Dr. Peter Bechtold (Referee #1):

The authors present modifications of the Tiedtke convection scheme and apply and evaluate these in the 4 km nested runs over Taiwan. I like the presentation of the manuscript as the modifications are presented and evaluated step by step for case studies followed by a general evaluation, the manuscript is also well written in general. I also broadly agree with these modifications (see below) and the discussion of the convective features related to model deficiencies.

The authors thank Dr. Peter Bechtold for his encouraging and helpful comments. Our point-by-point responses are provided below and marked in blue text.

Specific comments:

- SCA: yes the mass flux scaling should definitely be applied before applying the CFL criterium. Could you mention what model time step you use? Also in the CFL criterium computation it might be better to use for very small time steps eg dp/(g*max(dt,300))

  The time step used in our TGFS nested simulations is 225 seconds. We appreciate the suggestion to compute the CFL criterion as dp/(g* max(dt, 300)), which helps prevent excessive updraft mass flux when using small time steps. We plan to evaluate this refinement in future model developments.

- Cloud top criterium: yes the convective cloud top height is definitely overestimated in the original version, you might also want to test an additional criterium on the cloud top height that has been introduced in the German weather service (DWD) and ECMWF, ie for the updraught to continue in the vertical $dT/dz < -3.e-3$ and $Buo > -2$

  Thank you for pointing out the criteria used in DWD and ECMWF. We conducted a sensitivity test by introducing the overshooting limiter you suggested into the TGFS nested model. The experiment using the overshooting limiter was conducted with the southwesterly flow case discussed in section 5.2 and denoted as OSL.

  As shown in Fig. R1, compared to CUP, OSL shows a reduction in heavy rainfall, particularly along the southwestern coast of Taiwan. In addition, the vertical cross-sections of hydrometeor mixing ratios (for ice, snow and graupel) indicate that the cloud top in OSL is indeed lowered (Fig. R1d). On the other hand, compared to TOP in this study (which uses a revised criterion for defining cloud tops), OSL similarly achieves the goal of lowering convective cloud tops; however, the rain band in OSL does not shift as far offshore (Fig. R1c) as seen in TOP (Fig. 6e) and observation (Fig. 6a). This is likely due to the revised criterion (TOP) leads to a higher restriction than the OSL approach, resulting in a lower cloud top (around 16 km in Fig. 8g) than OSL (around 17 km in Fig. R1d). Consequently, TOP generates less compensating subsidence, creating a more favorable environment for new updraft to form in the upstream region (farther from the coast), as discussed in Fig. 10.

Nevertheless, we agree that the approach you suggested introduces a thermodynamic constraint dependent on the environmental thermal structure, which is more physically robust. Therefore, we will continue to assess this approach across different cases and weather regimes.

In addition, in response to Referee #4's comment, we have added an explanation about the physical mechanism that makes the TDK scheme sensitive to the definition of convective cloud top (Lines 177-182).

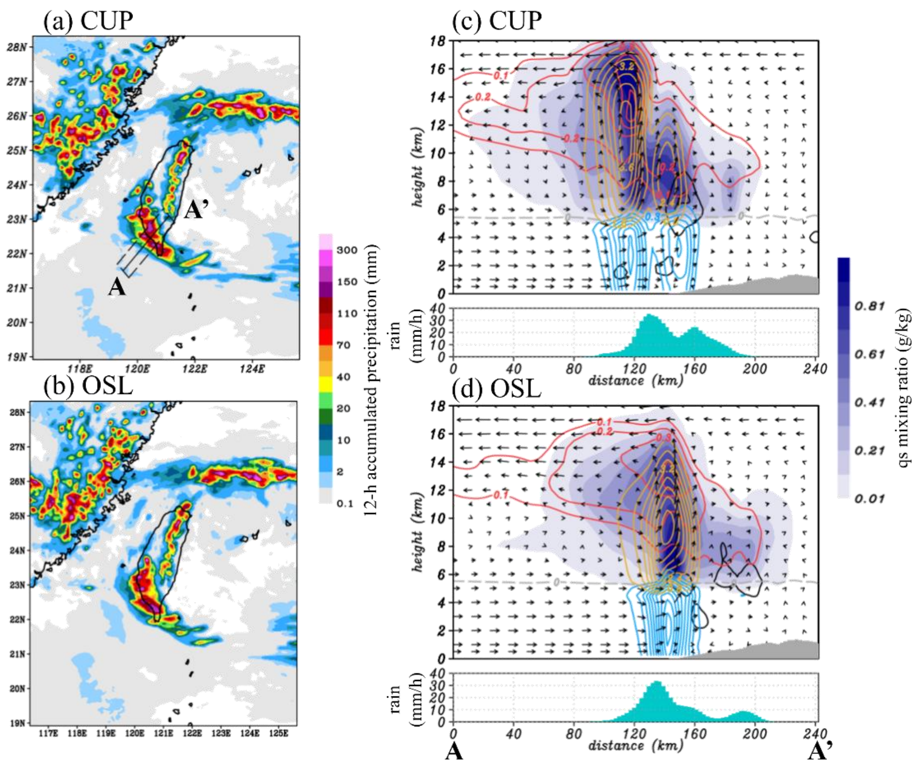

Figure R1: The 48–60-h accumulated precipitation forecasts from the (a) CUP and (b) OSL experiments, and the vertical cross sections along the A-A' line in Fig. a of hydrometeor mixing ratios (g kg^{-1}) and along-section vertical circulations (vectors; 50 m s^{-1}) for (c) CUP and (d) OSL at 50-h forecasts. The cross sections are computed by averaging along the short axis of the dashed box denoted in (a). Gray shading represents the averaged terrain height. Different contour colors represent the mixing ratios of cloud water (black; 0.2 g kg^{-1} interval), rain water (blue; 0.3 g kg^{-1} interval), cloud ice (red; 0.1 g kg^{-1} interval), and graupel (yellow; 0.8 g kg^{-1} interval), while the purple shading denotes the snow mixing ratio (g kg^{-1}). The greenish-blue histogram denotes the rain rate (mm h^{-1}).

- Entrainment modification: Here I find it less convincing, you say it further reduces "convection" but the results show more light precipitation indicating more widespread light convection. Indeed, when looking at your formula it appears that for z=100 m you get entrainment rates of 10^{-3} m^{-1} which is similar to the original, but for z=500 m (a typical cloud base height) it is 2×10^{-4} which is already much smaller than the original (Note also you say d1 is non-dimensional but it has units m^{-1}).....??? At least in your conclusions you seem not to have adopted this version for operations.

  We thank Dr. Peter Bechtold for this insightful comment and for carefully checking the formula. Yes, the unit of d_1 in Eq. (10) in the revised manuscript [Eq. (5) in the previous version] should be m^{-1} rather than non-dimensional. We have corrected this in the revised manuscript (Line 214). Regarding the increase in light precipitation, we agree that the entrainment is decreased when replacing Eq. (8) with Eq. (10), and the statement in our manuscript was imprecise. A lower entrainment rate allows the parameterized convection to consume more moisture and environmental instability. The "reduction in convection" mentioned in our manuscript should refer more precisely to the suppression of unrealistic grid-scale heavy rainfall events, achieved by a greater contribution from subgrid-scale processes to stabilize the environment. Accordingly, the production of widespread light precipitation is a consequence of this more active convection scheme. We have revised the relevant description in Section 3.4 (Lines 218-220), Table 1, and the discussion on CRH to clarify this mechanism (Lines 428-434).

- You also discuss in detail - a discussion which is welcome - reasons for having precipitation bands sometimes too far offshore compared to observations. Then you mention at the end that this problem is even more widespread in winter over a relatively warm sea. Indeed, this problem is shared by all global modelling centres employing a convective parametrization. The reasons are as you broadly mentioned the interaction between heating and the circulation (forming a quasi stationary near coast circulation, having updraught and downdraught in the same grid cell and the lack of advection. We could largely address this problem in the upcoming operational version at ECMWF (cycle 50r1, April 2026) by handing over a significant amount of convective precipitation to the large-scale cloud scheme where it is advected and evaporated (no publication available)

Thank you for sharing this valuable information that handing over convective precipitation to the large-scale cloud scheme helps address the offshore precipitation bias in winter. We have also conducted studies on this issue, and found that in addition to the convection and cloud microphysics schemes, the boundary layer scheme may also play an important role. The forecasted boundary layer instability and the resulting Froude number affect the low-level onshore wind speed, which in turn strongly influences the distribution and intensity of offshore rain bands.

Referee #2:

To improve summer precipitation forecasts in the Taiwan Global Forecast System (TGFS), authors modified the Tiedtke cumulus parameterization with scale-aware treatments and adjusted convection constraints. These updates, including revised cloud-top definitions and increased sensitivity to humidity, effectively reduced precipitation biases and improved the accuracy of afternoon thunderstorm patterns. The manuscript is well-written and offers valuable insights for enhancing the convection parameterization scheme. I find it suitable for publication, but recommend that the authors address following points.

The authors thank Referee #2 for the positive evaluation and constructive suggestions. Our point-by-point responses are provided below and marked in blue text.

1. As the authors note, the enhanced contribution from the convection scheme consumes more environmental instability through subgrid-scale processes, resulting in the suppression of grid-scale convective updrafts and a corresponding reduction in precipitation intensity. This is clearly demonstrated by the scale-aware adjustment experiment (adj_SCA in Table 2), where a larger cloud-base mass flux increases the sub-grid scale convection and consequently reduces the overestimated total precipitation, compared to the SCA experiment (Figs. 6 and 7). Conversely, the CUP, TOP, and CRH experiments (Table 2) were intended to reduce the sub-grid scale convection intensity by extending the adjustment time scale, lowering the convective cloud top, and increasing entrainment as a function of environmental RH. These changes were expected to increase total precipitation due to reduced suppression of environmental instability. However, as the authors note, CUP, TOP, and CRH appear to further reduce the total precipitation (Fig. 6). The authors must address this inconsistency between the strength of sub-grid scale convection and the total precipitation by providing the ratio of sub-grid scale precipitation to total precipitation for the CUP, TOP, and CRH experiments, compared with the adj_SCA experiment.

   Thank you for pointing out the inconsistent effects among our different modifications to the convection schemes and recommend providing the ratio of subgrid-scale convection and total precipitation for all these experiments. We have updated Fig. 7 in the manuscript (also attached below) to provide the ratio of sub-grid scale precipitation to total precipitation also for CUP, TOP, and CRH. It shows that the contribution of subgrid-scale precipitation is slightly reduced in CUP and TOP compared to adj_SCA. However, this does not lead to an increase in total precipitation, likely due to the complex interaction between the convection and microphysics schemes. Although the subgrid-scale convection is relatively suppressed, the overall environmental instability may not be sufficiently favorable or efficient for the microphysics scheme to create grid-scale rainfall. The results suggest that the instability retained by the weakened subgrid-scale processes might be converted into cloud water or light stratiform rain rather than heavy precipitation. We have incorporated this discussion in Lines 354-363 in the revised manuscript. Regarding the CRH experiment, the discussion is included in our response to Comment 2.

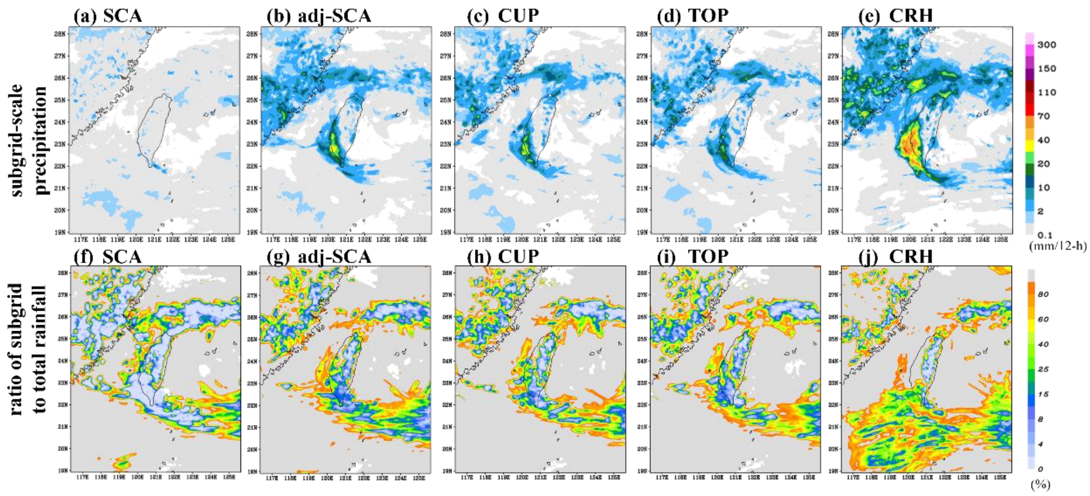

Figure 7 (Figure R2): (a)–(e) Subgrid-scale precipitation (mm) and (f)–(j) the ratio (%) of subgrid-scale precipitation to total (subgrid + grid) precipitation from the (a), (f) SCA, (b), (g) adj-SCA , (c), (h) CUP , (d), (i) TOP and (e), (j) CRH experiments at 48–60-h forecasts.

2. Is the increased widespread light rain in the CRH mainly from the sub-grid scale precipitation or from the grid-scale precipitation? If it is mainly from the latter, the increased sub-grid scale convection intensity may help to reduce the widespread light rain. Therefore, it would be valuable for the authors to present a sensitivity analysis of the widespread light rain in response to varying sub-grid scale convection intensity.

We found that the increased widespread light precipitation in CRH is primarily attributed to the subgrid-scale precipitation, as shown in Fig. 7e, j, even though the modified convective trigger was intended to suppress the convection in lower-RH environments and thereby hopefully reduce the production of light rain. This result stems from the modifications to the entrainment and detrainment rates, where the formulations in Eqs. (8) and (9) are replaced by those in Eqs. (10) to (13). These changes lead to a greater contribution from the subgrid-scale processes.

Consequently, the increased consumption of environmental instability by subgrid-scale convective processes further reduces the heavy precipitation bias associated with the grid-scale processes, but it enhances the light precipitation bias linked to the subgrid-scale processes. We have incorporated these descriptions into Lines 428-434 in the revised manuscript to improve clarity.

Referee #3:

The manuscript is well written and provides sufficient detail regarding the changes the authors made to the Tiedtke scheme in TGFS v1.1, as well as the experimental design used to demonstrate the positive effects of these changes. Most of the modifications to the Tiedtke scheme are derived from other schemes. From a dynamical perspective, these modifications are not entirely independent in their effects on controlling precipitation strength associated with unresolved convection.

The authors thank Referee #3 for the supportive assessment and constructive feedback. Our point-by-point responses are provided below and marked in blue text.

For readers like me, it is important that the manuscript include discussions that clarify which changes are most effective at alleviating precipitation forecast biases. I recommend that the authors revise the manuscript to expand Figure 3 by incorporating results from all experiments summarized in Table 2 for the afternoon thunderstorm case, as in Figure 6 for the southwesterly flow case.

We thank the reviewer for the valuable suggestion. The expanded version of Fig. 3 is shown here in Fig. R3, which incorporates results from all experiments in Table 2 (and additionally the "RSP" experiment discussed later). Unlike the southwesterly flow case discussed in Section 5.2, the differences among these new experiments for the afternoon thunderstorm case are relatively smaller. Except for CRH and RSP, the results from adj_SCA, CUP, and TOP are not very different from the SCA experiment; CRH leads to a smaller peak amount of rainfall, which is closer to the observation, and shifts the rainfall location slightly southwestward, but the overall rainfall pattern does not show an improvement; RSP will be discussed later.

We think that the modifications beyond SCA are likely more effective under conditions with strong synoptic forcing, such as in the southwesterly flow case that exhibits a strong interaction between the convective systems and the prevailing environmental flow. We also note that, as we explained in the manuscript (Lines 310-316), the primary motivation for the series of modifications beyond SCA is the recurrent overprediction of rainfall during the summertime, for which southwesterly flow heavy rainfall events are more representative. Therefore, considering the course of the development in this study and the insensitivity of these modifications in the afternoon thunderstorm case, we would like to retain the original structure of the manuscript, restricting the afternoon thunderstorm case (Section 5.1) to the ORI and SCA experiments only, and reserving all the discussion of the subsequent modifications for the southwesterly flow cases (Section 5.2) and the two-month evaluation (Section 5.3).

We have added a short paragraph in the revised manuscript (Lines 435-439) to briefly describe the additional experiments with the afternoon thunderstorm case and the smaller sensitivity of these modifications in this case.

For related discussion with the southwesterly flow case, especially for the discussion associated with the newly added RSP experiment, please see our response to your next point below.

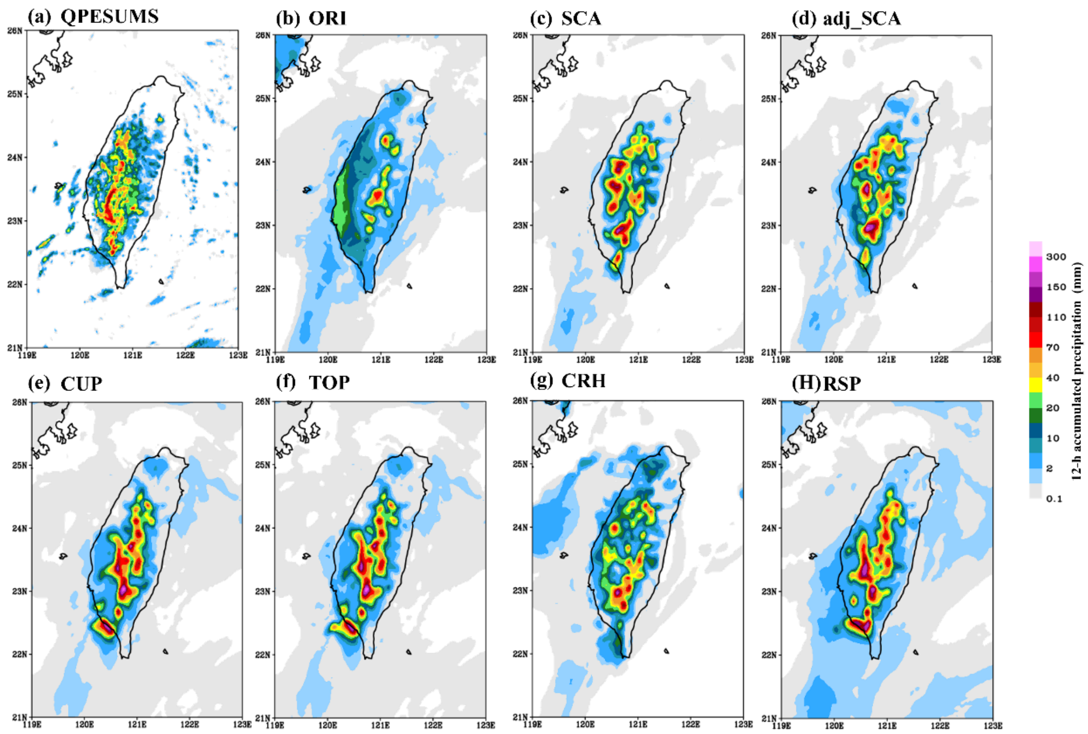

Figure R3: 12-h accumulated precipitation (mm) from 00 to 12 UTC on 26 August 2023 in (a) QPESUMS observation and TGFS nested-domain forecasts from the (b) ORI, (c)SCA, (d) adj_SCA, (e) CUP, (f) TOP, (g) CRH, and (h) RSP experiments initialized at 00 UTC on 26 August 2023.

Given the partition of resolved and unresolved air motion within the TGFS numerics, the modified Tiedtke scheme—due to its suitability for gray-zone resolutions—should represent the unresolved convective mass flux relative to the resolved counterpart in a manner that diminishes as grid size decreases. Therefore, I also recommend that the revised manuscript include a discussion, supported by numerical evidence if necessary, addressing whether the overestimate of precipitation shown in Figure 4 for the SCA experiment can be alleviated solely by reducing the mass flux scaling factor. This discussion is essential to help readers determine whether the other changes, aside from the mass flux scaling, are equally important in making the modified Tiedtke scheme scale-aware.

We thank the reviewer for providing valuable feedback. To address the question whether the overestimated precipitation in SCA can be alleviated solely by decreasing the scaling parameter σ_1, we conducted a sensitivity experiment denoted as RSP (reduced scale-aware parameter) for both the afternoon thunderstorm case and the southwesterly flow case. The RSP experiment was based on adj-SCA, but we changed the constant $\Delta 1$ in the equations for the scale-aware parameter σ_1 [Equation (2) in Kwon and Hong 2017] from 5000 m to 4000 m, which effectively reduced σ_1 from 0.55 to 0.28 at the grid size in the TGFS nested simulation, 4.8 km (Fig. R4). We selected adj-SCA rather than SCA as the base experiment because, as discussed in Section 3.1, it is more reasonable to apply the scaling factor before checking CFL criterion to avoid a double reduction of convective mass flux.

We note that the discussion below regarding the RSP experiment differs slightly from our previous author comment in the interactive discussion (AC3), as we realized that our earlier comment lacked precision and required refinement.

As shown in Fig. R3 and Fig. 6 in the manuscript (also attached below), by reducing the value of σ_1 by almost half at a 4.8-km grid size, RSP exhibits changes in rainfall forecasts compared to adj-SCA in both cases. However, the overestimates of heavy precipitation (> 200 mm/12 h) are not much mitigated. Regarding the rainfall locations, the rainfall pattern in the afternoon thunderstorm case is not improved; the location of the rain band along the southwestern coastal area in the southwesterly flow case is not changed and thus the onshore bias of the rain band is not corrected. On the other hand, RSP tends to induce more widespread light precipitation (< 10 mm/12 h), especially in the afternoon thunderstorm case (Fig. R3h). This overall behavior reduces the agreement with the observed precipitation distribution.

These results support that the various modifications in this study, including the constraints on convection, the revised cloud top criterion, and the increased dependency on RH, may not be entirely critical in the afternoon thunderstorm case, but are necessary in other summertime rainfall cases, especially for those with strong southwesterly flow. They not only reduce overestimated precipitation but also inhibit unrealistic convective initiation, improve spatial distribution, and achieve a more reasonable convective structure. Merely lowering the mass flux scaling parameter σ_1 without implementing the other physical constraints is insufficient to mitigate the overestimation of heavy rainfall and tends to retain some of the same issues as in the (adj-)SCA experiment.

We have included the RSP experiment for the southwesterly flow case in the revised manuscript (Lines 241-243; Table 2; Figure 6), and added the above discussion in a new paragraph in Section 5.2 (Lines 440-450) and also in the conclusion section (Lines 517-520) to clarify the limitation of the pure adj-SCA approach and better demonstrate the respective importance of the different modifications to the Tiedtke scheme.

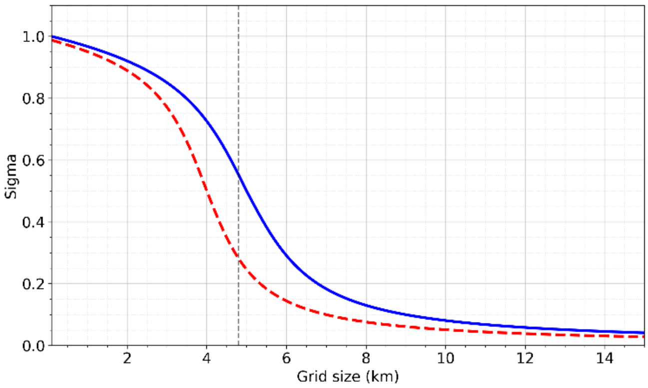

Figure R4: Variation of the scale-aware parameter σ_1 with model grid size. The blue solid line represents the parameter based on Kwon and Hong (2017), which is used in this study. The red dashed line denotes the decreased parameter applied in the RSP experiment. The vertical black dashed line indicates the 4.8 km grid size.

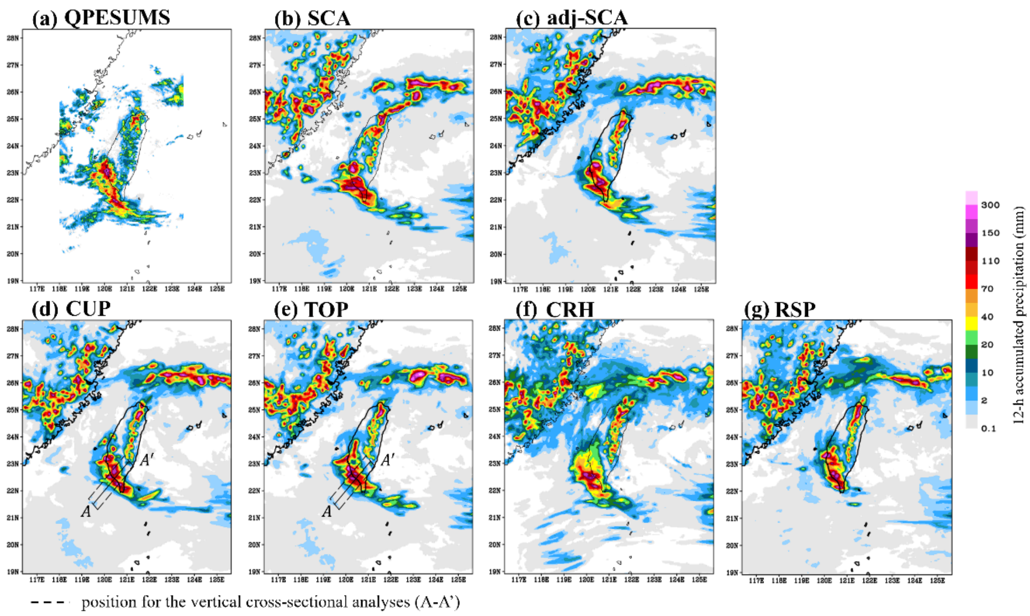

Figure 6 (Figure R5): (a) 12-h accumulated precipitation (mm) from 00 to 12 UTC on 10 August 2023 based on QPESUMS observation. The 48–60-h accumulated precipitation forecasts valid at the same period from the (b) SCA, (c) adj-SCA, (d) CUP, (e) TOP, (f) CRH, and (g) RSP experiments.

Dr. J. M. Piriou (Referee #4):

In this study, the authors start with a 2016 version of the Tiedtke-Bechtold (TDK) scheme, which they modify significantly to meet the needs of Taiwanese forecasters, in particular to reduce precipitation and improve its localization in a 5 km grid model. This work updates TDK based on other published work.

The authors thank Dr. J. M. Piriou for his insightful comments and valuable suggestions. Our point-by-point responses are provided below and marked in blue text.

More specific comments:

- It is interesting, as you do, to validate the modifications by stacking them on top of each other: ORI, SCA, …, CRH.

  Thank you for the positive feedback. We are pleased that this experimental design is useful.

- Figure 4 shows the temporal sequence of precipitation, with precipitation forecasts showing a 4 hours lead. It would be interesting to plot the diurnal cycle of precipitation over a period of one month to see how much of this time lead is a systematic flaw in the convection scheme.

  We thank Dr. J. M. Piriou for this valuable comment. To investigate how much the convection scheme is systematically biased towards early initiation and early peaking of afternoon thunderstorms, we plotted in Fig. R6 the mean hourly precipitation rates averaged over Taiwan's land area, based on 18 selected days in July 2023 characterized by afternoon thunderstorm-type weather.

  With these 18 cases, both ORI (blue line) and SCA (red line) successfully capture the peak rainfall time at 16:00 local time, which is consistent with the observation (black line). This indicates that the early peaking of rainfall in Fig. 4 is associated with this specific case and may not be systematic. However, regarding the convective initiation time, a time lead of about 2 to 3 hours remains clear in ORI. This systematic flaw is primarily driven by the overly active subgrid-scale processes, which respond too quickly to the daytime surface heating and CAPE generation. This issue is largely solved by applying the scale-aware parametrization in the TDK scheme (SCA) to reduce the updraft mass flux, which effectively delays the precipitation initiation time. Nevertheless, the rainfall intensity in SCA increases too rapidly and causes a significant overestimation of the maximum rainfall. This notable problem would require the other modifications in this study to mitigate it.

To provide this information about the diurnal cycle of precipitation averaged from multiple cases, we have added a few sentences to briefly summarize the above results (Lines 287-292; without showing figures).

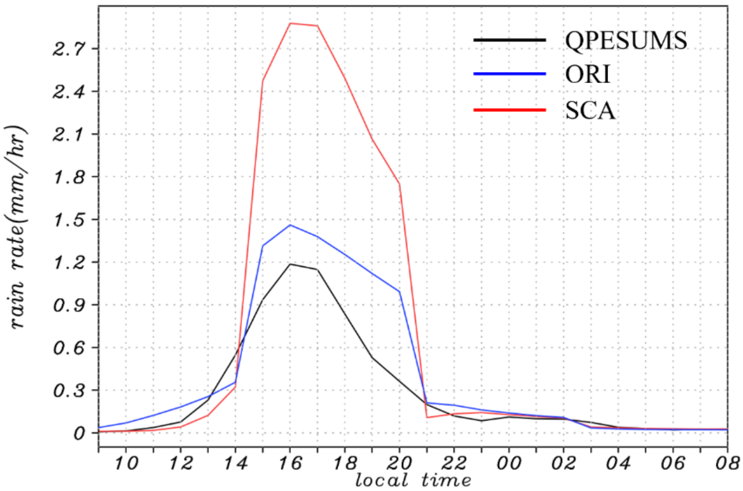

Figure R6: Diurnal evolution of hourly precipitation rates (mm h^{-1}) averaged over Taiwan's land area during the 24-h period starting from 00 UTC (8:00 local time). The results represent a composite of 18 afternoon thunderstorm cases in July 2023 for the ORI (blue line) and SCA (red line) experiments. The black line shows the observed precipitation rate from QPESUMS.

- Section 3.4 (from line 171) "Dependency on environmental relative humidity for convection triggering, entrainment, and detrainment" also aims to reduce intense precipitation (see line 172). The revised entrainment values are based on ... Bechtold 2008, which is not recent, especially since this work develops a 2016 version of the MPAS of the Tiedtke scheme, which is more recent. It seems that your work would have been easier if you had based it on a more recent version of the Tiedtke scheme.

  We decided to replace the entrainment rate formulation from Bechtold et al. (2014) back to the earlier version (Bechtold et al. 2008) because the earlier version provides a lower entrainment rate, allowing the parameterized convection to consume more environmental instability and moisture. Consequently, the increased consumption by subgrid-scale convective processes successfully reduces the heavy precipitation bias. We have added more discussion in the revised manuscript to better explain the results from the CRH experiment (Lines 428-434), which uses the entrainment rate from Bechtold et al. (2008). At the same time, we have updated Fig. 7 to include CRH, partly in response to Referees #1 and #2's comments.

In addition, we also evaluated the performance of entirely updating the Tiedtke scheme to a more recent version (i.e., the scheme in WRF version 4.5). However, we found that the heavy rainfall bias still exists and was even more severe. Therefore, we decided to stay largely with the 2016 MPAS version of the Tiedtke scheme, taking an even older version of the entrainment rate from Bechtold et al. (2008), and only updating items related to the constraints on convective updrafts from the more recent WRF version 4.5 (tested with the CUP experiment). Our evaluation demonstrates that this combination results in a reduction in rainfall bias and a more accurate precipitation distribution, suitable for summertime forecasts over the Taiwan area.

- In section 3.1, starting at line 125, "Scale-aware parameterization," the authors do not describe how they handle mesh dependency, but simply cite publications. It would be good to briefly describe the process with a few simple equations, so that this article would be more "stand alone."

  We thank Dr. J. M. Piriou for the valuable suggestion. We will revise the manuscript to briefly describe the scale-aware parameterization to make this article more stand alone (Lines 139-152):

  The scale-aware formulations for the cloud-base mass flux, M_u, and the trigger function, TRG, are defined as follows:

$$M_u = (1-\sigma_1)(1-\sigma_2)M_u^{\mathrm{org}} \quad , \qquad (1)$$

$$\mathrm{TRG} = (1-\sigma_1)\mathrm{TRG}^{\mathrm{org}} \qquad (2)$$

  where the superscript "org" represents their original values before applying the scale-aware treatments. The first scale-aware parameter σ_1 is defined as:

$$\sigma_1 = 1 - \frac{1}{\pi}\left\{\tan^{-1}[\sigma_{\mathrm{con}}(\Delta x - \Delta 1)] + \frac{\pi}{2}\right\}, \qquad (3)$$

$$\sigma_{\mathrm{con}} = \frac{\tan(0.4\pi)}{\Delta 1 - \Delta 2} \qquad (4)$$

  where Δx is the horizontal grid size in meters, and $\Delta 1$ and $\Delta 2$ are constants whose values are set to 5000 m and 1000 m, respectively. It is noted that Equation (2) in Kwon and Hong (2017), as well as Equation (4) in Lin et al. (2022), appear to contain a typo, and the correct formulation is given in Equation (3) here. The other scale-aware parameter σ_2 is defined as the ratio of the grid scale vertical velocity, $\overline{w}$, to the subgrid-scale vertical velocity, $\overline{w}_c$:

$$\sigma_2 = \frac{\overline{w}}{\overline{w_c}} \quad (5)$$

where the overbar denotes the mean value over the layer between the cloud base and the cloud top.

- In section 3.3, "Definition of convective cloud top," by changing the threshold from 0 to 10^-8 kg/kg, the height of convective clouds is significantly reduced and the intensity of precipitation decreases (see line 170). This surprising result needs to be explained: what physical mechanisms make the TDK scheme so sensitive to this threshold? Could you explain?

  In the TDK scheme, the cloud-base mass flux is determined by the required consumption of Convective Available Potential Energy (CAPE) within a given adjustment time scale (Bechtold et al. 2014). Therefore, if the cloud top level is higher, the vertical integration depth for buoyancy is increased. Consequently, the updraft mass flux becomes more intense to consume the environmental instability. This more intense mass flux transports more moisture upward, leading to higher condensation rates and producing greater precipitation. Revising the criterion to 10^{-8} kg/kg effectively restricts the cloud top to a lower level, thereby reducing the estimation of CAPE and suppressing the heavy rainfall bias.

  We also note that due to the coarser vertical resolution at higher levels and also the numerical errors, when the cloud top criterion is set to exactly 0, the convection scheme may struggle to find a cloud top at a reasonable height, which, in turn, can affect the cloud-base mass flux calculation through the mechanism described above. Modifying this threshold slightly from 0 to a small positive value effectively avoids these problems. We have added the above discussion, particularly regarding the physical mechanism that makes the TDK scheme sensitive to the definition of convective cloud top, in the revised manuscript (Lines 177-182).

Additionally, one of the reviewers, Dr. Peter Bechtold (Referee #1), suggested applying an overshooting limiter to constrain the convective cloud top, which depends on the environmental thermal structure and is physically more robust. We conducted an experiment following the suggested approach for comparison to the current cloud-top approach. Please see our response to Referee #1 for more details.

- In section 5.2, "Southwesterly flow case," it is surprising that you used 48- to 60-hour lead time, because in an operational context, 24- to 36-hour lead time are more important for decision-making. Is there a reason for this? Similarly, in Figure 11, you show precipitation between 96 and 108 hours, which sounds like a methodological problem, because if we are interested in such distant lead times, we should also show the 24-36 hour, 48-60 hours (which you have done), and 72-84 hours, which would give an idea of the spread linked to the lead time itself.

We thank Dr. J. M. Piriou for raising this important point. While we agree that typically earlier forecast lead times such as 24 to 36 hours are important for decision-making, we would like to point out that longer forecast lead times up to even 108 hours are still within the scope of interests from the operational perspectives of CWA's forecasters. Therefore, if we can show that the model development improves the forecasts at certain lead times within this range, it is indeed valuable to the operation. We also note that although the predictability of convective systems is regarded generally low at longer lead times, for several cases in the Taiwan area the predictability can often be extended due to the existence of the height terrain in Taiwan (i.e., the so-called "terrain-locking effect").

For Figs. 6–10 and Fig. 11 in Section 5.2, we selected 48- to 60-hour and 96- to 108-hour lead times, respectively, to demonstrate the impacts of the modifications in the TDK scheme. These choices are primarily based on the degree of improvements we obtained in the experiments: We intentionally presented the results during the periods where the improvements achieved by the modifications can be most clearly seen. However, the positive impacts in CRH compared to SCA are not limited to these selected lead times. Figures R7 and R8 show the precipitation forecasts valid at the same 12-h accumulation period but with different forecast lead times (i.e., different initial times) for the 10 August and 17 August 2023 cases, respectively. As shown in Fig. R7, CRH consistently inhibits the occurrence of unrealistic rainfall over the inland area of Taiwan and suppresses the overestimated heavy rainfall for the rain band along the southwestern coast of Taiwan across various lead times. In Particular, the results from the forecast lead time of 48–60-h clearly show that CRH not only effectively reduces the forecasted rainfall but also captures a more accurate location of the rain band, shifted far from the southwestern coast, to match better with the observation. In Fig. R8, similar results can be found in the other case. These results reveal that CRH consistently improves the rainfall prediction in a wide range of forecast lead times.

We have added a sentence to describe the consistent improvements in CRH across a range of forecast lead times in the revised manuscript (Lines 455-456).

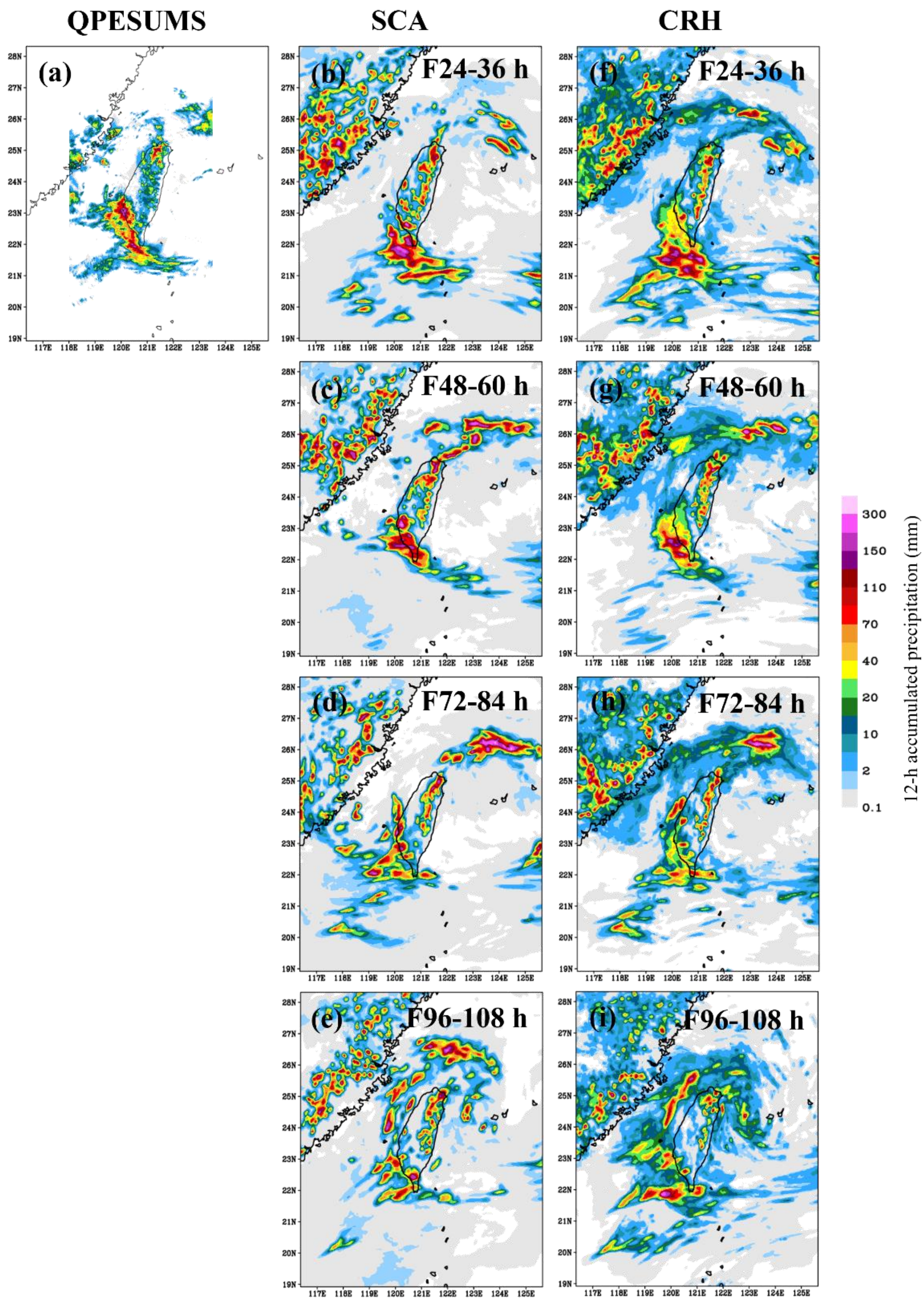

Figure R7: (a) 12-h accumulated precipitation (mm) from 00 to 12 UTC on 10 August 2023 based on QPESUMS observation. The 12-h accumulated precipitation forecasts from the (b)–(e) SCA and (f)–(i) CRH experiments for various lead times of (b), (f) 24–36-h, (c), (g) 48–60-h, (d), (h) 72–84-h and (e), (i) 96–108-h.

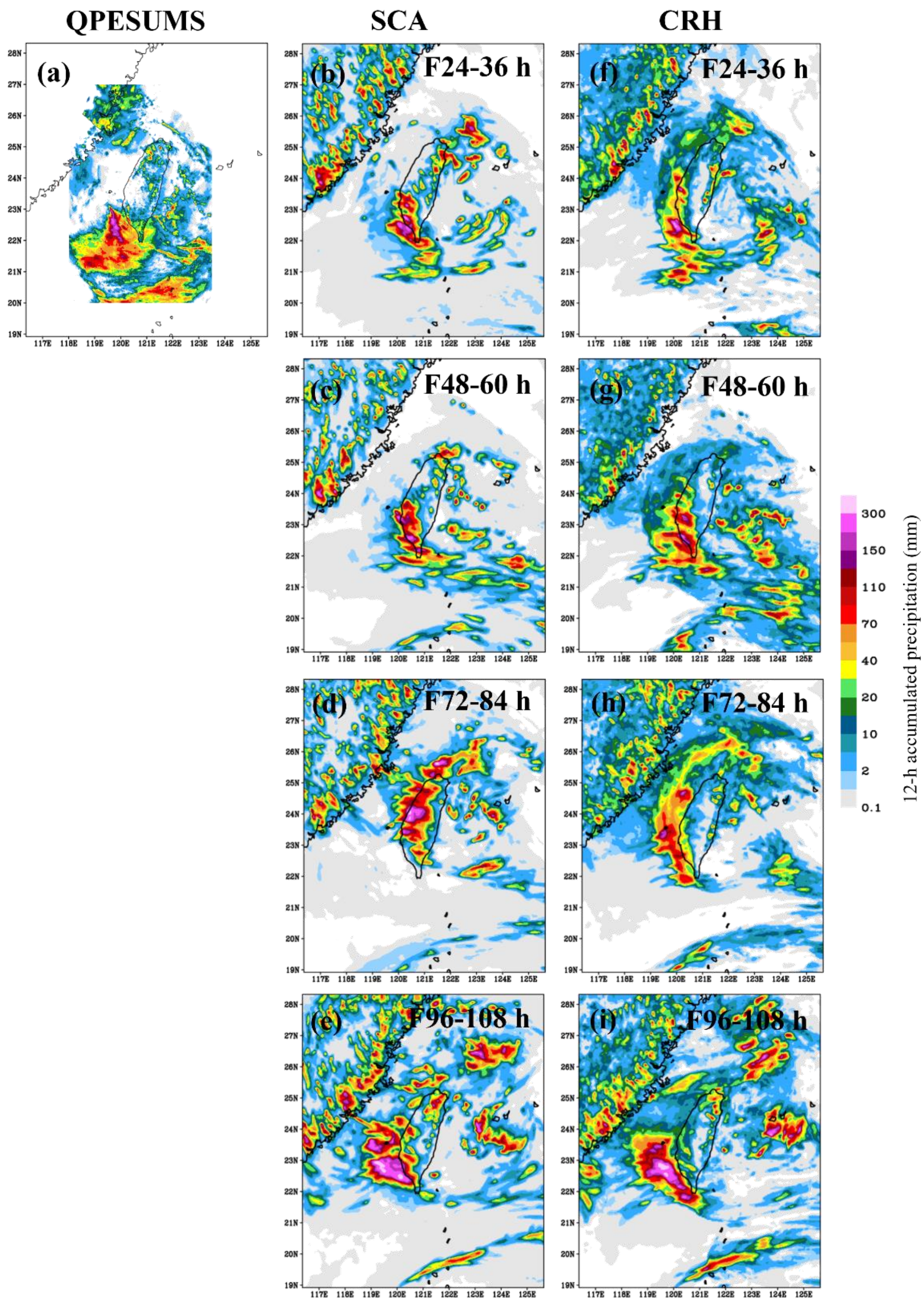

Figure R8: Same as Fig. R7, but for the case on 17 August 2023.

- You mention in line 106 that you are using the Bechtold et al. 2014 approach, which delays the diurnal cycle by modifying the CAPE based on criteria related to atmospheric boundary layer turbulence. Our experience with the Tiedtke scheme indicates that this delay, which is formulated differently over land and over ocean, tends to favor rainfall over ocean versus rainfall over land, which is particularly clear on precipitation fields near the coasts. You could also look into this for your future studies.

Thank you for sharing this valuable information. The approach in Bechtold et al. (2014), which modifies the CAPE by considering boundary layer forcing to delay the peak rainfall time over land, may favor rainfall production near the coasts. This is likely one of the key mechanisms that causes the TGFS nested domain to overestimate coastal precipitation. We will continue to evaluate this process in our future studies.

Reference:

Kwon, Y.-C., and Hong, S.-Y.: A mass-flux cumulus parameterization scheme across gray-zone resolutions, Mon. Weather Rev., 145, 583–598, https://doi.org/10.1175/MWR-D-16-0034.1, 2017.

Lin, C.-H., Yang, M.-J., Hsiao, L.-F., and Chen, J.-H.: The Impact of Scale-Aware Parameterization on the Next-Generation Global Prediction System in Taiwan for Front Predictions, Atmosphere-Basel, 13, 1063, https://doi.org/10.3390/atmos13071063, 2022.

Bechtold, P., Semane, N., Lopez, P., Chaboureau, J.-P., Beljaars, A., and Bormann, N.: Representing equilibrium and nonequilibrium convection in large-scale models, J. Atmos. Sci., 71, 734–753, https://doi.org/10.1175/JAS-D-13-0163.1, 2014.