

1 **Sensitivity of the Summertime Diurnal Precipitation Cycle over _**
2 **Three Representative Regions of China to Convective Trigger and**
3 **Closure Treatments in a Single-Column Model**

4 **Xiaocong Wang^{1*}, Yanjie Liu^{1, 2}, Yimin Liu^{1, 2}**

5
6 *¹Institute of Atmospheric Physics (IAP), Chinese Academy of Sciences (CAS), Beijing, China*

7 *²College of Earth and Planetary Sciences, University of Chinese Academy of Sciences (UCAS),*
8 *Beijing, China*

9
10 Submitted to *Atmospheric Chemistry and Physics* (*revised*)

11 September 18, 2026

12
13
14
15
16
17
18
19
20 Correspondence to:

21 X. Wang, wangxc@lasg.iap.ac.cn
22
23

删除了:

删除了: July

删除了: 5

Abstract:

Using a single-column model, we investigate how trigger and closure treatments in ZM, TDK, and UNICON convection schemes affect the diurnal cycle of precipitation over China. For late-afternoon rainfall, TDK and ZM schemes with standard CAPE closure simulate precipitation peaks around noon, substantially earlier than observed. The UNICON scheme, with cold-pool feedback deactivated, also produces a noontime peak. For nocturnal rainfall, all schemes spuriously produce a noontime peak, in stark contrast to the observed nocturnal maximum. These behaviors are closely related to closure assumptions and the resulting cloud-base mass flux, which is primarily governed by CAPE in ZM and TDK, and responds more directly to surface fluxes in UNICON. By accounting for the imbalance between deep convection and boundary-layer production through specific modifications: adopting the dCAPE trigger in ZM, activating cold-pool feedback in UNICON, and applying the non-equilibrium closure in TDK, the simulated afternoon precipitation is delayed and in better agreement with observations. In addition, allowing elevated convection in ZM and UNICON improves nocturnal rainfall. The improved diurnal cycle is also evident in the diabatic heating fields. All modifications lead to a delayed and more pronounced upward-tilting heating structure as a result of the suppression of early-afternoon convection, with ZM and TDK extending to higher altitudes, while both intensified and extended in UNICON. These changes alleviate the upper-level cold bias in TDK and ZM. In UNICON, however, the overly strong convection reverses the upper-tropospheric bias from cold to warm with stronger magnitude, thereby worsening the bias.

1. Introduction

The diurnal cycle of precipitation (DCP), which plays a critical role in modulating the surface energy budget and hydrology, has long been recognized as a fundamental mode of variability in the climate system (Trenberth et al., 2003). In addition, DCP also acts as a building block for the large-scale organization of precipitation systems, including convectively coupled equatorial waves and the Madden–Julian Oscillation (Mapes et al., 2006). Therefore, accurate simulation of DCP is not only essential for advancing the precision of “timing–location–intensity” in fine-scale forecasting (Dai and Trenberth, 2004; Chen et al., 2017), but also important for improving processes across a range of temporal and spatial scales—from convective systems to intraseasonal disturbances (Benedict et al., 2013). Nevertheless, DCP modeling in general circulation models (GCMs) remains a persistent challenge, as evidenced by a premature afternoon peak over land and a frequent inability to capture nocturnal rainfall maxima downwind of major orography (Dai, 2006; Lee et al., 2007; Tang et al., 2022).

Over land, the observed DCP typically peaks in late afternoon during summer, partly due to the strong diurnal cycle of surface heat flux that modulates convection (Dai et al., 1999; Li et al., 2008). However, on the leeward side of mountainous regions such as the Tibetan Plateau and the Rockies, the maximum precipitation is often observed in late night, owing to the propagation of mesoscale convective systems induced by terrain–forced circulations (Carbone and Tuttle, 2008; Zhang et al., 2014). Because DCP is closely related to changes in surface temperature and boundary-layer structure on much shorter timescales, it poses a fundamental challenge to the equilibrium

71 assumption commonly used in convection parameterizations (Davies et al., 2013). In
72 this sense, DCP provides a measure of how well a GCM represents the response of
73 cumulus convection to large-scale and surface forcing. Many schemes initiate
74 convection based on convective available potential energy (CAPE), which responds
75 rapidly to solar heating, resulting in overly frequent and premature triggering of
76 afternoon convection (e.g., Xie and Zhang, 2000; Lee et al., 2007; Yang et al., 2018).
77 On the other hand, the failure to capture nocturnal precipitation is often attributed to the
78 inadequate representation of elevated convection originating above the boundary layer.
79 (Lee et al., 2008; Wang et al., 2015; Xie et al., 2019). To overcome these deficiencies,
80 increasing efforts have been devoted to developing improved trigger and closure
81 treatments. For example, Xie and Zhang (2000) proposed dynamic CAPE (dCAPE)
82 triggering, which initializes convection only when the large-scale CAPE production
83 exceeds a critical value. Bechtold et al. (2014) accounted for CAPE consumption by
84 shallow convection and modified the closure to subtract its contribution from the total
85 mass flux. Park (2014a) incorporated subgrid mesoscale organized flow and its
86 feedback into the convection parameterization, enabling the successful simulation of
87 various convection-related transitional phenomena including DCP. To better simulate
88 nocturnal rainfall, Wang et al. (2015) allows parcels to be initiated from above the
89 boundary layer, thereby improving the simulation of elevated nocturnal convection over
90 the central Great Plains. This triggering concept was later used in Xie et al. (2019) and
91 Park et al. (2024). While these modifications have mitigated certain DCP biases at the
92 testing sites, it remains unclear how well they generalize to regions with markedly

different climatic and topographic conditions, such as China. The present study is therefore motivated to assess their effectiveness of DCP simulation over China. Additionally, despite the documented improvements in DCP simulation achieved by various approaches, a systematic intercomparison of their performance and underlying mechanisms has yet to be conducted. Liu et al. (2026) performed a process-oriented analysis that traces DCP errors over China in three reanalyses to specific parameterized physical processes, highlighting the critical role of convective trigger in shaping DCP. This study builds on Liu et al. (2026) by using a single-column model (SCM) to further explore the sensitivity of DCP to modifications in convective trigger and closure treatments. Specifically, we assess how precipitation varies diurnally under different trigger and closure treatments, aiming to elucidate the physical mechanisms behind. The remainder of this paper is structured as follows. Section 2 describes the case setup, model configurations, and experimental design. Section 3 presents modifications to the convection schemes and examines the DCP sensitivity to different parameterization settings, along with the underlying mechanisms. Section 4 analyzes the diurnal variations of diabatic heating and convective eddy transport of moist static energy (MSE). Section 5 discusses the implications for temperature and moisture simulations, and Section 6 summarizes the main findings.

删除了: for

删除了: elucidating

2. Case, Model and Experiments

2.1 Case Description

The three representative regions used in this study are $4^{\circ}\times 4^{\circ}$ subregions of those in Liu

et al. (2026): the Tibetan Plateau (TP, 31°–35°N, 90°–94°E), southeastern China (SECN, 24°–28°N, 112°–116°E), and the Sichuan Basin (SCB, 28°–32°N, 103°–107°E). Among these, TP and SECN are characterized by late-afternoon rainfall regimes, while SCB features a nocturnal regime. For each region, DCP is simulated and analyzed over the summer from 1 June to 31 August 2021. The initial and large-scale forcing fields used to drive SCMs are derived from ERA5 reanalysis (Hersbach et al., 2020), facilitated by the open-source Python package named the “Large-eddy simulation and Single-column model—Large-Scale Dynamics” (van Stratum et al., 2023). Note that although ERA5 remains one of the most reliable reanalyses, it carries inherent uncertainties. However, considering that this study focuses on the sensitivity of different trigger and closure treatments in influencing DCP, ERA5 forcing suffices for this purpose.

2.2 Model and Experimental Design

We use the single column version of the Community Atmospheric Model (CAM) for SCM simulations, which features a suite of parameterization schemes for cumulus convection (Gettelman et al., 2019). In this study, three distinct configurations are compared: CAM_ZM, CAM_UNICON, and CAM_TDK. In the CAM_ZM setup, deep convection is parameterized using the Zhang & McFarlane (1995) scheme, whereas shallow convection is treated with the Park & Bretherton (2009) scheme. CAM_UNICON employs a unified framework for both shallow and deep convection (Park, 2014a). In addition to ZM and UNICON, the bulk mass-flux scheme originally

删除了: Note that although ERA5 remains one of the most reliable reanalyses in dynamic and thermodynamic fields, it still shows limited capability in representing the accurate diurnal cycle of diabatic heating, as documented in Liu et al. (2026). Therefore, the results should be interpreted with caution when compared against ERA5-derived fields.

设置了格式: 字体: 倾斜

删除了: are

146 proposed by Tiedtke (TDK; 1989) and later updated by Bechtold et al. (2014) was also
147 implemented for comparison, referred to as CAM_TDK. Other parameterizations are
148 set the same across all configurations. The parameterization of ~~planetary~~ boundary layer
149 (PBL) turbulence is according to Bretherton & Park (2009). Cloud microphysics is
150 represented by the double moment scheme of Morrison & Gettelman (2008). Radiative
151 transfer is calculated with the Rapid Radiative Transfer Model for GCMs (Clough et al.,
152 2005). For each convection scheme, two simulations are conducted: a control
153 experiment (CTRL) and a sensitivity experiment (SENS). For CAM_ZM, the
154 sensitivity experiment adopts the dCAPE trigger ~~of Xie & Zhang (2000)~~ and permits
155 elevated convection ~~as in~~ Xie et al. (2019). In CAM_UNICON, the control experiment
156 disables cold-pool feedback, whereas the sensitivity experiment activates cold-pool
157 feedback and allows elevated convection as described in Park et al. (2024). For
158 CAM_TDK, the control experiment employs the equilibrium closure, while the
159 sensitivity experiment applies the non-equilibrium closure as proposed by Bechtold et
160 al. (2014). Table 1 summarizes the key differences in parameterization components
161 across various configurations. To reduce model error accumulation, all simulations are
162 reinitialized daily at 00 UTC from June 1 to August 31 and integrated for 36 hours
163 ~~without relaxation~~. The last 24 hours of each 36-hour simulation are retained for
164 analysis.

删除了: planet

删除了: ,

删除了: following

删除了: While momentum fields are relaxed toward the reanalysis with a 3-hour timescale, no relaxation is applied to other variables.

删除了: ↵

↵

↵

Table 1 Parameterization configurations

Parameterization		CAM_ZM	CAM_TDK	CAM_UNICGN	格式化表格
convection	Deep	CTRL	CAPE-based trigger and closure <i>Zhang & McFarlane [1995]</i>	Equilibrium closure <i>Bechtold et al. [2014]</i>	Cold-pool feedback disabled <i>Park [2014a]</i>
	SENS	dCAPE trigger + elevated convection <i>Xie & Zhang [2000]; Xie et al. [2019]</i>	Non-equilibrium closure <i>Bechtold et al. [2014]</i>	Cold pool + elevated convection <i>Park et al. [2024]</i>	删除了: allowed
					删除了: -
	Shallow convection		<i>Bretherton & Park [2008]</i>	<i>Park [2014a]</i>	删除了: feedback enabled
	PBL turbulence		<i>Bretherton & Park [2009]</i>		删除了:
Cloud macrophysics			<i>Park et al. [2014]</i>		删除了: allowed
Cloud microphysics			<i>Morrison & Gettelman [2008]</i>		
Radiation			<i>Clough et al. [2005]</i>		

180 **2.3 Composite Analysis**

181 To isolate the typical DCP behavior, we performed a composite analysis by selecting
182 precipitation events that represent the characteristic DCP category for each region.
183 Following Liu et al. (2026), we selected afternoon-peaking (12:00–20:00 LST, local
184 solar time) days for TP and SECN, and nocturnal-peaking (20:00–08:00 LST) days for
185 SCB. We also required the daily maximum precipitation to exceed thresholds of 5 mm
186 d⁻¹ for TP and 10 mm d⁻¹ for SECN and SCB, consistent with those used by Liu et al.
187 (2026). By doing so, the influence of dry days, light precipitation, and days with diurnal
188 phases inconsistent with the target regime is excluded, thereby enhancing the DCP
189 signal. Unlike Liu et al. (2026) that used different event dates across the datasets, we
190 used the same fixed event dates derived from precipitation observations for all model
191 simulations. Although only one summer (2021) is used, this season still provides a
192 sufficient number of precipitation events for robust composite analysis: 49 days over

设置了格式: 字体: (默认) Times New Roman, (中文) Times New Roman, 字体颜色: 黑色

TP, 45 over SECN, and 34 over SCB. These sample sizes are comparable to those used in the observational composites of Liu et al. (2026).

删除了: ↩

3. Sensitivity of Diurnal Precipitation to Convection Schemes

3.1 Diurnal Precipitation in the Control Experiments

Figure 1 presents the period-averaged and case-composite diurnal variations of precipitation over the three regions from the control experiment. The observation is the Integrated Multi-satellitE Retrievals for Global Precipitation Measurement (IMERG) Final Run Version 07B (Huffman et al., 2023), with ERA5 precipitation also superimposed for reference. A comparison between the upper and middle rows reveals that the composite cycles align closely with the period-mean in phase, and the diurnal signals are amplified due to the removal of light-precipitation days. Over TP and SECN, the IMERG precipitation peaks around 18:00 LST, whereas all simulations produce rainfall peaks notably earlier than observed, with the maximum occurring near noon. In comparison, the ZM and TDK schemes initiate rainfall even earlier than UNICON and tend to produce a secondary peak over SECN—at 19:00 LST for ZM and at 17:00 LST for TDK. Note that ERA5 also exhibits an early phase bias over TP and SECN relative to IMERG, though less pronounced than the SCM simulations. The convective precipitation shown in the bottom closely resembles the total precipitation, suggesting that deficiencies in convection parameterization are largely responsible for the poor simulation of DCP. Over SCB, the observed precipitation exhibits a distinct nocturnal maximum around 03:00 LST, in stark contrast to the late-morning peak simulated by

CAM_ZM (Figure 1f). While CAM_TDK reasonably captures the nocturnal peak, it also produces an additional noontime maximum. Similar to ZM and TDK, the UNICON scheme also produces a noontime peak in convective precipitation (Figure 1i), with nocturnal rainfall being primarily contributed by large-scale precipitation.

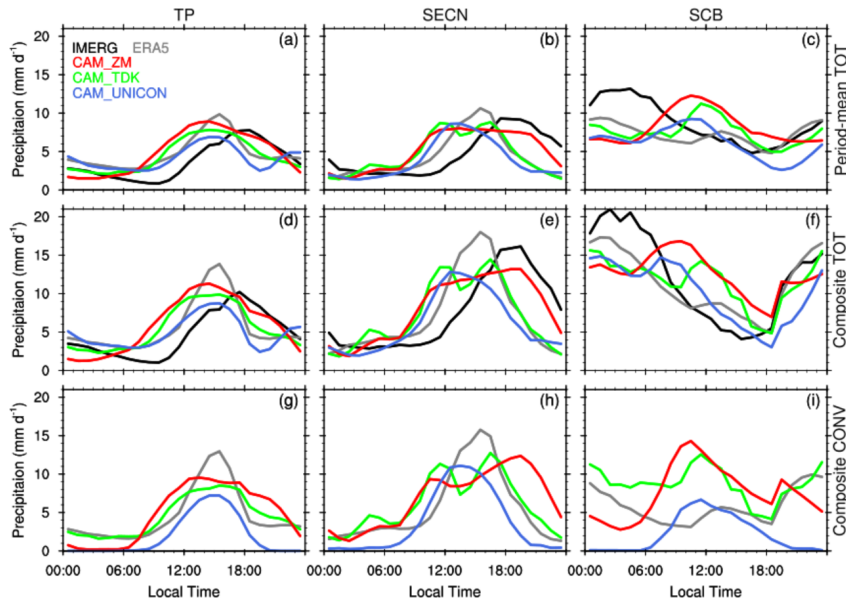


Figure 1 Period-averaged (a-c) and case-composite (d-i) diurnal precipitation cycles over TP (left), SECN (middle) and SCB (right) from IMERG, ERA5 and the SCM control simulation. Panels (g–i) show convective precipitation. In each panel, the red, green, and blue lines represent precipitation simulated by CAM_ZM, CAM_TDK, and CAM_UNICON, respectively.

To understand why SCM simulations produce noontime peaks in convective precipitation, we show in Figure 2 the cloud-base cumulus mass flux M_b and closure-related quantities in each convection scheme. Note that convective precipitation is proportional to the product of M_b and the updraft rain/snow content, with M_b itself

236 determined by the standard quasi-equilibrium closure as $\frac{CAPE}{\tau * F}$, where τ is the
 237 convective adjustment time scale and F is the CAPE consumption rate per unit mass
 238 flux. As noticed, M_b is generally in phase with PCAPE (density-weighted CAPE) in
 239 TDK, but shows little phase coherence with CAPE in ZM, both being computed within
 240 their respective convection schemes during active convection. Over TP, the ZM M_b
 241 peaks near 11:00 LST, well ahead of the CAPE maximum at 18:00 LST, due to the
 242 lower F at that time (Fig. S1 in the Supplement). The phase advance of M_b relative to
 243 CAPE is even more pronounced over SECN (Figure 2b). Higher CAPE is usually
 244 associated with deeper convection and greater vertically accumulated condensate,
 245 which, together with the M_b peak, tends to produce dual precipitation peaks in ZM
 246 (Figure 1h). The UNICON scheme does not rely on any equilibrium assumptions;
 247 instead, it initializes the thermodynamic properties of updraft plumes using the input
 248 surface flux. In all three regions, the UNICON M_b peaks around 14:00 LST, closely
 249 tracking the evolution of the launching vertical velocity derived from the surface
 250 turbulent kinetic energy (TKE).

删除了: ure

删除了: ; see Supplement for additional figures

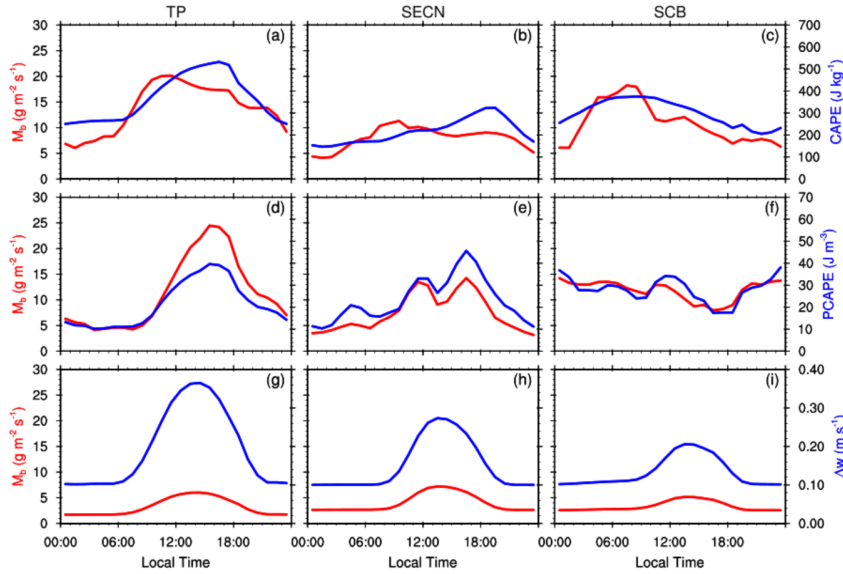


Figure 2 Cloud-base cumulus mass flux M_b and closure-related quantities in the control experiment of (a–c) CAM_ZM, (d–f) CAM_TDK and (g–i) CAM_UNICON over TP (left), SECN (middle) and SCB (right). The closure-related quantities are CAPE for ZM, PCAPE for TDK, and perturbations of updraft vertical velocity driven by symmetric turbulent eddies in the UNICON scheme.

3.2 Modification of Convection Schemes and Their Impact on Diurnal Precipitation

The cloud-base mass flux in ZM and TDK is based on the standard equilibrium closure, which assumes that CAPE is consumed at an exponential rate by cumulus convection with characteristic time scale. Donner and Phillips (2003) and Zhang (2002) pointed out that, although a CAPE quasi-equilibrium closure is well-suited for the free troposphere, it does not apply well to the entire troposphere including the boundary layer, particularly under rapidly varying boundary-layer forcing. Indeed, under weak large-scale forcing, boundary layer generation of CAPE dominates surface-driven

删除了: impact

convection (Bechtold et al., 2014). Hence, the strategy for improvement centers on how to properly account for the imbalance between deep convection and PBL production. Xie and Zhang (2000) addressed this by reducing M_b when dCAPE is below a threshold value of $100 \text{ J kg}^{-1} \text{ hr}^{-1}$, with the reduction factor linearly related to dCAPE:

$$M_b = \begin{cases} \frac{\text{CAPE}}{\tau.F} & \text{if } d\text{CAPE} > 100 \\ \frac{\text{CAPE}}{\tau.F} \cdot \frac{d\text{CAPE}}{100} & \text{if } d\text{CAPE} \leq 100 \end{cases} \quad (1)$$

The underlying reasoning is that when large-scale dynamic forcing is weak, *i.e.*, small positive dCAPE, the convective adjustment time scale is typically larger. Bechtold et al. (2014) addressed this by subtracting from the total mass flux a fraction of shallow convective contribution that is supposed to approximately balance the boundary layer forcing. Park (2014a) attributed the inability to accurately simulate the DCP, in part, to the absence of plume memory under the diagnostic quasi-equilibrium approximation. He then developed an approach that incorporates additional plume memory through the prognostic cold pool and employs this memory to reconstruct convective plumes at subsequent time steps. Figure 3 presents M_b for each scheme in the sensitivity experiment, with the aforementioned modifications applied. A notable change is that for both TP and SECN, the M_b peak shifts to approximately 18:00 LST across all schemes, matching the observed precipitation peak much more closely. Each scheme accomplishes this improvement through a different mechanism. In CAM_ZM, this improvement primarily stems from dCAPE trigger, as for daytime convection, the launching level remains near the surface even though the implementation of elevated convection allows parcels to be launched above PBL. As noticed, dCAPE (dashed lines

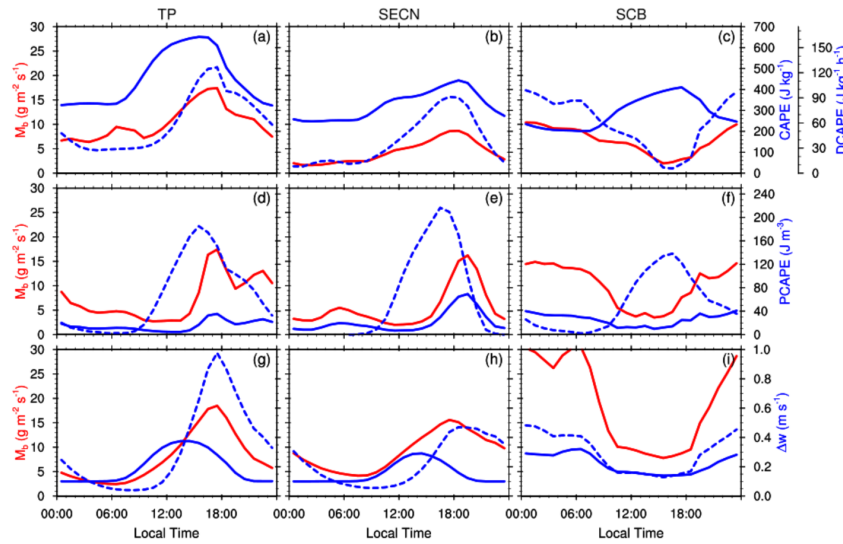
删除了:.

设置了格式: 字体: (默认) Times New Roman, (中文) Times New Roman, 字体颜色: 黑色

设置了格式: 字体: (中文) 宋体

带格式的: 正文, 两端对齐, 段落间距段前: 6 磅, 段后: 6 磅, 行距: 单倍行距, 制表位: 3 字符, 列表制表位

in Figure 3a, b) peaks around 18:00 LST and is much smaller near noon, which suppresses the early M_b peak in CTRL and shifts the main maximum toward 18:00 LST. In CAM_TDK, the PBL contribution to PCAPE peaks around 16:00 LST (dashed lines in Figure 3d, e), accounting for a large portion of the total PCAPE at that time. After subtracting this contribution, the resulting PCAPE and M_b peaks are delayed to 17:00 LST over TP and 19:00 LST over SECN, approximately 1–2 hours later than in CTRL. It is worth noting that the dual M_b peak in the control experiment of both CAM_ZM and CAM_TDK over SECN now merges into a single peak. In CAM_UNICON, while the updraft perturbations from symmetric turbulent eddies still peak around noon, the enabled cold-pool-driven mesoscale flow generates pronounced dynamic uplift forcing around 18:00 LST, ultimately shifting the M_b peak toward 18:00 LST.



删除了: ←

306 **Figure 3** Same as Figure 2, but for the sensitivity experiments. The dashed blue lines in each row
307 denote, respectively: dCAPE in ZM, the PBL contribution to PCAPE in TDK, and perturbations
308 induced by subgrid cold pools and external mesoscale upflow in UNICON.

309

310 For elevated convection over SCB, Figure 4 compares the time-pressure cross-sections
311 of the launching level frequency and updraft mass flux between the control and
312 sensitivity runs. In all control simulations except CAM_TDK, afternoon convection
313 prevails, whereas nocturnal convection remains very weak. Both CAM_ZM and
314 CAM_UNICON restrict the launch level to near the surface, inhibiting convection
315 initialization during nighttime because of the strong nocturnal inversion that develops
316 above the PBL. CAM_TDK, however, is not subject to this restriction. It produces
317 significant updraft mass during nighttime and early morning, frequently triggering
318 elevated convection below 800 hPa (Figure 4b). Notably, sporadic launching-level
319 peaks occur at levels ever higher than 600 hPa, directly related to the TDK's treatment
320 of mid-level convection. Removing the boundary-layer origin constraint in ZM and
321 UNICON leads to stronger nocturnal convection, weaker afternoon convection, and a
322 markedly raised launch level relative to the control runs (Figure 4d, f). This
323 improvement is also manifested in the diurnal variation of M_b (rightmost column of
324 Figure 3), with a maximum at night and a minimum around midday. Most strikingly,
325 CAM_TDK also yields stronger nocturnal convection in the sensitivity run (Figure 4e),
326 likely because the exclusion of PBL-contributed PCAPE, (Figure 3f) suppresses,
327 daytime convection, thereby favoring subsequent nocturnal development.

328

删除了: 7

设置了格式: 字体: 小四

删除了: PCAPE

删除了: by PBL

删除了: during the daytime

删除了: the suppression of daytime

删除了: thus

删除了: s

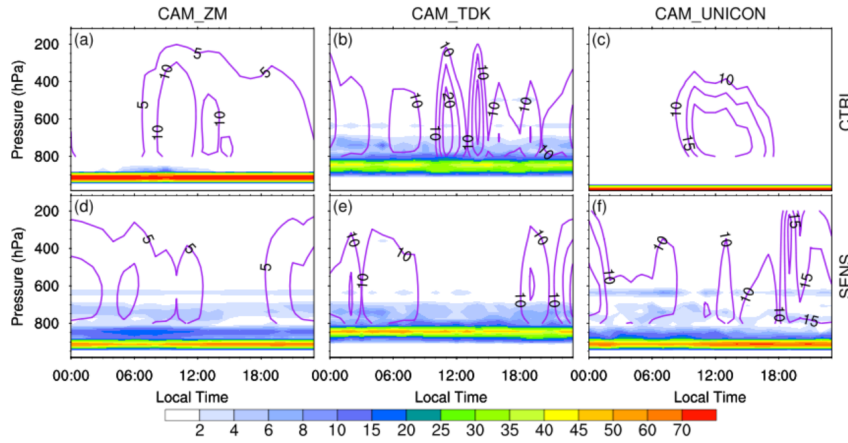


Figure 4 Time-pressure cross-sections of launching-level frequency (shaded, units: %) and updraft mass flux (contour, units: $\text{g m}^{-2} \text{s}^{-1}$) over SCB for the control (top) and sensitivity (bottom) experiments. From left to right, the panels show results from CAM_ZM, CAM_TDK, and CAM_UNICON, respectively.

Figure 5 compares the DCP simulation between CTRL and SENS experiments. As anticipated, all modifications result in improved diurnal precipitation cycles when compared with the control runs. For all three schemes, the premature afternoon precipitation over TP and SECN is substantially delayed, aligning better with observations. This delayed response is largely attributable to the delay in simulated convective precipitation (dashed lines). Note the stronger precipitation in the CAM_UNICON sensitivity experiment is due to positive perturbations in updraft vertical velocity, temperature, and moisture, driven by mesoscale organized flow (Park, 2014b; Wang et al., 2026). Over SCB, the excessive afternoon rainfall and insufficient nocturnal precipitation in the control experiments of CAM_ZM and CAM_UNICON are substantially improved in the sensitivity experiments. Although no explicit modification is made for elevated convection in CAM_TDK, nocturnal precipitation is

354 also enhanced in the sensitivity experiment (Figure 5f), presumably due to the reduced
355 afternoon convective stabilization resulting from the removal of shallow convective
356 contribution in the closure. A similar daytime-to-nocturnal convective interaction has
357 also been documented by Xie et al. (2019) and Park et al. (2024), who found that
358 suppressing daytime convection can strengthen nocturnal precipitation.

359 We note that each sensitivity experiment for ZM and UNICON modifies two factors
360 simultaneously. For example, in CAM_ZM, the M_b scaling that primarily targets
361 afternoon convection also influences nocturnal convection. To address this confounding
362 issue, we performed additional isolated experiments and examined the individual
363 contributions. The trigger-only experiment behaves similarly to CTRL and does not
364 improve nocturnal precipitation (purple curves in Figs. S2a and S2b). In contrast, the
365 elevated-convection-only experiment captures the nocturnal precipitation peak but
366 overestimates daytime precipitation. Only the combined experiment, which includes
367 both the dCAPE trigger and elevated convection, reproduces the nocturnal precipitation
368 peak as well as the daytime precipitation minimum well. For UNICON, we conducted
369 a similar set of experiments but did not isolate the elevated-convection-only case,
370 because elevated convection is intrinsically coupled to the cold-pool-driven mesoscale
371 flow in this scheme. The cold-pool feedback alone substantially enhances convective
372 precipitation relative to CTRL (Fig. S2d). However, total nocturnal precipitation is
373 slightly lower than in CTRL (Fig. S2c). Therefore, the improvement in nocturnal
374 precipitation is achieved only when elevated convection is included.

设置了格式: 字体: (默认) Times New Roman, (中文) Times New Roman, 字体颜色: 黑色

设置了格式: 字体: (默认) Times New Roman, (中文) Times New Roman, 字体颜色: 黑色

设置了格式: 字体: (默认) Times New Roman, (中文) Times New Roman, 字体颜色: 黑色

带格式的: 正文, 两端对齐, 段落间距段前: 6 磅, 段后: 6 磅, 制表位: 3 字符, 列表制表位

设置了格式: 字体: (默认) Times New Roman, (中文) Times New Roman, 字体颜色: 黑色

设置了格式: 字体: (默认) Times New Roman, (中文) Times New Roman, 字体颜色: 黑色

设置了格式: 字体: (默认) Times New Roman, (中文) Times New Roman, 字体颜色: 黑色

设置了格式: 字体: (默认) Times New Roman, (中文) Times New Roman, 字体颜色: 黑色

设置了格式: 字体: (默认) Times New Roman, (中文) Times New Roman, 字体颜色: 黑色

设置了格式: 字体: (默认) Times New Roman, (中文) Times New Roman, 字体颜色: 黑色

设置了格式: 字体: (默认) Times New Roman, (中文) Times New Roman, 字体颜色: 黑色

设置了格式: 字体: (默认) Times New Roman, (中文) Times New Roman, 字体颜色: 黑色

设置了格式: 字体: (默认) Times New Roman, (中文) Times New Roman, 字体颜色: 黑色

设置了格式: 字体: (默认) Times New Roman, (中文) Times New Roman, 字体颜色: 黑色

设置了格式: 字体: (默认) Times New Roman, (中文) Times New Roman, 字体颜色: 黑色

设置了格式: 字体: (默认) Times New Roman, (中文) Times New Roman, 字体颜色: 黑色

设置了格式: 字体: (默认) Times New Roman, (中文) Times New Roman, 字体颜色: 黑色

设置了格式: 字体: (默认) Times New Roman, (中文) Times New Roman, 字体颜色: 黑色

设置了格式: 字体: (默认) Times New Roman, (中文) Times New Roman, 字体颜色: 黑色

设置了格式: 字体: (默认) Times New Roman, (中文) Times New Roman, 字体颜色: 黑色

设置了格式: 字体: (默认) Times New Roman, (中文) Times New Roman, 字体颜色: 黑色

设置了格式: 字体: (默认) Times New Roman, (中文) Times New Roman, 字体颜色: 黑色

设置了格式: 字体: (默认) Times New Roman, (中文) Times New Roman, 字体颜色: 黑色

设置了格式: 字体: (默认) Times New Roman, (中文) Times New Roman, 字体颜色: 黑色

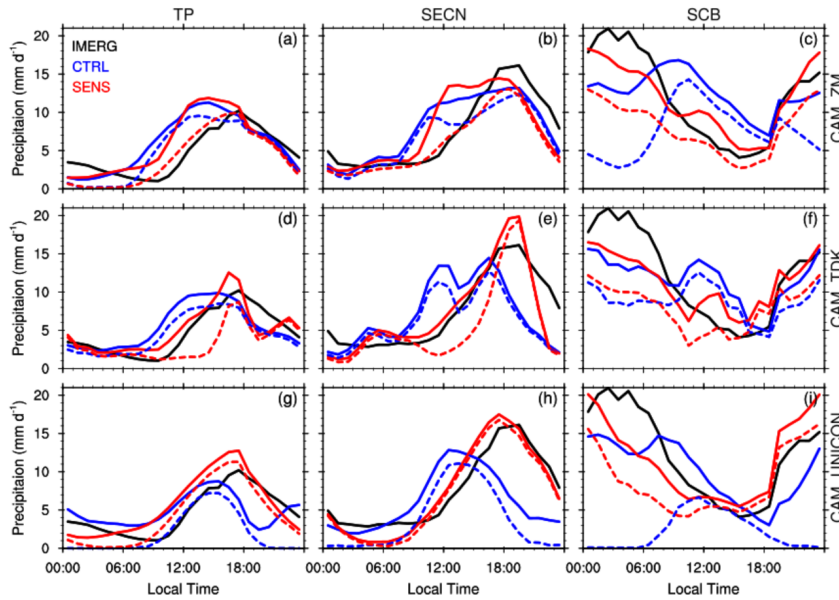


Figure 5 Diurnal cycles of total (solid) and convective (dashed) precipitation over TP (left), SECN (middle), and SCB for the control (blue) and sensitivity (red) runs of each convection scheme. From top to bottom, the panels show DCP simulated by CAM_ZM, CAM_TDK, and CAM_UNICON, respectively.

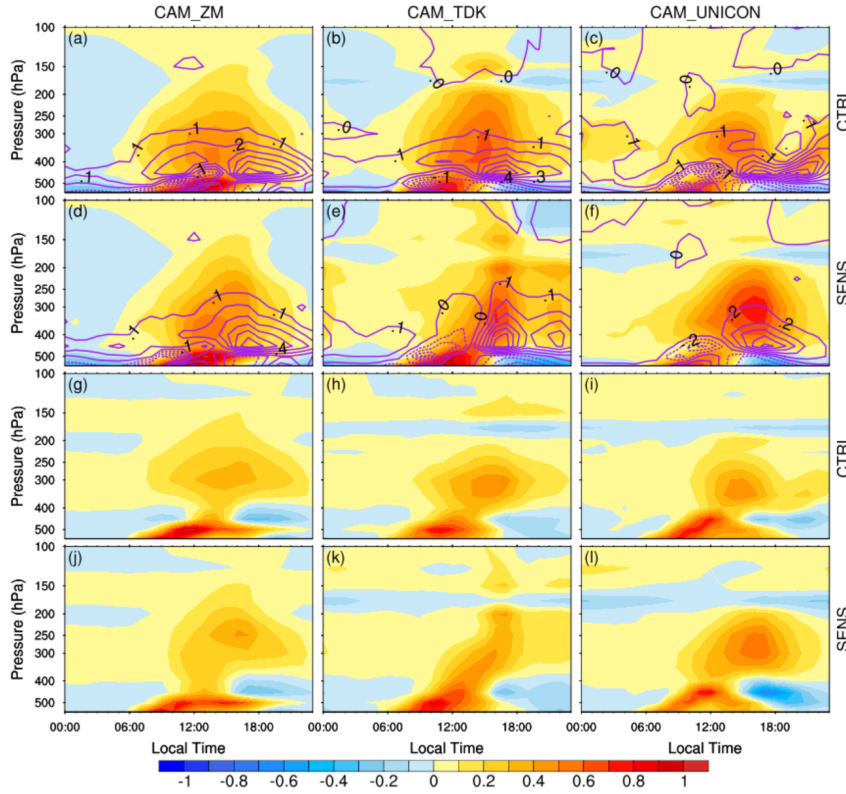
4. Diurnal Variation of Diabatic Heating

删除了: variation

To examine the impact of modified convection schemes on diabatic heating, Figure 6 presents the diurnal cycles of apparent heating Q_1 and moisture sink Q_2 over TP for both control and sensitivity experiments. These quantities are computed as the sum of tendencies from individual parameterizations. A common feature is the upward-tilting Q_1 structure, which extends from PBL in the morning to mid-tropospheric levels later in the day. This evolution features an early stage with positive Q_1 and negative Q_2 in the lower troposphere, followed by a transition to positive values for both Q_1 and Q_2 aloft once deep convection develops. Although all SCMs reasonably reproduce this

392 upward-tilting structure, they differ notably in the timing and height of the peak heating.
 393 Relative to their control experiments, CAM_TDK and CAM_UNICON delay and
 394 elevate the heating peak, resulting in a more pronounced upward-tilt structure (Figure
 395 6e, f). Moreover, CAM_UNICON exhibits a stronger heating amplitude, consistent
 396 with its intensified convection. While the ZM heating center shows no clear phase shift
 397 between the control and sensitivity experiments, it tends to extend upward to higher
 398 altitudes over time in the sensitivity run (Figure 6d). Notably, the noontime Q_2 peak
 399 near 400 hPa is strongly suppressed in all sensitivity experiments, thereby alleviating
 400 the overly strong early-afternoon precipitation in the control. The lower positioning of
 401 the Q_2 peak relative to Q_1 is indicative of pronounced subgrid-scale MSE transport,
 402 which is presented in the bottom two rows of Figure 6 as the term $Q_1 - Q_2 - Q_{rad}$,
 403 where Q_{rad} denotes radiative heating. After sunrise, $Q_1 - Q_2 - Q_{rad}$ is initially
 404 positive and continues to rise due to subgrid-scale transport from turbulence and
 405 shallow convection. As the cycle progresses, a characteristic dipole structure emerges
 406 in its vertical profile—negative anomalies dominate below 400 hPa, while positive
 407 anomalies prevail aloft—a typical signature of well-organized deep convection. All
 408 three schemes show a more pronounced upward-tilting structure in the sensitivity
 409 experiment than in the control, owing to the delayed onset of deep convection.

410



411

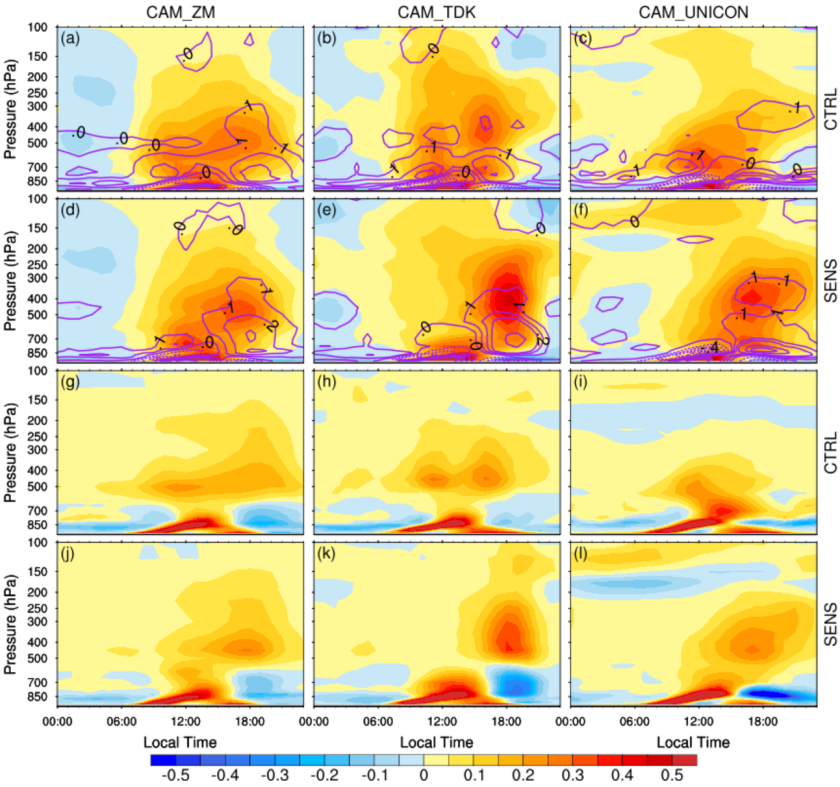
412 **Figure 6** The diurnal cycles of (a–f) apparent heating Q_1 (shaded), moisture sink Q_2 (contour)
 413 and (g–l) subgrid-scale MSE transport $Q_1 - Q_2 - Q_{rad}$ over TP for both control and sensitivity
 414 experiments. From left to right, the panels show results from CAM_ZM, CAM_TDK, and
 415 CAM_UNICON, respectively. In the upper two panels, solid lines are for contours greater than
 416 or equal to zero and dashed lines for contours less than zero. Units: $K h^{-1}$.

417

418 Similar discrepancies between control and sensitivity runs are also evident over SECN
 419 (Figure 7). All sensitivity runs exhibit a suppression of the early Q_2 peak,
 420 accompanied by a delayed and elevated Q_1 peak and a more pronounced
 421 upward-tilting structure in subgrid-scale MSE transport. It is worth noting that
 422 CAM_UNICON exhibits more coherent vertical organization in subgrid-scale MSE

transport than CAM_ZM and CAM_TDK, particularly during the transition from shallow to deep convection, underscoring the benefit of UNICON's unified convection framework. Figure 8 presents the diurnal cycles of diabatic heating over SCB, where a notable difference from TP and SECN is the dominance of nocturnal heating. This nocturnal heating in the control runs of CAM_ZM and CAM_UNICON is primarily due to large-scale condensation, as indicated by the relatively weak subgrid-scale MSE transport at night (Figure 8g, 8i). In contrast, the stronger MSE transport in CAM_TDK (Figure 8h) suggests that convection contributes substantially to its heating. All sensitivity experiments exhibit enhanced nocturnal convection, with both Q_1 and subgrid-scale MSE transport strengthened during nighttime. Conversely, the diabatic heating at noontime is substantially suppressed, in line with the reduced precipitation at that time.

435

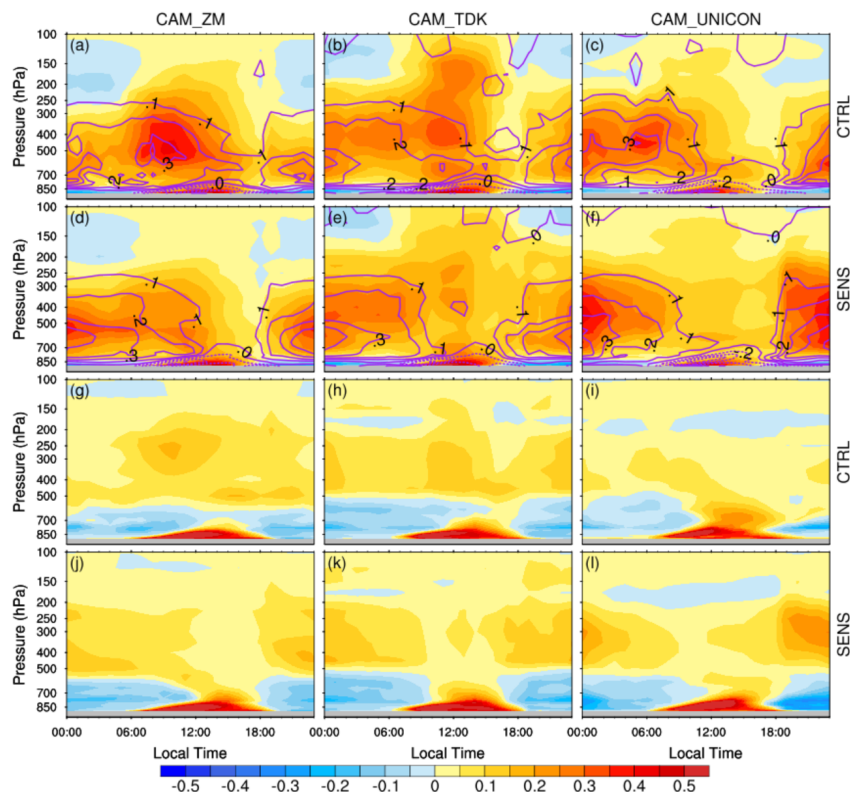


436

437 **Figure 7** Same as Figure 6, but for SECN.

438

439



440

441 **Figure 8** Same as Figure 6, but for SCB.

442

443 **5. Impact of Convection Scheme Modifications on Thermodynamic**
444 **Fields**

445 While the modified convection schemes improve the diurnal phase of precipitation and
446 associated diabatic heating, they also tend to produce deep and/or stronger convection,
447 particularly in CAM_UNICON. To assess whether these changes have an adverse
448 impact on temperature and moisture biases, we examine the model's thermodynamic
449 performance in this section.

449

设置了格式: 字体: (中文)+中文正文 (DengXian)

5.1 Diurnally Averaged Q_1 and Q_2 : Simulation vs. ERA5

Figure 9 compares the simulated diurnally averaged Q_1 and Q_2 profiles against ERA5-derived ones, along with their deep convective contributions in each SCM. The Q_1 and Q_2 derived from ERA5 reanalysis are calculated as residuals of the thermodynamic equation and moisture continuity equation, following Yanai et al. (1973). Relative to ERA5, the CAM_TDK control run over TP exhibits a positive Q_1 bias of approximately 2 K d^{-1} throughout the troposphere and a negative Q_2 bias of approximately 2 K d^{-1} between 400 and 450 hPa (Figure 9d). While these biases are considerably alleviated in the sensitivity experiment below 450 hPa, a positive Q_1 bias is exaggerated aloft, largely a consequence of convection penetrating to higher altitudes. The CAM_UNICON control run exhibits a bias pattern similar to that of CAM_TDK (Figure 9g), yet the biases are further amplified in the sensitivity run, as a result of the strengthened deep-convective component. The ZM scheme shows a notably smaller Q_1 bias than TDK and UNICON above 450 hPa, yet exhibits a pronounced positive bias of up to 6 K d^{-1} near 500 hPa (Figure 9a). While the Q_1 and Q_2 profiles remain broadly comparable between the control and sensitivity experiments, the convective component is notably weaker in the latter, implying that other physical processes (e.g., large-scale condensation) compensate for the reduced convective heating (Wang and Zhang, 2013). Over SECN, the Q_1 simulations from all SCMs show better overall performance than over TP, with biases remaining mostly within $\pm 1 \text{ K d}^{-1}$. Compared with ERA5, all simulations systematically overestimate Q_2 in the lower troposphere and underestimate it in the upper troposphere. As over the TP, the convective component in

删除了: averaged

删除了: Observation vs.

设置了格式: 字体: (中文)+中文正文 (DengXian)

删除了: observations

删除了: observed

删除了: are

删除了: observations

删除了: observations

479 the sensitivity runs of CAM_TDK and CAM_ZM extends to higher altitudes, while in
480 CAM_UNICON it is both intensified and extends further upward. For nocturnal
481 convection over SCB, the ZM scheme performs satisfactorily for Q_2 , yet exhibits a
482 positive Q_1 bias below 500 hPa and a negative bias above. In contrast,
483 CAM_UNICON simulates Q_1 well, but substantially underestimates Q_2 across the
484 entire troposphere. In comparison, CAM_TDK exhibits overall good agreement with
485 ERA5 for both Q_1 and Q_2 . While the modifications substantially improve Q_2 in
486 UNICON, they yield no marked improvement in Q_1 for ZM. It should be noted that
487 the ERA5 reference used here carries inherent uncertainties associated with its
488 convection scheme. By definition, Q_1 and Q_2 are derived as residuals of the
489 thermodynamic and moisture continuity equations, both of which involve vertical
490 advection terms. Vertical advection depends on vertical velocity, which is itself
491 strongly influenced by the model's physical parameterizations—especially convection.
492 For example, if convection is under-represented in ERA5, the associated vertical
493 velocity would be weaker, leading to an underestimation of Q_1 and Q_2 .

删除了: observations

设置了格式: 字体: (中文) 宋体, 字体颜色: 自动设置

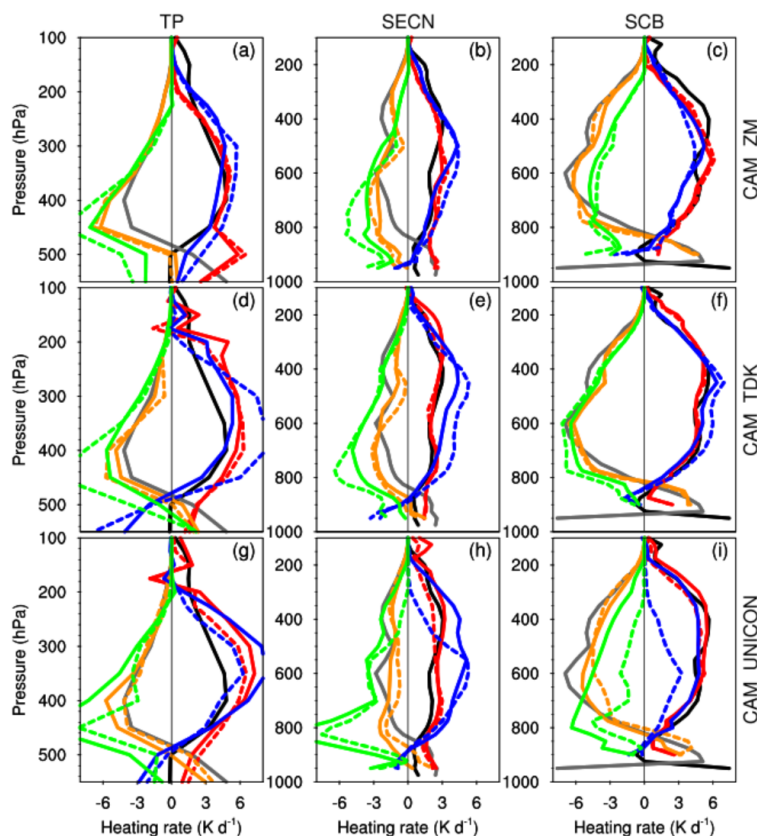


Figure 9 Simulated profiles of Q_1 (red) and Q_2 (orange) compared with **ERAS** (black for Q_1 , gray for Q_2), along with the deep convective component of Q_1 (blue) and Q_2 (green) in each SCM. Dashed and solid lines denote the control and sensitivity experiments, respectively. From top to bottom, the panels show results from CAM_ZM, CAM_TDK, and CAM_UNICON, respectively. Units: K d^{-1} .

5.2 Temperature and Moisture Biases

Figures 10 and 11 show the temperature and moisture differences, respectively, between the control run and ERA5 reanalysis (shaded), overlaid with the sensitivity-control differences (contours). Over TP, all three schemes exhibit a band of cold bias of up to 2 K in the upper troposphere during the late afternoon, as well as cold biases of similar

删除了: observations

删除了: moisture

删除了: biases

带格式的: Body 1, 左, 段落间距段前: 0 磅, 段后: 0 磅, 行距: 2 倍行距, 制表位: 不在 3 字符

510 magnitude near the surface at noon. Note that the surface cold bias is accompanied by
511 a dry bias of -1 g kg^{-1} , reflecting excessive subgrid-scale MSE transport at noon. A dry
512 bias is also found around 400 hPa after 18:00 LST in CAM_ZM and CAM_TDK, which
513 is consistent with their excessive precipitation relative to ERA5 (Figure 1d). In the
514 sensitivity experiments, the upper-level cold bias in CAM_TDK and CAM_UNICON
515 is substantially reduced (Figures 10d, g), consistent with the enhanced Q_1 above
516 250 hPa (Figures 9d, g). The ZM scheme exhibits no significant differences, owing to
517 the close resemblance in Q_1 between the two runs (Figure 9a). The late-afternoon dry
518 bias is also alleviated in the modified TDK and ZM schemes (Figures 11a, d). In
519 CAM_UNICON, the delayed onset and enhanced intensity of convection in the
520 sensitivity run cause the original mid-to-lower tropospheric wet bias into a dry bias
521 (Figure 11g, Fig. S3g). The bias patterns over SECN are broadly analogous to those
522 over TP, characterized by a cold bias above 200 hPa, a cold and dry bias near the surface
523 at noontime, and a negative moisture bias in the lower troposphere during the late
524 afternoon. Moreover, a warming bias between 200 and 700 hPa around noon is present
525 in all three schemes, which is linked to excessive early-afternoon convection. This bias
526 is largely alleviated in the modified runs, as reflected by the negative SENS-CTRL
527 differences (dashed lines in the middle column of Figure 10), owing to the suppression
528 of early convective activity. As over the TP, the lower-tropospheric dry bias after 18:00
529 LST is also reduced in the modified TDK and ZM schemes (Figure 11 b, e). In
530 CAM_UNICON, the temperature differences between sensitivity and control runs are
531 generally opposite in sign to the control bias, largely offsetting the bias (Figure 10h).

删除了: ure

删除了: 2

534 Nevertheless, the magnitude of these differences is so large that the sign is reversed
 535 completely, leaving a residual warm bias aloft and a cold bias in the lower troposphere
 536 (Fig. S4h). Over SCB, the mid-tropospheric warm and dry bias in CAM ZM is
 537 substantially alleviated in the sensitivity run (Figure 10c; Figure 11c), owing to the
 538 suppression of overly active early-afternoon convection. Isolated experiments indicate
 539 that the dCAPE trigger helps mitigate the late-afternoon warm and dry biases in CTRL,
 540 with active nocturnal convection over SCB further reducing them (Figs. S5a and S6).
 541 In the UNICON sensitivity run, the overly strengthened convection warms the upper
 542 troposphere, yielding a positive bias of up to 2.5 K (Figure S3i), similar to that over TP
 543 and SECN. The Q_{400} profiles (Fig. S5b), together with the temperature biases in Fig. S7,
 544 indicate that the warm bias seen in the UNICON sensitivity run is attributable to
 545 cold-pool feedback. This raises a caveat for the UNICON scheme: while enabling
 546 cold-pool feedback may improve the diurnal cycle, the overly strong intensity,
 547 stemming from positive perturbations in plume initialization, may adversely affect
 548 thermodynamic fields.

删除了: ure

删除了: 3

删除了: However,

删除了: i

设置了格式: 字体: (中文)+中文正文 (DengXian), 小四

设置了格式: 字体: (中文)+中文正文 (DengXian), 小四

设置了格式: 字体: (中文)+中文正文 (DengXian), 小四

设置了格式: 字体: (中文)+中文正文 (DengXian), 小四

设置了格式: 字体: (中文)+中文正文 (DengXian), 小四

设置了格式: 字体: (中文)+中文正文 (DengXian), 小四

设置了格式: 字体: (中文)+中文正文 (DengXian), 小四

设置了格式: 字体: (中文)+中文正文 (DengXian), 小四

设置了格式: 字体: (中文)+中文正文 (DengXian), 小四

设置了格式: 字体: (中文)+中文正文 (DengXian), 小四

设置了格式: 字体: (中文)+中文正文 (DengXian), 小四

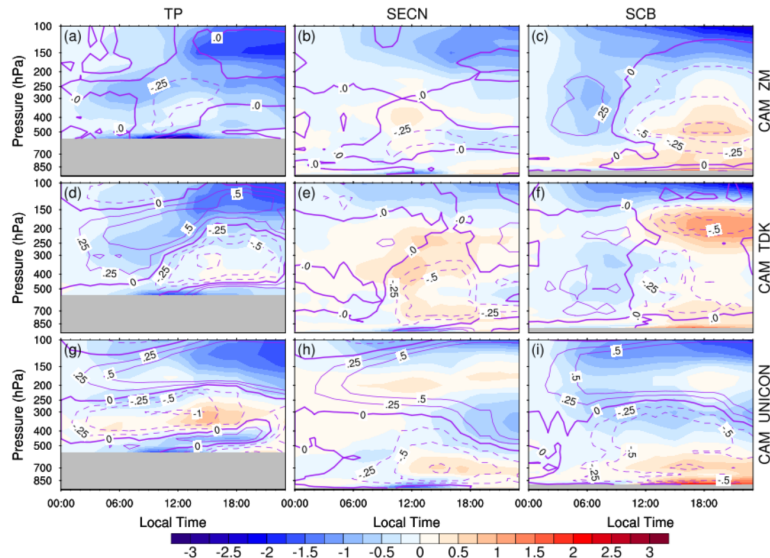


Figure 10 Temperature differences between the control run and ERA5 reanalysis (CTRL – ERA5, shading) and between the sensitivity and control runs (SENS – CTRL, contours) over TP (left), SECN (middle), and SCB (right). Panels from top to bottom show results from CAM_ZM, CAM_TDK, and CAM_UNICON. In these figures, solid lines are for contours greater than or equal to zero and dashed lines for contours less than zero. Units: K.

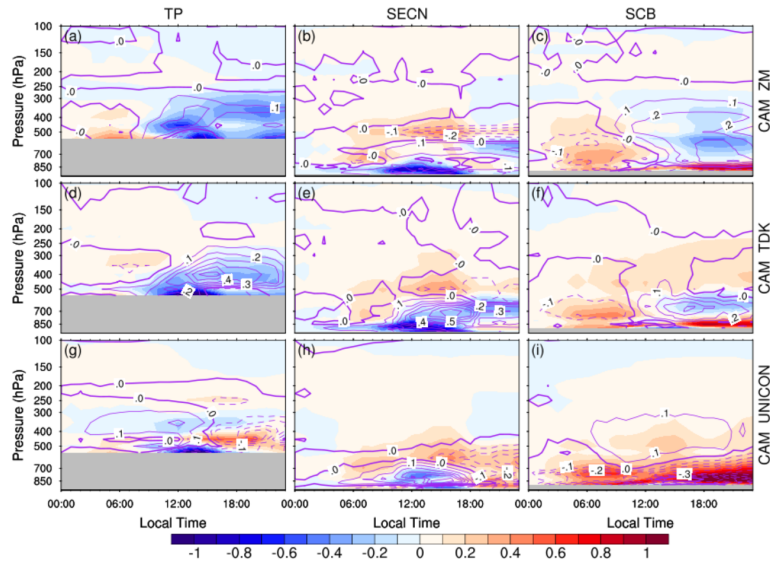


Figure 11 Same as Figure 10, but for specific humidity (units: g kg^{-1}).

6. Conclusions

Using a single-column model, this study investigates the impact of convective trigger and closure treatments on the summertime diurnal cycle of precipitation over China, with a focus on three convection schemes: ZM, TDK, and UNICON. The analysis targets two regions characterized by late-afternoon rainfall (TP and SECN) and one region with a nocturnal regime (SCB). Over TP and SECN, the TDK and ZM schemes with the standard CAPE closure simulate precipitation peaks that are substantially earlier than the observed. The UNICON scheme, with cold-pool feedback deactivated, also exhibits a noontime peak, albeit with a somewhat delayed initiation relative to ZM and TDK. Over SCB, both ZM and UNICON produce a pronounced noontime precipitation peak, in stark contrast to the observed nocturnal maximum. TDK reasonably reproduces the nocturnal peak, yet it also produces an additional noontime maximum. These SCM precipitation behaviors are closely related to closure assumptions and the resulting cloud-base mass flux. While convective precipitation in ZM and TDK is more closely tied to CAPE, in UNICON it aligns more directly with the surface fluxes.

Modifications were then applied to each scheme: adopting the dCAPE trigger and permitting elevated convection in ZM; activating cold-pool feedback and allowing elevated convection in UNICON; and applying the non-equilibrium closure in TDK. A notable improvement is evident for both late-afternoon and nocturnal rainfall. Over TP and SECN, the precipitation peak shifts to approximately 18:00 LST across all schemes,

584 aligning much more closely with the observation. Each scheme achieves this
585 improvement through a distinct mechanism. In ZM, the dCAPE constraint suppresses
586 the early peak at 10:00 LST and redirects the main peak toward 18:00 LST. In TDK,
587 subtracting the boundary-layer contribution to PCAPE delays the precipitation peak to
588 19:00 LST. In UNICON, the cold-pool-driven mesoscale flow generates pronounced
589 dynamic uplift forcing around 18:00 LST, ultimately shifting the peak toward that time.
590 Over SCB, permitting convection to be launched above PBL in ZM and UNICON
591 enhances nocturnal convection while suppressing afternoon convection. Although no
592 explicit modification is made for elevated convection in TDK, applying the
593 non-equilibrium closure also enhances nocturnal precipitation, due to the reduced
594 convective stabilization in the afternoon.

595 The improved diurnal cycle is manifested in the diabatic heating fields as well. All
596 modifications lead to a delayed and more pronounced upward-tilting Q_1 heating
597 structure. Subgrid-scale MSE transport is likewise delayed and more upward tilted, with
598 ZM and TDK extending to higher altitudes, while in UNICON it is both intensified and
599 extends further upward. These changes alleviate the upper-level cold bias in TDK and
600 ZM and largely reduce the late-afternoon dry bias in the lower troposphere. However,
601 the overly strengthened convection in UNICON yields a warm bias of up to 2.5 K in
602 the upper troposphere, as the positive perturbations in plume properties induced by
603 mesoscale organized flow are too strong and deteriorate the thermodynamic fields.

删除了: s

605 **Data availability**

606 The simulation data used in this study are available at <https://doi.org/10.5281/zenodo.21207758> (Wang
607 and Liu, 2026).

608 **Author contribution**

609 XW: conceptualization, funding acquisition, methodology, validation, writing (original draft, review
610 and editing). YL: data curation, visualization, writing (review and editing). YL: resources, writing
611 (review and editing).

612 **Competing interests**

613 The authors declare that they have no conflict of interest.

614 **Disclaimer**

615 Publisher's note: Copernicus Publications remains neutral with regard to jurisdictional claims in
616 published maps and institutional affiliations.

617 **Acknowledgements**

618 ~~The authors would like to thank the two anonymous reviewers for their constructive comments that~~
619 ~~helped to clarify and improve the original paper.~~ The authors ~~also~~ thank the GPM, ERA5, NCAR
620 science teams for providing ~~the data and model used in this study.~~

621 **Financial support**

622 This research is jointly supported by the National Key Research and Development Program of China
623 (Grants 2022YFF0802003), the National Natural Science Foundation of China (Grants 42575163), and
624 the National Key Scientific and Technological Infrastructure project "Earth System Science Numerical
625 Simulator Facility" (EarthLab).

626

627 **References**

628 Bechtold, P., Semane, N., Lopez, P., Chaboureau, J.-P., Beljaars, A., and Bormann, N.: Representing
629 Equilibrium and Nonequilibrium Convection in Large-Scale Models, *Journal of the Atmospheric*
630 *Sciences*, 71, 734–753, <https://doi.org/10.1175/JAS-D-13-0163.1>, 2014.
631 Benedict, J. J., Maloney, E. D., Sobel, A. H., Frierson, D. M., and Donner, L. J.: Tropical Intraseasonal
632 Variability in Version 3 of the GFDL Atmosphere Model, *Journal of Climate*, 26, 426–449,
633 <https://doi.org/10.1175/JCLI-D-12-00103.1>, 2013.

设置了格式: 字体: (默认) Times New Roman, 10 磅, 英语(英国)

设置了格式: 字体: (默认) Times New Roman, 英语(英国)

删除了: would

删除了: like to

删除了: excellent and

删除了: accessible

删除了: products

删除了: that made

删除了: possible

- Bretherton, C. S. and Park, S.: A New Bulk Shallow-Cumulus Model and Implications for Penetrative Entrainment Feedback on Updraft Buoyancy, *Journal of the Atmospheric Sciences*, 65, 2174–2193, <https://doi.org/10.1175/2007JAS2242.1>, 2008.
- Bretherton, C. S. and Park, S.: A New Moist Turbulence Parameterization in the Community Atmosphere Model, *Journal of Climate*, 22, 3422–3448, <https://doi.org/10.1175/2008JCLI2556.1>, 2009.
- Carbone, R. E. and Tuttle, J. D.: Rainfall Occurrence in the U.S. Warm Season: The Diurnal Cycle, *Journal of Climate*, 21, 4132–4146, <https://doi.org/10.1175/2008JCLI2275.1>, 2008.
- Chen, G., Sha, W., Iwasaki, T., and Wen, Z.: Diurnal Cycle of a Heavy Rainfall Corridor over East Asia, *Monthly Weather Review*, 145, 3365–3389, <https://doi.org/10.1175/MWR-D-16-0423.1>, 2017.
- Clough, S. A., Shephard, M. W., Mlawer, E. J., Delamere, J. S., Iacono, M. J., Cady-Pereira, K., Boukabara, S., and Brown, P. D.: Atmospheric radiative transfer modeling: A summary of the AER codes, *Journal of Quantitative Spectroscopy and Radiative Transfer*, 91, 233 – 244, <https://doi.org/10.1016/j.jqsrt.2004.05.058>, 2005.
- Dai, A. and Trenberth, K. E.: The Diurnal Cycle and Its Depiction in the Community Climate System Model, *Journal of Climate*, 17, 930 – 951, [https://doi.org/10.1175/1520-0442\(2004\)017<0930:TDCAID>2.0.CO;2](https://doi.org/10.1175/1520-0442(2004)017<0930:TDCAID>2.0.CO;2), 2004.
- Dai, A., Giorgi, F., and Trenberth, K. E.: Observed and model-simulated diurnal cycles of precipitation over the contiguous United States, *Journal of Geophysical Research: Atmospheres*, 104, 6377–6402, <https://doi.org/10.1029/98JD02720>, 1999.
- Dai, A.: Precipitation characteristics in eighteen coupled climate models, *Journal of Climate*, 19, 4605–4630, <https://doi.org/10.1175/JCLI3884.1>, 2006.
- Davies, L., Plant, R. S., and Derbyshire, S. H.: Departures from convective equilibrium with a rapidly varying surface forcing, *Quarterly Journal of the Royal Meteorological Society*, 139, 1731–1746, <https://doi.org/10.1002/qj.2065>, 2013.
- Donner, L. J. and Phillips, V. T.: Boundary layer control on convective available potential energy: Implications for cumulus parameterization, *Journal of Geophysical Research: Atmospheres*, 108, <https://doi.org/10.1029/2003JD003773>, 2003.
- Gottelman, A., Truesdale, J. E., Bacmeister, J. T., Caldwell, P. M., Neale, R. B., Bogenschutz, P. A., and Simpson, I. R.: The single column atmosphere model version 6 (SCAM6): Not a scam but a tool for model evaluation and development, *Journal of Advances in Modeling Earth Systems*, 11, 1381–1401, <https://doi.org/10.1029/2018MS001578>, 2019.
- Hersbach, H., Bell, B., Berrisford, P., Hirahara, S., Horányi, A., Muñoz-Sabater, J., Nicolas, J., Peubey, C., Radu, R., Schepers, D., Simmons, A., Soci, C., Abdalla, S., Abellan, X., Balsamo, G., Bechtold, P., Biavati, G., Bidlot, J., Bonavita, M., De Chiara, G., Dahlgren, P., Dee, D., Diamantakis, M., Dragani, R., Flemming, J., Forbes, R., Fuentes, M., Geer, A., Haimberger, L., Healy, S., Hogan, R. J., Hólm, E., Janisková, M., Keeley, S., Laloyaux, P., Lopez, P., Lupu, C., Radnoti, G., De Rosnay, P., Rozum, I., Vamborg, F., Villaume, S., and Thépaut, J.: The ERA5 global reanalysis, *Quarterly Journal of the Royal Meteorological Society*, 146, 1999–2049, <https://doi.org/10.1002/qj.3803>, 2020.
- Huffman, G. J., Stocker, E. F., Bolvin, D. T., Nelkin, E. J., and Tan, J.: GPM IMERG Final Precipitation L3 Half Hourly 0.1 degree x 0.1 degree V07, Greenbelt, MD, Goddard Earth Sciences Data and Information Services Center (GES DISC) [data set], <https://doi.org/10.5067/GPM/IMERG/3B-HH/07>, 2023.

- Lee, M.-I., Schubert, S. D., Suarez, M. J., Held, I. M., Lau, N.-C., Ploshay, J. J., Kumar, A., Kim, H.-K., and Schemm, J.-K. E.: An analysis of the warm-season diurnal cycle over the continental United States and northern Mexico in general circulation models, *Journal of Hydrometeorology*, 8, 344–366, <https://doi.org/10.1175/JHM581.1>, 2007.
- Lee, M.-I., Schubert, S. D., Suarez, M. J., Schemm, J.-K. E., Pan, H.-L., Han, J., and Yoo, S.-H.: Role of convection triggers in the simulation of the diurnal cycle of precipitation over the United States Great Plains in a general circulation model, *Journal of Geophysical Research: Atmospheres*, 113, D02111, <https://doi.org/10.1029/2007JD008984>, 2008.
- Li, J., Yu, R., and Zhou, T.: Seasonal variation of the diurnal cycle of rainfall in southern contiguous China, *J. Clim.*, 21, <https://doi.org/10.1175/2008JCLI2188.1>, 2008.
- Liu, Y., Wang, X., Liu, Y., Tang, S., and Miao, H.: A process-oriented analysis of the summertime diurnal cycle of precipitation and diabatic heating over China in three reanalyses, *Atmospheric Chemistry and Physics*, 26, 6763–6779, <https://doi.org/10.5194/acp-26-6763-2026>, 2026.
- Mapes, B., Tulich, S., Lin, J., and Zuidema, P.: The mesoscale convection life cycle: Building block or prototype for large-scale tropical waves?, *Dynamics of Atmospheres and Oceans*, 42, 3–29, <https://doi.org/10.1016/j.dynatmoce.2006.03.003>, 2006.
- Morrison, H. and Gettelman, A.: A New Two-Moment Bulk Stratiform Cloud Microphysics Scheme in the Community Atmosphere Model, Version 3 (CAM3). Part I: Description and Numerical Tests, *Journal of Climate*, 21, 3642–3659, <https://doi.org/10.1175/2008JCLI2105.1>, 2008.
- Park, S. (2014a). A Unified Convection Scheme (UNICON). Part I: Formulation. *Journal of the Atmospheric Sciences*, 71(11), 3902–3930. <https://doi.org/10.1175/JAS-D-13-0233.1>
- Park, S. (2014b). A unified convection scheme (UNICON). Part II: Simulation. *Journal of the Atmospheric Sciences*, 71(11), 3931–3973. <https://doi.org/10.1175/JAS-D-13-0234.1>
- Park, S. and Bretherton, C. S.: The University of Washington Shallow Convection and Moist Turbulence Schemes and Their Impact on Climate Simulations with the Community Atmosphere Model, *Journal of Climate*, 22, 3449–3469, <https://doi.org/10.1175/2008JCLI2557.1>, 2009.
- Park, S., Bretherton, C. S., and Rasch, P. J.: Integrating Cloud Processes in the Community Atmosphere Model, Version 5, *Journal of Climate*, 27, 6821–6856, <https://doi.org/10.1175/JCLI-D-14-00087.1>, 2014.
- Park, S., Song, C., Kim, S., and Kim, J.: Parameterization of the elevated convection with a unified convection scheme (UNICON) and its impacts on the diurnal cycle of precipitation, *Journal of Advances in Modeling Earth Systems*, 16, e2023MS003651, <https://doi.org/10.1029/2023MS003651>, 2024.
- Tang, S., Xie, S., Guo, Z., Hong, S., Khouider, B., Klocke, D., Köhler, M., Koo, M., Krishna, P. M., Larson, V. E., Park, S., Vaillancourt, P. A., Wang, Y., Yang, J., Daleu, C. L., Homeyer, C. R., Jones, T. R., Malap, N., Neggers, R., Prabhakaran, T., Ramirez, E., Schumacher, C., Tao, C., Bechtold, P., Ma, H., Neelin, J. D., and Zeng, X.: Long-term single-column model intercomparison of diurnal cycle of precipitation over midlatitude and tropical land, *Quarterly Journal of the Royal Meteorological Society*, 148, 641–669, <https://doi.org/10.1002/qj.4222>, 2022.
- Tiedtke, M.: A comprehensive mass flux scheme for cumulus parameterization in large-scale models, *Monthly Weather Review*, 117, 1779 – 1800, [https://doi.org/10.1175/1520-0493\(1989\)117<1779:ACMFSF>2.0.CO;2](https://doi.org/10.1175/1520-0493(1989)117<1779:ACMFSF>2.0.CO;2), 1989.

- Trenberth, K. E., Dai, A., Rasmussen, R. M., and Parsons, D. B.: The changing character of precipitation, *Bulletin of the American Meteorological Society*, 84, 1205–1218, <https://doi.org/10.1175/BAMS-84-9-1205>, 2003.
- van Stratum, B. J. H., van Heerwaarden, C. C., and Vilà-Guerau de Arellano, J.: The Benefits and Challenges of Downscaling a Global Reanalysis with Doubly-Periodic Large-Eddy Simulations, *Journal of Advances in Modeling Earth Systems*, 15, e2023MS003750, <https://doi.org/10.1029/2023MS003750>, 2023.
- Wang, X. and Zhang, M.: An analysis of parameterization interactions and sensitivity of single-column model simulations to convection schemes in CAM4 and CAM5, *Journal of Geophysical Research: Atmospheres*, 118, 8869–8880, <https://doi.org/10.1002/jgrd.50690>, 2013.
- Wang, X., Liu, Y., Zhang, M., Liu, Y., Tang, S., Guo, Z., Wang, K., and Zheng, X.: Evaluation of CAM Single - Column Models in Simulating Convectively Coupled Rossby Gravity Waves During TRMM - KWAJEX, *Journal of Geophysical Research: Atmospheres*, 131, e2025JD045016, <https://doi.org/10.1029/2025JD045016>, 2026.
- Wang, X., and Liu, Y.: Simulation Data for the Sensitivity of Summertime Diurnal Precipitation Cycle over China to Convective Trigger and Closure Treatments in a Single-Column Model, Zenodo [data set], <https://doi.org/10.5281/zenodo.21207758>, 2026.
- Wang, Y.-C., Pan, H.-L., and Hsu, H.-H.: Impacts of the triggering function of cumulus parameterization on warm-season diurnal rainfall cycles at the Atmospheric Radiation Measurement southern Great Plains site, *Journal of Geophysical Research: Atmospheres*, 120, 10681 – 10702, <https://doi.org/10.1002/2015JD023337>, 2015.
- Xie, S. and Zhang, M.: Impact of the convection triggering function on single-column model simulations, *Journal of Geophysical Research: Atmospheres*, 105, 14983 – 14996, <https://doi.org/10.1029/2000JD900170>, 2000.
- Xie, S., Wang, Y., Lin, W., Ma, H., Tang, Q., Tang, S., Zheng, X., Golaz, J., Zhang, G. J., and Zhang, M.: Improved diurnal cycle of precipitation in E3SM with a revised convective triggering function, *Journal of Advances in Modeling Earth Systems*, 11, 2290 – 2310, <https://doi.org/10.1029/2019MS001702>, 2019.
- Yanai, M., Esbensen, S., and Chu, J.-H.: Determination of bulk properties of tropical cloud clusters from large-scale heat and moisture budgets, *Journal of the Atmospheric Sciences*, 30, 611 – 627, [https://doi.org/10.1175/1520-0469\(1973\)030<0611:DOBPOT>2.0.CO;2](https://doi.org/10.1175/1520-0469(1973)030<0611:DOBPOT>2.0.CO;2), 1973.
- Yang, B., Zhou, Y., Zhang, Y., Huang, A., Qian, Y., and Zhang, L.: Simulated precipitation diurnal cycles over East Asia using different CAPE-based convective closure schemes in WRF model, *Climate Dynamics*, 50, 1639–1658, <https://doi.org/10.1007/s00382-017-3712-z>, 2018.
- Zhang, G. J. and McFarlane, N. A.: Sensitivity of climate simulations to the parameterization of cumulus convection in the Canadian Climate Centre General Circulation Model, *Atmosphere-Ocean*, 33, 407–446, <https://doi.org/10.1080/07055900.1995.9649539>, 1995.
- Zhang, G. J.: Convective quasi-equilibrium in midlatitude continental environment and its effect on convective parameterization, *Journal of Geophysical Research: Atmospheres*, 107, 4220, <https://doi.org/10.1029/2001JD001005>, 2002.
- Zhang, Y., Zhang, F., and Sun, J.: Comparison of the diurnal variations of warm-season precipitation for East Asia vs. North America downstream of the Tibetan Plateau vs. the Rocky Mountains, *Atmospheric Chemistry and Physics*, 14, 10741–10759, <https://doi.org/10.5194/acp-14-10741-2014>, 2014.