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NUMERICAL STUDY OF COLD AIR IMPACT ON RAINFALL REINFORCEMENT ASSOCIATED WITH TROPICAL CYCLONE TALIM (2005): I. IMPACT OF DIFFERENT COLD AIR INTENSITY

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Abstract: In 2005, significant rainfall reinforcement and severe disaster was induced by tropical cyclone (TC) Talim after it made landfall on the east of China. Observational analyses show that it has relationship with cold air intrusion. For investigating the impact of cold air intensity, we make use of Weather Research and Forecasting (WRF) model, the synthesizer of NCEP/NCAR reanalysis data and Japan regional spectral model data, to carry out numerical experiments. Results show that rainfall reinforcement occurs in all experiments. Different intensity of cold air can modify the rainfall distribution and intensity significantly. In the rainfall center, the increment maximum of rainfall is twice as large as that of the minimum. Moderate cold air intrusion may result in the strongest rainfall reinforcement. Different cold air intensity can lead to different motion of low-level convergence lines and fronts. There is a good relationship between the rainfall region and the eastern part of the front. On one hand, strong cold air weakens the TC intensity by its intrusion into the TC center and results in weak convergence and a convergent zone and a rain band shifted southward. On the other hand, weak cold air reduces the convergence and moves the convergent zone and rain band northward. Moderate cold air intrusion maintains strong low-level convergence and high-level divergence, keeping strong upward motion over certain regions. Consequently, the rain band begins to stagnate and rainfall reinforces abruptly therein.

Key words: numerical study; cold air; tropical cyclone; rainfall reinforcement

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1 INTRODUCTION

Cold air impact on tropical cyclone (TC) rainfall has received a lot of attention[1, 2]. Chen and Ding[1] pointed out that it can enhance the instability, low-level convergence and uplifting, favoring transition from TC to extratropical cyclone. For various intensity and location of cold air intrusion, its effect is different. Moderate cold air intrusion is favorable for rainfall increase[3]. Tao et al.[4] also indicated that there is a close relationship between cold air and the rainstorm cases in August 1975 in Henan and in October 1967 in Taiwan respectively. Westerly troughs as well as cold air are one of the key factors of TC extratropical transition process[5], which may bring about unexpected strong wind and heavy rainfall[6-9]. Xu et al.[10] showed that there exists a positive correlation between TC rainfall intensity and front intensity. Analysis of heavy rainfall associated with TC Sinlaku (2002)[11] indicated that cold air intrusion into the TC center can weaken rainfall near it but increase the rainfall in the TC periphery. In a diagnostic study, Li[12] illustrated that a convergence line is formed between the cold air and the easterly flow of TC, which helps to trigger deep convection. In their work on TC rainfall over Liaodong peninsula, Liang et al.[13] demonstrated that rainfall is enhanced

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when cold air intrudes the TC periphery.

The researches above mainly focus on the heavy rainfall process in some regions. The cold air impact on rainfall reinforcement after TC landfall has been scarcely addressed[14]. Moreover, rainfall reinforcement is worth studying for its severe disaster, prediction difficulty and complex mechanism. Talim is a good case in this point. It made landfall on Fujian province at 0630 Coordinated Universal Time (UTC) September 1, 2005 and moved northwestward inland with the intensity decaying. In the early morning of the second day, it entered Jiangxi province and weakened to a tropical depression. Then, in the late afternoon of the same day, Talim slowed down and stagnated in northwestern Jiangxi. Finally, it dissipated at 1300 UTC September 3. Due to the effect of Talim, significant rainfall reinforcement occurred September 3, resulting in severe flooding and landslides. A total of 15.4 billion yuan (about $1.9 billion at that time) was lost and 145 people were killed during this calamity. An analysis by Dong[15] shows that the intrusion of low-level cold air leads to the genesis of a front at this level during the heavy rainfall period. Temperature evolution at 925 hPa in Figure 1 displays that a cold air mass with the minimum temperature below 16°C approaches the TC from the northeast and then enters the west part of the TC circulation. In the frontier of the cold air mass there is a front (denoted by a bold, black line in Figure 1) moving southwardly and approaching Talim with the cold air intrusion. At 0000 UTC September 3, as the front passes through the TC, it began to undergo extratropical transition. Moreover, the location of the eastern front has good relationships with the heavy rain band. What is the contribution of cold air intensity and location to rainfall reinforcement in this case? How is the process? These issues are worth investigating.

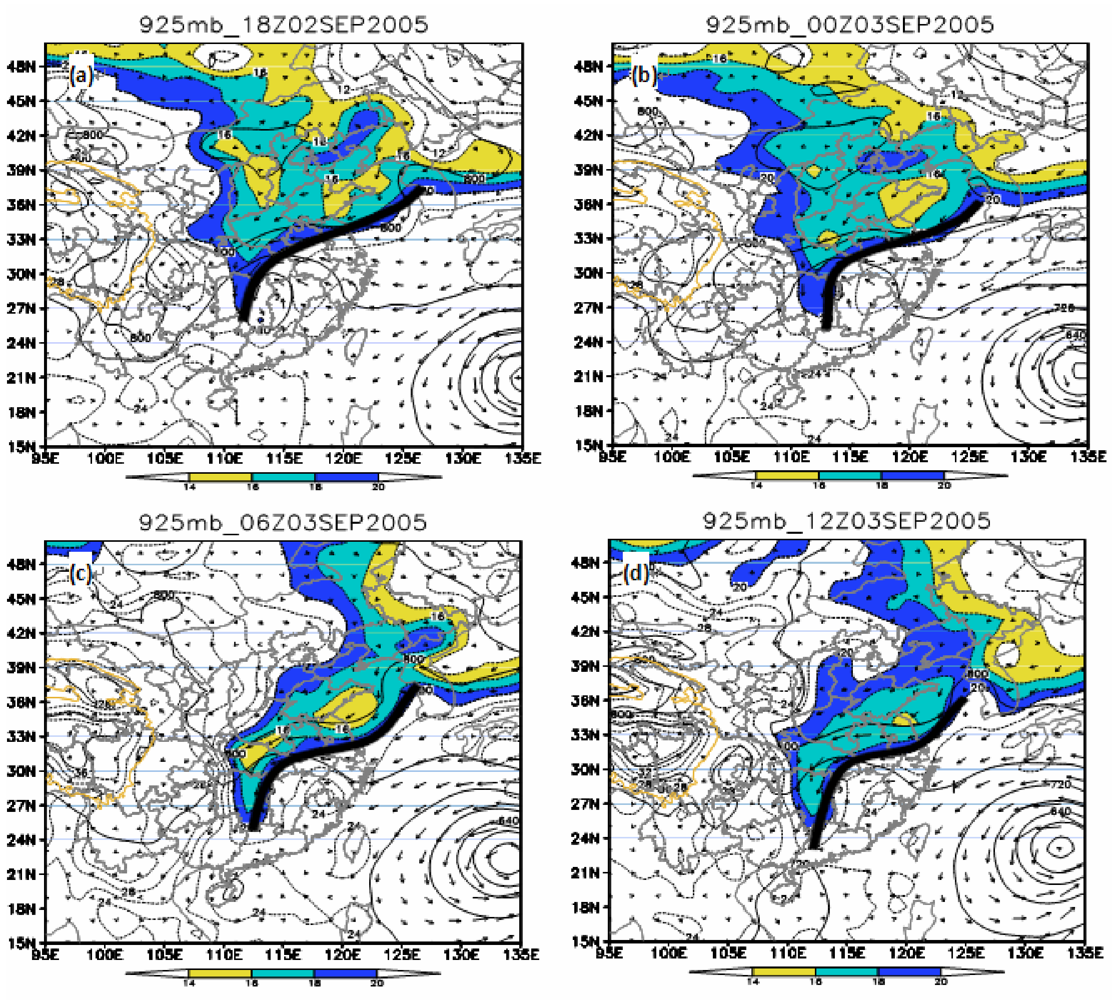


Figure 1. Temperature (dashed, unit: °C), geopotential (solid line, unit: gpm) and wind (vector, unit: m s^{-1}) field at 925 hPa at 1800 UTC September 2 (a); 0000 UTC September 3 (b); 0600 UTC September 3 (c); 1200 UTC September 3 (d). The shaded areas display the temperature between 14°C and 20°C; the bold black lines indicate the front.

Presently, for the shortcomings of low resolution and sparse coverage of observations over the ocean, numerical simulation is an effective tool to investigate the TC evolution. It is indicated that the Weather

Research and Forecasting (WRF) model performs well in simulation[16-19]. Therefore, we use the WRF model to investigate the mechanism of cold air impact on rainfall reinforcement of landfalling TCs. This study is the first part of a two-part series of papers on the impact of cold air intensity on rainfall reinforcement associated with TC Talim (2005). Impact of cold air location on rainfall reinforcement will be presented in the second paper. In this paper, section 2 introduces the design of experiments. Section 3 discusses the results from simulations. Section 4 presents a brief summary.

2 EXPERIMENT DESIGN

Detailed configuration of the control experiment (CON) and the initialization are the same as in Dong et al.[20], in which the model performed a relatively successful simulation for Talim's track, intensity and rainfall. On the basis of it, two sensitivity experiments are designed as follows (see Table 1): a weak cold air experiment (CD) and a strong cold air experiment (CI). The initial temperature field at 850 hPa at 1200 UTC September 1, 2005 is shown in Figure 2, where the region surrounded by a thick frame (105–125°E, 39–45°N) indicates the source of cold air and the region for temperature modification in the sensitivity experiments. Using Legendre's filtering method[21], we decompose the initial field into high-frequency spectrum and low-frequency spectrum components, and then restructure it with decreased or increased cold air intensity by modifying the weight of high-frequency spectrum. Meng et al.[22] and Li et al.[23] successfully modified the westerly trough intensity by using this method. Specifically, we choose a 7-wave truncation to decompose the initial field A into a high-frequency field A_H and a low-frequency field A_L as shown in Eq. (1).

Table 1. Experiments design.

Experiment	Description
CON	Control run
CD	Weak cold air intensity by increasing temperature locally
CI	Strong cold air intensity by decreasing temperature locally

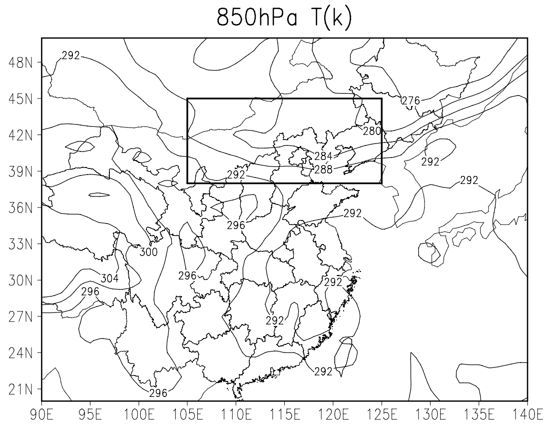


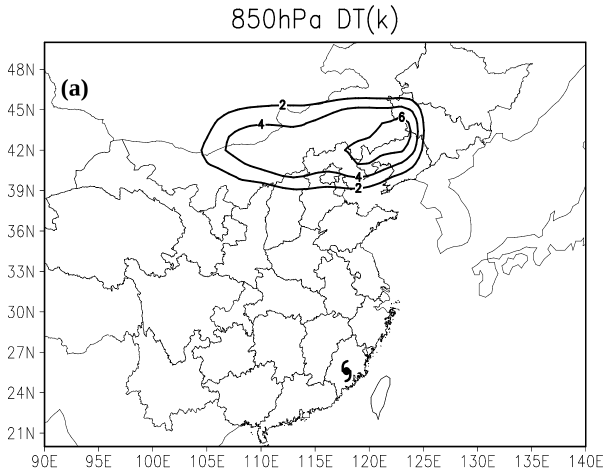
Figure 2. Initial temperature (contour, unit: K) field at 850 hPa at 1200 UTC September 1, 2005. The rectangle indicates the region for temperature modification (105-125ºE, 39-45ºN).

$$A = A_H + A_L \quad (1)$$

Then, we design the modified field A' by changing the coefficient c in Eq. (2)

$$A' = A_L + c \times A_H \quad (2)$$

Here, c takes 0.1 and 3.0 for experiments CD and CI respectively. The difference in the modified temperature and initial field for CD and CI are indicated in Figures 3a and 3b, respectively. It is easy to see that temperature increases (decreases) from 1 to 6 (1 to 14) degrees for the weak (strong) cold air experiment in the research region, which can basically satisfy the purpose of this study. With such initial condition, we carry out 48-hour simulations for all experiments.



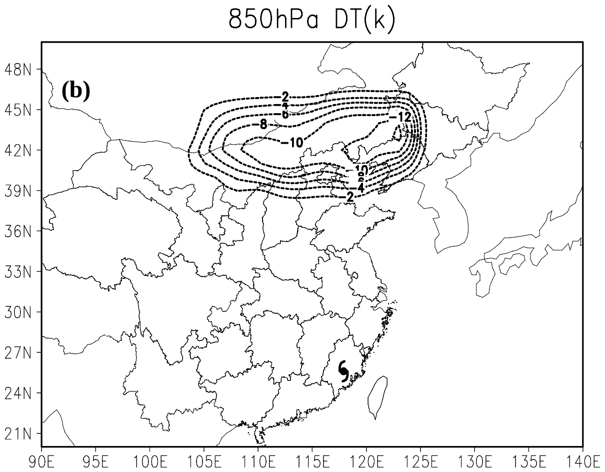
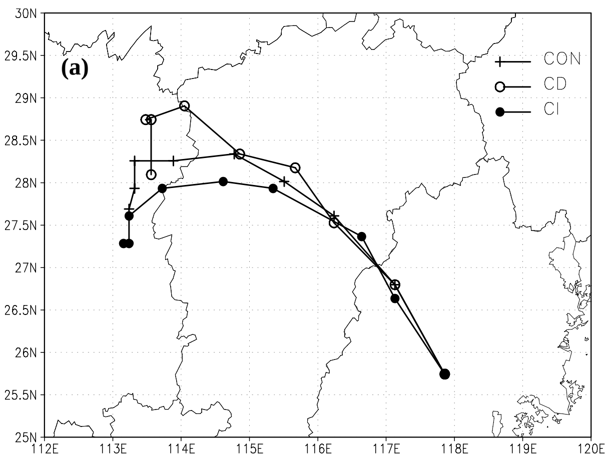


Figure 3. Temperature difference (contour, unit: K) field between sensitivity experiments and control experiment at 850 hPa on 1200 UTC September 1, 2005. a: CD minus CON; b: CI minus CON.

3 RESULTS OF SIMULATIONS

3.1 *Track and intensity*

The simulated TC tracks for all experiments are shown in Figure 4a, which displays that cold air intensity mainly influences the track during the later 24 hours of simulation. The TC moves more northward when weak cold air intrudes than in moderate cold air intrusion. On the contrary, the TC moves off to the south with strong air cold influence. However, stagnations in the later period occur in the sensitivity experiments. As shown in Figure 4b, the intensity difference—determined by subtracting the sensitivity experiment from the control experiment—indicates that, for experiment CD, weak cold air has a minor impact on TC intensity with the difference below 1 hPa. However for experiment CI, after 36 hours of integration, strong cold air intrusion obviously weakens TC intensity with the difference up to 5 hPa.



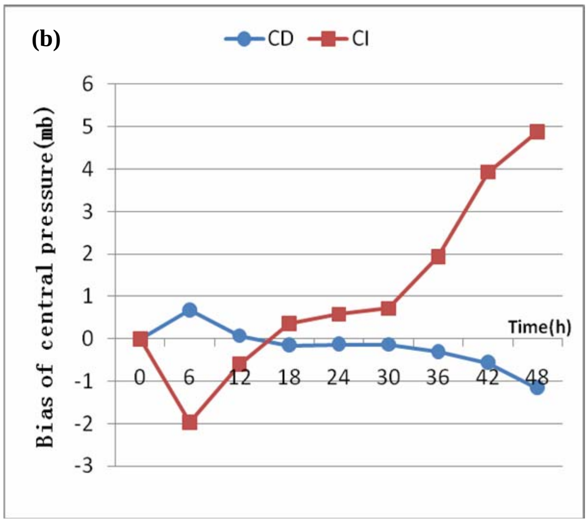


Figure 4. TC Track simulations (a: cross, open circle and solid circle denote experiments CON, CD and CI, respectively) and difference of minimum sea level pressure between the sensitivity experiment and experiment CON (b: solid circle and solid square indicate experiments CD minus CON, and CI minus CON, respectively).

3.2 *Precipitation*

Comparisons illustrate that precipitation is sensitive to different cold air intensity intrusion (Figures 5a to 5f). From 0 to 24 h of the integration, accumulated rainfall increases with the intensity of cold air, i.e., 240, 277 and 342 mm for experiment CD, CON and CI, respectively. The maximum rainfall simulated by the experiments is located over the Lushan Mountain. The rainfall ranges of experiments CD and CON are similar. However, for experiment CI, there is another rainfall region in southeastern Hunan province. That is to say, when cold air is far away from Talim, cold air mainly influences the periphery of the TC and is favorable to rainfall enhancement. During the period of the later 24 hours, Talim continues to move inland, a simulated rain band moves southward with the increase of cold air intensity. Nevertheless, the rainfall maximum fluctuates from 510 to 577 mm then to 474 mm. From the rainfall evolution we can see that rainfall reinforcement occurs in all experiments, but the intensity of rainfall reinforcement is different, and compared with experiment CON, the rates are about 45% and 90% in experiments CI and CD respectively. Analysis on regional mean increments for 24-hour accumulated rainfall equal to or greater than 200 mm also shows that the maximum is 50 mm (increasing from 221 to 271 mm) in experiment CON and the minimum is 7 mm (increasing from 218 to 263 mm) in experiment CI.

The results above show that cold air affects rainfall reinforcement significantly, leading to obvious change of rainfall bands and rainfall intensity by up to 50% in the center of rainfall reinforcement (and the increment maxima can be twice as much as the minima), with the occurrence of moderate cold air intrusion resulting in maximum rainfall reinforcement.

3.3 *Cold air and front*

Evolution of atmospheric circulation at 850 hPa in Figure 6 displays that cold air intrudes the TC gradually from the east of TC circulation. At 1200 UTC September 2 (Figures 6a to 6c), cold air below 18°C began to enter the west part of Talim in the control experiment while it only reaches the northern TC in experiment CD. In contrast, for CI experiment, cold air below 18°C almost covers the western TC where a cold air mass below 14°C is embedded. Figures 5d to 5f show the weather patterns at 0000 UTC September 3. In experiment CI, the intruded cold air degrades the TC intensity and forms a cold air center below 12°C in the southwest portion of TC circulation. However, only cold air between 14 and 16°C (16 to 18°C) influences Talim in experiment CON (CD). At 1200 UTC September 3, as indicated in Figures 5g to 5i, a north-to-south front was generated within the TC, which then experienced extratropical transition.

The motion of fronts at 925 hPa for all experiments indicates that a quasi-zonally oriented front moves southward and encounters with Talim, and as a result, the west part of the front moves southward quickly and turns the front orientation to north-south. The east part of the front moves southward slowly. Comparisons show that the motion of the front in experiment CI is the fastest. While the front in experiment CD has the slowest motion, the west front moves to the Talim center and the east front arrives in the middle of Jiangsu and Anhui provinces until 0600 UTC September 3. For all experiments, the east fronts have good relationships with the heavy rain bands. In other words, fronts play a major role in the location of rainfall. Researches of Bosart and Dean[24] and Gao et al.[25] also show close relationships between fronts and heavy rainfall.

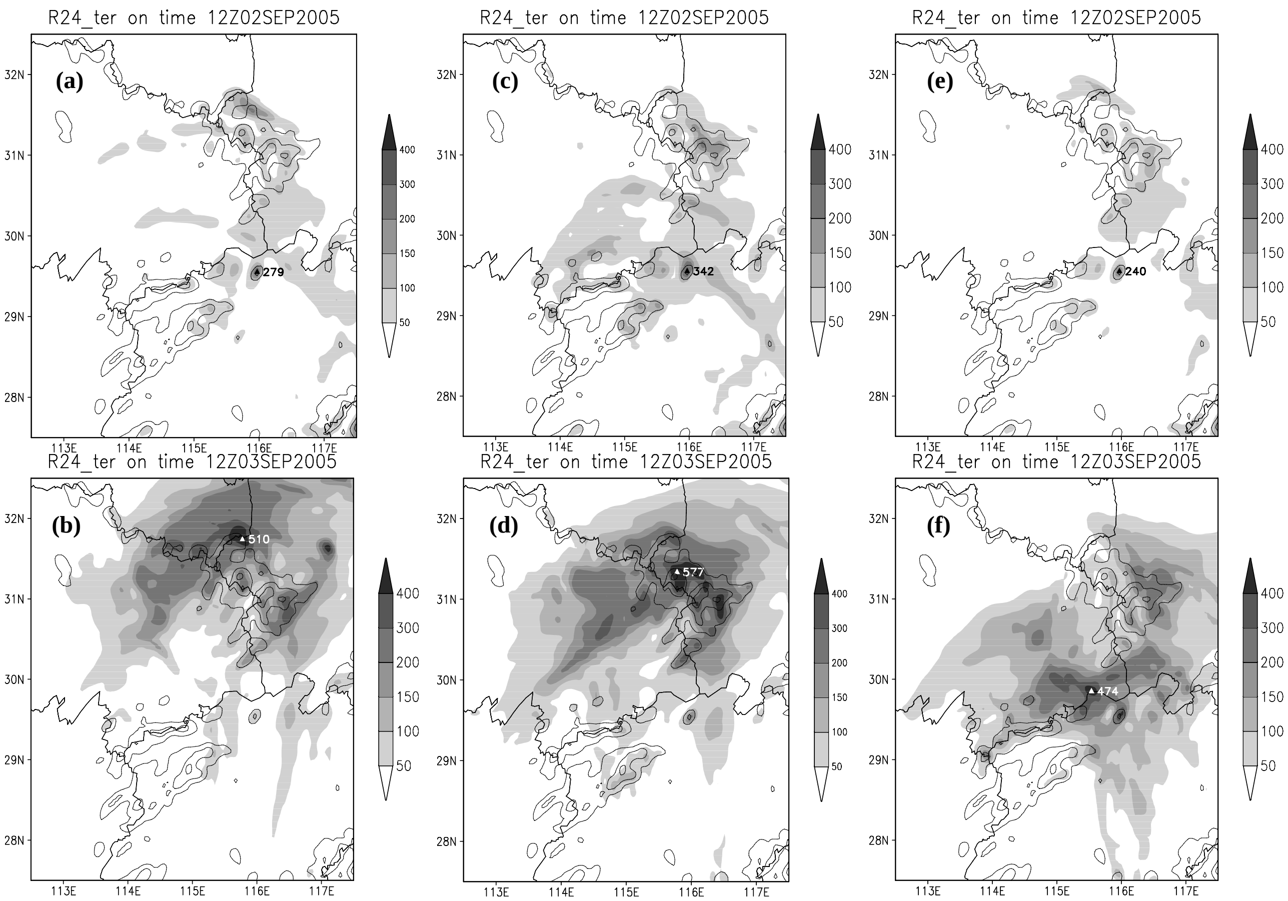


Figure 5. 24-hour rainfall accumulation (shaded, unit: mm) for experiments CON (a, b), CD (c, d) and CI (e, f) from 1200 UTC September 1 to 1200 UTC September 2, 2005 (a, c, e) and from 1200 UTC September 2 to 1200 UTC September 3, 2005 (b, d, f). The contours show the terrain.

3.4 *Convergence line*

In all experiments, corresponding to the activity of cold air and fronts, there is a convergence line, located between the cold air and Talim, moving southward gradually and then joining Talim's inverted trough at 0600 UTC September 3, just as indicated in Figure 7. As a result, strong convergence (shaded in the figure) is situated between an inverted trough and the convergence line. Among them, the weakest convergence with the most southward location is present in experiment CI (Figure 7c) while the strongest one with the middle location appears in experiment CON (Figure 7a). As weak cold air weakens the northeasterly to the north of the convergence line in experiment CD, the convergence intensity decreases and the convergent zone shifts northward (Figure 7b). Similarly, because of the intrusion of strong cold air into the Talim center, the south portion of the convergence line weakens, shifting the convergent band southward. These results imply that moderate cold air intrusion favors the maintenance and enhancement of the convergence, which then leads to the amplification of heavy rainfall.

3.5 *Convection instability and frontal slope*

The meridional cross section of pseudo-equivalent temperature θ_{se} through the rainfall center indicates that dry cold air with low θ_{se} intrudes the TC from the near-surface level and as a result θ_{se} increases with height ($\frac{\partial \theta_{se}}{\partial p} < 0$), making the atmosphere stable in lower troposphere. However, the depths of cold air are different for different intensity. As to the height of 346K of θ_{se} (Figure 8), the deepest one, reaching 700 hPa, is shown in experiment CON, while the shallowest one, at about 850 hPa, is indicated in experiment CI, and 800 hPa, the one that comes in between, is in experiment CD. Accordingly, the frontal slope with moderate cold air intrusion is steepest and that with strong cold air intrusion is smoothest. As the warm-moist flow encountering with cold air, the steeper the frontal slope is, the stronger the converging and lifting will be, resulting in more warm-moist air transferring upward and rainfall reinforcement.

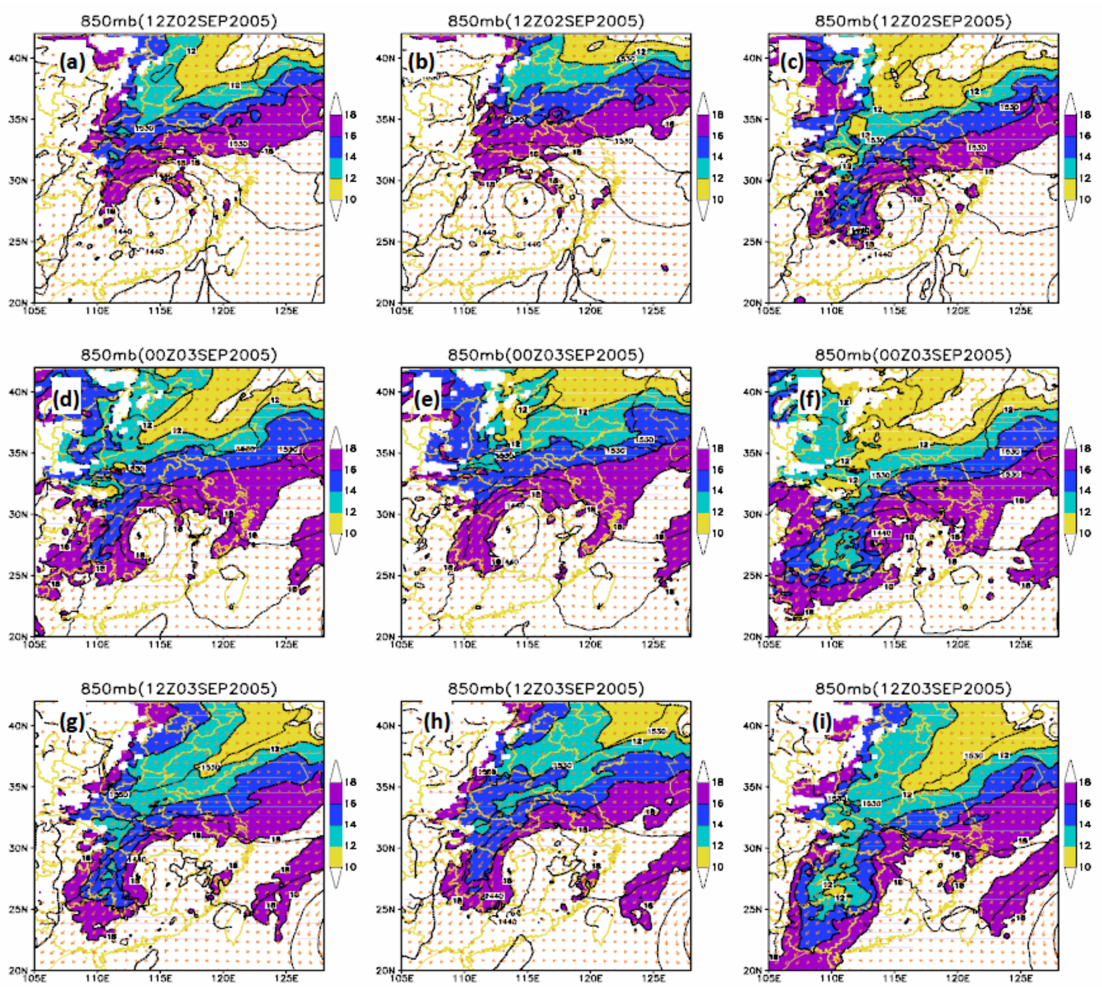


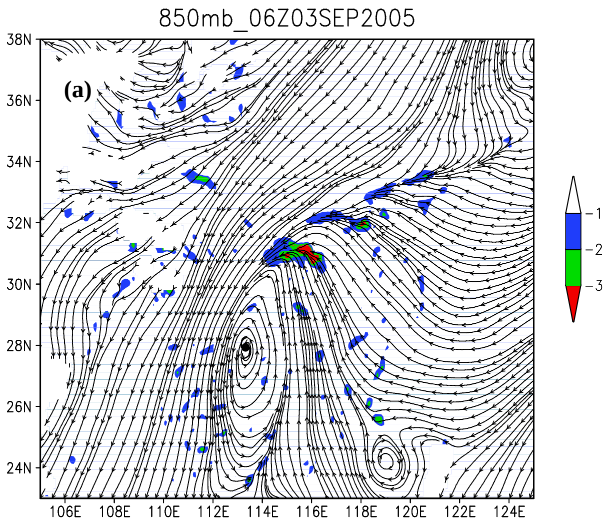
Figure 6. The evolution of temperature (dashed, unit: °C, shaded areas denote temperature from 14°C to 20°C), height (solid line, unit: gpm) and wind (arrow, unit: m s^{-1}) at 850 hPa for experiments CON (a, d, g), CD (b, e, h) and CI (c, f, i) at 1200 UTC September 2, 2005 (a to c), 0000 UTC September 3, 2005 (d to f), and 1200 UTC September 3, 2005 (g to i).

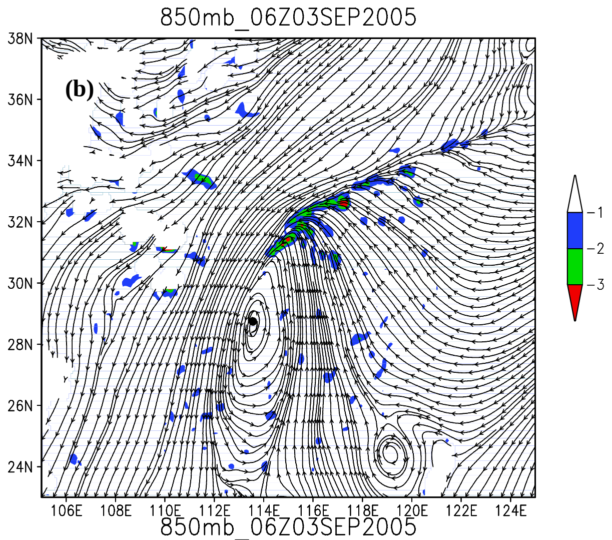
3.6 *Vertical motion*

Temporal averages of vertical motion from 1200 UTC September 2 to 1200 UTC September 3 over the heavy rainfall region are displayed in Figure 9, which shows that the strongest upward motion (about 0.53 m s^{-1} at 600 hPa) is identified in the control experiment, and the weakest one is 0.3 m s^{-1} at 700 hPa, in CI experiment. Different cold air mainly leads to different vertical motion in upper levels higher than 700 hPa. The level of maximum upward velocity decreases with the increase of cold air intensity while moderate cold air intrusion results in the strongest ascent.

3.7 *Divergence*

For various cold air intensities, divergence profiles over the heavy rainfall region are also different. Figure 10 shows the mean divergence profiles over the heavy rainfall region during the rainfall reinforcement period, with the strongest low-level convergence and high-level divergence both present in the control experiment, in which the depth of convergence is the thickest. In contrast, they are evidently weaker in the sensitivity experiments. Such results indicate that moderate cold air intrusion may increase the depth and intensity of low-level convergence as well as upper-level divergence, leading to rainfall enhancement. Moreover, the values of divergence have the same dimension as mesoscale systems at $10^{-4}s^{-1}$[26], indicating that mesoscale systems are very active when moderate cold air intrudes Talim.





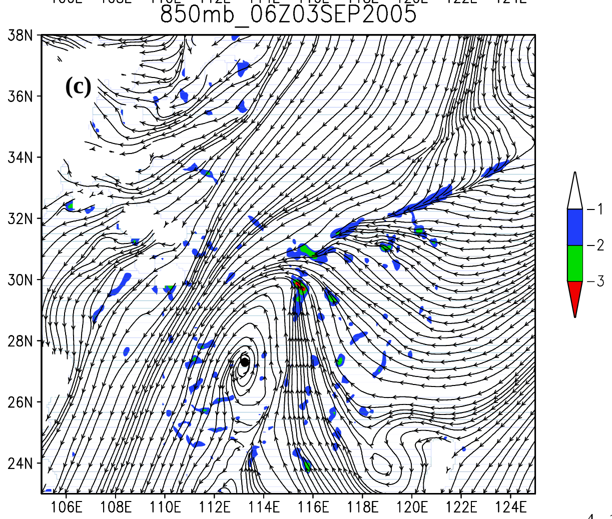


Figure 7. The stream and divergence (shaded, unit: $10^{-4}s^{-1}$, only those below $-1\times10^{-4}s^{-1}$ are displayed here) at 850 hPa for experiments CON (a), CD (b) and CI (c) at 0600 UTC September 3, 2005.

3.8 *Moisture flux divergence*

The maxima of low-level convergence and high-level divergence of moisture flux as well as the deepest convergence layer simultaneously occur in the experiment with moderate cold air (see Figure 11). Plenty of moisture converges below 650 hPa and diverges at upper levels with the maximum at 500 hPa. Sensitivity experiments also indicate low-level convergence and high-level divergence but with weak intensity as well as shallow depth of convergence, with the shallowest in experiment CI (only 800 hPa). From this we can draw the conclusion that the intrusion of moderate cold air can transfer more moisture into high levels for condensation, which is favorable to rainfall reinforcement.

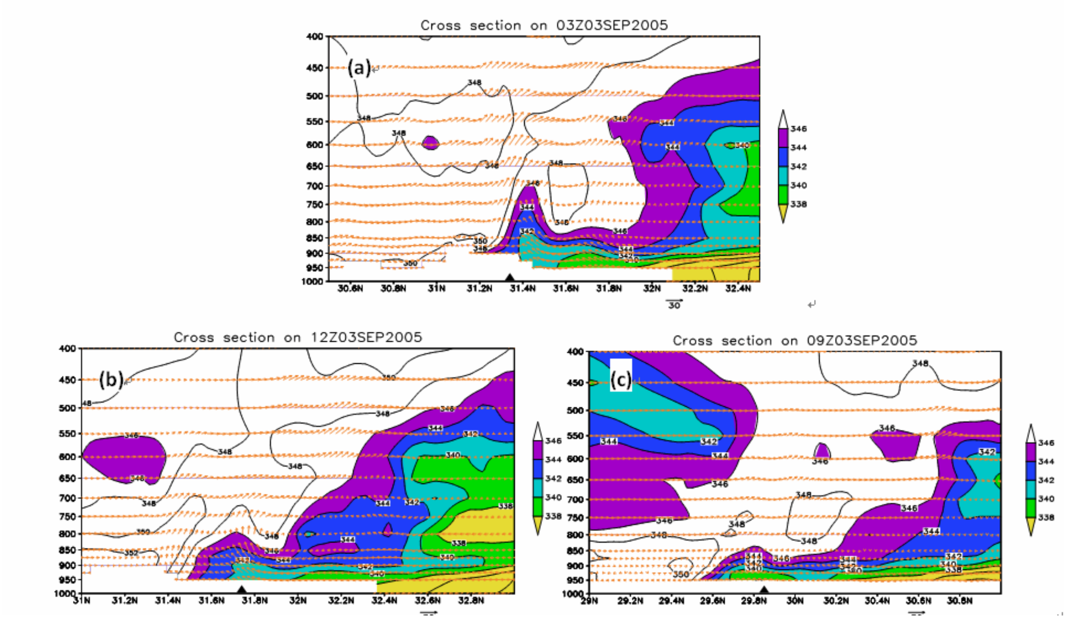


Figure 8. Meridional cross sections of pseudo-equivalent temperature (unit: K) through the rainfall center for experiments CON at 0300 UTC September 3 (a), CD at 1200 UTC September 3 (b) and CI at 0900 UTC September 3 (c) respectively. The black solid triangle denotes the rainfall center.

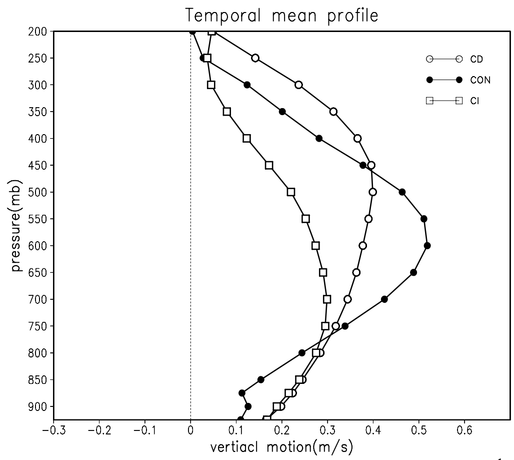


Figure 9. Temporal mean of vertical motion (unit: m s^{-1}) from 1200 UTC September 2 to 1200 UTC September 3 over the heavy rainfall region. Lines with open circle, solid circle and open frame denote experiments CON, CD, and CI, respectively.

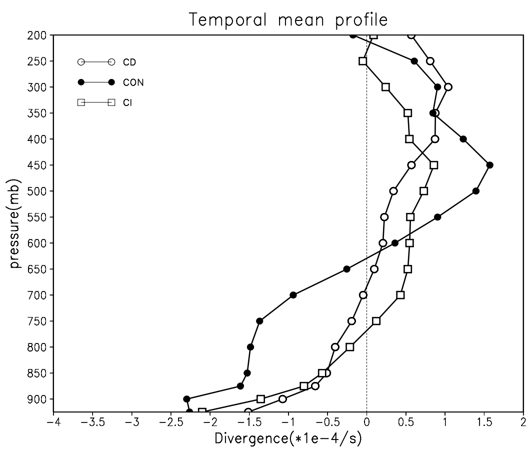


Figure 10. As in Figure 9 but for the temporal mean of divergence (unit: 10^{-4}s^{-1}).

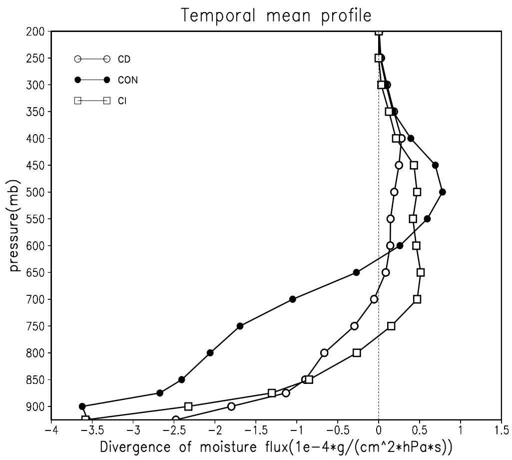


Figure 11. As in Figure 9 but for the temporal mean of moisture divergence (unit: 10^{-4}g cm^{-2} hPa^{-1} s^{-1}).

4 CONCLUSIONS

Numerical experiments are designed and performed to investigate the impact of different cold air intensity on rainfall reinforcement associated with Talim (2005). Main results are summarized as the follows.

(1) The change of cold air intensity can affect TC track obviously (especially in the later period of simulation), weaker (stronger) cold air shifts the track northward (southward). Weak cold air plays a negligible role in the TC intensity, but strong cold air can weaken TC intensity in the later period.

(2) All experiments induce the rainfall reinforcement, but the region and the increment of precipitation are different in the experiments. The strongest increment appears in the experiment with moderate cold air, about 2.2 times of that in strong

cold air and 1.1 times of that in weak cold air. The simulated rainfall regions also change for the intrusion of cold air of different intensity, which may move southward with the intensification of cold air.

(3) With the intrusion of cold air of different intensity, the motions of fronts and convergence lines are different too. Among them, the case with strong cold air intrusion is fastest. At the same time, the east part of the front is well related with the rainfall band. Strong/weak cold air intrusion can weaken the southeast/northeast flow to the south/north of convergence line, leading to weak convergence and shifting convergent zones and rainfall bands southward/northward.

(4) Calculations of physical variables show that moderate cold air intrusion can maintain strong low-level convergence and high-level divergence, keeping strong upward motion and more condensation over some regions. Consequently, the rain band begins to stagnate and rainfall enhances abruptly therein.

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