175/JCLI-D-23 0317.1, **2024**."

Congratulations on the excellent research. I am looking forward to seeing it published!

Thank you.

Regards,

Ralph Trancoso

Citation: https://doi.org/10.5194/egusphere-2025-5847-RC2