Characterising Convection Schemes Using Their Linearised Responses to Tendency Perturbations

Yi-Ling HWONG

Steve Sherwood, Siwon Song, Alison Stirling, Robert Plant, Chimene Daleu, Catherine Rio, Romain Roehrig, David Fuchs, Penny Maher, Ludovic Touzé-Peiffer

Improvement and calibration of clouds in models, 12 – 16 April 2021

Background

- No consensus on how convection should be parameterised in GCM
- Common issues:
  - Rain too often, too little
  - Too much high clouds, too little shallow clouds
  - Spatial organisation of convection
  - Diurnal cycle of convection
- Choice of convection scheme strongly influences simulated phenomenon, e.g. rainfall pattern
- Need to better understand convective parameterisation

Objectives

- Evaluate convection schemes currently used in operational models with single-column model (SCM) simulations under idealised RCE conditions.
- Conventional methods: compare model outputs with observational case studies
- Our approach:
  - Apply standardised test to different convection scheme
  - "What does the scheme actually do?"

Linear Response Function

Convective tendencies

$$\frac{d\mathbf{x}}{dt} = \mathrm{M}\,\mathbf{x}$$

dT/dt, dq/dt, …

Large-scale profiles

T', q', …

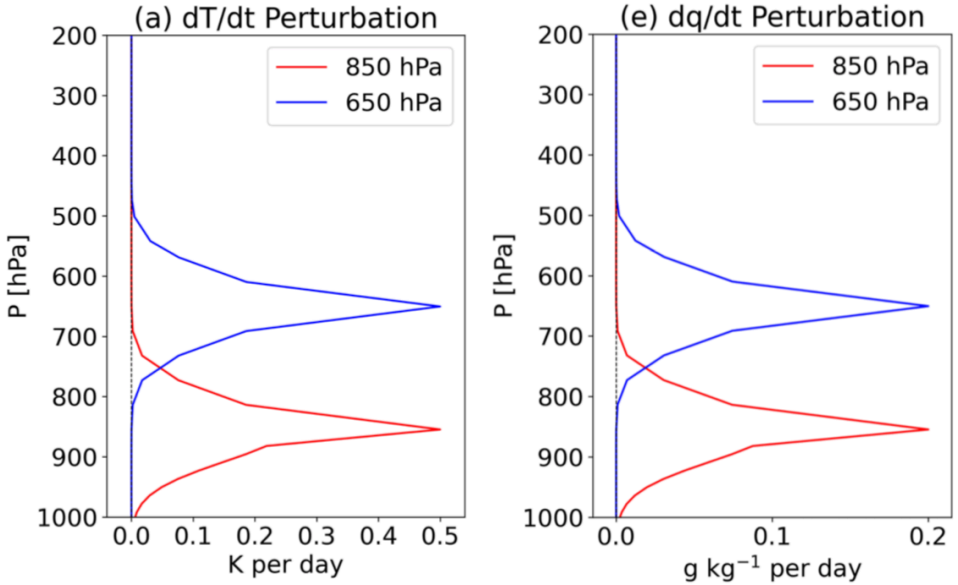
- Systematically consider small perturbations to an RCE state
- If perturbation is small enough, convective response is linear (Kuang, 2010)
- Force a single-column model with a set of anomalous temperature and moisture tendencies (dT/dt, dq/dt) and examine the deviation of the new time-averaged T and q from the control (T' and q')

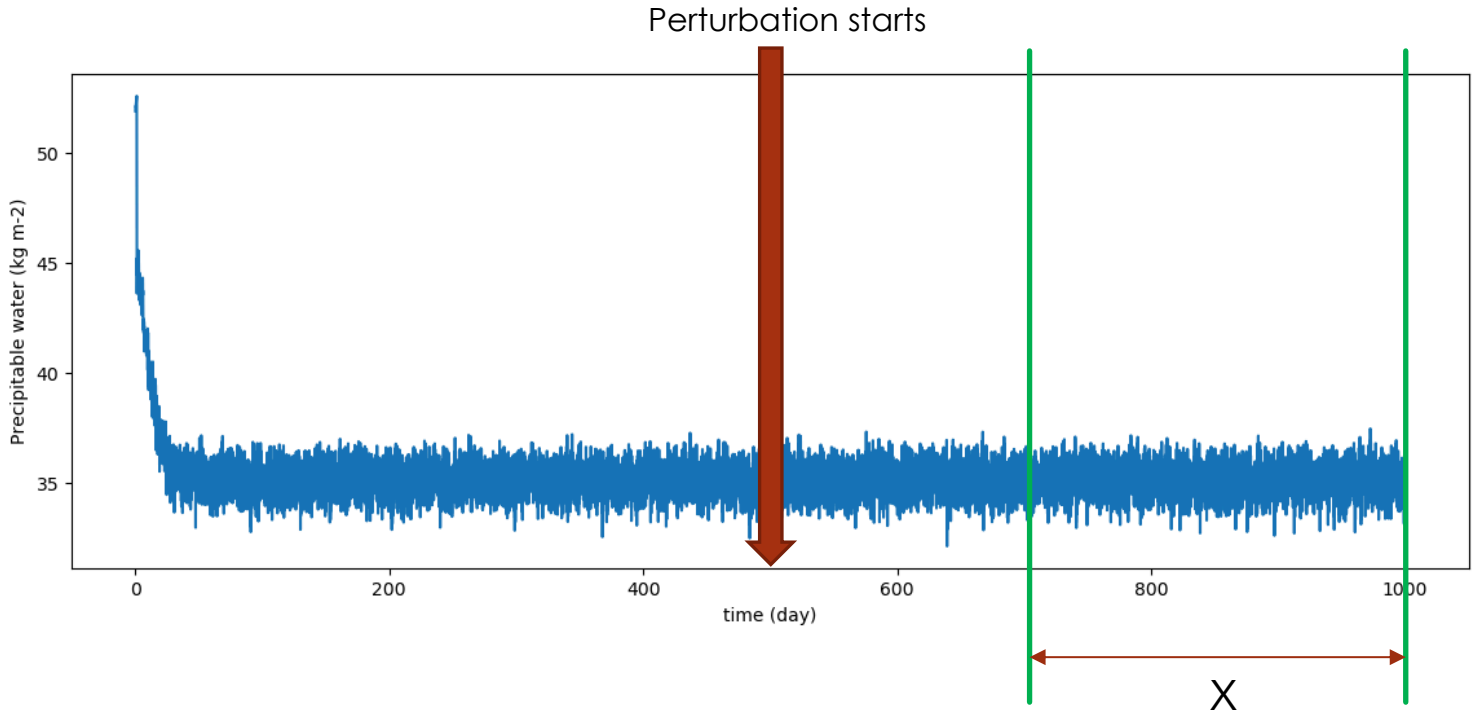
$$\mathrm{M}^{-1} = \mathbf{x} / \frac{d\mathbf{x}}{dt}$$

- M^{-1} matrices (steady-state response per unit perturbation) constructed using a CRM can be compared with those using convection schemes (Herman & Kuang, 2013)

Simulation setup

- No rotation, SST=28°C, relax U=4.8 m/s, V=0, surface fluxes with bulk aerodynamic formula (fixed surface wind and exchange coefficients)
- Fixed radiative cooling profile (-1.5 K/day from surface to near 200 hPa, decreases linearly to zero)
- RCE around day 300 for all SCMs
- Perturbations of successive model levels (separate runs), at every timestep until new equilibrium reached
- Anomalous state vectors $\mathbf{x} = \mathbf{x}_{perturbation} - \mathbf{x}_{control}$





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Single-Column Models (SCMs)

- LMDZ (versions 5A, 6A, 6Ab; Emanuel scheme+)
- WRF, with:
  - Zhang-McFarlane (1995) & Park-Bretherton (2009)
  - Kain-Fritsch (2004)
  - New Tiedtke (2017)
  - Han & Pan simplified Arakawa-Schubert (2011)
  - Betts-Miller-Janjic (1986, 1994, 2000)
- CAM5 (Zhang-McFarlane (1995) & Park-Bretherton (2009))
- UM, with:
  - Simplified Betts-Miller (2007)
  - UM 6A Mass-flux scheme (2019)
- CNRM (PCMT)

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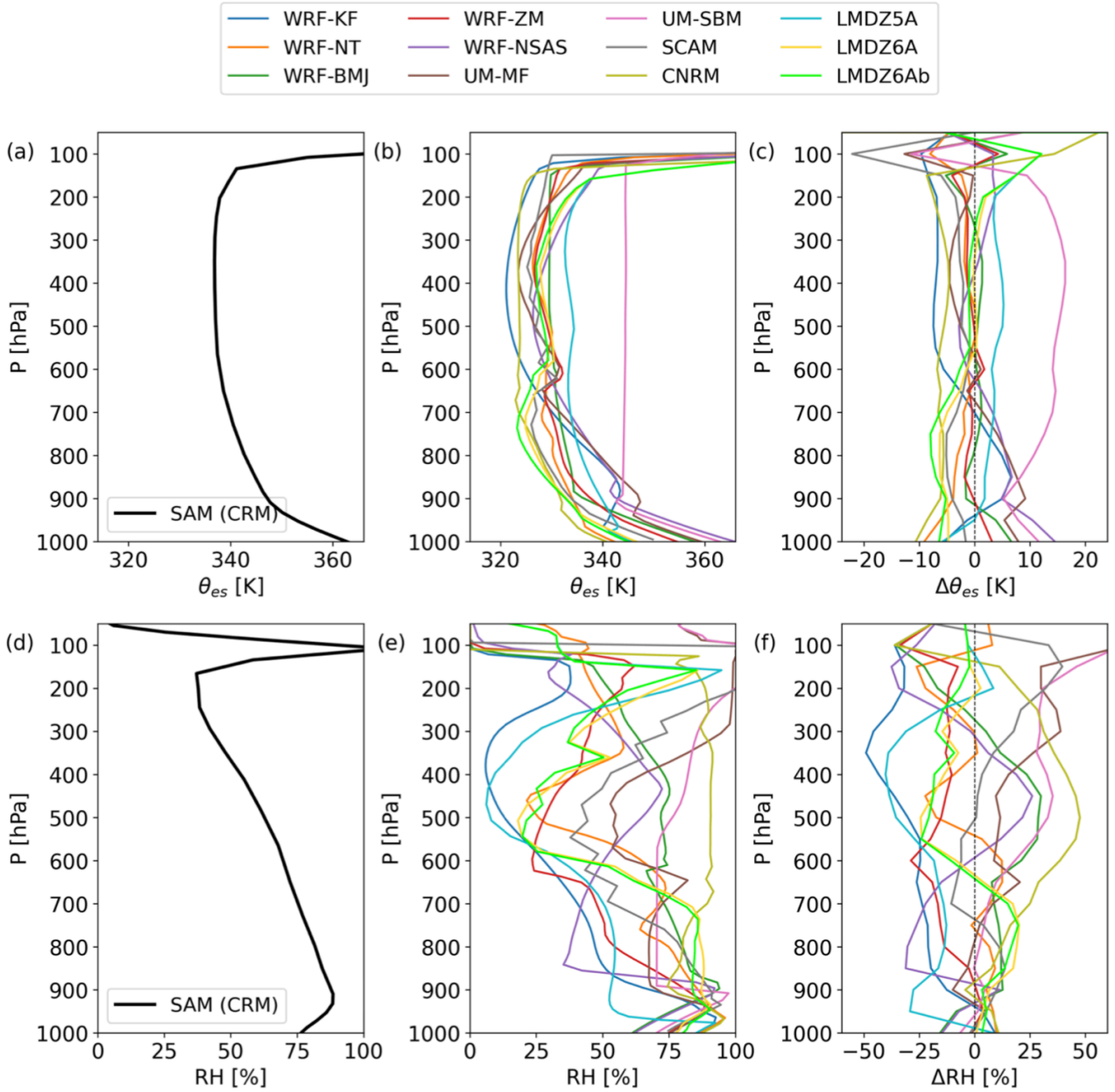
RCE mean profiles

T (θ_{es})

RH



- Temperatures vary by ~ 5 K near surface, and ~ 8 K in free troposphere
- Wide range of RH profiles, similar to comparable studies (e.g., RCEMIP project, Wing et al., 2020)

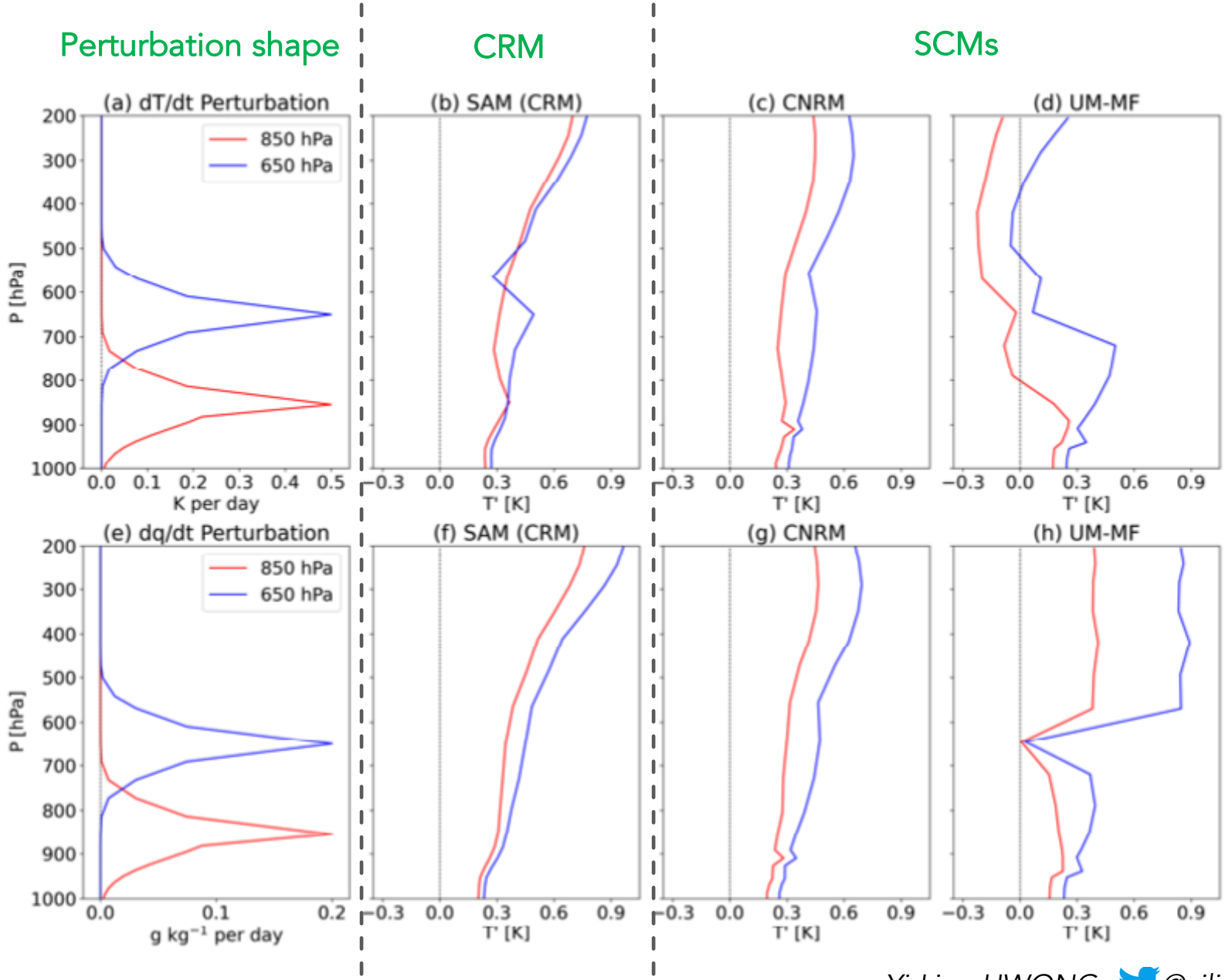
(Hwong et al., 2021, JAMES)

Selected perturbation results

Perturbation shape | CRM | SCMs

ΔT to heating perturbation

ΔT to moistening perturbation



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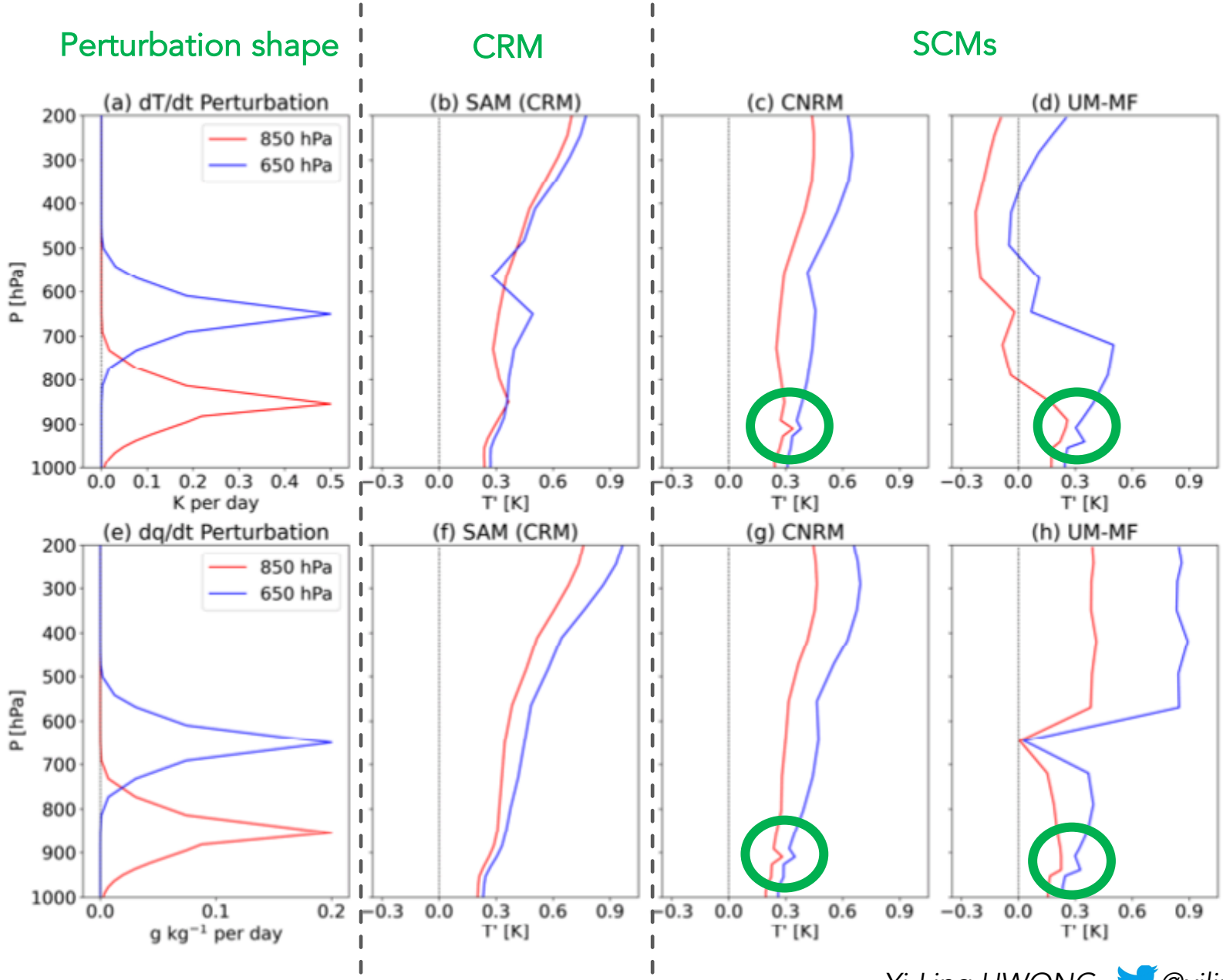

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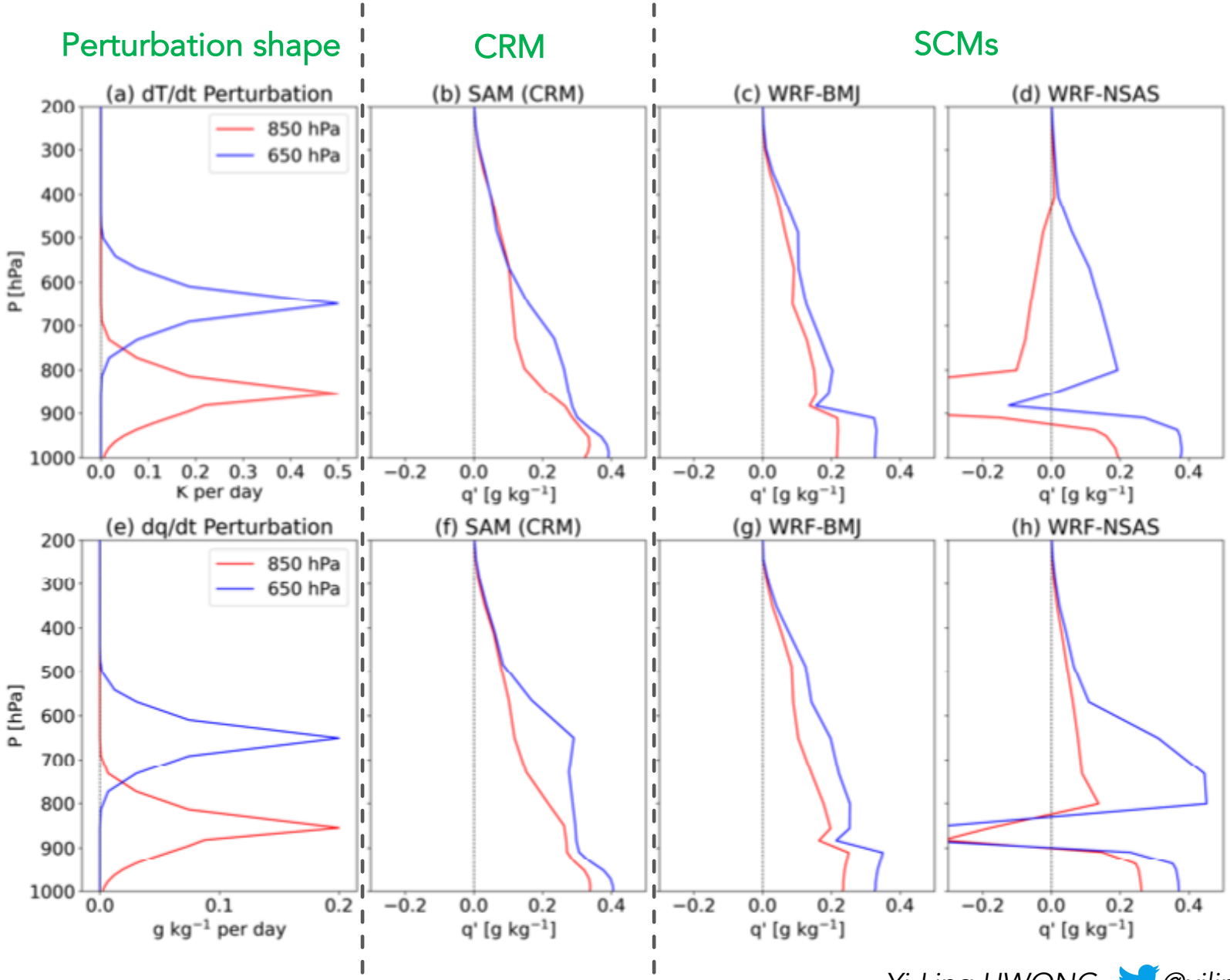
Δ*q* to heating perturbation

Δ*q* to moistening perturbation



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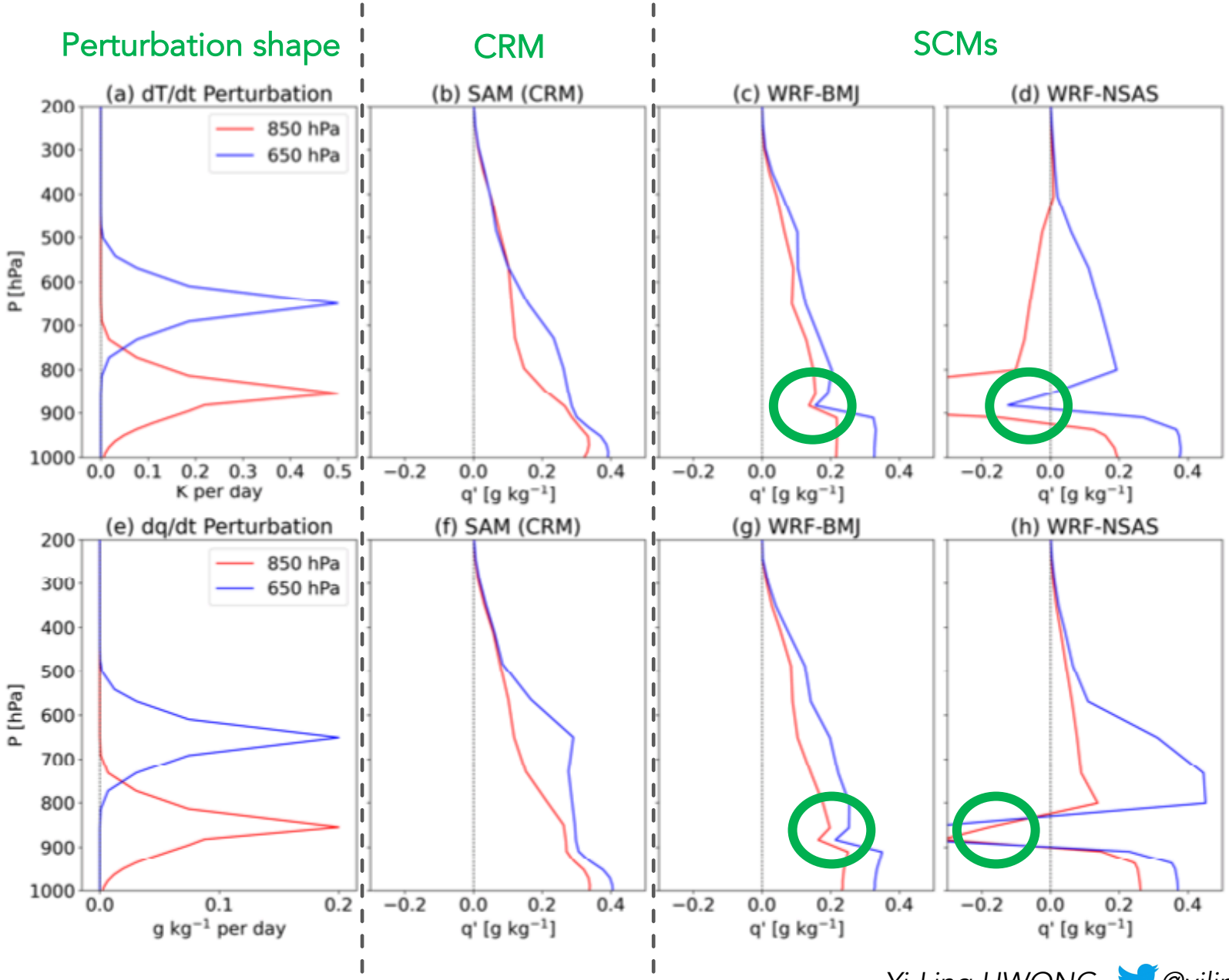

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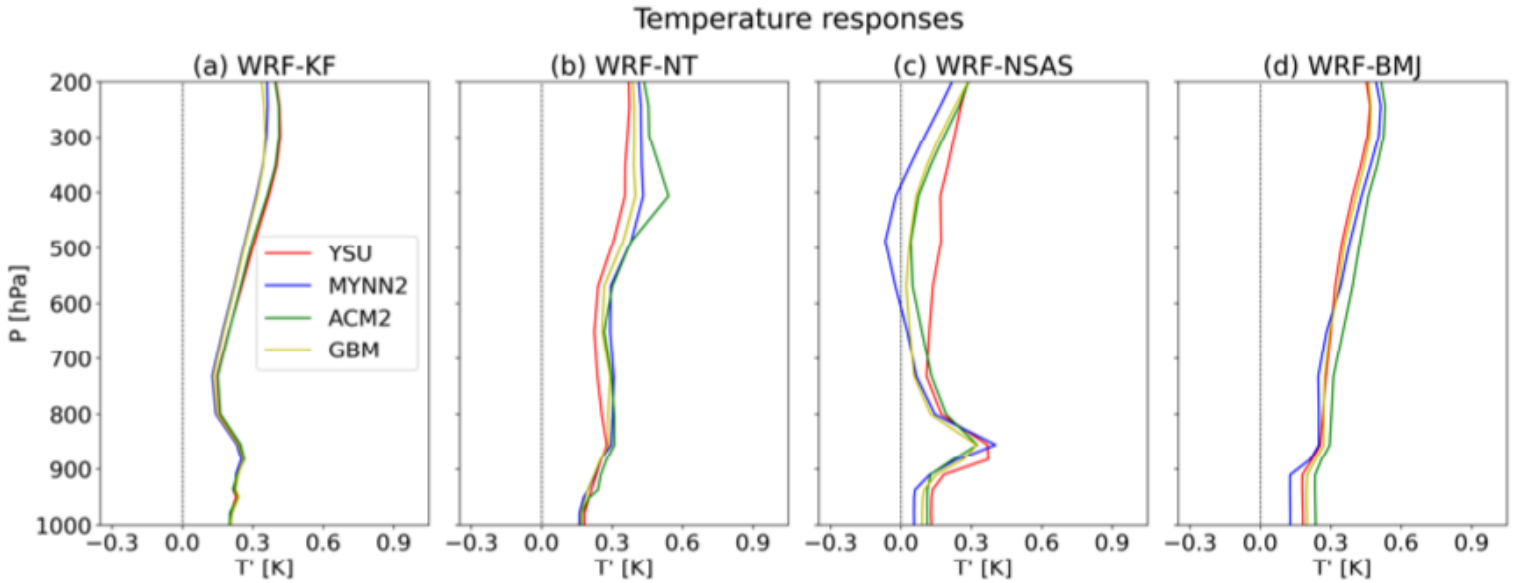
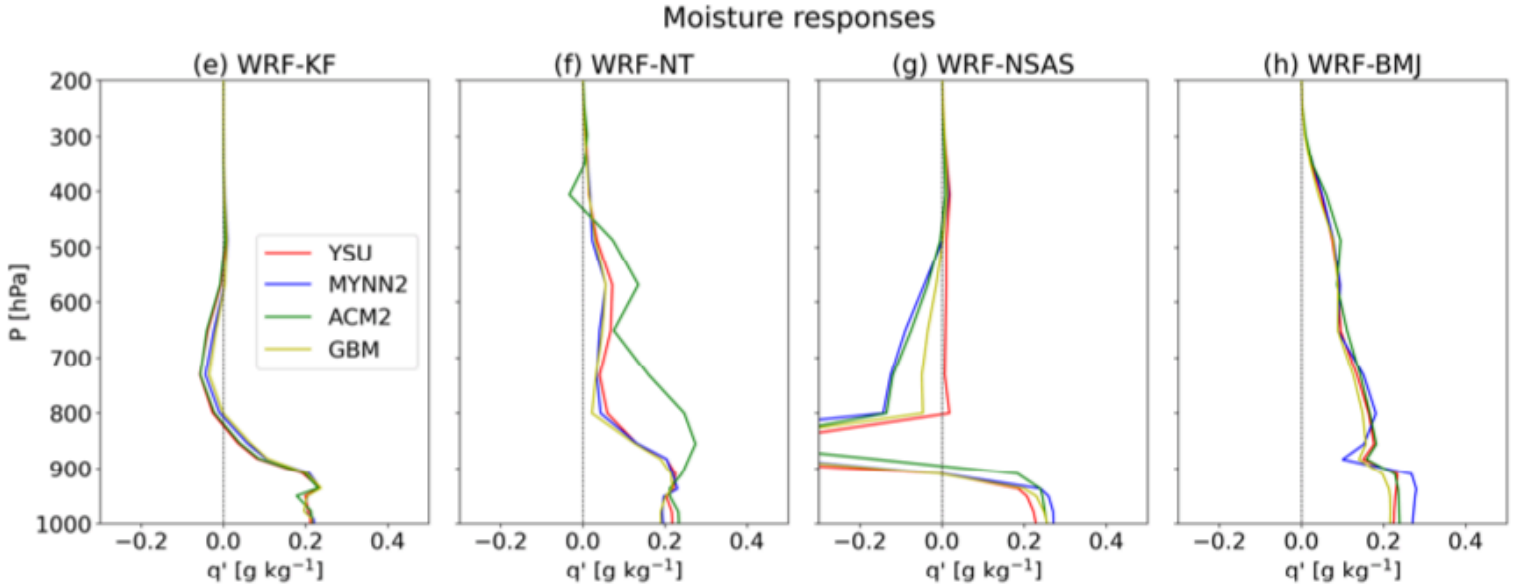
Sensitivity to PBL scheme

ΔT (average)



Perturbation @850 hPa

Δq (average)



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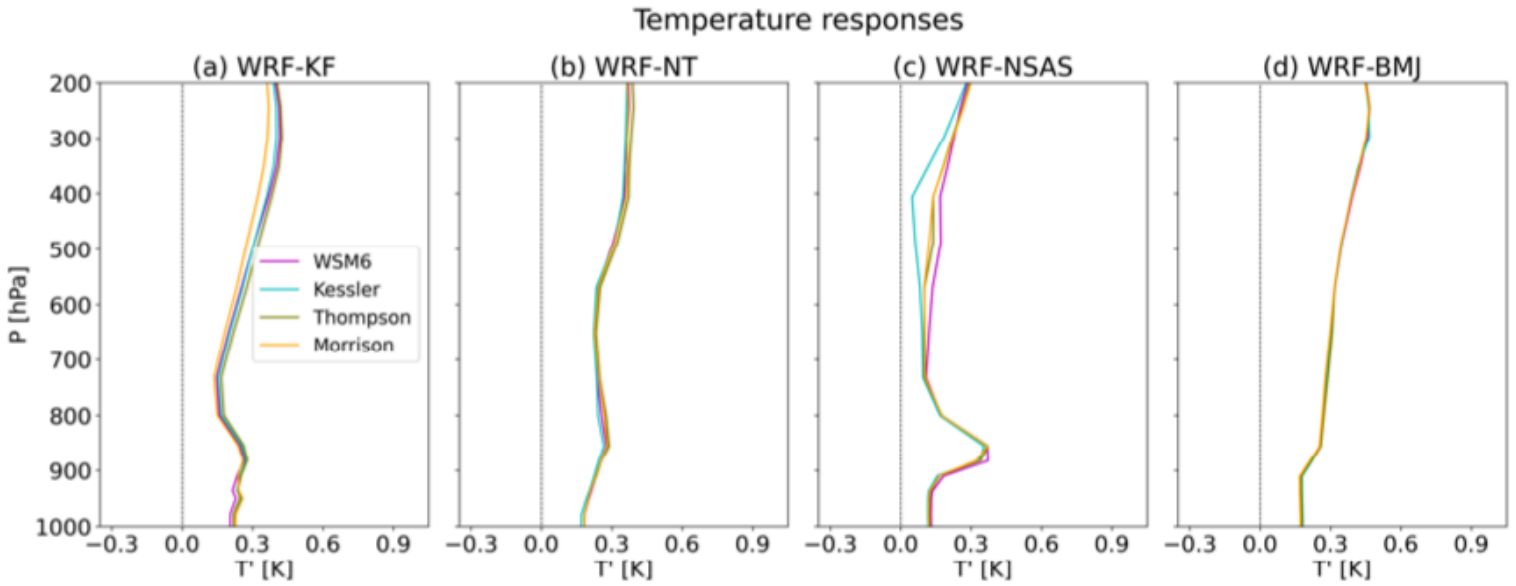
Sensitivity to microphysics scheme

ΔT (average)



Perturbation @850 hPa

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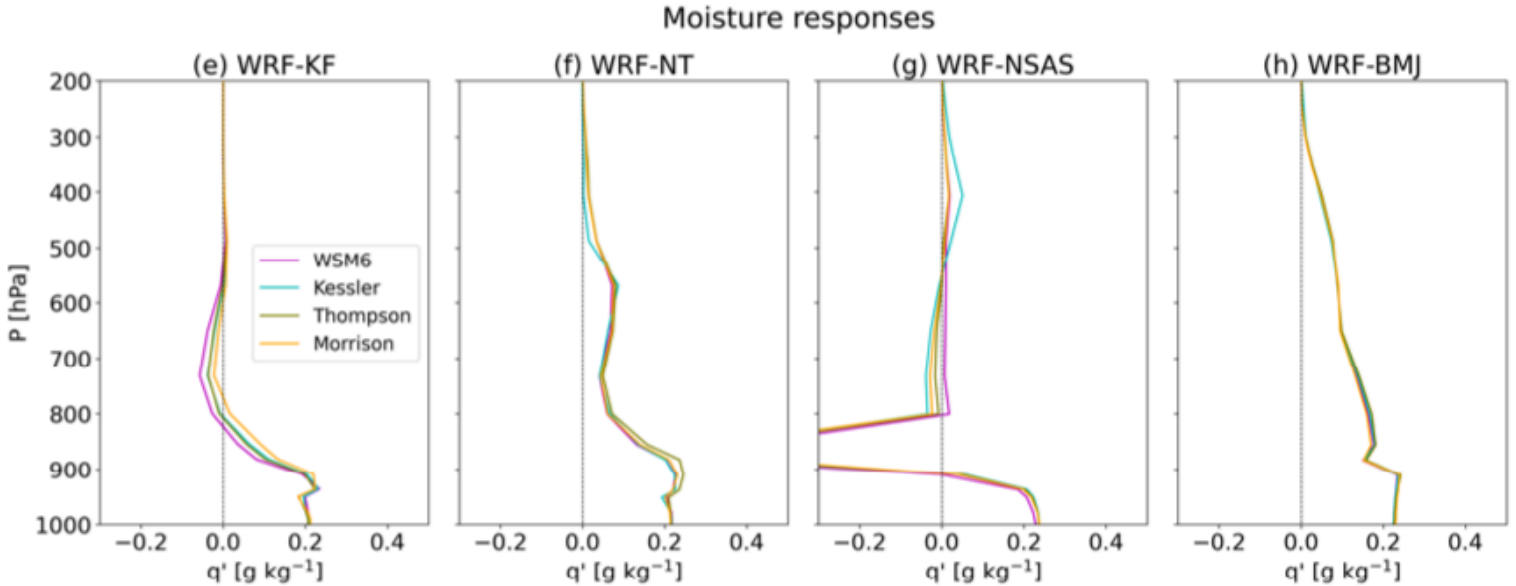
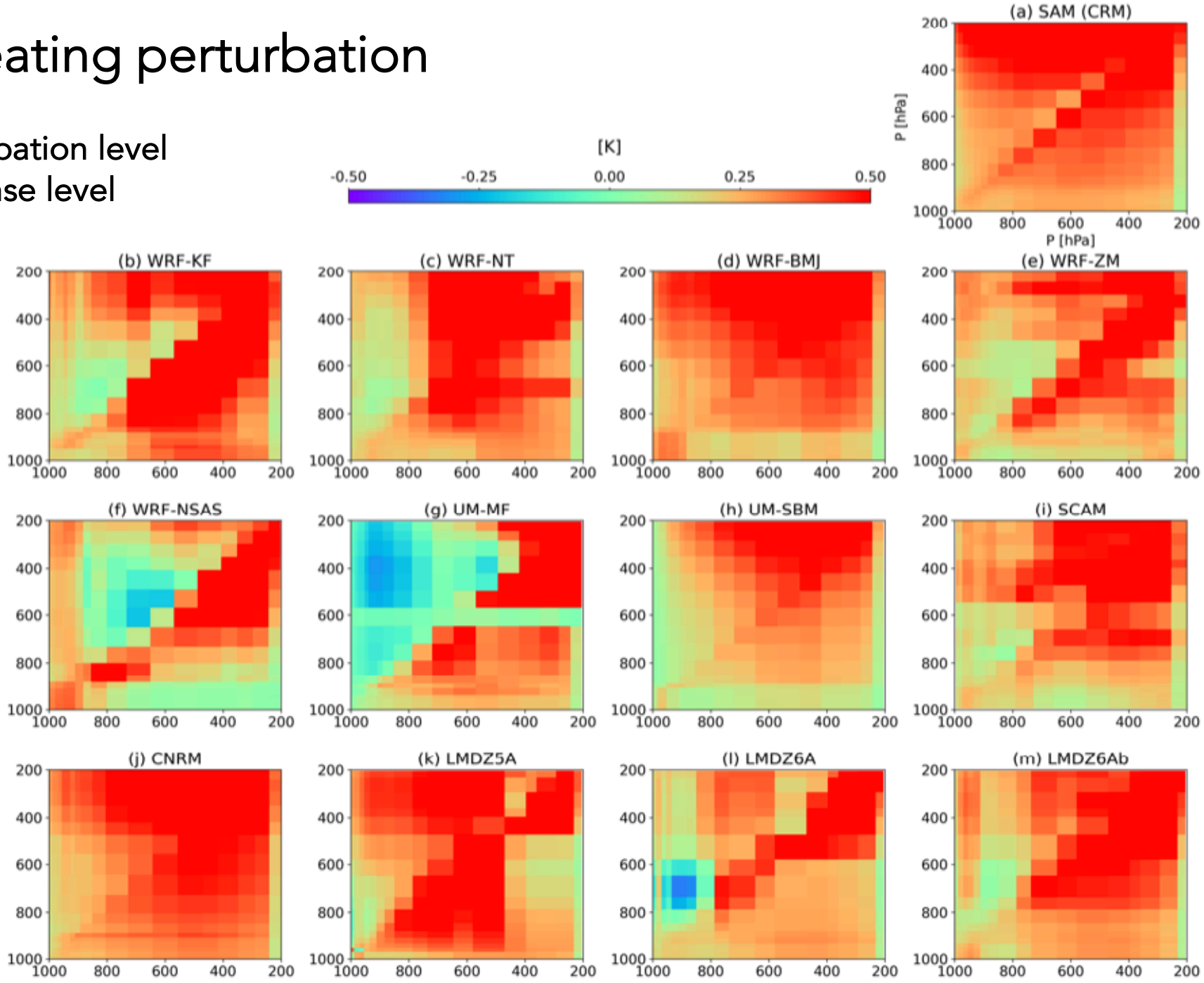


Linear responses are largely decided by the convection scheme, i.e., our method isolates the effects of convection scheme

ΔT to heating perturbation

x-axis: perturbation level
y-axis: response level



CRM

SCMs

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ΔT to heating perturbation

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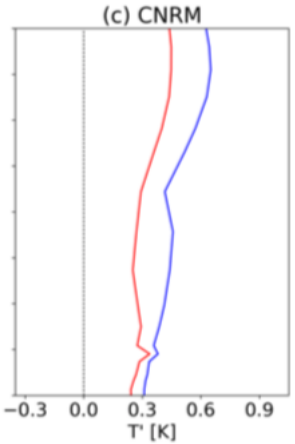
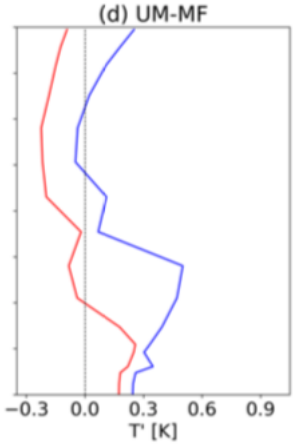
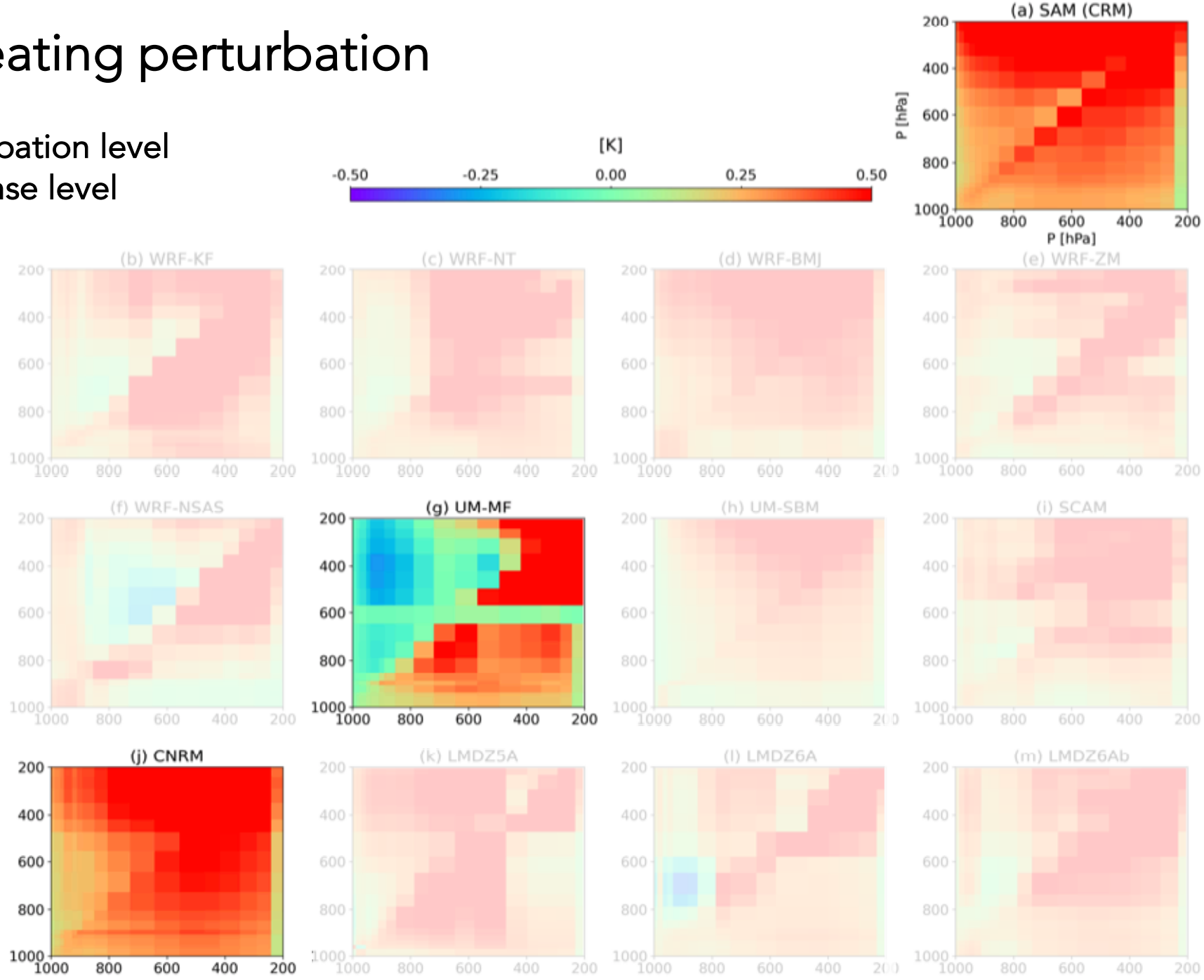
y-axis: response level







CRM

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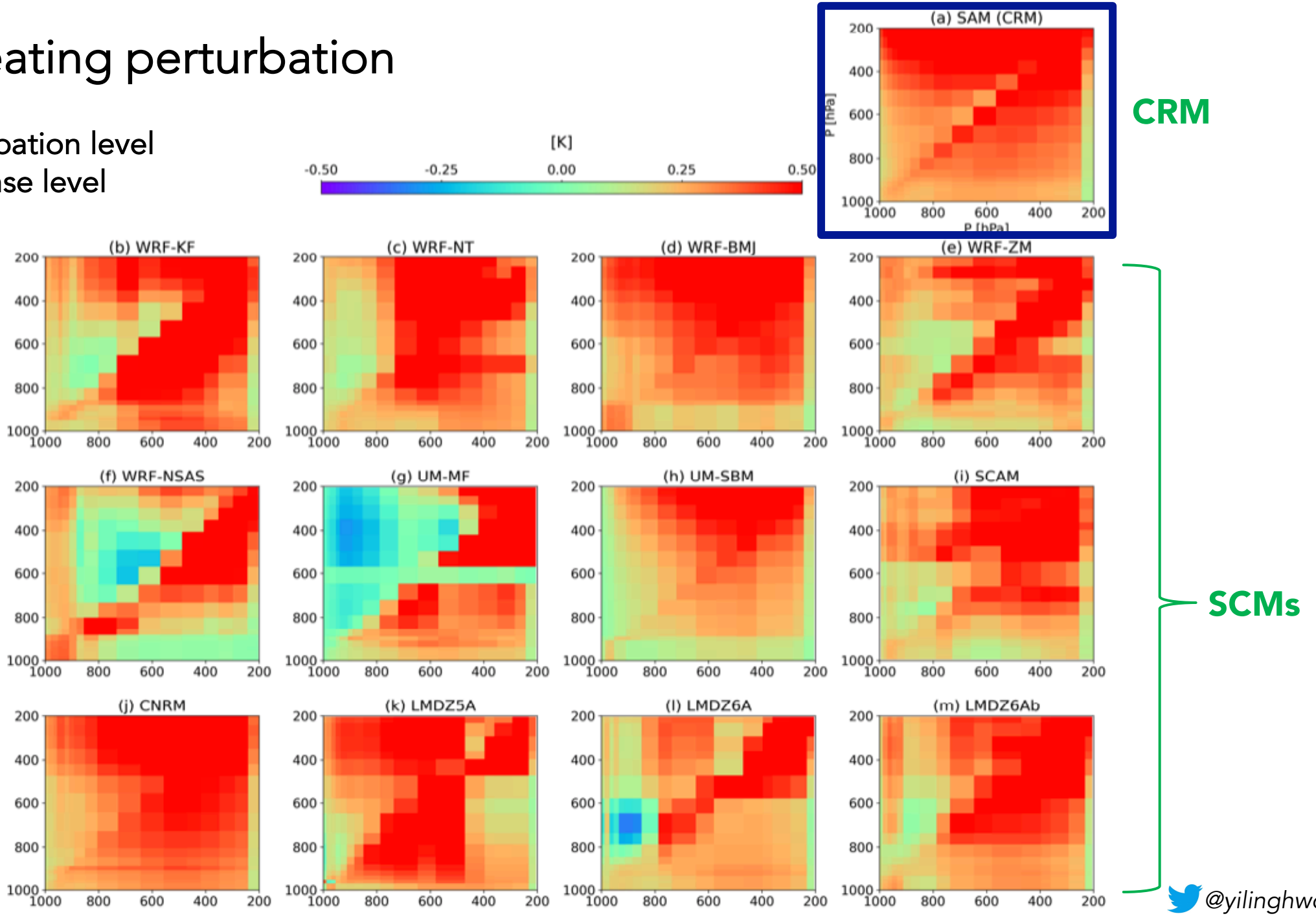

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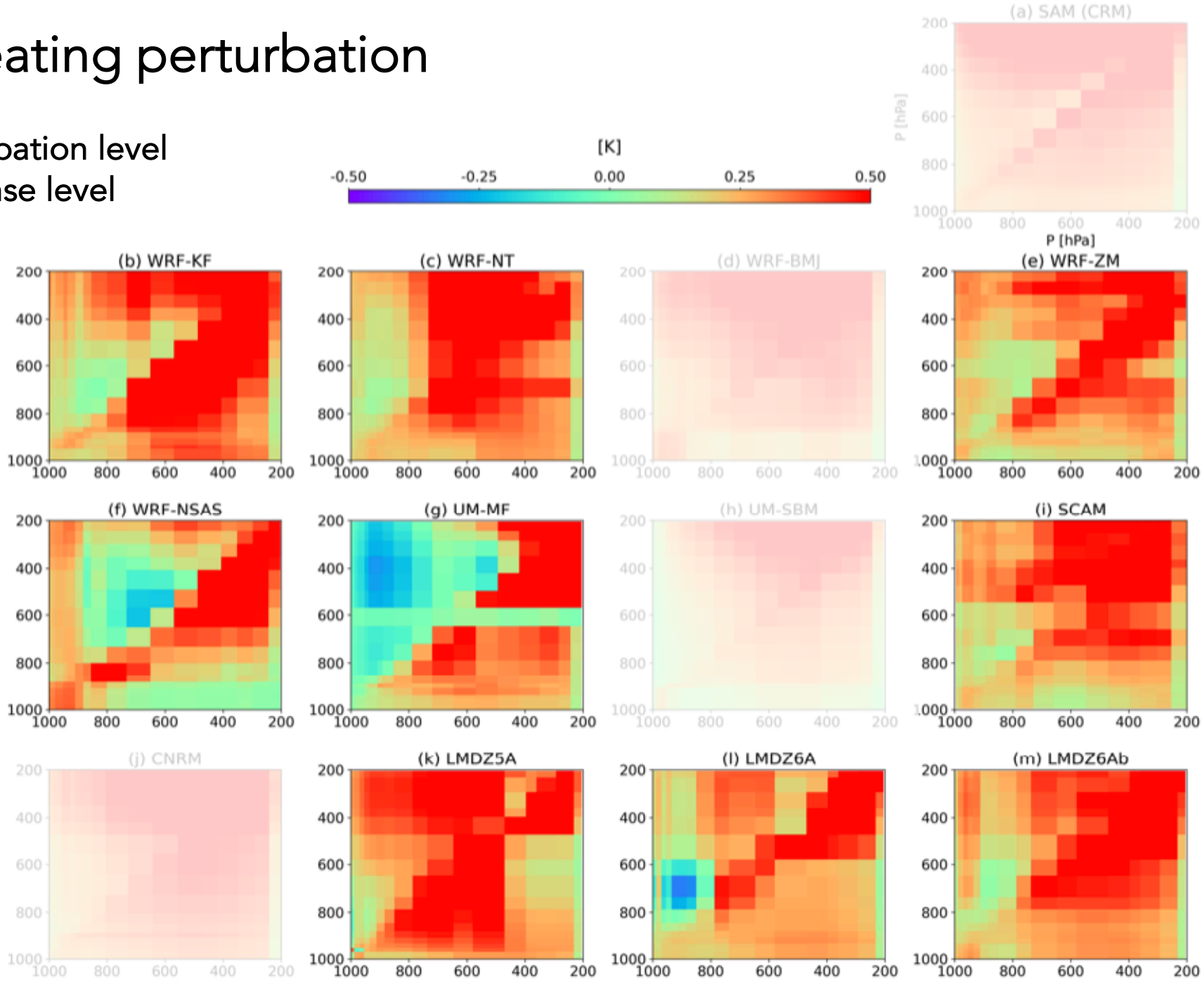

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ΔT to heating perturbation

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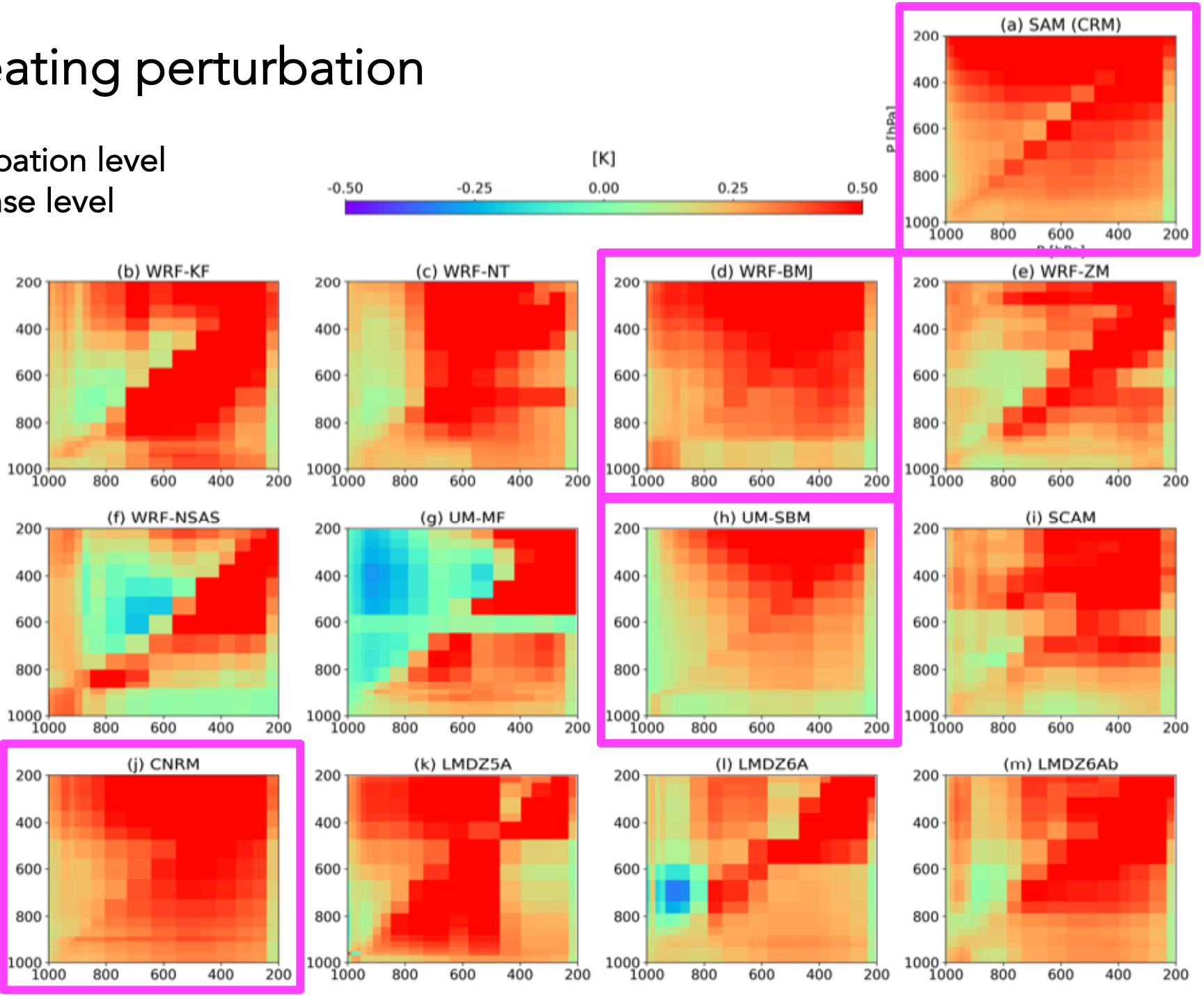

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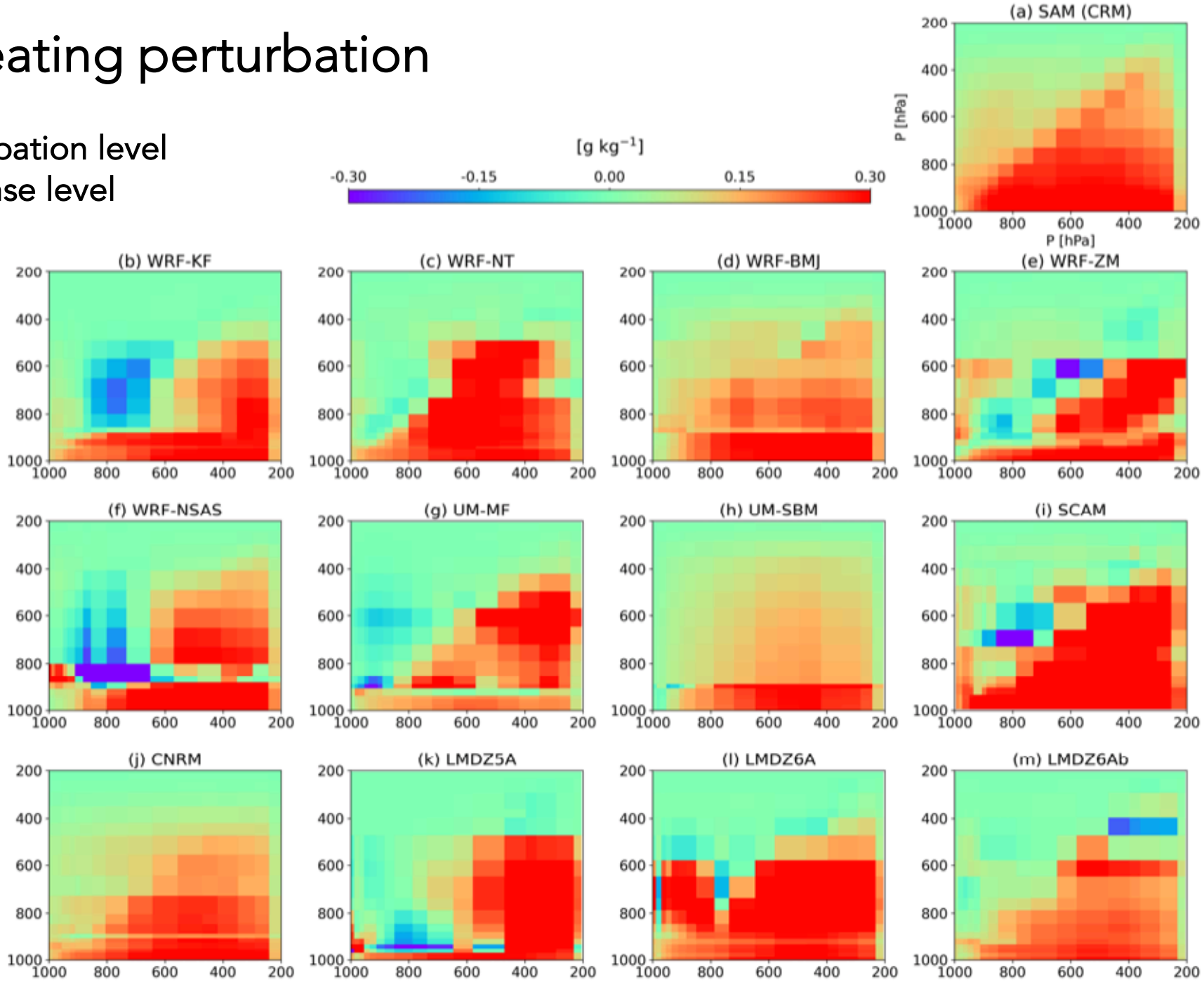
Δq to heating perturbation

x-axis: perturbation level
y-axis: response level



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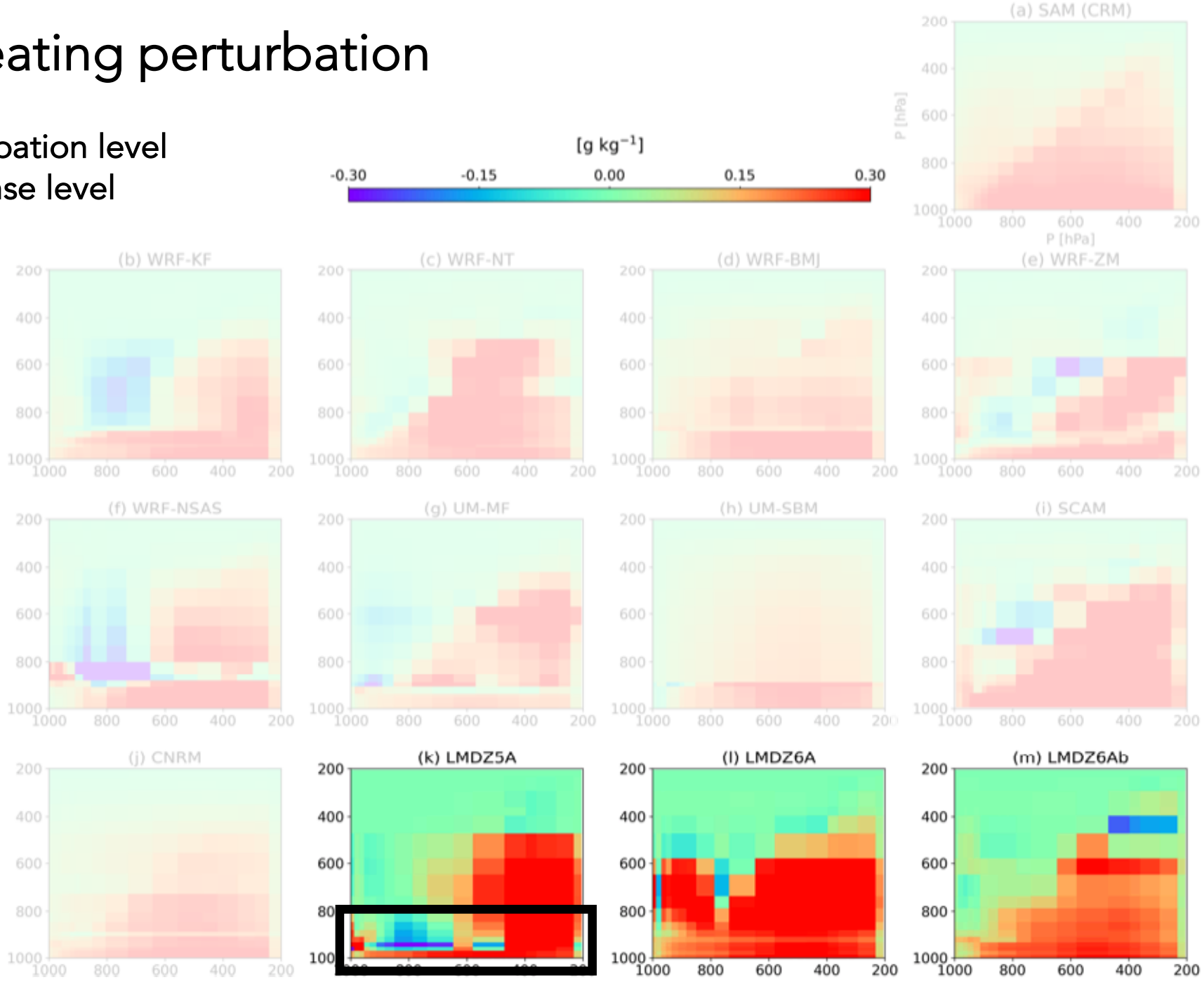
Δq to heating perturbation

x-axis: perturbation level
y-axis: response level



Δ*q* to heating perturbation

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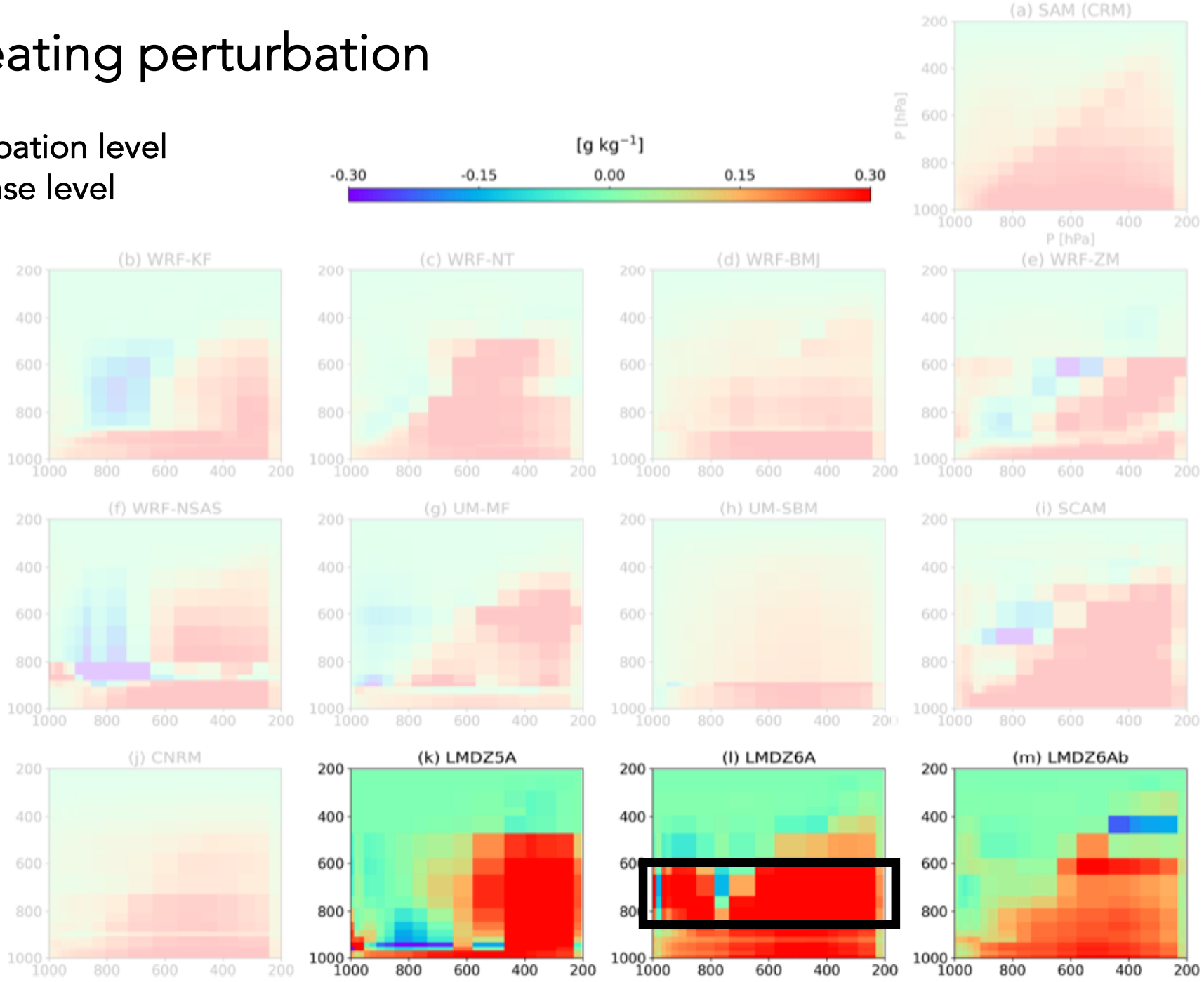
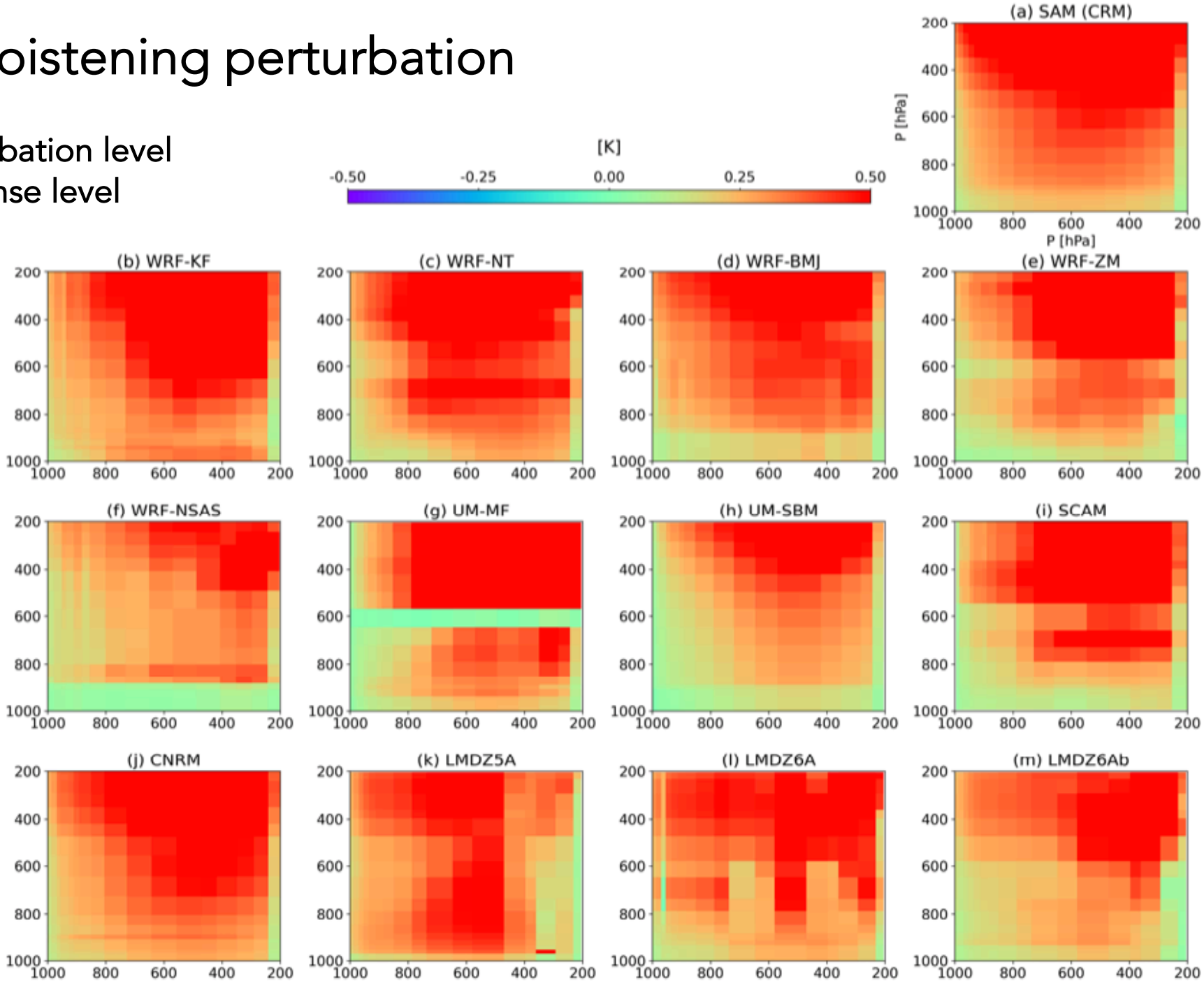
y-axis: response level



ΔT to moistening perturbation

x-axis: perturbation level
y-axis: response level



CRM

SCMs

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Δq to moistening perturbation

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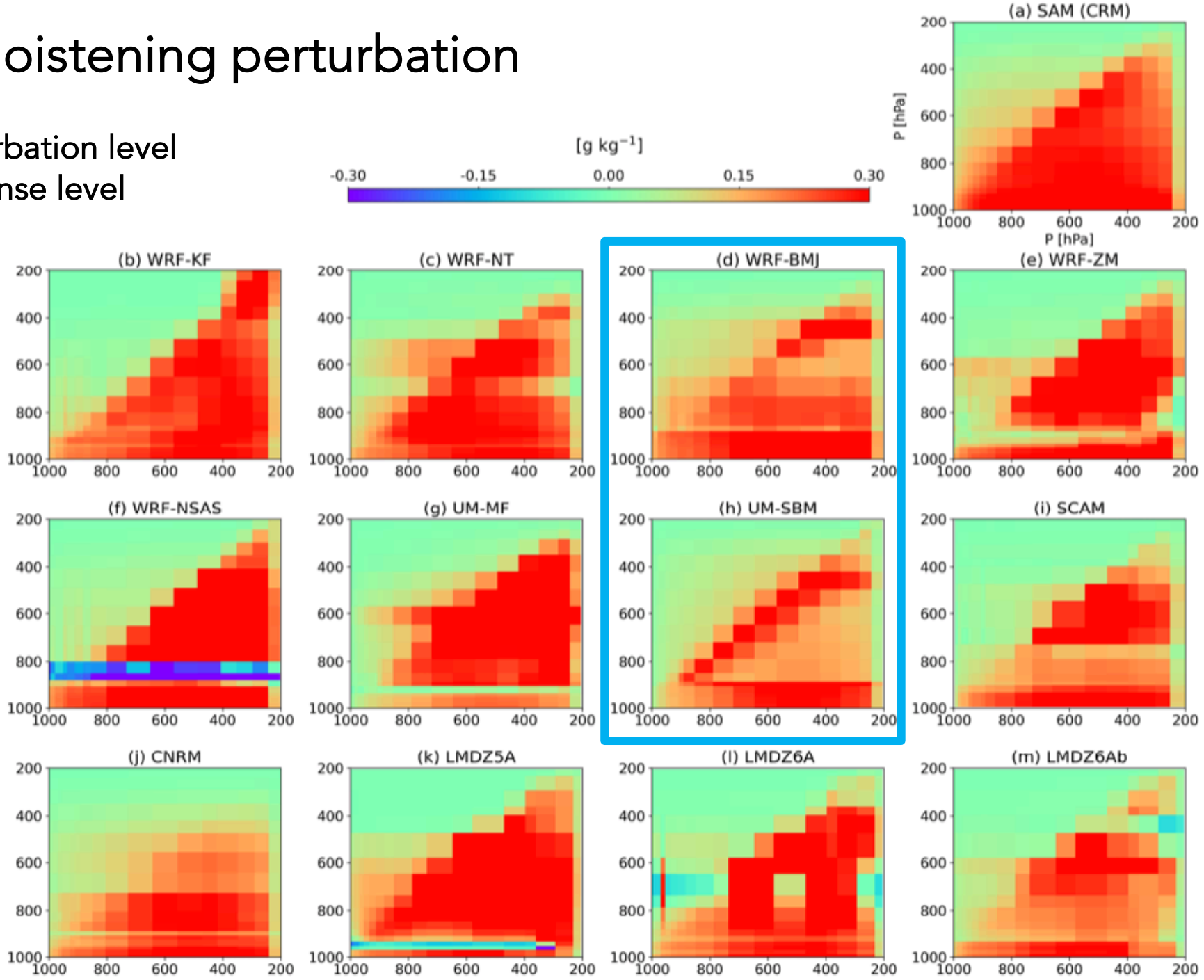

CRM

SCMs

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Summary

- The linear response function idealised framework (fixed radiation, constrained surface fluxes) is able to isolate the effects of convective parameterisation, potentially lead to improvement (e.g., LMDZ6Ab)
- Some areas of agreement between the schemes, but also substantial differences between them, which in some cases can be related to scheme design
- All SCMs show discontinuities in behaviour that are likely related to threshold-related mechanisms in convection schemes, and which do not appear in the CRM
- Demonstrate the usefulness of the LRF framework as a diagnostic / evaluation tool, but further studies needed to provide physical explanations for behaviour identified

Hope to see you soon ☺

Photo credit: Con Arronis

Additional slides

Perturbation shape: $$f_j(p_i) = \frac{1}{2}\left\{\delta_{ij} + exp\left[-\left(\frac{p_j - p_i}{75\ hPa}\right)^2\right]\right\}$$

Bulk aerodynamic formula:

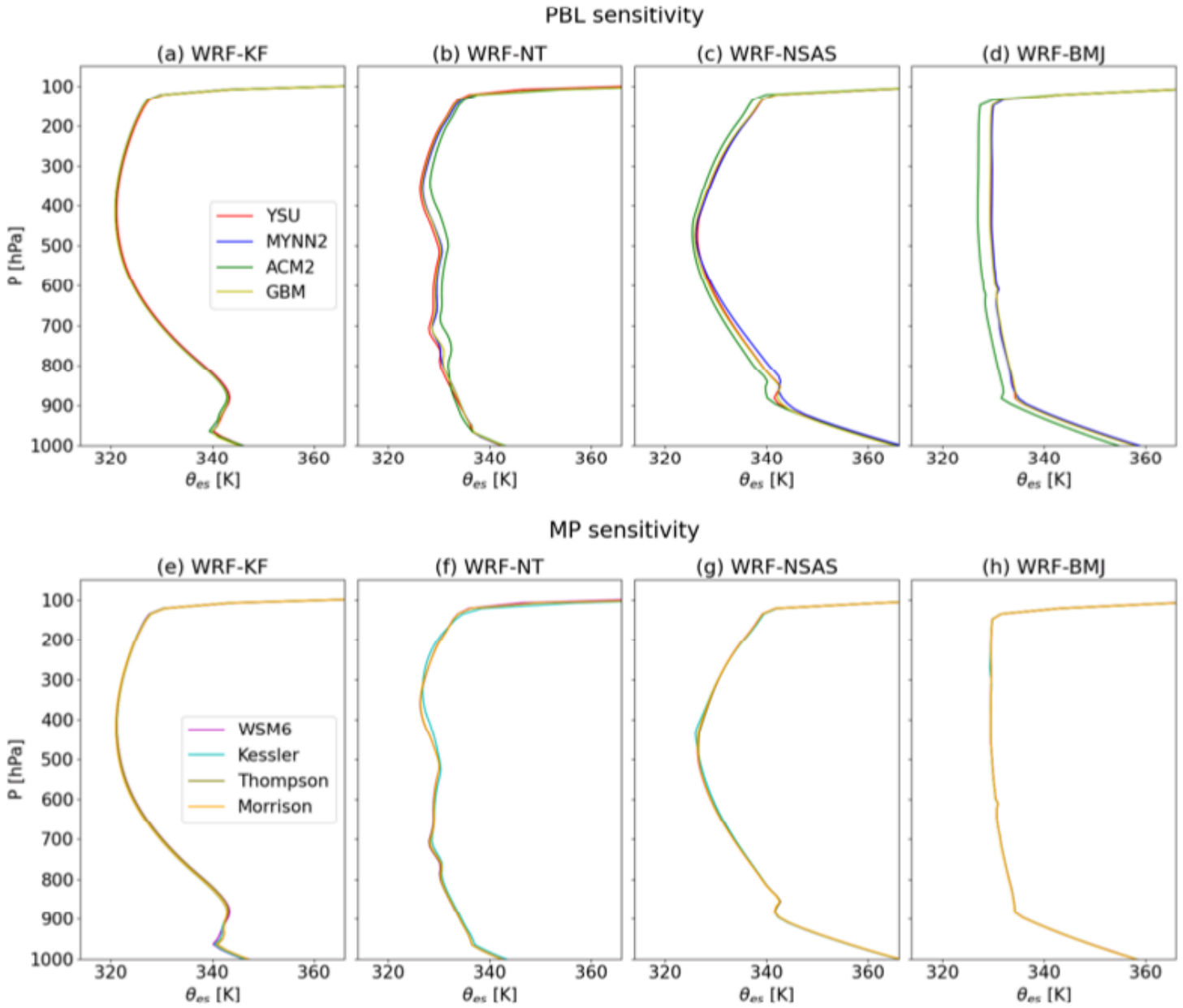
$$SH = \rho_1 c_p C_h U\left[T_s - \frac{\pi_s}{\pi_1} T_1\right]$$

$$LH = \rho_1 L_v C_e U[q_{sat}(T_s, p_s) - q_1]$$

Which physics scheme(s) decide the RCE profiles?

Sensitivity to PBL scheme

Sensitivity to microphysics scheme



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Which physics scheme(s) decide the RCE profiles?

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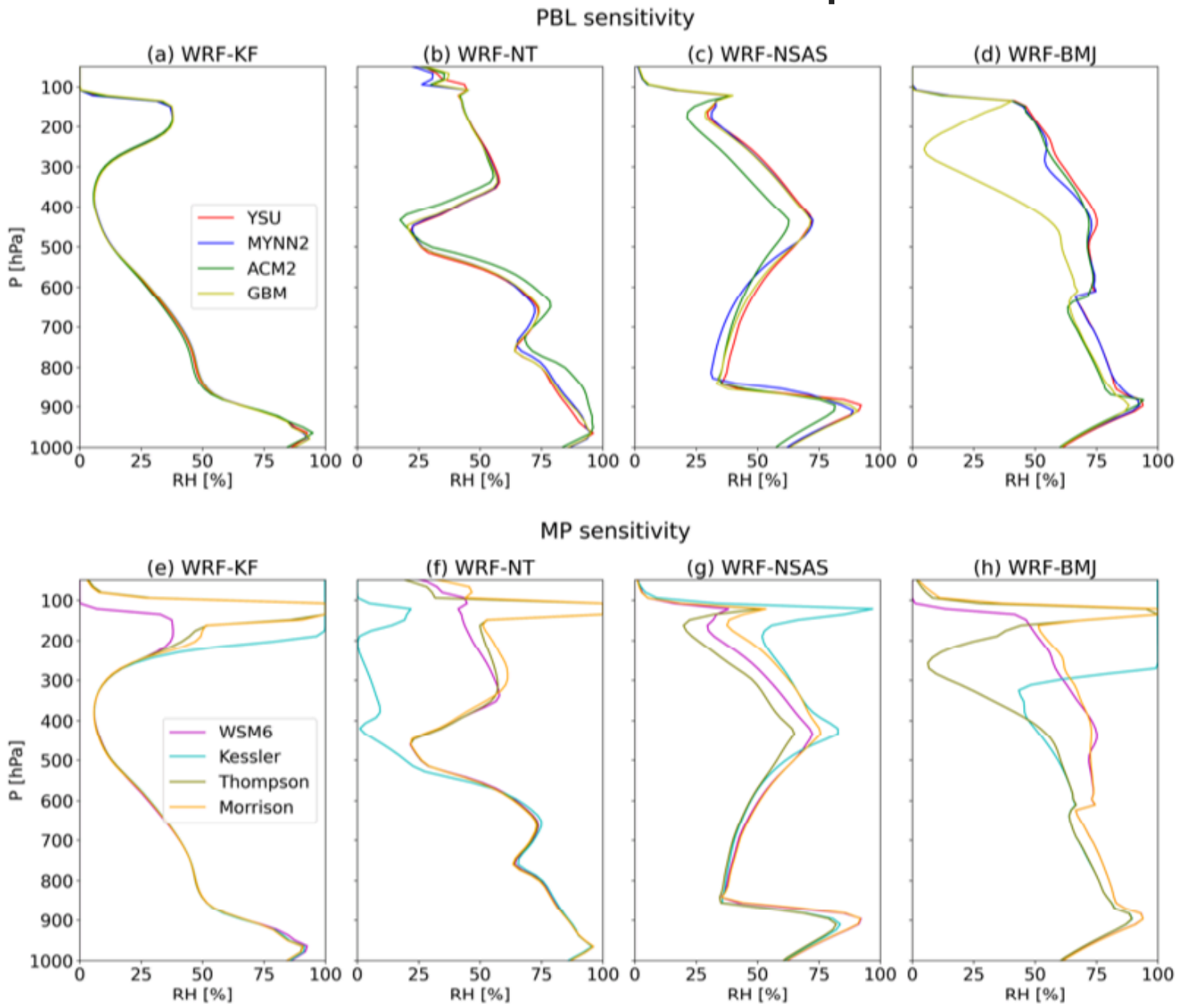

RH

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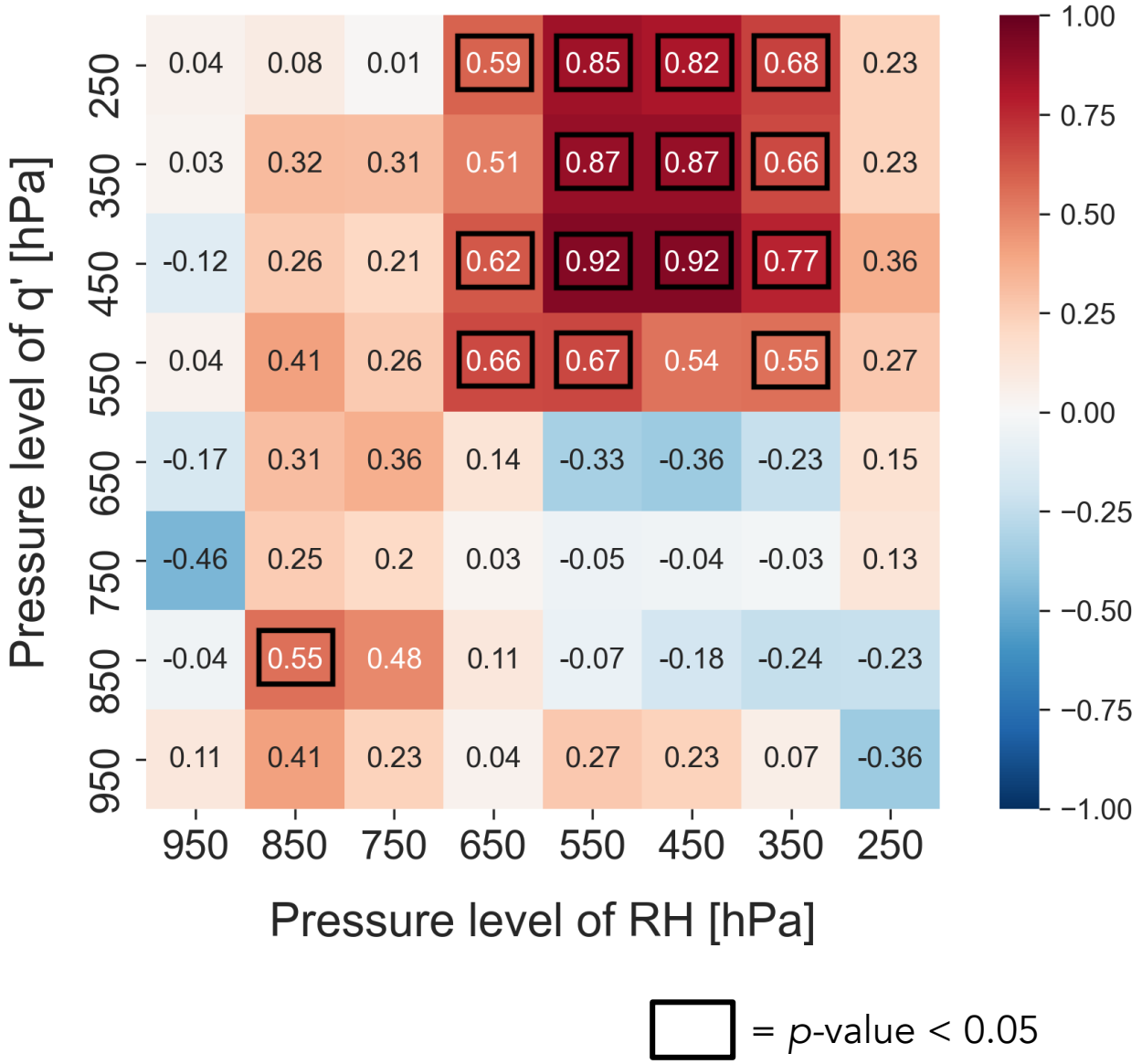
Relationship between RCE mean state and perturbation responses?



- RCE relative humidity strongly correlated with moisture response locally and at nearby levels (especially in upper troposphere)
- No correlations between RCE RH and ΔT, or between RCE Temperature profile and ΔT or Δq