

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 to 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 will add a few sentences to briefly summarizing the above results (without showing figures).

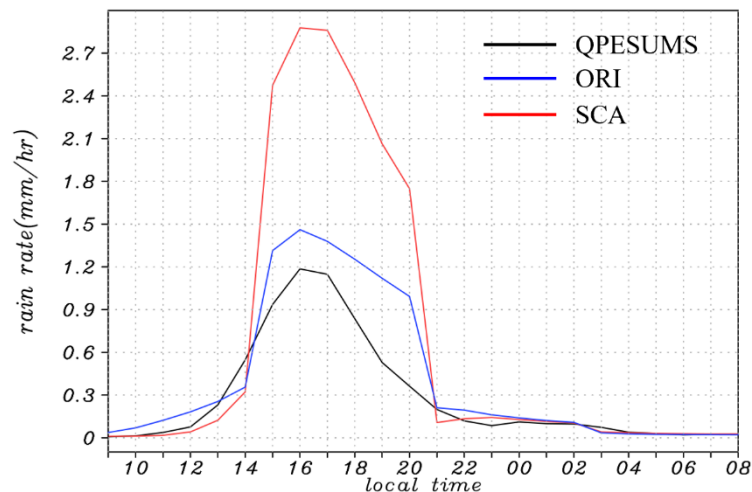


Figure R6: Diurnal evolution of hourly precipitation rates (mm h^{-1}) averaged over Taiwan's land area during the 24-h period starting from 00 UTC (8:00 local time). The results represent a composite of 18 afternoon thunderstorm cases in July 2023 for the ORI (blue line) and SCA (red line) experiments. 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 will add more discussion in the revised manuscript to better explain the results from the CRH experiment, which uses the entrainment rate from Bechtold et al. (2008), and 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:

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

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

$$\text{TRG} = (1 - \sigma_1)\text{TRG}^{\text{org}} \quad (2)$$

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

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

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

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, \bar{w} , to the subgrid-scale vertical velocity, \bar{w}_c :

$$\sigma_2 = \frac{\bar{w}}{\bar{w}_c} \quad (5)$$

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 will add 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.

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 can improve the forecasts at certain lead times within this range, it is in any way 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 lead time and 96- to 108-hour lead time, 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 captured a more accurate location of the rain ban, 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 will add a sentence to describe the consistent improvements in CRH across a range of forecast lead times in the revised manuscript.

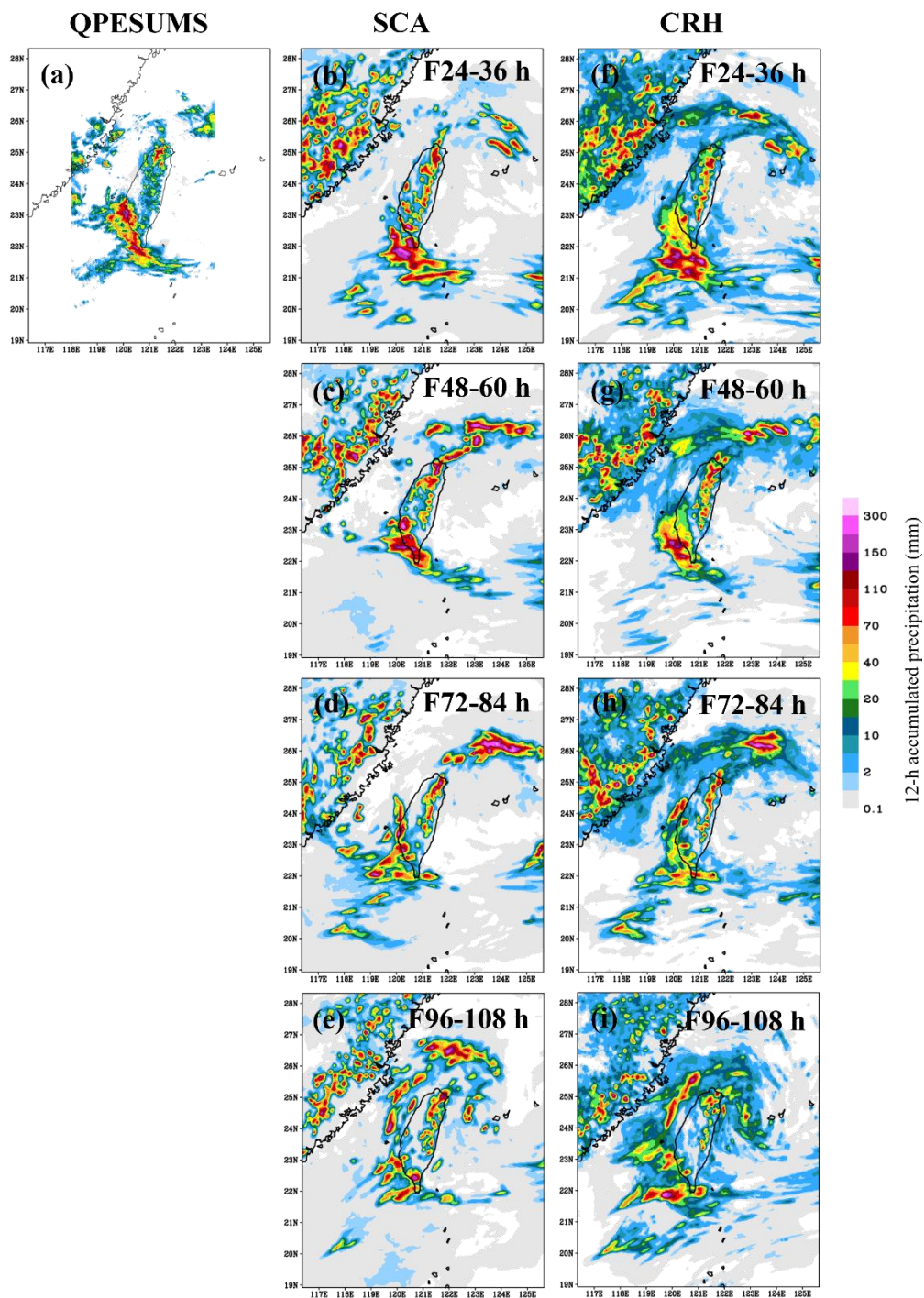


Figure R7: (a) 12-h accumulated precipitation (mm) from 00 to 12 UTC on 10 August 2023 based on QPESUMS observation. The 12-h accumulated precipitation forecasts from the (b)–(e) SCA and (f)–(i) CRH experiments for various lead times of (b), (f) 24–36-h, (c), (g) 48–60-h, (d), (h) 72–84-h and (e), (i)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

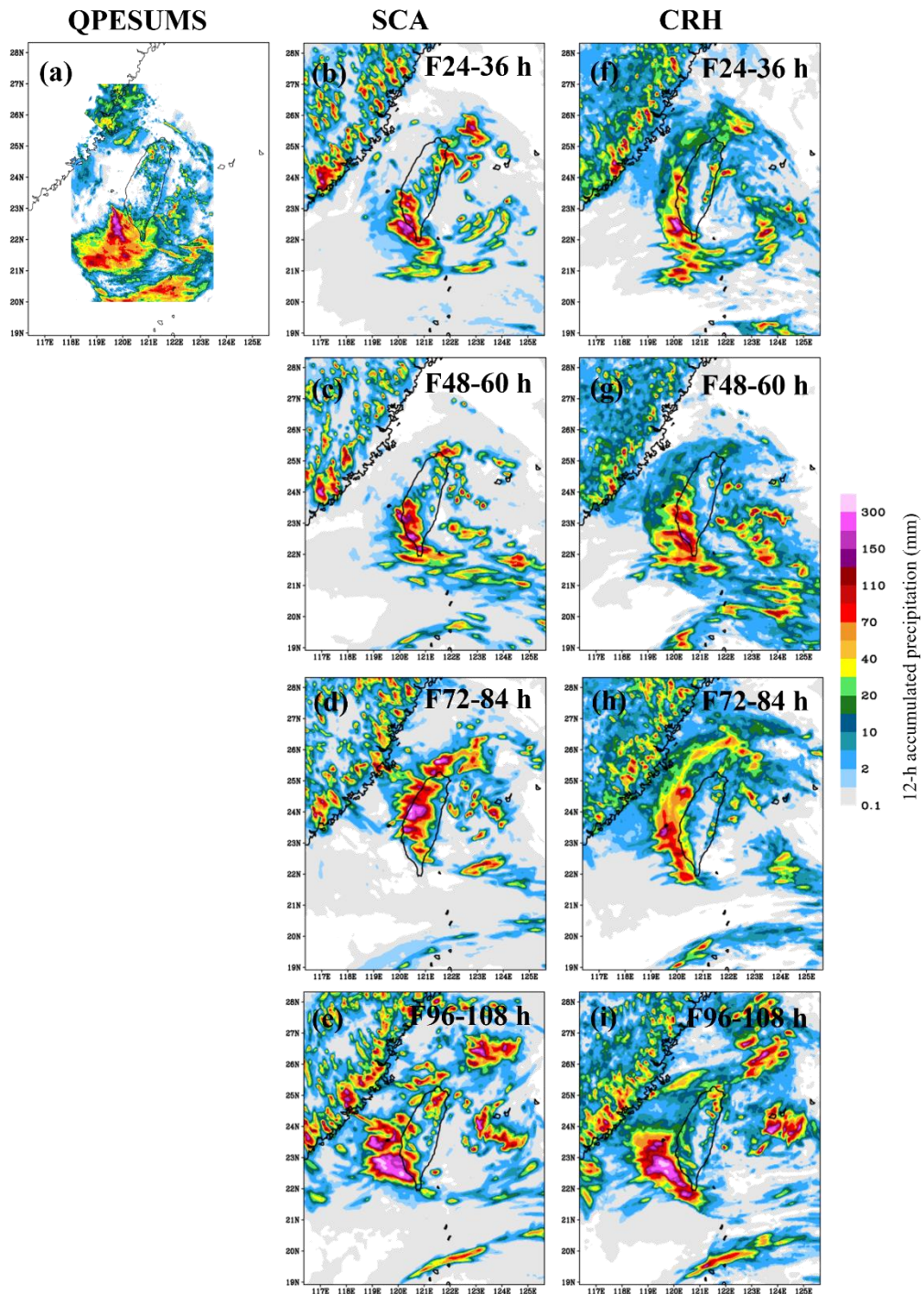


Figure R8: Same as Fig. R7, but for the case on 17 August 2023.

- 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.