Assessing parameter sensitivity of Zhang-McFarlane deep convection scheme in TaiESM1

YUN-ZHEN WU[1] (aswyz4260@gmail.com), YI-HSUAN CHEN[2] (Advisor),
[1]Dept. of Atmospheric Sciences, National Central University
[2]Research Center for Environmental Changes, Academia Sinica

1. Introduction

Deep convection is unresolved on model grids and requires parameterization of sub-grid updrafts/downdrafts, condensational heating, and moisture budgets. The widely used Zhang–McFarlane (ZM) scheme employs a mass-flux framework for triggering, entrainment/detrainment, closure, and precipitation efficiency; yet most configurations assume independent parameters, which may conflict with physical couplings. Using single-column model in TaiESM1 with ARM95 large-scale forcing and observations, we conduct one-at-a-time (OAT) local sensitivity experiments to quantify impacts of deep-convection parameters on the event scale (rainfall) and the structural scale (ZMMU, Q1, Q2 profiles). The results establish a high-leverage parameter set and an evaluation framework, laying the groundwork for quantitative studies of parameter non-independence and interactions.

2. Methods

Model/Case → **SCAM-ZM scheme** (ARM95 IOP forcing & observations)

Design → **OAT local sensitivity** Default x 1 + (min/max) x 6 parameters → 13 simulations (+ obs)

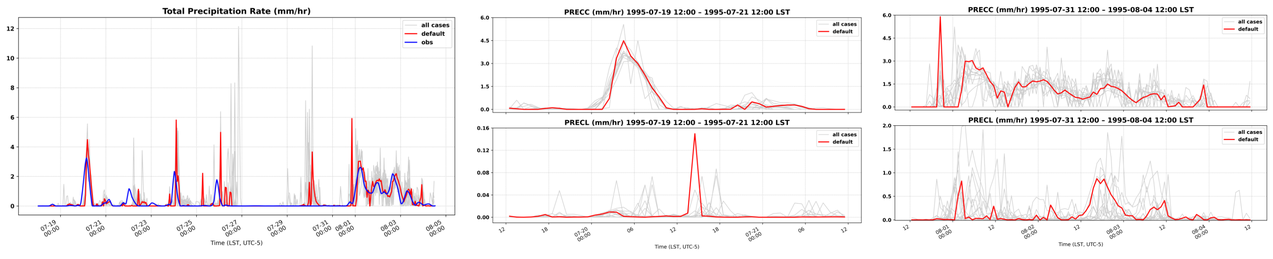
Analysis → **period-1 (single-day)** Rainfall event; **period-2 (multi-day)** Vertical profiles

parameter sensitivity ranked by max(MAE_min, MAE_max), including both positive and negative

Parameter	Description	minimum	default	maximum
c0_lnd	Deep conv. Precipitation efficiency over land	2.95E-3	5.90E-3	8.85E-3
ke	Evaporation efficiency of prec.	5.0E-7	1.0E-6	1.5E-6
tau	Timescale for consumption rate deep CAPE	1800	3600	5400
capelmt	Threshold value for CAPE	35	70	105
alfa	Maximum cloud downdraft mass flux fraction	0.05	0.1	0.15
dmpdz	Air parcel fractional mass entrainment rate	-2.0E-4	-1.0E-3	-2.0E-3

3. Results

(a) Rainfall Series of ARM95

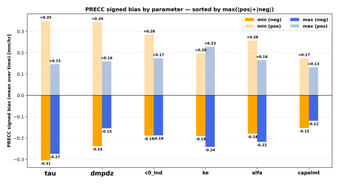


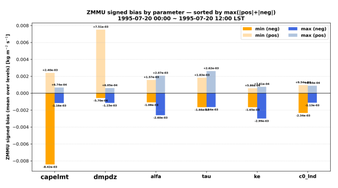
Two analysis periods are defined from the rainfall time series where the model aligns with observations; gray lines denote results from all parameter-perturbation runs.

(1) 1995-07-19 12:00 to 1995-07-21 12:00 (LST) — a short-duration, intense convective rainfall event. Model output indicates precipitation is dominated by the convective component. Vertical profiles are averaged over the convective period.

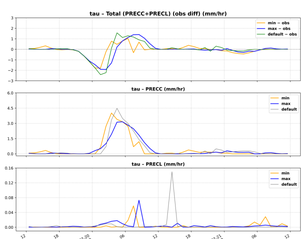
(2) 1995-07-31 12:00 to 1995-08-04 12:00 (LST) — a multi-day continuous rainfall episode. Vertical profiles are averaged over the full window.

(b) Time Period 1 – single day

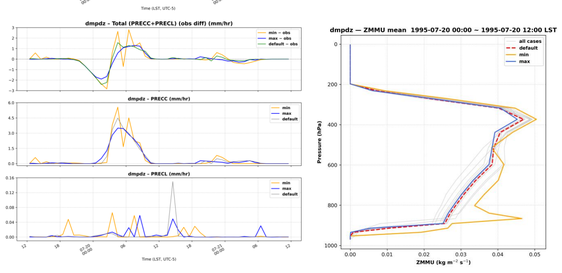




- **PRECC sensitivity.** Deviation of convective precipitation rate from the default, measured by Mean Absolute Error (MAE).
- **τ (tau)** and **dmpdz** are the most sensitive parameters, i.e., their perturbations produce the largest rainfall changes.
- **ZMMU sensitivity. dmpdz** is sensitive for the convective-intensity profile (ZMMU), indicating that entrainment/dilution chiefly controls plume depth and updraft-core structure. **capelmt** also affects ZMMU in this window (triggering/timing), but ranks lower for rainfall MAE.

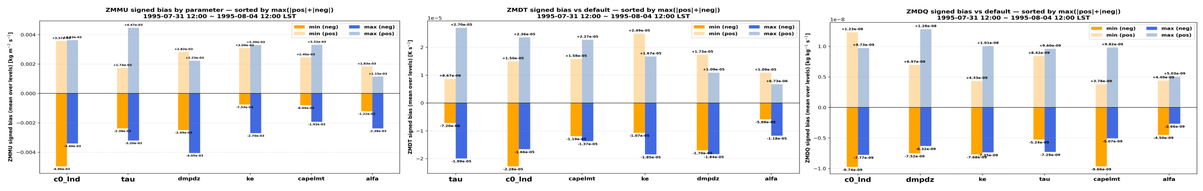


- **τ hyetograph.** The three curves start at nearly the same time; the default has the sharpest, highest peak.
  max (blue): larger timescale → delayed, widened peak.
  min (orange): smaller timescale → earlier, less sharp.
- **dmpdz hyetograph.** max (blue) suppresses and flattens the peak.
  min (orange) gives a higher, more concentrated peak;

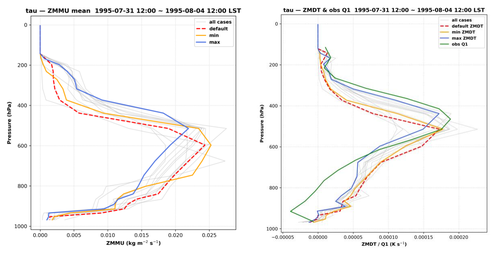


- **dmpdz ZMMU profile.**
  max (blue): weak dilution → deeper/stronger convective core, with a large departure from the default.
  min (orange): strong dilution → thinned, shallower core and a reduced rainfall peak.

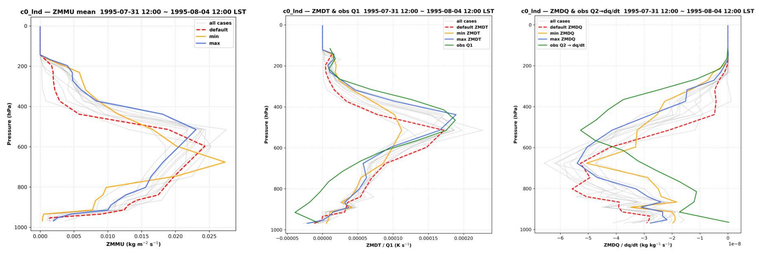
(c) Time Period 2 – multiple day



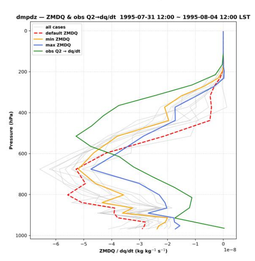
- **ZMMU — *Mass flux* (updraft intensity):** a proxy for the convective core's strength and depth at each level.
- **ZMDT — *Heating rate* (T tendency, ZM moist convection):** dominated by latent-heat release within updrafts; its vertical shape typically aligns with ZMMU.
- **ZMDQ — *Moisture tendency* (ZM moist convection):** updraft export of lower-level moisture yields lower-level drying (−) and mid–upper moistening (+); the zero-crossing height generally coincides with the ZMMU core.



- **ZMMU:** With max tau, the mean profile is thicker than default (slightly enhanced aloft); with min tau, it is thinner.
- **ZMDT**: Max tau yields broader, more sustained mid–upper heating, closer to observed Q1; min tau is weaker and lower.
- A larger tau sustains updrafts and heating, producing a thicker and more top-heavy structure; a smaller tau markedly increases convective intensity.



- **ZMMU:**
  max → thicker/higher profile with a stronger mid–upper bulge;
  min → thinner overall with a low-level peak.
- **ZMDT:** max → broader, sustained mid–upper heating (closer to obs); min → weaker/shallower
- **ZMDQ:** vs default, max shifts left (drying ↑), min shifts right (drying ↓).
- Efficiency ↑ : stronger/deeper mass flux ⇒ deeper convection (ZMMU thicker/higher; Q1 more top-heavy; Q2 lower-dry/upper-moist). Efficiency ↓ : shallower/weaker convection.



- **ZMDQ:** At ~800–900 hPa, max lies right of default → weaker low-level drying; min lies left → stronger low-level drying.
- Curves converge above ~600–500 hPa; the zero-crossing height shifts only slightly.
- Entrainment ↑ dilutes the plume and limits BL-moisture export → drying concentrated less near the surface and a shallower ascent; Entrainment ↓ does the opposite.

4. Conclusion

- Period-1 (event): τ on peak timing/width; dmpdz on intensity/depth.
- Period-2 (mean): c0_lnd on ZMMU & Q2 (drying↑); τ on Q1 thickening/top-heaviness; dmpdz on Q2 vertical redistribution (low-level drying↓, zero-crossing↑).
- c0_lnd (efficiency): ↑ deeper/stronger convection; Q1 better aligned with ZMMU; Q2 drying↑; ↓ shallower/weaker, drying↓.
- τ (timescale): ↑ peak delayed/broadened, ZMMU/Q1 thicker/top-heavy; ↓ earlier/thinner.
- dmpdz (entrainment scale): ↑ shallower/thinner cores; low-level drying↓ (zero-crossing↑); ↓ deeper/thicker; low-level drying↑ (zero-crossing↓).
- c0_lnd–τ–dmpdz are the core controls for timing, depth/efficiency, and moisture redistribution.

5. Future Work

- **Beyond OAT:** Quantify **interactions** among **τ–c0_lnd–dmpdz** (synergy/antagonism; non-independence).
- **Normalized sensitivity:** Compare responses per unit parameter (MAE/|Δθ|) to prioritize the most leverageable controls.
- **Layer-wise localization:** Identify the most sensitive layers (1000→200 hPa) and link them to physical mechanisms.
- **Cross-scale/case robustness:** Check consistency between event signatures (timing/peak) and structural signatures (thickening/drying) across windows and cases.
- **Stability & limits:** Map a safe operating space; flag parameter combinations leading to unrealistic states or blow-ups.
- **Uncertainty quantification & calibration:** Propagate forcing/obs/parameter uncertainty to PRECC/ZMMU/Q1/Q2; report confidence bands and rank stability; use sensitivities to guide multi-objective calibration.

6. References

- Guo **et al.** (2024). *LB-SCAM: a learning-based method for large-scale sensitivity analysis and tuning of SCAM.* **GMD**, 17, 3975–3992.
- Neale **et al.** (2012). *Description of the NCAR Community Atmosphere Model (CAM5.0).* **NCAR Tech Note** NCAR/TN-486+STR.
- Gettelman **et al.** (2019). *The Single Column Atmosphere Model Version 6 (SCAM6): Not a Scam but a Tool for Model Evaluation and Development.* **JAMES**, 11, 1381–1401.