Differences in precipitation efficiency and their probable mechanisms between the warm sector and cold front stages of a heavy rainfall event over Beijing

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1 INTRODUCTION

The study of precipitation efficiency (PE) began in the late 1940s during the Thunderstorm Project (Braham, 1952). Palmén and Newton (1969) established a moisture budget of a synoptic system and set the PE as the ratio of surface precipitation to total available water vapor. Doswell et al. (1996) defined the large-scale precipitation efficiency (LSPE) as the ratio of surface rain rate to total moisture and the cloud-microphysics precipitation efficiency (CMPE) as the ratio of surface rain rate to total hydrometeors.

A heavy rainfall event that occurred in Beijing on July 21, 2012 was simulated successfully using the Weather Research and Forecasting model, and the precipitation efficiency (PE) during different rainfall stages was studied. The results showed that both the large-scale precipitation efficiency (LSPE) and the cloud-microphysics precipitation efficiency (CMPE) in the peak of the warm sector stage (T1) were significantly higher than those in the cold front stage (T2). The higher LSPE was related to the water vapor advection, which played a positive role in T1 due to the warm and moist advection in the lower troposphere, and a negative role in T2 because of the cold and dry airflow in the middle level. The snow-related microphysical processes had similar tendencies to the CMPE, in which the higher rain–snow collection and deposition of water vapor brought about the higher CMPE in T1. Analysis of the underlying mechanisms proved that the LSPE and CMPE were subject to the large-scale environment and cloud microphysical features.

KEYWORDS
cloud microphysics, heavy rainfall, large-scale environment, precipitation efficiency, WRF simulation

Effects of physical factors on PE have been investigated in many studies. Fankhauser (1988) suggested that the relationship between PE and vertical wind shear is not a simple inverse dependence, and thus other environmental parameters should be considered together. Doswell et al. (1996) pointed out that the entrainment rate is an important factor affecting PE, since unsaturated environmental air brought into clouds will decrease the PE. McCaul et al. (2005) revealed that cases of low ambient precipitable water have larger environment-relative PE due to stronger peak updraft speeds. Kirshbaum and Grant (2012) showed that increased liquid-water supply and longer residence times of raindrops will lead to a sharp enhancement in PE.
To date, there have been many reports on the PE of typhoon-derived or tropical convective cases (Sui et al., 2005; Gao and Li, 2011), but comparative studies on the differences in PE among various precipitation types have rarely been reported. Thus, some important questions remain unanswered. For example, what are the key physical factors affecting LSPE and CMPE? And what are the probable physical mechanisms leading to the differences in PE? To address these questions, a torrential heavy rainfall event that occurred on July 21, 2012 (referred as the “721” rainstorm), killing 79 people and causing US $1.6 billion in damages (Zhang et al., 2013; Wang et al., 2015), was investigated. Observations show that the event can be divided into two stages: (a) a warm sector rainfall stage, from 0000 to 1200 UTC 21 July; and (b) a cold front rainfall stage, from 1200 UTC 21 July to 0000 UTC 22 July. Therefore, this case is a unique subject for studying the differences in PE.

2 | MODEL AND METHODOLOGY

2.1 | Model description

The model used in this study was the Advanced Research Weather Research and Forecasting (WRF) model, version 3.6.1, which is a nonhydrostatic, three dimensional (3D) model. The domain had 38 uneven vertical levels with a model top at 50 hPa, and a 3,000-m horizontal grid spacing with 421 × 331 grid points. The physical schemes included the Morrison microphysics scheme, Yonsei University planetary boundary layer parameterization, Dudhia shortwave scheme, and the Rapid Radiative Transfer Model longwave scheme. The initial and boundary conditions were 6-hourly reanalysis data with a 0.5° latitude–longitude resolution from the European Centre for Medium-Range Weather Forecasts. The model integration covered the period 0000 UTC 21 July to 0000 UTC July 22, 2012, with a time step of 30 s. To improve the simulation results, the Local Analysis and Prediction System (LAPS) was used in our study. The Doppler radar data located in Beijing, Tianjin and Shijiazhuang were available every 6 min at 11 elevation angles. Both the reflectivity and radial wind were used, with resolutions of 1.0 km and 250 m, respectively. Data assimilation was carried out at 0000 UTC 21 July with 1.0 hr time window.

2.2 | PE calculation method

The methods for calculating PE can be broadly divided into two categories. One is LSPE, which reflects the large-scale environment, and the other is CMPE, which reflects the cloud microphysical processes. The calculation of LSPE and CMPE was based on the surface rainfall equation (Gao et al., 2005). The Morrison two-moment bulk schemes have two prognostic variables (Morrison et al., 2009), which can be used to describe both the mass mixing ratio and number concentration. Due to its good performance in forecasting of heavy flood event (Campos and Wang, 2015), the Morrison scheme was selected to calculate PE. The 3D WRF-based LSPE and CMPE were derived as follows:

\[ P_s = Q_{WVT} + Q_{WVF} + Q_{WVE} + Q_{CM}, \]  
\[ P_s - Q_{CM} = Q_{WVS}, \]  
\[ Q_{WVT} + Q_{WVF} + Q_{WVE} = Q_{WVS}, \]  
\[ P_s = \rho \left( w_{Tq} + w_{Ts} q + w_{Tg} q_g \right), \]  
\[ Q_{WVT} = -\frac{\partial [q]}{\partial t}, \]  
\[ Q_{WVF} = -\frac{\partial (uq)}{\partial x} + \frac{\partial (vq)}{\partial y}, \]  
\[ Q_{WVE} = E_{S}, \]  
\[ Q_{CM} = \frac{-\partial [q]}{\partial t} - \left[ \frac{\partial [uq]}{\partial x} + \frac{\partial [vq]}{\partial y} \right], \]  
\[ q = \{ q_r, q_i, q_c, q_s, q_g \} \]  
\[ Q_{WVS} = [PCC(>0)] + [PRD] + [PRDS] + [PRDG] \]  
\[ -[PCC(<0)] - [PRE] - [EPRD] - [EPRDS] - [EPRDG] \]  
\[ -[EVPMS] - [EVPMG], \]  
\[ LSPE = \frac{P_s}{H(Q_{WVT})Q_{WVT} + H(Q_{WVF})Q_{WVF} + Q_{WVE} + H(Q_{CM})Q_{CM}}, \]  
\[ CMPE = \frac{P_s}{H(Q_{WVS})Q_{WVS} + H(Q_{CM})Q_{CM}}. \]

Here, \( P_s \), the surface rain rate, is equal to the sum of water vapor processes, including local atmospheric drying/moistening \( Q_{WVT} \), water vapor flux convergence/divergence \( Q_{WVF} \), surface evaporation \( Q_{WVE} \) and cloud processes, including hydrometeor loss/convergence or hydrometeor gain/divergence \( Q_{CM} \). \( Q_{WVS} \) is the net amount of water vapor consumed by microphysical processes (see Appendix A). Some variables from the WRF simulation data were used to calculate the aforementioned ones, such as the average atmospheric density \( (\rho) \); the terminal velocities of rain, snow and graupel \( (w_{Tr}, w_{Ts}, w_{Tg}) \); the mixing ratios of water vapor, cloud water, rain water, cloud ice, snow and graupel \( (q_r, q_i, q_c, q_s, q_g) \); the zonal and meridional winds \( (u, v) \); and the surface evaporation \( (E_S) \). Here, \( \int_{z_t}^{z_b} \rho(z)dz \) denotes the mass vertical integration, where \( z_t \) and \( z_b \) are the top and bottom height of
the model atmosphere, respectively. $H(Q_X)Q_X$ means that only a value of $Q_X$ greater than 0 is taken to ensure that the calculated LSPE and CMPE range from 0 to 100% (Sui et al., 2005).

3 | RESULTS

3.1 | Key physical factors causing differences in LSPE

Figure 1a shows the time series of the area-averaged (38°–42°N, 113°–119°E), observed and simulated rainfall rates. The observational data used here were the 0.1° × 0.1° merged precipitation products of automatic weather station data in China and the CMORPH satellite data (Shen et al., 2014). Due to the excessive moisture in the data assimilation of multiple radars, the precipitation in the warm sector was overestimated by the model. In contrast, the simulated precipitation was underestimated in the cold front stage because of the faster moving convection systems compared with the observation. Nevertheless, the simulated precipitation resembled the observed data both in its evolution and magnitude. The model data could be used to calculate the LSPE and CMPE.

Figure 1b shows the time series of the area-averaged PE, where distinct anomalies existed during the first few hours because the WRF model needed time to spin up (Done et al., 2004). Accordingly, we focused on the differences in PE between the peak of the warm sector stage (0600–1200 UTC, referred to as “T1”) and that of the cold front stage (1200–1800 UTC, referred to as “T2”). Generally, the temporal evolutions of LSPE and CMPE were very similar. However, the mean values of LSPE and CMPE were 36.09 and 60.66% in T1, and 32.12 and 54.02% in T2, respectively, revealing that both the LSPE and CMPE in T1 were obviously higher.

To determine the key physical factors, the numerator and denominator terms of LSPE were analyzed (Equations (1) and 10). In general, the $Q_{WVF}$ and $Q_{WVT}$ had a significant impact on the $P_S$ (Figure 2a). The $Q_{WVF}$ was the main positive contributor to the water vapor in T1, but it began to decrease gradually when entering T2, with the $Q_{WVT}$ beginning to play a positive role. During the T1 period, the local atmospheric drying ($H(Q_{WVT})Q_{WVT}$) played a significant role in the supply of water vapor—even greater than the water vapor flux convergence ($H(Q_{WVF})Q_{WVF}$, Figure 2c). However, the heavy rainfall processes conversely moistened the local atmosphere ($Q_{WVT} < 0$), the $Q_{WVF}$ made the greatest contribution to $P_S$ in T1 (Figure 2a). By comparison, the $Q_{WVT}$ had an increasingly positive effect due to the lack of water vapor supply caused by the weakening of $Q_{WVF}$ in T2 (Figure 2a). The $Q_{CM}$ made a weak and negative contribution to $P_S$ in both stages because the heavy rainfall processes were always associated with a local increase in the concentration of hydrometeors ($Q_{CM} < 0$, Figure 2a, c). In short, both $Q_{WVF}$ and $Q_{WVT}$ contributed greatly to $P_S$, but the effect of the latter depended on the former, implying that $Q_{WVF}$ is the most critical physical factor in LSPE.

To understand the influence of $Q_{WVF}$ on differences in LSPE, $Q_{WVF}$ can be further decomposed into (a) the water vapor convergence ($Q_{GRADV}$) and (b) the water vapor advection ($V_{GRADQ}$):

$$Q_{GRADV} = -q_v \left( \frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} \right), \quad (13)$$

$$V_{GRADQ} = -q_v \left( \frac{\partial q_v}{\partial x} + v \frac{\partial q_v}{\partial y} \right), \quad (14)$$

It is clear that $Q_{GRADV}$ comprised a more significant portion of the $Q_{WVF}$, the magnitudes of which were very...
similar in the two stages (Figure 3a). However, the VGRADQ played an opposite role in the QWVF during the T1 and T2 periods, which naturally brought about the higher LSPE in T1.

Furthermore, the vertical profile of the non-integral water vapor convergence (qgradv) and water vapor advection (vgradq) are given in Figure 3b,c, respectively. The vertical characteristics of qgradv in both stages were relatively close, but those of vgradq were significantly different. In the lower troposphere, the vertical integration of the wet advection (vgradq > 0) in T1 was 4.81 times larger than that in T2, implying that the stronger QWVF in T1 was related to the vigorous wet advection. In the middle level, the largest layer of the dry advection (vgradq < 0) in T1 was 4.81 times larger than that in T2, implying that the stronger QWVF in T1 was related to the vigorous wet advection. In the middle level, the largest layer of the dry advection (vgradq < 0) in T1 was 4.81 times larger than that in T2, implying that the stronger QWVF in T1 was related to the vigorous wet advection. In the middle level, the largest layer of the dry advection (vgradq < 0) in T1 was 4.81 times larger than that in T2, implying that the stronger QWVF in T1 was related to the vigorous wet advection.

The above studies proved that both QWVF and QWVT need to be considered in the prediction of the heavy rainfall events. Both of the strong and the weak low-level water vapor advection can lead to the strong precipitation. It should be noted that the sustained supplement of water vapor can happened in the environment of the weak low-level water vapor advection, which gives a clue for the forecast and simulation of the heavy precipitation cases.

3.2 Key physical factors causing differences in CMPE

The impacts of physical factors on CMPE are discussed in this section. Figure 2b shows the hourly area-averaged numerator terms of CMPE (Equations (2) and 11). Clearly, the QWVS played a decisive role in CMPE during the two stages. Although the hydrometeor loss/convergence (H(QCM)QCM) accounted for over 30% of the water vapor...
supply, the $Q_{CM}$ only took a negative proportion in the numerator. The reason was that the local increase of hydrometeors ($Q_{CM} < 0$) consumed a lot of water vapor accompanied by the heavy rainfall process (Figure 2b, d).

The net consumption of water vapor ($Q_{CM}$) is equal to the sum of the net increase in hydrometeors, so we analyzed indirectly the impacts of the hydrometeors on CMPE. In terms of magnitude, the QSTEN and QRTEN terms had the greatest influence on the surface precipitation (Figure 4a). The correlation coefficient between QSTEN and CMPE was significantly higher than that between QRTEN and CMPE, revealing that QSTEN played the most significant role in CMPE.

$$Q_{STEN} = \frac{1}{C_{138}} [PRAI + PRCI + PRDS + PRACS + PRACIS + PIACRS + PIACR + PRACG - EVPMS - PSACR - PSMLT]$$

$$Q_{RTEN} = \frac{1}{C_{138}} [PRA + PRC + PGMLT + PSMLT - PRE - PIACRS - PRACS - MNUCCR - PGRACS - PIACR - PRACG],$$

The magnitude of the snow-related microphysical processes (QSTEN) in T1 was significantly higher than that in T2 (Figure 4b). During the T1 period, CMPE was closely connected to PRACS and PRDS. Additionally, it was highly correlated with PRCI, PSACWS, PRACIS and PRAI in T2. The degree of correlation between QSTEN and CMPE in T1 was greater than that in T2. Considering the magnitude and relevance, the rain–snow collection (PRACS) and the deposition of water vapor (PRDS) were the key processes in CMPE. By comparison, the correlation between the largest contribution term (PRA) of QRTEN and CMPE was only 0.35 (Figure 4c). Besides, more sink terms of QRTEN were highly and negatively correlated with CMPE than those of...
QSTEN, which explains why QSTEN had more of an impact on CMPE than QRTEN.

3.3 Probable mechanisms related to the differences in PE

3.3.1 Probable mechanism in LSPE

From the above results, it was found that the dry and wet advection of water vapor was the key physical factors in LSPE, and the snow-related source terms were crucial in CMPE. To validate these conclusions, a diagnostic study of the environmental and microphysical variables was further performed. During the T2 period, relative humidity perturbation maintained a declining trend, with the maximum value appearing at 0700 UTC, which was consistent with that of CMPE and LSPE (Figure 5a). The whole tendency of potential temperature perturbation resembled that of relative humidity, although the maximum value appeared an hour later than it did for relative humidity in T1, and obvious fluctuations existed in T2 (Figure 5b). Generally, the relative humidity and potential temperature perturbation ascended in T1 and descended in T2, proving that the higher LSPE in T1 resulted from the warm and wet advection and the lower LSPE in T2 was due to the cold and dry advection.

Figure 5c shows the hourly area-averaged maximum updraft and downdraft. It is clear that the convergence condition of water vapor due to the stronger updraft in T1 was better than that in T2, which corresponded to the higher $Q_{WVF}$ and LSPE. To diagnose the thermodynamic properties of convection, the vertical component of the convective vorticity vector ($CVV_z$; Gao et al., 2007) and horizontal components of the dynamic vorticity vector ($DVV_x$, $DVV_y$; Ping et al., 2008) were calculated (Figure 5d). Due to the high correlation between $CVV_z$ and the cloud hydrometeor mixing ratios (Gao et al., 2004), the higher $CVV_z$ indicated that the stronger convective activity in T1 caused the higher LSPE. The zonal component of the DVV is related to the interaction between the vorticity, buoyancy and vertical pressure gradient (Gao, Cui, Zhou, Li, and Tao, 2005), therefore the high magnitude of $DVV_y$ in T1 suggested that the meridional convective forcing was also a probable reason behind the higher LSPE.
\[
\mathbf{CVV}_z = \left| \mathbf{e} \times \nabla \theta_z \right| / \rho = \left| \left( \frac{\partial w}{\partial y} - \frac{\partial v}{\partial z} \right) \frac{\partial \theta_z}{\partial y} - \left( \frac{\partial u}{\partial z} - \frac{\partial w}{\partial x} \right) \frac{\partial \theta_z}{\partial x} \right| / \rho
\]

(17)

\[
\mathbf{DDV}_X = \left| \mathbf{e} \times \nabla \hat{V} \right| / \rho = \left| w \left( \frac{\partial u}{\partial z} - \frac{\partial w}{\partial x} \right) - v \left( \frac{\partial v}{\partial x} - \frac{\partial u}{\partial y} \right) \right| / \rho
\]

(18)

FIGURE 5  Hourly area-averaged (a) relative humidity perturbation, (b) potential temperature perturbation, (c) maximum updraft and downdraft, (d) vertical component of convective vorticity vector and horizontal component of dynamic vorticity vector, (e) ice water path (IWP) and liquid water path (LWP), and (f) eight rainfall types, in which T, t, F, f, M and m represent $Q_{WVT} > 0$, $Q_{WVT} < 0$, $Q_{WVF} > 0$, $Q_{WVF} < 0$, $Q_{CM} > 0$, $Q_{CM} < 0$ and the solid and dotted lines denote the convective and stratiform types, respectively.
\[ \left| \overline{DDV}_y \right| = \left| \left( \overrightarrow{e} \times \nabla \right) / \rho \right| y = \left[ u \left( \frac{\partial v}{\partial x} - \frac{\partial u}{\partial y} \right) - w \left( \frac{\partial w}{\partial y} - \frac{\partial v}{\partial z} \right) \right] / \rho \]

Here, \( \overrightarrow{e} \), \( \theta \), and \( \rho \) are the vorticity vector, the equivalent potential temperature and the atmospheric density, respectively.

3.3.2 Probable mechanism in CMPE

Figure 5e shows the hourly area-averaged ice water path (IWP) and liquid water path (LWP; Sui and Li, 2005). It is apparent that the former had a more similar evolution to CMPE. The IWP was considerably greater than the LWP in T1, while the gap between them became smaller due to the maintained trend of LWP and the decrease of IWP in T2, which demonstrates the different effects of QSTEN and QRTEN on CMPE.

To study the effect of different rainfall types, Shen et al. (2010) proposed an eight-rainfall-type separation scheme according to the different combinations of three precipitation processes (QWVT, QWVF, QCM). These types are TFM, TFm, tFm and so on (Figure 5f), where T, t, F, f, M and m represent QWVT > 0, QWVT < 0, QWVF > 0, QWVF < 0, QCM > 0 and QCM < 0, respectively (see Appendix B). It was noted that only tfm was a non-precipitation type (Figure 5f, gray line), while the rest were rainfall types. Based on this, Li et al. (2014) defined a new convective-stratiform rainfall separation scheme, in which TFM, TFm, tFm are the convective rainfall type (Figure 5f, black, blue, orange line) and the tFM, Tm, TFM and tFM were classified as stratiform (Figure 5f, green, magenta, red, coral line). To study the effect of rainfall types on CMPE, we calculated their correlation coefficients with CMPE. The coefficient of the tfm (stratiform) and TFM (convective) types were more than 0.5 in the two stages, while TFM and TFm were always less than −0.5 due to their markedly opposite trend to CMPE (Figure 1b, 5f). This revealed that the rainfall types with local atmospheric drying (t) and water vapor convergence (F) were highly correlated with CMPE. Furthermore, the stratiform type (tFM) comprised a higher proportion than the convective type (tFm), which was clear evidence that QSTEN can significantly affect the CMPE.

4 CONCLUSION

The “721” heavy rainfall event was simulated successfully using the WRF model. Based on the simulation data, the LSPE and CMPE in the warm sector and cold front precipitation stages were calculated and their probable physical mechanisms were explored. The main conclusions from the study can be summarized as follows:

1. The LSPE in the peak of the warm sector stage (T1) was obviously higher than that in the cold front stage (T2). Quantitative analysis of the LSPE showed that a marked difference in water vapor advection existed between the two stages; specifically, the water vapor advection contributed positively to the LSPE in T1 but negatively in T2. This was mainly because strong warm and moist advection existed in the lower troposphere in T1, whereas strong cold and dry advection appeared in the middle level in T2.

2. The CMPE showed a similar variation tendency as the LSPE. Budget analysis of the microphysical processes indicated that the snow-related microphysical processes impacted significantly on the CMPE, with the mean value in T1 being 7–10% higher than in T2. We concluded this was because of the higher rain–snow collection (PRACS) and the higher deposition of water vapor (PRDS) in T1.

3. The differences in LSPE and CMPE between T1 and T2 were mainly contributed by the large-scale environment and cloud microphysical features. For the LSPE, the warm sector precipitation occurred in the high warm and wet environment, and the stronger dynamic forcing associated with water vapor occurred in T1. From the budget analysis of CMPE, the ice water path (IWP) and stratiform rainfall type (tFM) were significantly higher in T1.

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**APPENDIX A**

**Microphysical processes in the Morrison scheme of the WRF model**

| Abbreviation | Microphysical processes of Morrison scheme | From | To |
|--------------|------------------------------------------|------|----|
| EPRD         | Sublimation cloud ice                     | QI   | QV |
| EPRDG        | Sub of graupel                            | QG   | QV |
| EPRDGS       | Sublimation snow                          | QS   | QV |
| EVPMDG       | Change Q melting of graupel and evaporation| QG   | QV |
| EVPMS        | Change Q melting snow evaporating         | QS   | QV |
| PCC(+)       | Cond droplets                             | QV   | QC |
| PCC(−)       | Evap droplets                             | QC   | QV |
| PGMLT        | Change Q melting of graupel               | QG   | QR |
| PGRACS       | Conversion Q to graupel due to collection droplets by snow | QR | QS |
| PGSACW       | Conversion Q to graupel due to collection droplets by snow | QC | QG |
| PIACR        | Change Q, ice-rain collection             | QR   | QG |
| PIACRIS      | Change Q, ice rain collection, added to snow | QR   | QS |
| PRA          | Accretion droplets by rain                | QC   | QR |
| PRACG        | Change in Q collection rain by graupel     | QR   | QG |
| PRACI        | Change Q, ice-rain collection             | QI   | QG |
| PRACIS       | Change Q, ice rain collection, added to snow | QI   | QS |
| PRACS        | Change Q rain-snow collection             | QR   | QS |
| PRAI         | Change Q accretion cloud ice by snow      | QI   | QS |
| PRC          | Autoconversion droplets                   | QG   | QR |
| PRCI         | Change Q autoconversion cloud ice to snow  | QI   | QS |
| PRD          | Dep Cloud ICE                             | QV   | QI |
| PRDG         | Dep of graupel                            | QV   | QG |
| PRDS         | Dep snow                                 | QV   | QS |
| PRE          | Evap of rain                              | QR   | QV |
| PSACR        | Conversion due to coll of snow by rain    | QS   | QG |
| PSACWG       | Change in Q collection droplets by graupel | QC   | QG |
| PSACWI       | Change Q droplet accretion by cloud ice   | QC   | QI |
| PSACWS       | Change Q droplet accretion by snow        | QC   | QS |
| FSMILT       | Melting snow to rain                      | QS   | QG |

**APPENDIX B**

Summary of the eight-rainfall-type separation scheme

| Type | Description |
|------|-------------|
| TFM  | Local atmospheric drying (Q_{WVT} > 0) Water vapor convergence (Q_{WVF} > 0) Hydrometeor convergence (Q_{CM} > 0) |
| TFM  | Local atmospheric drying (Q_{WVT} > 0) Water vapor convergence (Q_{WVF} > 0) Hydrometeor divergence (Q_{CM} < 0) |
| tFM  | Local atmospheric moistening (Q_{WVT} < 0) Water vapor convergence (Q_{WVF} > 0) Hydrometeor divergence (Q_{CM} > 0) |
| tFM  | Local atmospheric moistening (Q_{WVT} < 0) Water vapor divergence (Q_{WVF} < 0) Hydrometeor convergence (Q_{CM} > 0) |
| TFM  | Local atmospheric drying (Q_{WVT} > 0) Water vapor divergence (Q_{WVF} < 0) Hydrometeor divergence (Q_{CM} < 0) |
| tFM  | Local atmospheric moistening (Q_{WVT} < 0) Water vapor divergence (Q_{WVF} < 0) Hydrometeor convergence (Q_{CM} > 0) |
| TFM  | Local atmospheric drying (Q_{WVT} > 0) Water vapor divergence (Q_{WVF} < 0) Hydrometeor divergence (Q_{CM} < 0) |
| tFM  | Local atmospheric moistening (Q_{WVT} < 0) Water vapor divergence (Q_{WVF} < 0) Hydrometeor convergence (Q_{CM} > 0) |

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