The contribution of the dry intrusion, conditional, inertial and symmetric instabilities to the evolution of the Mei-Yu rainband in an idealized model

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1.Motivations

Banded precipitation and clouds are commonly seen along the Mei-Yu front. The typical width of these banded clouds varies from 50 km to 100km. Observations and numerical simulations have shown that the upright and slantwise circulations can coexist across these bands. Two instability mechanisms, Conditional Symmetric Instability (CSI) and Delta-M (the absolute momentum anomaly) adjustment have been examined in the literature to explain the formation of banded clouds in the vicinity of fronts. Additionally, the convergent mesoscale boundary, intrusion of cold fry air, density currents associated with a spreading cold pool also play essential roles on triggering successive convections. For the Mei-Yu front, more attentions were mainly paid on the large-scale environments, such as the East Asia monsoon, the southwesterly low-level jet, diurnal cycle of local precipitation, so that a detailed description of the quasi-two dimensional circulations cross a Mei-Yu frontal plane, including their structures, formation and maintenance mechanisms, is still lacking.

6.Conclusions

- The formation and maintenance of the Mei-Yu rainband is investigated through idealized numerical simulations. This rainband shows a core-gap structure and a gradual propagation toward the south.
- The entire rainfall process experiences two distinct reinvigorations, therefore it is divided into three episodes. In the first stage, the coexistence of two slantwise circulations is found and their generations are associated with the combined effect of the release of CSI and Delta-M adjustment.
- The intrusion of cold dry air is responsible for the onset of reinforced rainfall periods and their later redevelopments are the results of the combination of inertial instability (II) and conditional instability (CI) which likely plays a primary role.
- Sensitivity experiments reveal that the stronger inertial adjustment collocated with more release of CSI, implying the Delta-M adjustment can precondition the atmosphere for the CSI formation. It is also suggested that the moisture contrast should be considered in realistic Mei-Yu front initialization.

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Reference

Peng J., Zhang L., Luo Y. and Zhang Y., 2014: Mesoscale energy spectra of the Mei-Yu front system. Part I: Kinetic energy spectra. J. Atmos. Sci., 71, 37-55.

2.Model Description

1) The model

Three-dimensional model ARW, version 3.2 is employed to build the Mei-Yu front which is assumed to be oriented in east-west direction and is forced by shearing deformation. Specific model modifications can refer to Peng et al. (2014).

2) Brief introduction to initialization

The meridional geostrophic wind, $V_g(z) = 5.0\,m\,s^{-1} - (10.0\,m\,s^{-1})\tanh(z/7000\,m)$.

The analytic form of the initial wind, $u_0(y,z) = -\frac{L-y}{2y_0}u_m\{1-\tanh[\beta(L-y+\alpha z-y_0)]\}$.

The potential temperature and mixing ratio of water vapor are divided into

$$\theta_0(y,z) = \bar{\theta}(z) + \theta'_0(y,z) \quad \text{and} \quad q_{v0}(y,z) = \overline{q_v}(z) + q'_{v0}(y,z)$$

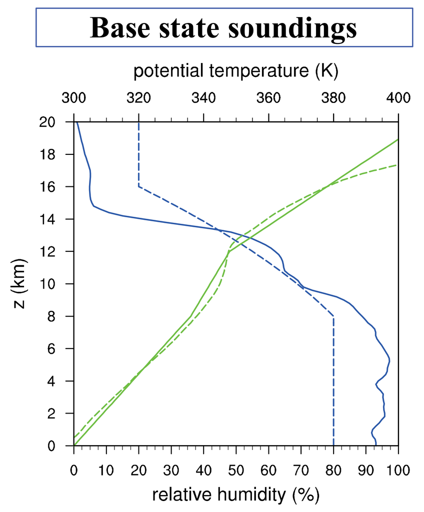
and the vertical shear of the initial zonal wind,

$$\frac{\partial\theta'_0}{\partial y} + \frac{0.61\theta_0}{(1+0.61q_{v0})}\frac{\partial q'_{v0}}{\partial y} = -\frac{f\theta_r}{g}\frac{\partial u_0}{\partial z}.$$

To highlight the strong contrast of the cross-front water vapor gradient in the Mei-Yu front,

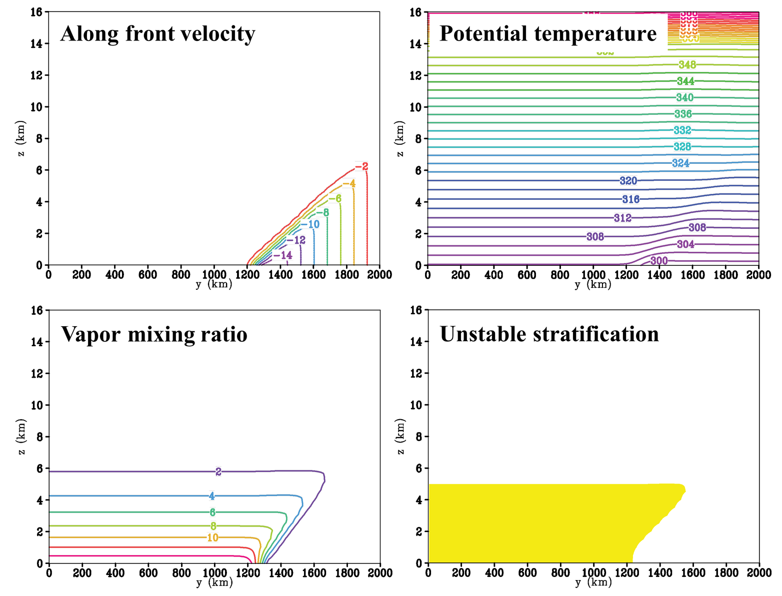
$$\frac{\partial\theta'_0}{\partial y} = (1-\gamma)[-\frac{f\theta_r}{g}\frac{\partial u_0}{\partial z}] \quad \text{and} \quad \frac{\partial q'_{v0}}{\partial y} = \gamma\frac{(1+0.61q_{v0})}{0.61\theta_0}[-\frac{f\theta_r}{g}\frac{\partial u_0}{\partial z}], \text{ where } \gamma = 0.5.$$

Base state soundings



The base states are referred to a real sounding averaged (solid lines) over a heavy Mei-Yu rainfall center.

Initial Profiles



3.Diagnostics

1) Instabilities

VRS (Vertically-integrated extent of realizable symmetric instability):

- negative MPV^* (saturated moist potential vorticity)
- convective stability (saturated potential temperature increases with height, $\partial\theta_e^*/\partial z > 0$)
- relative humidity greater than 95%
- positive vertical velocity
- inertial stability (positive absolute vorticity, $\zeta + f > 0, \zeta = -\partial u/\partial y$)

Absolute momentum M: $M = u - fy$

2) Energetics

VKE (Mass-weighted vertical kinetic energy):

$$VKE = \iiint \frac{1}{2}\rho w^2\,dxdydz / \iiint \rho dxdydz,$$

Energy conversion: **EKE** $\overline{K_e}(y,z,t) = \frac{1}{2}(u'^2 + v'^2 + w'^2)$

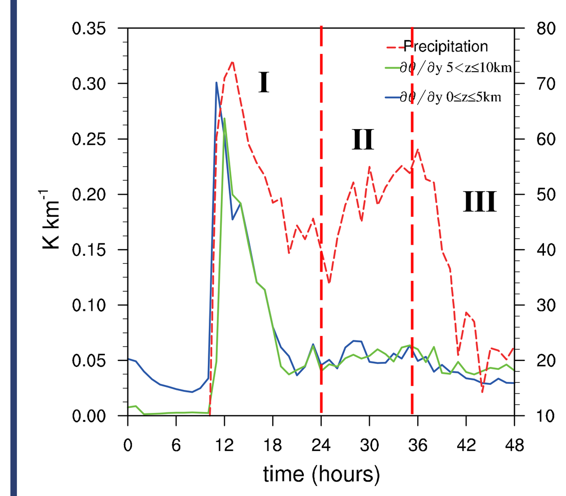
$$\frac{\partial\overline{K_e}}{\partial t} = \underbrace{-\overline{v_i'v'}\frac{\partial\bar{v}_i}{\partial y}}_{HS} \underbrace{-\overline{v_i'w'}\frac{\partial\bar{v}_i}{\partial z}}_{VS} + \underbrace{\overline{B'w'}}_{BP} - \frac{1}{\rho}(\frac{\partial(\overline{p'v'})}{\partial y} + \frac{\partial(\overline{p'w'})}{\partial z}) - (\bar{v}\frac{\partial}{\partial y} + \bar{w}\frac{\partial}{\partial z})\overline{K_e} - \frac{1}{\rho}\overline{p'\nabla\cdot v'} - \overline{v'\cdot\nabla K_e} - ds$$

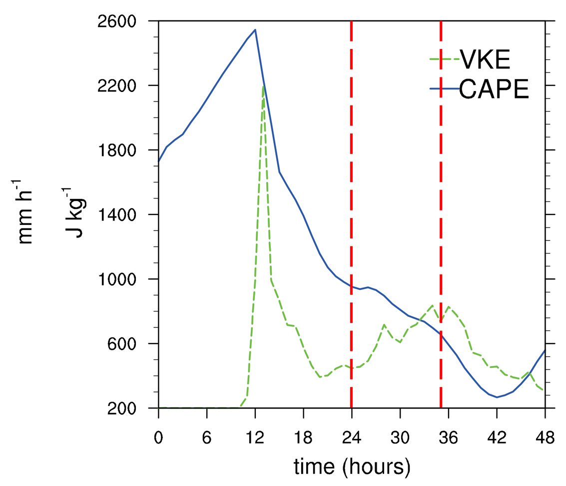
HS: horizontal shear term

VS: vertical shear term

BP: buoyance production

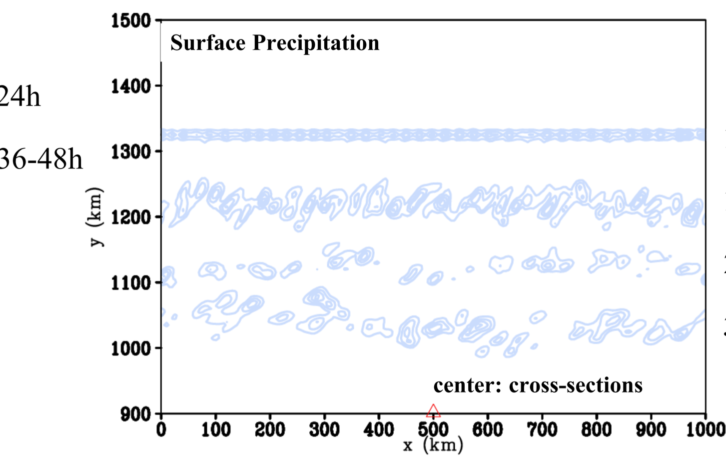
4.Control model results





Three rainfall episode:

- the first frontogenesis period 11-24h
- two reinvigorations 25-35h and 36-48h



- Core-gap structure
- Southward propagation

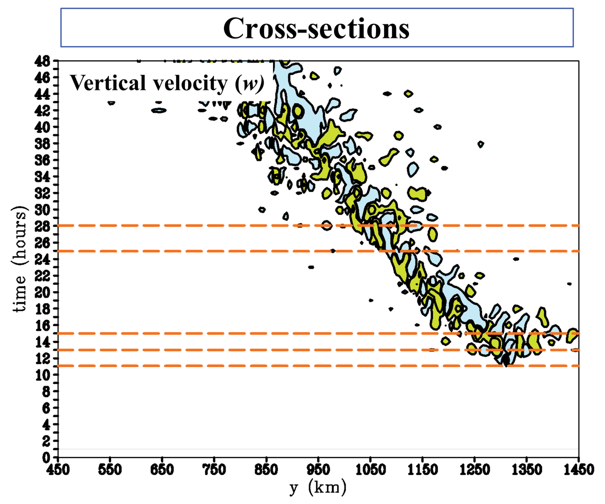
11h

17h

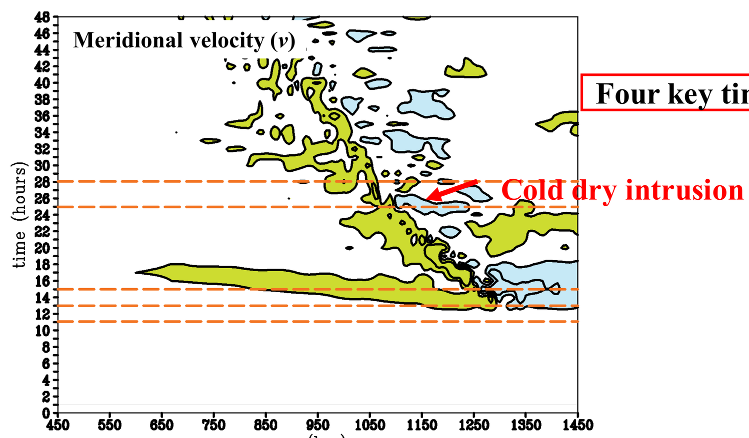
25h

35h

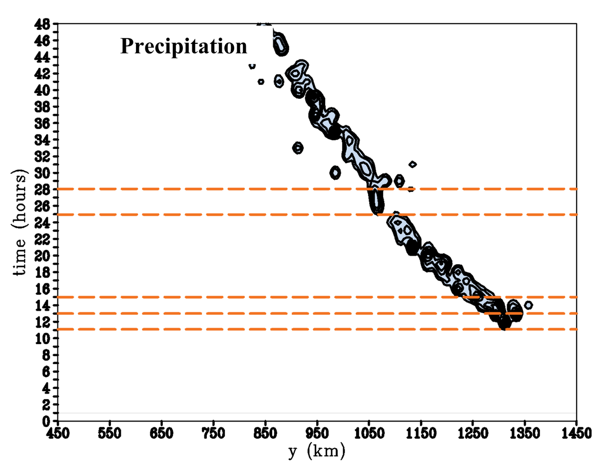
Cross-sections



Blue: negative; Bluish-yellow: positive

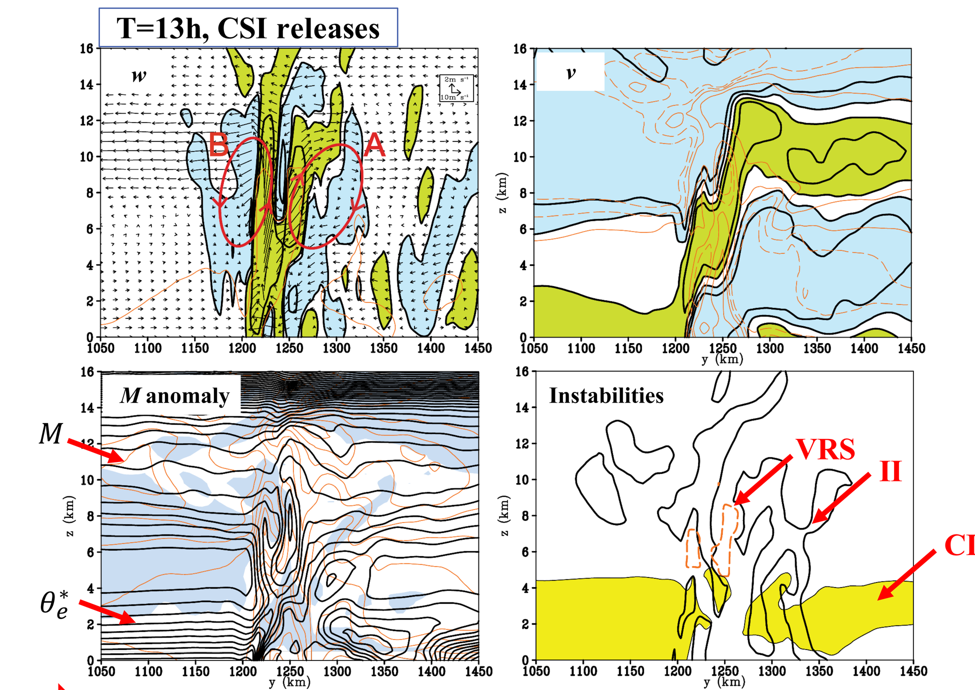


Blue: negative; Bluish-yellow: positive



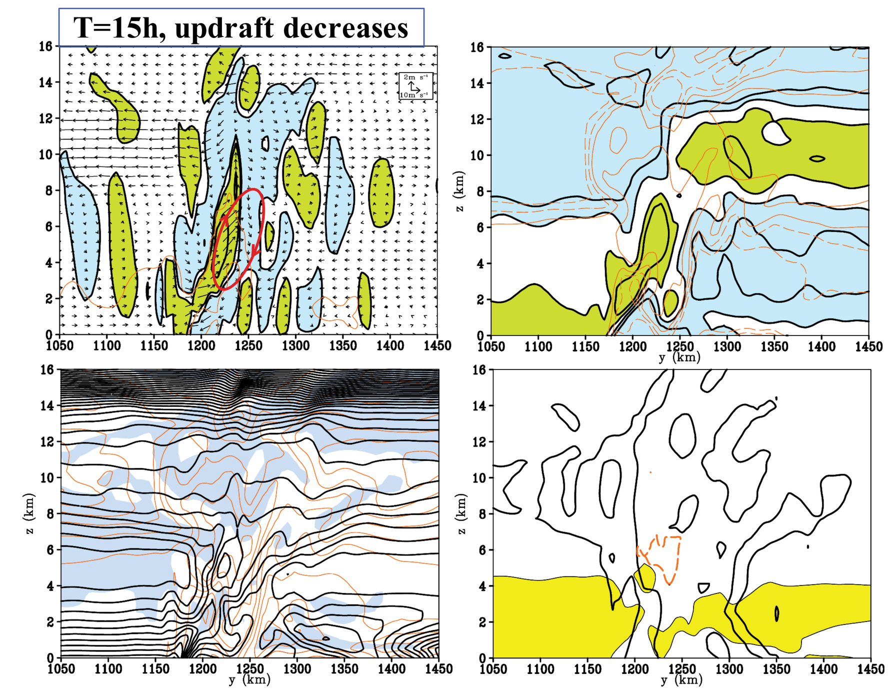
Four key times

T=13h, CSI releases



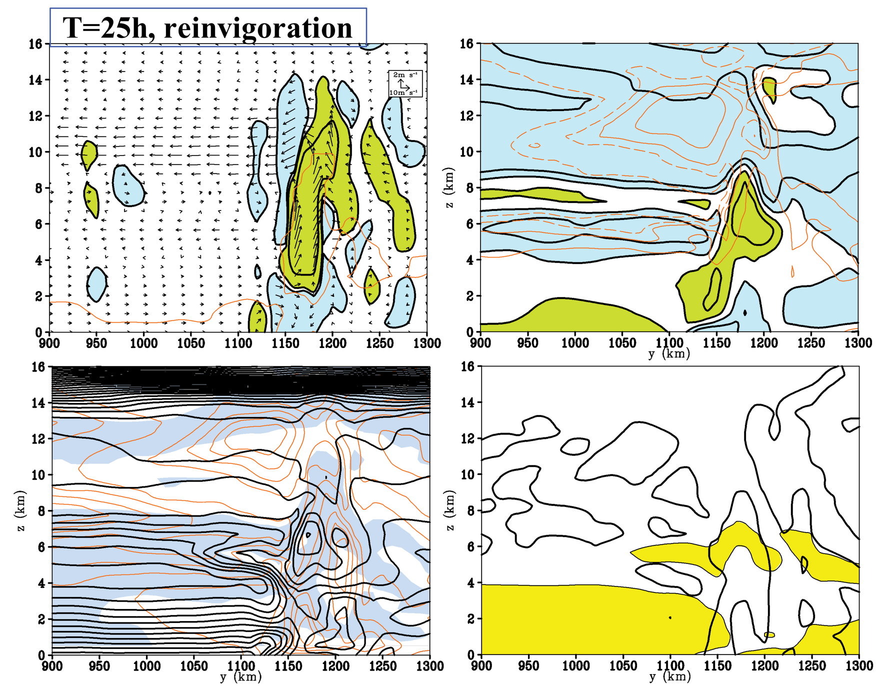
- Two slanted couplets of updraft/downdraft

T=15h, updraft decreases



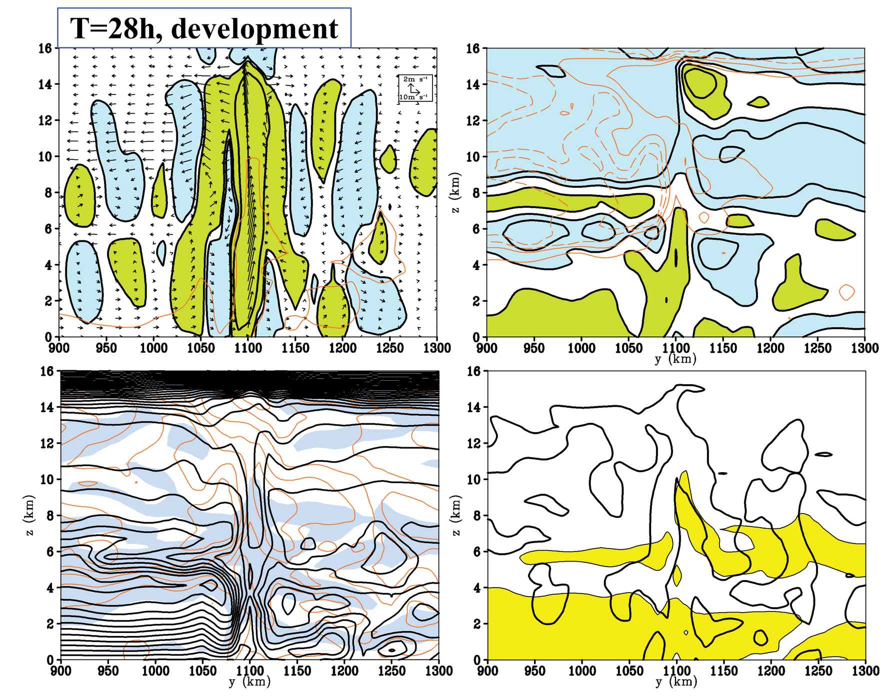
- Reduced low-level convergence

T=25h, reinvigoration

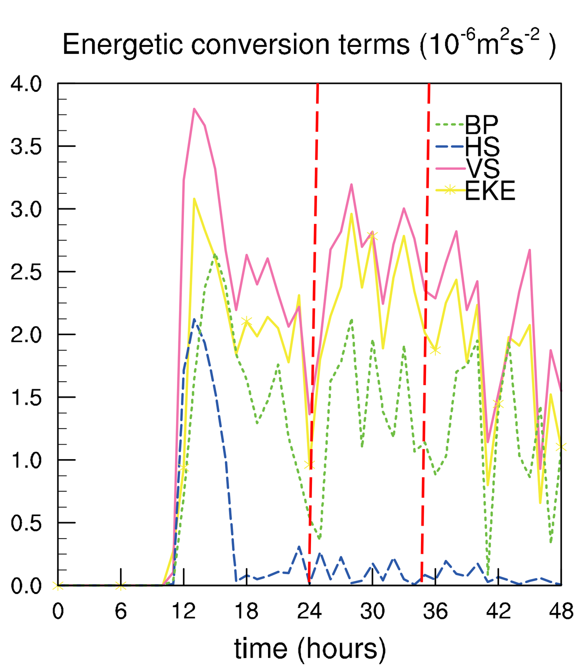


- Cold dry intrusion

T=28h, development



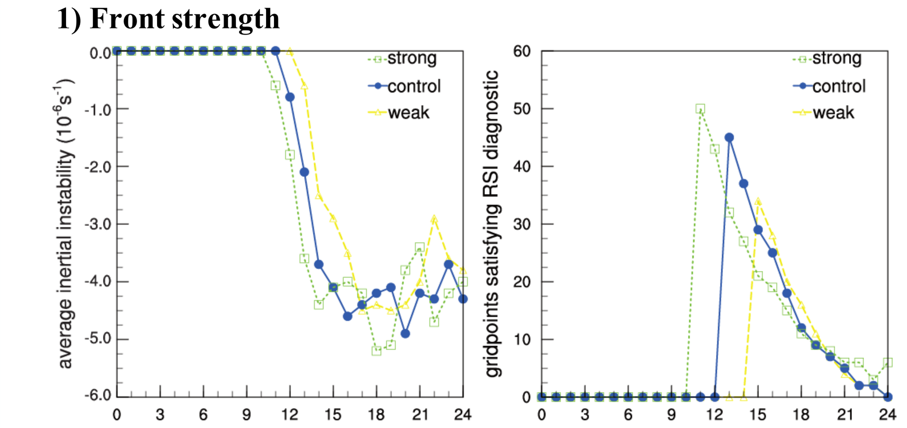
- Mid-layer CI increases



- The vertical shear VP and buoyancy production BP are the main energy sources supporting the convective activities whereas the term VP contributes the most and dominates in this cycle.

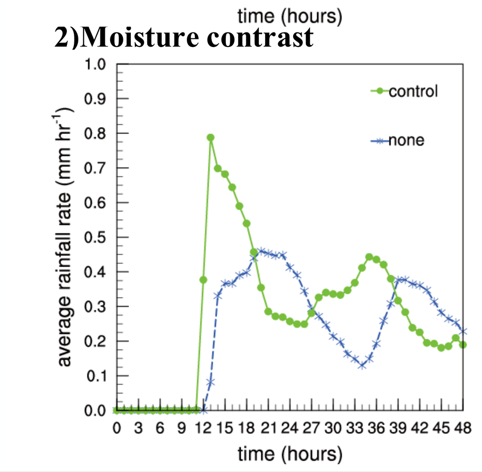
5.Sensitivities

1) Front strength



- Strong frontal strength (frontogenesis) ->strong convections->strong momentum adjustment (more inertial instability) -> more RSI grid points (increased CSI)

2)Moisture contrast



- Moisture difference across the Mei-Yu front is of significant importance in the formation and maintenance of the Mei-Yu rainband.