

This discussion paper is/has been under review for the journal Atmospheric Chemistry and Physics (ACP). Please refer to the corresponding final paper in ACP if available.

Impacts of the mountain-plains solenoid and cold pool dynamics on the diurnal variation of precipitation over Northern China

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Received: 29 August 2012 – Accepted: 2 October 2012 – Published: 24 October 2012

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Published by Copernicus Publications on behalf of the European Geosciences Union.

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Abstract

Convection-permitting numerical experiments using the Weather Research and Forecasting (WRF) model are performed to examine the impact of a thermally-driven Mountain-Plains Solenoid (MPS) on the diurnal variation of warm-season precipitation over Northern China. The focus of the analyses is a 15-day simulation that uses the 8-day average of the NCEP GFS gridded analyses at 00:00 UT between 17 and 24 June 2004 for the initial conditions and the 8-day averages at 00:00, 06:00, 12:00, and 18:00 UT for the lateral boundary conditions. Despite differences in rainfall intensity and location, the control experiment captures the essence of the observed diurnal variation of warm-season precipitation in North China. Consistent with observations, the simulated local precipitation peak initiates in the afternoon on the eastern edge and the immediate lee of the mountain ranges due to the upward branch of the MPS. The peak subsequently propagates downslope and southeastward along the steering-level mean flow, reaching the Central North China Plains around midnight and early morning hours resulting in a broad area of nocturnal precipitation maxima over the Central plains. Sensitivity experiments show that besides the impact of the MPS, cold pool dynamics play an essential role in the propagation and maintenance of the precipitation peak over the plains.

1 Introduction

Precipitation is closely related to human activity and is one of atmospheric parameters that are difficult to predict. Furthermore, the latent heat of condensation released from the precipitation is an important energy source for driving the global atmospheric circulation (Nober et al., 2003). The diurnal cycle of precipitation is one of the most basic forms of climate patterns and has a considerable influence on the regional weather and climate (Dai, 2001; Yang and Slingo, 2001; Liang et al., 2004). The diurnal cycle of precipitation is often used to verify weather and climate models (Dai et al., 1999; Lin

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large-scale basins and several plateaus, with elevations between 1000 and 2000 m. A northeast-southwest oriented mountain line (which includes the Great Khingan, Taihangshan Mountain, Wushan Mountain and Xufeng Mountain) divides the second and third steps. The third step consists of plains and hills with a mean elevation of less than 500 m. Due to the strong heating effect of the Tibetan Plateau on the regional weather and climate, most studies on the diurnal cycle of precipitation focus on the Tibetan Plateau and the adjacent lee regions with lower terrain. These studies found that the diurnal precipitation peak usually begins over the Tibetan Plateau in the early afternoon and then propagates eastward (Asai et al., 1998; Wang et al., 2004, 2005; Fujinami et al., 2005; Yu et al., 2007; Zhou et al., 2008; Chen et al., 2009a, b; Xu and Zipser 2011; Bao et al., 2011). The plateaus and mountains of the second step also have an important influence on the local diurnal variation of precipitation: because they are much higher than the plains of the third step, the differential solar heating rate between these two steps yields a temperature gradient that can give rise to the MPS circulation. Nevertheless, only a few studies have explored the relation of MPS circulation and diurnal precipitation variations with a focus on these second and third steps over China (HZ10; Bao et al., 2011; Sun and Zhang, 2012).

HZ10 explored the diurnal variations of warm-season precipitation over Northern China using the CMORPH dataset and the NCEP GFS analysis. Figure 1a (Fig. 2b from HZ10) shows the phase fronts of the warm-season diurnal precipitation peaks at different times from CMORPH observations, whereas Fig. 1b shows the distance-time Hovmöller diagram of the normalized hourly precipitation deviation averaged along a northwest-southeast cross section in the focus domain. HZ10 found that the diurnal precipitation peaks initiate over the mountains in the early afternoon and then propagate downslope and southeastward to the plains at a speed of $\sim 13 \text{ ms}^{-1}$ (Fig. 1b), and that the diurnal variation of the MPS circulation is one of the important factors on the diurnal cycle of precipitation. But HZ10 did not investigate the detailed evolution of the MPS or its influence on the diurnal variation in precipitation because of the coarse temporal and spatial resolution of their dataset. The current study follows HZ10

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but uses higher resolution numerical simulations to try to determine the causes of the diurnal variation in precipitation over Northern China and the influence of the MPS circulation (between the aforementioned second and third steps). The current work also complements the recent high-resolution modeling study of Sun and Zhang (2012) which examined the impact of the MPS on the diurnal variations of precipitation and mesoscale convective vortices along the mei-yu front over the East China Plains.

To be consistent with HZ10, the focus area of this study is over the Yanshan-Taihangshan Mountain ranges along the eastern peripheries of the Loess-Mongolian Plateaus and the adjacent North China Plains (Fig. 1a); here, the terrain decreases from northwest to southeast in a two-step pattern. The Weather Research and Forecasting (WRF) modeling system is used to simulate the propagation of the diurnal precipitation peak during 17–24 June 2004. The primary objective of the current study is to examine the impacts of the MPS on the diurnal variation of precipitation over Northern China. Section 2 provides a description of the experimental design. Section 3 presents an overview of the simulations and a comparison with the observations. The interactions of the MPS circulation and the diurnal precipitation variation over Northern China are discussed in detail in Sect. 4. Two sensitivity tests with respect to latent heating and cooling are reported in Sect. 5. Section 6 gives the concluding remarks of the study.

2 Numerical model and experimental design

Version 3.2 of the Advanced Research WRF (WRF-ARW) model (Skamarock et al., 2008) is employed in this study. The NOAA Global Forecast System (GFS) $1^\circ \times 1^\circ$ operational analyses every 6 h are used to produce the initial and lateral boundary conditions. The experimental runs all have one domain that covers North China and adjacent areas with 749×701 horizontal grid points and 3 km grid spacing (Fig. 2a). There are 31 vertical levels with the top at 50 hPa. The model employs the Yonsei University (YSU) PBL scheme (Hong et al., 2006), the RUC land surface model, and the Rapid Radiative Transfer Model longwave (Mlawer et al., 1997) and Dudhia (1989) shortwave

radiation schemes. The WSM6 scheme is used for the microphysics parameterization (Hong and Lim, 2006). No cumulus parameterization is used.

The primary goal of the experiments is not to recreate any single precipitation episode, but to capture more general characteristics of the diurnal cycle of warm-season precipitation over Northern China and to examine the influence of the MPS. We choose 17–24 June 2004 as the study period because there were several observed diurnally recurring episodes of precipitation propagating from the mountains to the plains (Fig. 3a). A distance-time Hovmöller diagram of the rain rate averaged along the northwest-southeast cross section over the region ABEF (see Fig. 2b) during 00:00 UT 17 June–00:00 UT 25 June 2004 from CMORPH data (Fig. 6a) shows a similar feature of the diurnal cycle of warm-season local precipitation (Fig. 1b).

Table 1 lists the experiments conducted in this study and gives a brief description of each. Experiment REAL is initialized at 00:00 UT 17 June 2004 with the lateral boundary conditions updated every 6 h provided directly by the reanalysis from 00:00 UT 17 June to 00:00 UT 25 June 2004. Following Trier et al. (2010) and Sun and Zhang (2012), a 15-day diurnal control experiment (CNTL) is run in order to reproduce the diurnal variation of precipitation and research how the MPS influences the diurnal precipitation cycle. The CNTL experiment is initialized using the 8-day (17–24 June 2004) averaged 00:00 UT GFS analyses, with lateral boundary conditions derived from the 8-day averaged 00:00 UT, 06:00 UT, 12:00 UT, and 18:00 UT GFS analyses.

Two sensitivity experiments are designed to examine the impact of latent heating and cooling on the diurnal variation and propagation of the local peak precipitation. Experiment “Fake-dry” includes 10 consecutive 24 h simulations configured the same as CNTL except that all forms of latent heating and cooling (between ice, liquid, and vapor) are turned off; each simulation is initialized with the 00:00 UT forecast of the last 10 days of the CNTL simulation. Experiment “NOVAP” is also configured the same as CNTL, except that only the cooling associated with the evaporation of liquid water is turned off, which essentially shuts off the mechanisms for cold pool formation from moist convection.

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3 The simulated results and comparison with observations

Figure 2a shows the 8-day 00:00 UT average of the 500 hPa relative vorticity, horizontal wind, and geopotential height derived from the FNL analyses during 17–24 June 2004. A quasi-steady low pressure system – often referred to as China’s “Northeast Cold Vortex” (NECV) – is located to the north of the focus domain (box ABCD). This subsynoptic cut-off low is one of the most important warm-season rain producers over North and Northeast China (Zhang et al., 2008; Hu et al., 2010). Over this 8-day period, under the influence of NECV, the flow is predominantly northwesterly over the southwestern half of the focus domain (box ABEF). Figure 2b shows the observed daily-mean precipitation averaged over the 8-day period from the CMORPH¹ dataset. There are two rainfall maxima in ABCD: one to the north over the immediate foothills of the northern mountain ranges, and the other to the south over the center of the North China Plains. We will focus on ABEF because the southern rainfall maximum results primarily from the nearly daily nocturnal precipitation peaks.

3.1 Overview of the rainfall simulations

The observational rainfall data from CMORPH (Fig. 2b) is compared with the mean daily precipitations of the four experiments: the 8 days of REAL, the last 10 days of CNTL (the first 5 days are ignored to lessen the sensitivity to the initial conditions), and the 10 consecutive 24 h forecasts of Fake-dry and NOVAP (Fig. 4). As a whole, REAL reproduces the overall features of rainfall over Northern China, but shows less

¹ The high-resolution global precipitation dataset from the NOAA Climate Prediction Center’s morphing technique (CMORPH, Joyce et al., 2004) with a spatial resolution of 0.07277° is used as the observation. CMORPH has been verified with Chinese rain gauge reports from ~2000 stations and exhibits the best performance among satellite precipitation estimates in depicting the spatial and temporal variations of precipitation (Shen et al., 2010). The CMORPH dataset is used to study the diurnal cycle of precipitation over different domains of China (e.g. HZ10; Bao et al., 2011; Sun and Zhang, 2012).

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intense precipitation in the southeastern region (Fig. 4a). Despite slightly stronger intensity and smaller coverage, CNTL simulates reasonably well the maximum rainfall area in the southern domain. However, the northern rainfall in this experiment occurs to the east of the rainfall estimated by CMORPH (Fig. 2b); this difference is likely due to the impact of the transient weather systems embedded within the NECV that are purposely filtered out for the control simulations. The intensities and locations of rainfall in experiments Fake-dry and NOVAP (Fig. 4c and d) are quite different from each other (as well as both REAL and CMORPH observations). For CNTL, precipitation covers the whole southeast region and the maximum daily precipitation occurs over the plains. In Fake-dry, the precipitation is much less than that of CNTL, is barely existent near the mountains, and essentially disappears over the plains in the south region. In NOVAP, on the other hand, the precipitation is about four times larger than that of CNTL; apart from the plains, another maximum in daily precipitation is located on the southeast edge of the south domain. The local convection is enhanced in the absence of evaporative cooling. Thus, turning off evaporative cooling (NOVAP) significantly increases precipitation, but turning off both heating and cooling for all phase changes (Fake-dry) yields a large decrease in precipitation. Overall, latent heating and cooling make a significant contribution to the initiation and intensity of precipitation over North China, especially over the plains.

3.2 The diurnal cycle of simulated precipitation

Figure 3a shows a Hovmöller diagram of rain rate averaged along a northwest-southeast cross section in ABEF (marked in Fig. 2b) for CMORPH observations during 17–24 June 2004. Consistent with the warm-season average from HZ10, there are at least five episodes of diurnally varying southeastward-propagating rain streaks during this 8-day period, with rainfall peaks beginning near the eastern top of the mountain ranges in the afternoon and subsequently propagating southeastward to the plains overnight. Figure 3b shows the corresponding Hovmöller diagram for the last 10 days of the control experiment. As in Trier et al. (2010) and Sun and Zhang (2012), with diur-

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nally varying boundary conditions and after a 5-day spin-up period, the southeastward propagating rain streaks become more regular and occur every day for the last 10 days of CNTL. These streaks take around 18 h to propagate from near the eastern top of the mountain ranges in the afternoon to the southeast edge of the focus domain in the morning, with a phase speed of $\sim 12 \text{ ms}^{-1}$. This is approximately the mean steering flow speed in the mid-levels, and is also similar to the 7-yr warm-season average in HZ10 over this area. As shown in Fig. 1, HZ10 found the propagation speed of diurnal precipitation peak to be $\sim 13 \text{ ms}^{-1}$.

Experiment CNTL reproduces the diurnal variations of precipitation over Northern China. In order to present the diurnal variations of precipitation in detail, Fig. 5a–h show the diurnal hourly precipitation rate averaged over the final 10 days at different times. Similar to Fig. 1a from HZ10, Fig. 5i uses isochrones to depict the locations of the diurnal precipitation peak for the different hours shown in Fig. 5a–h. The diurnal rainfall belt starts in the early afternoon (around 06:00 UT or 14:00 BST) on the lee of the mountain ranges. The rainfall belt intensifies as it heads downward along the eastern slope of the mountain ranges, and reaches the peak intensity on the western edge of the plains between 12:00–15:00 UT (20:00–23:00 BST). Propagating toward the southeast, the rainfall belt starts its gradual weakening just before midnight (15:00 UT or 23:00 BST) over the center of the plains; the belt reaches the eastern edge of the focus domain between 21 and 00:00 UT (05:00 and 08:00 BST), by which time the diurnal rainfall has almost completely faded away (Fig. 5a and h). There are different propagation features between the north and south regions (separated by the dashed line EF in Fig. 2b). It is clear that the diurnal precipitation variations in the south region are more similar to that of warm-season as in HZ10. This is the primary reason why we focus on the southern region (ABEF) to analyze the impact of the MPS on the diurnal variation in precipitation.

To further elucidate the diurnal variation and propagation features of the precipitation over Northern China from the different experiments, Hovmöller diagrams of the mean hourly precipitation along the northwest-southeast cross section in ABEF averaged

over 8 days for CMORPH, the simulated final 10 days for CNTL, and the simulated 10 days for Fake-dry and NOVAP are shown in Fig. 6. Consistent with the daily evolutions in Fig. 3b, the main characteristics of the mean diurnal cycle in CNTL (Fig. 6b) are broadly similar to those in CMORPH (Fig. 6a). The average phase speed of the southeastward-propagating rain belt is $\sim 12 \text{ ms}^{-1}$, which is similar to the observed climatological diurnal propagation phase speed estimated by HZ10. CNTL represents the main characteristics of the diurnal cycle described by HZ10 in terms of both timing and propagation, although the strongest rainfall happens over the central plains just before midnight (around 15:00 UT or 23:00 BST, Fig. 6b) instead of over the foothills of the mountains in the evening hours in CMORPH observations (around 12:00 UT or 20:00 BST, Fig. 6a). CNTL also reproduces well the diurnal variations of precipitation over ABEF. In the Fake-dry experiment, the diurnal precipitation is much weaker and is confined to the area just near the mountains in the late afternoon and the night (rather than propagating southeastward). In the NOVAP experiment, the mean diurnal precipitation is substantially higher than that of CNTL over the plains on the center and southeast edge of ABEF; unlike Fake-dry, NOVAP preserves the characteristics of the diurnal propagation (albeit with a speed of $\sim 9 \text{ ms}^{-1}$).

4 The MPS circulation and the diurnal precipitation variations over Northern China

As discussed before, the diurnal control experiment broadly reproduces (in agreement with HZ10) the diurnal variation of precipitation and southeastward propagation of the peak phase of the diurnal precipitation from the lee of Yanshan-Taihangshan Mountain Ranges to the North China Plains over Northern China. Using the rather coarse temporal and spatial resolution of the GFS analysis, HZ10 found that the MPS circulation has a close connection with the diurnal variation of warm-season precipitation over Northern China. To analyze the characteristics of the MPS circulation in further detail, the results of the CNTL, Fake-dry and NOVAP experiments are compared and discussed.

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4.1 The average MPS circulation and the diurnal variations of the MPS updraft

Figure 7 shows the mean and anomalous horizontal and vertical velocities at 3 km from the CNTL simulation. In order to ignore small-scale disturbances, scales smaller than 200 km are truncated in this figure with the same 2-D spectral decomposition technique used by HZ10. Height-distance cross-sections of mean and anomalous winds and potential temperature are shown in Fig. 8.

The average circulation over the last 10 days of CNTL (Fig. 7a) is similar to the initial circulation (Fig. 2a). Under the influence of the NECV in the northeast of the domain, northwesterly flow dominates over the south region (ABEF). Intense ascending motion (as high as 5 ms^{-1}) is located near the mountains, whereas the vertical motion over the plains is weak (in the range of -1 to 1 ms^{-1}). The average northwesterly component of wind speed increases gradually with height (Fig. 8a).

Consistent with the southeastward movement of diurnal precipitation peaks, an obvious belt of anomalous upward motion is located along the mountains around 06:00 UT (14:00 BST) and then propagates southeastward to the plains (Figs. 7d and 8d). A downdraft belt divides the updraft into two parts at 09:00 UT (17:00 BST, Figs. 7e and 8e), with the stronger one arriving at the northwest edge of the plains, and the weaker one remaining near the mountains. The updrafts are separated by 3 h in time or 300 km in distance. All vertical motions weaken by the early morning (18:00 UT or 02:00 BST). The main updraft gets to the southeast edge of ABEF, while the secondary updraft arrives at the central plains. At this time, the downward motion deviation begins to appear near the top of mountains (Figs. 7h and 8h). Three hours later (21:00 UT or 05:00 BST), the main updraft moves out of this south region and the secondary updraft reaches the southeast plain, downdraft appears on and near the mountains (Figs. 7i, 8i). The main updraft is primarily responsible for the occurrence of the diurnal precipitation and the southeastward propagation of the rainfall belt.

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4.2 Diurnal variation of the MPS circulation and its impacts

Past studies have found that the diurnal cycle of the MPS is composed of four stages: developing and peak daytime and nighttime phases (Wolyn and McKee, 1994; Zhang and Koch, 2000; Koch et al., 2001; Huang et al., 2010; Sun and Zhang, 2012). HZ10 discussed the characteristics of the MPS during these four different stages over Northern China. The peak daytime phase is during the afternoon, coincident with the maximum solar heating. At this time, the MPS updraft is located over the top and the slope of the mountain ranges, while the MPS downdraft is located over the plains. The peak nighttime phase is almost the reverse of the peak daytime phase.

In order to reveal the diurnal variation in the evolution of the MPS circulation, Fig. 8b–i show (at 3-h intervals) the potential temperature and *deviations from the daily mean* of the three-dimensional circulation along the northwest-southeast cross section averaged over ABEF of experiment CNTL.

A few hours after sunrise (00:00 UT or 08:00 BST, Fig. 8b), the MPS is still mostly in the nighttime phase, with the updraft over the plains (the maximum is over the southeastern plains) and the downdraft near the Taihang Mountain Range. Above 2 km, the wind is southeasterly, whereas below 2 km the wind is northwesterly. At 03:00 UT (11:00 BST, Fig. 8c), solar radiation (and therefore surface heating) begins to increase. Consequently, the mountains are heated more than the plains, reversing the direction of the temperature gradient and transforming the MPS from the nighttime pattern to the daytime pattern. The upward motion occurs near the top and the slope of the mountains and the downward motion diminishes further. The phenomenon illustrates that MPS circulation is in the developing daytime phase (Fig. 8c).

In the early afternoon (06:00 UT or 14:00 BST, Fig. 8d), near the time of maximum solar heating, the daytime temperature gradient between mountains and plains is at its strongest. Surface solar heating over the mountain ranges and the adjacent slopes has driven a flow reversal from the nighttime pattern, with upslope flow now prevailing in the lee of mountains. Because the temperature over mountains is higher than that over the

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downdraft near the mountains, signaling the development of the nighttime pattern of the MPS.

In the early morning of the second day (18:00 UT or 02:00 BST, Fig. 8h), the main updraft dissipates and moves out of the focus domain. In the meantime, a broad region of updraft begins to span over the northwestern plains while a downdraft develops over eastern edge of the mountains, signaling that the nighttime pattern is fully established. A few hours before sunrise (21:00 UT or 05:00 BST, Fig. 8i), the MPS is still in the nighttime pattern, and the broad updraft moves to the southeastern plains.

Hovmöller diagrams of the mean vertical velocity at 3 and 6 km (Fig. 9a and b) from CNTL show that the diurnal characteristics of vertical velocity change greatly with height. At 3 km, two parallel upward motion lines are present in the focus domain, separated by ~ 300 km in horizontal distance and ~ 6 h in time; both lines originate near the mountains and then move southeastward. The main updraft shows similar characteristics to the diurnal precipitation peaks and is likely the main precipitation triggering mechanism. At 6 km, the secondary (weaker) updraft line gradually weakens before finally fading away. Meanwhile, the main upward velocity belt becomes stronger at 6 km than it is at 3 km. A local upward velocity belt that is separate from the main updraft appears over the southeast part of the plains in the afternoon (06:00–12:00 UT or 14:00–20:00 BST) and is quite evident at 6 km. Consequently, the vertical velocity over the southeast domain of the plains has two diurnal peaks (i.e. a semi-diurnal variation). The feature of the diurnal vertical velocities at 6 km closely fits that of the diurnal precipitation peaks.

In summary, the main updraft branch of the MPS originates near the top of the Taihangshan Mountain Ranges in the afternoon during the strongest solar heating, and then propagates southeastward at an average speed of 12 ms^{-1} . Diurnal precipitation occurs behind the updraft, and the precipitation-induced downdraft divides the updraft into two parts (unlike the simple feature shown in HZ10). While the main updraft progresses to the lee of the mountains, the secondary updraft remains located near the southeast slope of mountains in the late afternoon (09:00 UT or 17:00 BST) before

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5 The impact of latent heating and cooling on the development of the MPS circulation

The above analysis shows that latent heating and (to a much greater extent) cooling are responsible for the development and propagation of the MPS circulation. The evaporative cooling from precipitation produces the cold pool, which enhances the precipitation while moving the MPS updraft and rainfall belt southeastward. The Fake-dry and NOVAP experiments are run to analyze how the latent heating/cooling and cold pool influence the diurnal variation of the MPS circulation and the associated precipitation. The results of the 10 consecutive simulations from Fake-dry and NOVAP are averaged every hour individually to get the diurnal characteristics of the environmental and precipitation fields. The 10 consecutive runs are used instead of one continuous simulation in CNTL to ensure that the synoptic flow patterns in Fake-dry and NOVAP do not differ greatly from CNTL.

The daily precipitation from the two sensitivity experiments is shown in Fig. 4c and d. As discussed before, the precipitation decreased drastically in Fake-dry and increased significantly in NOVAP compared with CNTL. Latent heating and cooling are the key factors of diurnal precipitation over Northern China, especially over the plains. Hovmöller diagrams of the hourly rainfall averaged along the northwest-southeast cross section in ABEF from the two sensitivity experiments are shown in Fig. 6c and d. For Fake-dry (Fig. 6c), precipitation only occurs near the eastern slope of the mountains from the afternoon through the early morning of the next day (09:00 UT–00:00 UT or 15:00 BST–08:00 BST) without apparent downslope propagation. Precipitation for NOVAP (Fig. 6d) is different than CNTL in terms of location and intensity but has the characteristics of a southeastward propagation, albeit at $\sim 2/3$ the speed of CNTL. This implies that the cold pool plays an important role in the intensity of the precipitation and the distance of its southeastward propagation, whereas without any latent heating or cooling, there will be no diurnal propagation of the precipitation.

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The height-distance cross-sections of potential temperature and the mean and anomalous three-dimensional circulation in ABEF from sensitivity experiments Fake-dry and NOVAP are shown in Figs. 10 and 11, respectively; Hovmöller diagrams of the mean vertical velocity at 3 km from these two experiments are shown in Fig. 9c and d. Figures 10a and 11a reveal the vertical structure of the averaged circulations from Fake-dry and NOVAP, respectively; each sensitivity experiment preserves some features of the CNTL MPS circulation. The vertical circulation from Fake-dry is similar to that of CNTL, with the updraft over the mountains and very weak² downdraft over the plains. For NOVAP, on the other hand, there is a remarkably strong updraft over almost the entire domain except at mid-levels over the mountains.

The diurnal variations in the vertical circulations of Fake-dry (Figs. 9c, 10b–i) and NOVAP (Figs. 9d, 11b–i) are substantially different from CNTL (Figs. 8b–i, 9a). The distinct differences between Fake-dry and CNTL first appear in the late afternoon (09:00 UT or 17:00 BST): unlike the two strong updrafts found in CNTL, there is only one weaker and slower-moving distinct updraft which barely reaches the center of the plains by the early morning of the second day (21:00 UT or 05:00 BST). The sole updraft in this experiment matches closely with the trailing updraft in CNTL before 12:00 UT (20:00 BST), except that the mean propagation speed is $\sim 6 \text{ ms}^{-1}$, which is about half of that in CNTL. In other words, the cold pool in CNTL acts to divide the MPS updraft into two parts and to push the precipitation southeastward while enhancing the precipitation by forcing a new updraft along its leading edge.

For NOVAP, the vertical circulation reveals some explicit features of the diurnal variation of the MPS circulation found in CNTL, but has a much stronger updraft. Similar to CNTL, the MPS updraft appears near the lee of the mountains at 06:00 UT (14:00 BST) and then propagates southeastward towards the eastern part of the plains at a speed of $\sim 9 \text{ ms}^{-1}$. Furthermore, in line with Fake-dry, there is neither a secondary updraft nor a cold pool. Nevertheless, the NOVAP experiment retains very clear signals of the

² It is only seen in the vector field with a magnitude smaller than the first negative value contoured in Fig. 8a.

MPS structure and the diurnal variation. Temperatures in NOVAP increase faster than both CNTL (because evaporative cooling is turned off) and Fake-dry (because latent heating is turned on). The higher temperatures enhance the development of local convection, and are the cause of the stronger updrafts over the central and eastern parts of the plains.

Under similar synoptic flow patterns with the same solar heating cycle, both Fake-dry and NOVAP preserve some of the diurnal variations found in CNTL, with the peak daytime pattern in the afternoon and the peak nighttime pattern at night. Nevertheless, without the cold pool, the MPS updraft is much weaker and moves downslope much more slowly. This is consistent with the control and fake-dry simulations of Koch et al. (2001) in their study of an MPS circulation and related precipitation over North America. The differences in the intensity of MPS circulation and the propagation speed of the MPS updraft between Fake-dry and NOVAP show that cooling from the evaporation of liquid water is the key factor in forming the cold pool, whereas latent heating plays an important role in the intensification and acceleration of the MPS updraft.

Some past studies have also noted that the mid-level flow is one of the key factors influencing the propagation speed of the diurnal precipitation peak and the MPS updraft (HZ10; Bao et al., 2011). Figures 8a, 10a, and 11a show the vertical profiles of the mean three-dimensional circulation from experiments CNTL, Fake-dry and NOVAP, respectively. As said before, the speed of the southeastward propagation of the updraft in Fake-dry (NOVAP) decreases to only about half (2/3) of that in CNTL. The thick blue lines are plotted to show where the northwesterly component of the wind is equal to 12 ms^{-1} (the propagation speed of the MPS updraft in CNTL). In Fake-dry (NOVAP), the intensity of the mid-level wind is only slightly weaker (stronger) than CNTL over the mountains, where the 12 ms^{-1} isotach is near 6 km in CNTL, 7 km in Fake-dry, and 5 km in NOVAP. Over the plains, the 12 ms^{-1} isotach in CNTL is slightly higher (lower) than Fake-dry (NOVAP). It is clear from these plots that changes in mid-level winds are not the primary reason for the differences in updraft propagation speed between the two sensitivity experiments and CNTL. This further demonstrates that the differential

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surface sensible heating is the main factor for the generation and evolution of the MPS circulation, whereas latent heating and cooling can enhance the MPS circulation and modulate its propagation.

6 Concluding remarks

5 This study follows HZ10 and examines the impact of the Mountain-Plains Solenoid (MPS) circulation on the diurnal cycle of warm-season precipitation over Northern China. Using high-resolution WRF simulations over several days, this study examines in detail the diurnal variations of precipitation and the MPS circulation.

10 The base period is 17–24 June 2004, which featured several episodes of southeastward-propagating precipitation over Northern China that originated from the “second-step” mountain ranges and moved to the “third-step” plains with an apparent diurnal cycle. The control experiment (CNTL) is a 15-day simulation that uses the 8-day average of the NCEP GFS gridded analyses at 00:00 UT for the initial conditions and the 8-day averages at 00:00 UT, 06:00 UT, 12:00 UT and 18:00 UT for the lateral boundary conditions (to allow for diurnal variations). In addition to the control experiment, two sensitivity experiments are performed to better understand the roles of evaporative cooling (for cold pool formation) and latent heating on the evolution of the MPS circulation.

15 Despite differences in the rainfall intensity and location, the control experiment successfully simulated the diurnal variation of precipitation and southeastward propagation of the peak phase of the diurnal precipitation from the lee of Yanshan-Taihangshan Mountain Ranges to the Northern China Plain (which have been presented in HZ10). The diurnal precipitation peak initiates on the lee of mountain ranges in the afternoon (06:00 UT or 14:00 BST) at the time of maximum solar heating and then propagates southeastward at a mean speed of 12 ms^{-1} . The peak reaches the plains in the night-
25 time hours, reaching its maximum intensity over the central plains before midnight

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(12:00–15:00 UT or 20:00–23:00 BST), and has a lag of 3 h or 200 km compared with HZ10.

Using the coarse spatial and temporal resolution of the GFS analysis, HZ10 found that the MPS circulation is closely connected with the diurnal variation in the warm-season precipitation over Northern China. In this study, CNTL captures (in high spatial and temporal resolution) the detailed evolutionary process of the MPS circulation. The MPS circulation possesses an apparent diurnal variation that is caused by the differential heating between mountains and plains, and has an important influence on the diurnal cycle of local precipitation. The MPS circulation is in the daytime peak pattern in the afternoon at the time of maximum solar heating, with the updraft over the lee of the mountains and the downdraft over the plains; the circulation then reverses to the nighttime peak pattern when the surface longwave cooling is much stronger over the mountains than over plains. The main updraft of the MPS circulation is shown to be the primary factor in the generation and propagation of the diurnal precipitation peak. The main updraft initiates on the southeast slope of the mountains in the afternoon, with precipitation occurring behind the updraft; both features propagate southeastward towards the plains.

In an experiment that turned off *all* latent heating *and* cooling (Fake-dry), the MPS circulation was still generated and had the diurnal variations of the control. Nevertheless, the MPS updraft was much weaker and slower in propagating southeastward compared with CNTL. The cold pool is not produced without evaporative cooling, which is also the reason why the updraft moves more slowly and then halts on the central plains. In an experiment that only turned off cooling from the evaporation of liquid water (NO-VAP), the MPS circulation was stronger than in CNTL but with a slower-moving updraft (although not as slow as Fake-dry). This result implies that latent heating plays an important role in determining the intensity of MPS circulation. The interaction between latent heating and cooling has a positive feedback effect on the propagation speed of the MPS updraft. The current study complements recent studies on the relationship between the MPS circulation and the diurnal variation of warm-season precipitation

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over the large-scale mountains and adjacent plains (HZ10, Bao et al., 2011; Sun and Zhang, 2012).

Acknowledgements. We are grateful to Yunqi Ni and Jianhua Sun for comments and suggestions. Proofreading by Benjamin Green is greatly appreciated. The authors are also thankful for computing support by TACC. This study is partially sponsored by US NSF Grant 0904635 and National Basic Research Program of China (973 Program) Grant 2012CB417205.

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Table 1. Summary of WRF numerical experiments.

Expt	Objectives	Initial condition	Lateral boundary condition	Description
REAL	Real data simulation for 8 days	00:00 UT 17 Jun 2004	Real data from 00:00 UT 17 through 00:00 UT 25 Jun 2004	Full physics
CNTL	Sensitivity to diurnal cycle and initial conditions	The mean of 00:00 UT from 17–24 Jun 2004	The means of 00:00, 06:00, 12:00, and 18:00 UT between 17–24 Jun 2004	As in REAL
Fake-dry	Sensitivity to both latent heating <i>and</i> latent cooling	The 00:00 UT forecasts of the last 10 days of CNTL	As in CNTL	No latent heating or latent cooling; sensible heating allowed
NOVAP	Sensitivity to evaporative cooling <i>only</i>	As in Fake-dry	As in CNTL	Latent heating is allowed; only cooling from the evaporation of <i>liquid water</i> is turned off.

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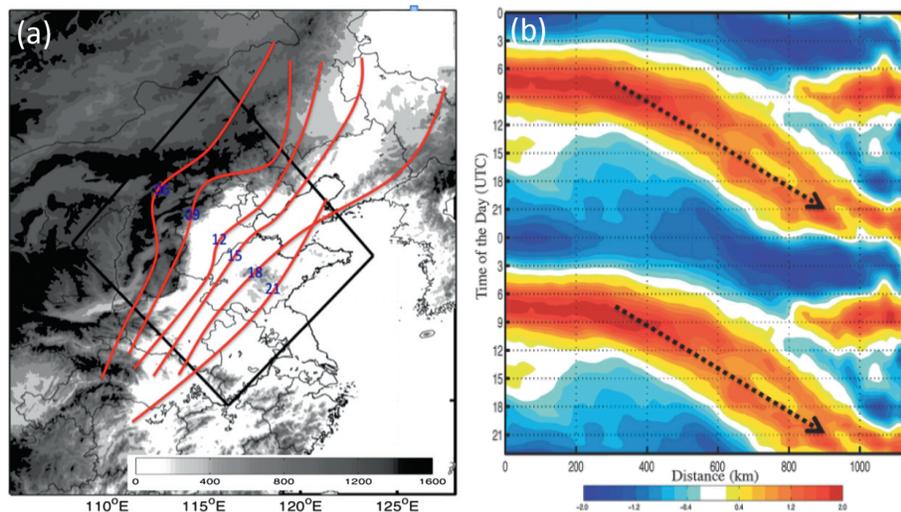


Fig. 1. (a) Isochrones (phase fronts) of the local diurnal precipitation peaks at different times with terrain elevation shaded every 200 m. The labels of the isochrones are in UT hours (8 h behind the local standard time, Beijing time). From Fig. 2b of HZ10. (b) Distance-time Hovmöller diagram of the normalized hourly precipitation deviation without filtering averaged along the northwest-southeast cross section within the black box in (a). The dashed arrows show the southeastward phase propagation of the diurnal precipitation peaks. From Fig. 4 of HZ10.

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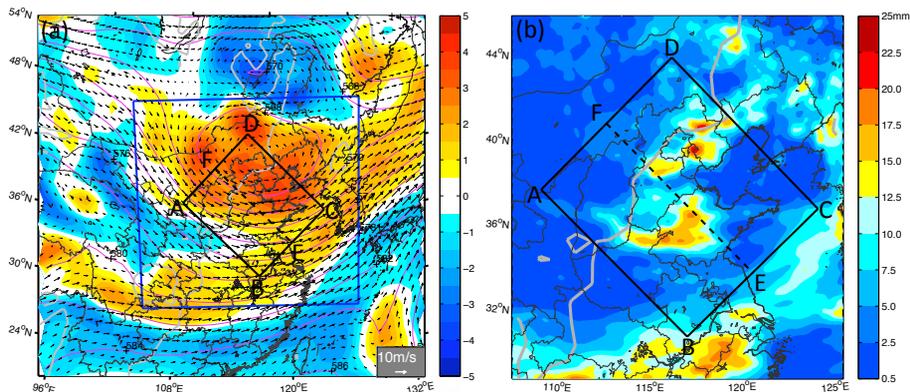


Fig. 2. (a) The average 500 hPa relative vorticity (10^{-5} s^{-1} , shaded), horizontal wind vectors, and geopotential height every 2-dam (magenta contours) between 00:00 UT 17 and 00:00 UT 24 June 2004 from GFS analysis. The blue box is the simulation domain. The rectangle ABCD indicates the focus area, and the dashed line EF divides ABCD into north and south domains. (b) Average daily precipitation (mm) between 17 and 24 June from CMORPH.

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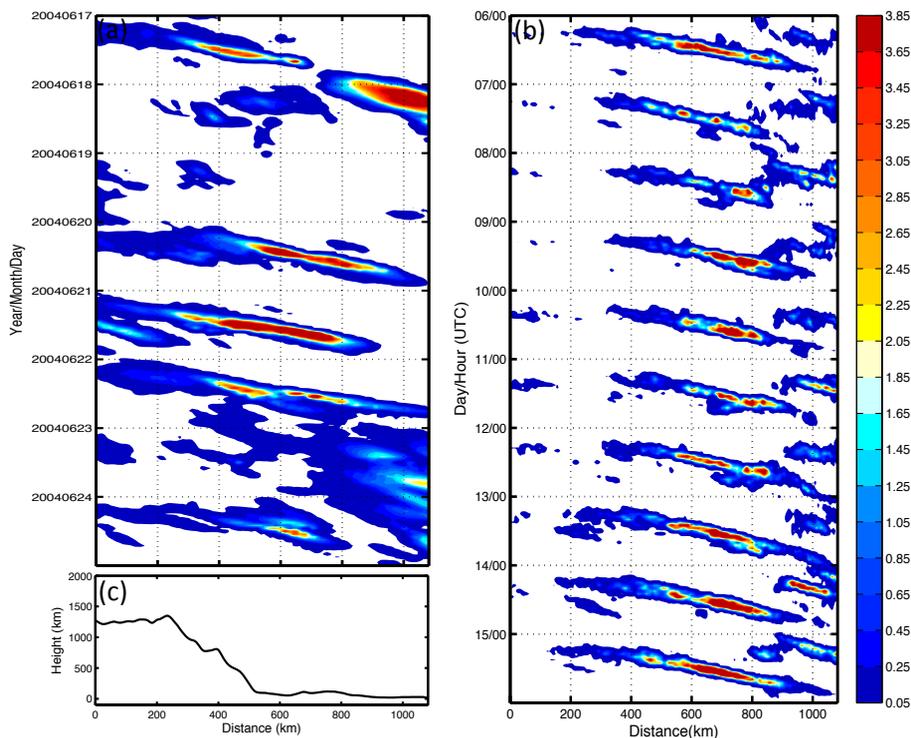


Fig. 3. Hovmöller diagram of the rain-rate (mm h^{-1}) averaged along the northwest-southeast cross section over ABEF for (a) 17–24 June 2004 from CMORPH and (b) the final 10 days of the control simulation (CNTL). (c) Averaged terrain elevation along northwest-southeast direction over ABEF.

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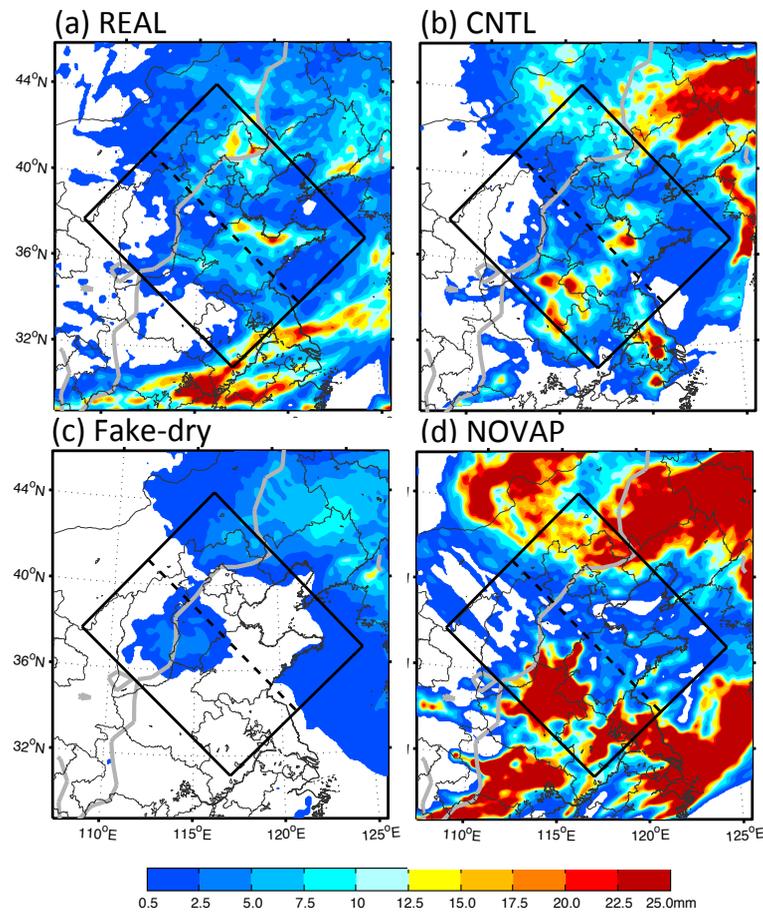


Fig. 4. Mean daily precipitation (mm) for (a) REAL; (b) CNTL; (c) Fake-dry; (d) NOVAP.

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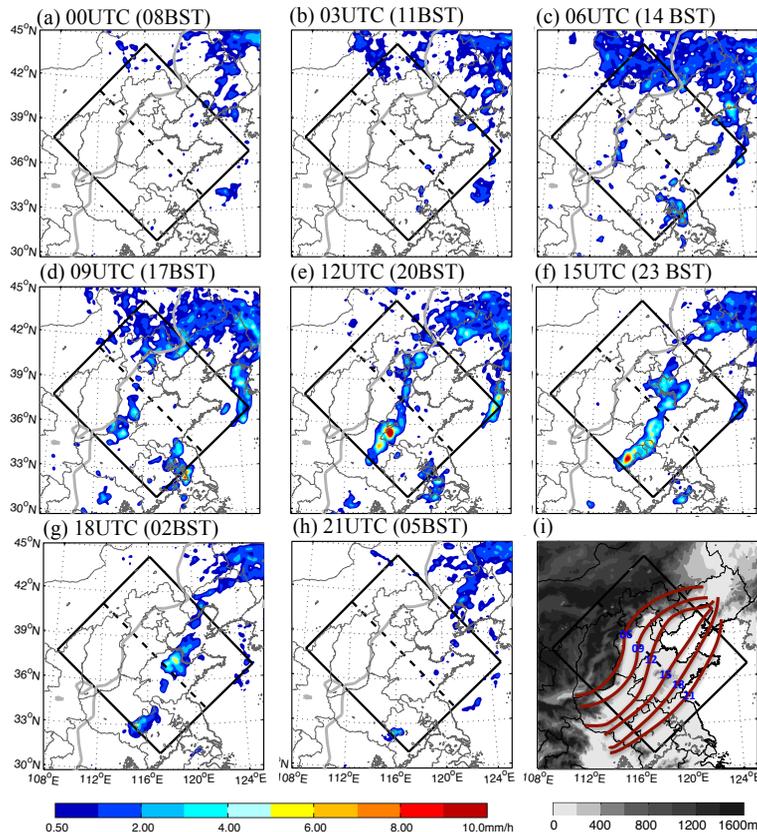


Fig. 5. Spatial distribution of diurnal hourly precipitation rate for the final 10 days of CNTL at: **(a)** 00:00 UT; **(b)** 03:00 UT; **(c)** 06:00 UT; **(d)** 09:00 UT; **(e)** 12:00 UT; **(f)** 15:00 UT; **(g)** 18:00 UT; and **(h)** 21:00 UT. **(i)** Isochrones (phase fronts) of the local diurnal precipitation peaks at different times with terrain elevations shaded every 200 m. The isochrones are labeled in UT hours.

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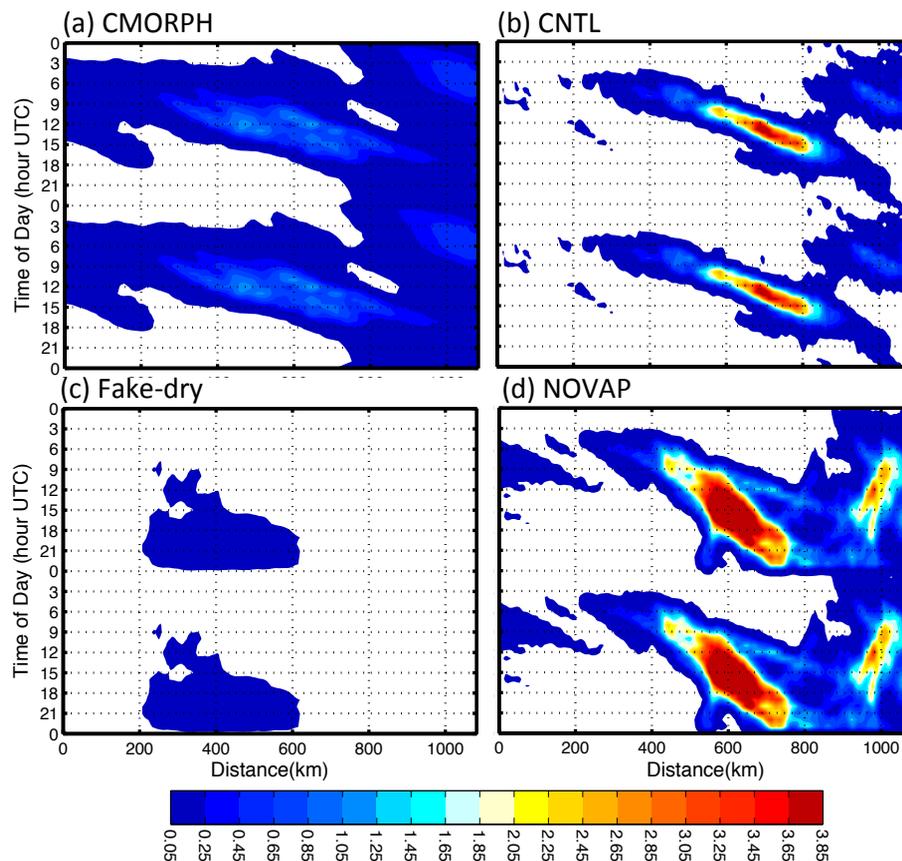


Fig. 6. Hovmöller diagrams of the rain-rate (mm h^{-1}) averaged along the northwest-southeast cross section over ABEF for **(a)** 17–24 June 2004 from CMORPH; **(b)** the final 10 days of CNTL; **(c)** the 10 days of Fake-dry; **(d)** the 10 days of NOVAP.

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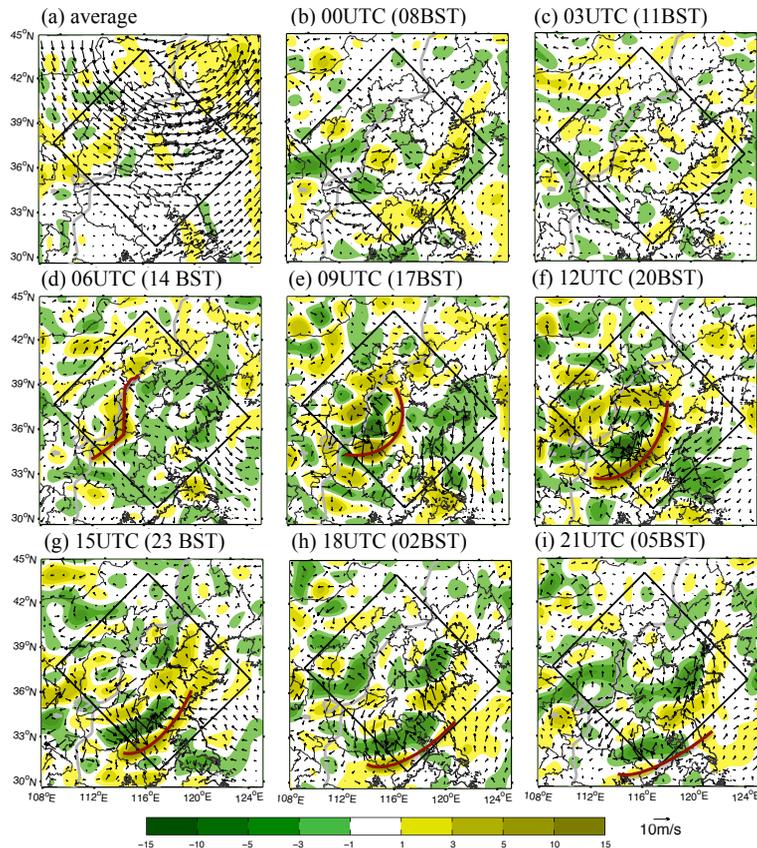


Fig. 7. (a) The average vertical velocity (shaded, cm s^{-1}) and horizontal wind vectors at 3 km AGL for CNTL. The diurnal variation of the deviations from these averages are plotted for (b) 00:00 UT; (c) 03:00 UT; (d) 06:00 UT; (e) 09:00 UT; (f) 12:00 UT; (g) 15:00 UT; (h) 18:00 UT; (i) 21:00 UT. The thick maroon line denotes the location of the phase fronts of the updraft.

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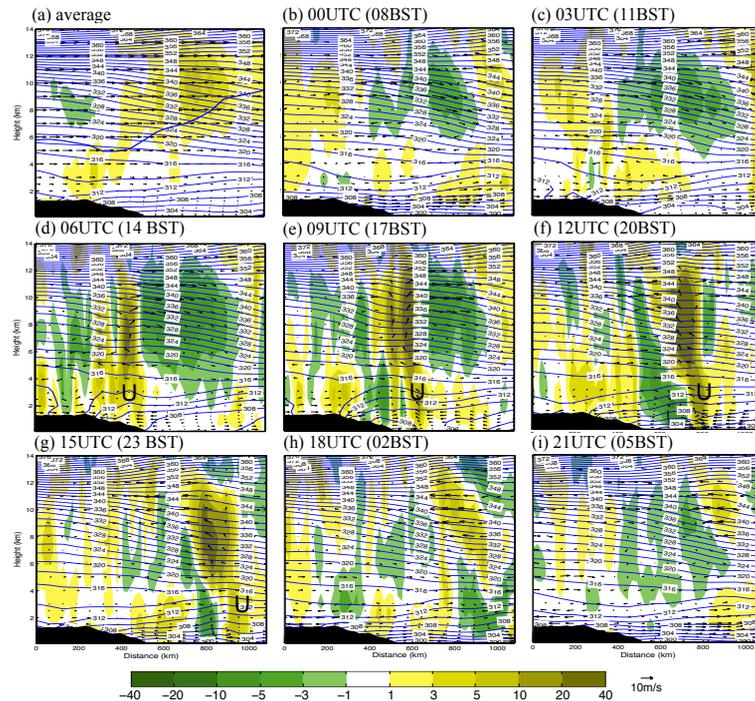


Fig. 8. (a) Height-distance cross section of daily mean potential temperature (solid lines, K), vertical velocity (shaded, cm s^{-1}) and the mean circulation vectors (horizontal wind component along the northwest-southeast cross section and 100 times the vertical velocity) averaged over ABEF from CNTL. The thick blue line shows where the northwesterly wind is equal to 12 m s^{-1} . (b)–(i) As in (a), except the vertical velocity and circulation vectors are the diurnal perturbations from the daily mean (potential temperature contours are of their full values). The black shading represents topography.

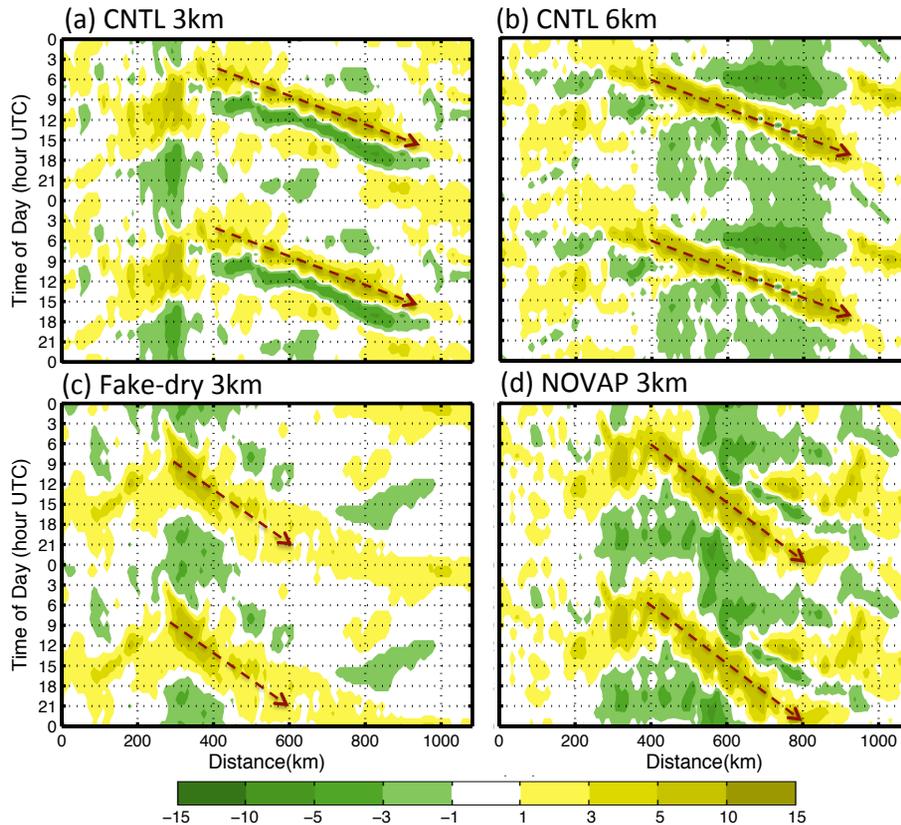


Fig. 9. Hovmöller diagrams of vertical velocity at **(a)** 3 km of CNTL; **(b)** 6 km of CNTL; **(c)** 3 km of Fake-dry; **(d)** 3 km of NOVAP averaged along the northwest-southeast cross-section through ABEF. The dashed arrows show the southeastward phase propagation of the updraft.

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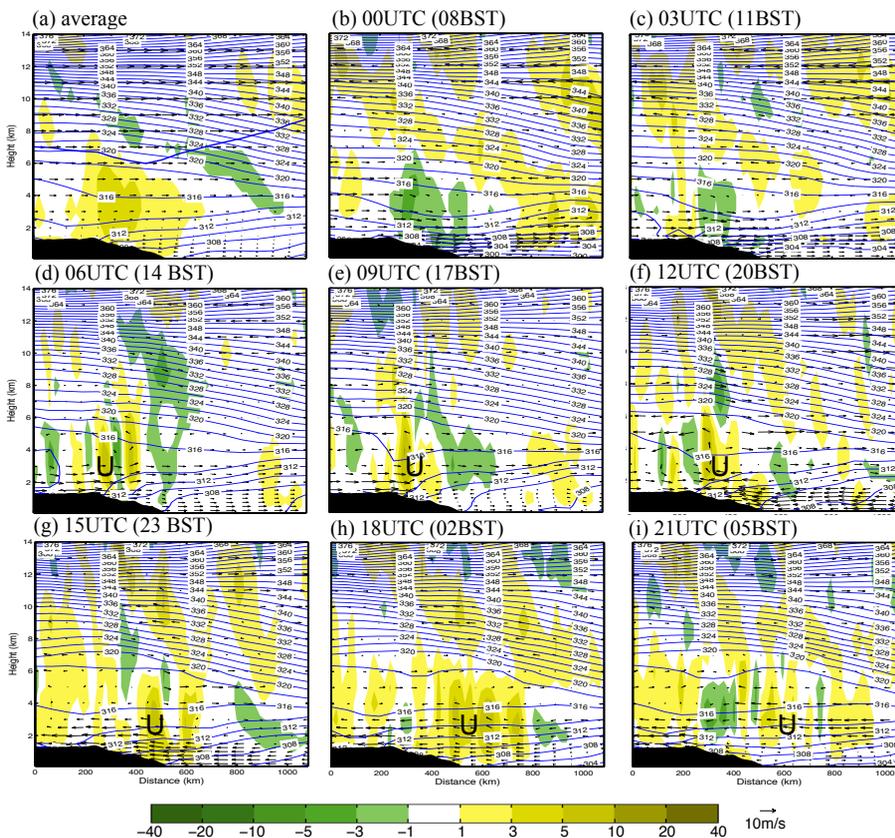


Fig. 10. As in Fig. 8, but for Fake-dry experiment.

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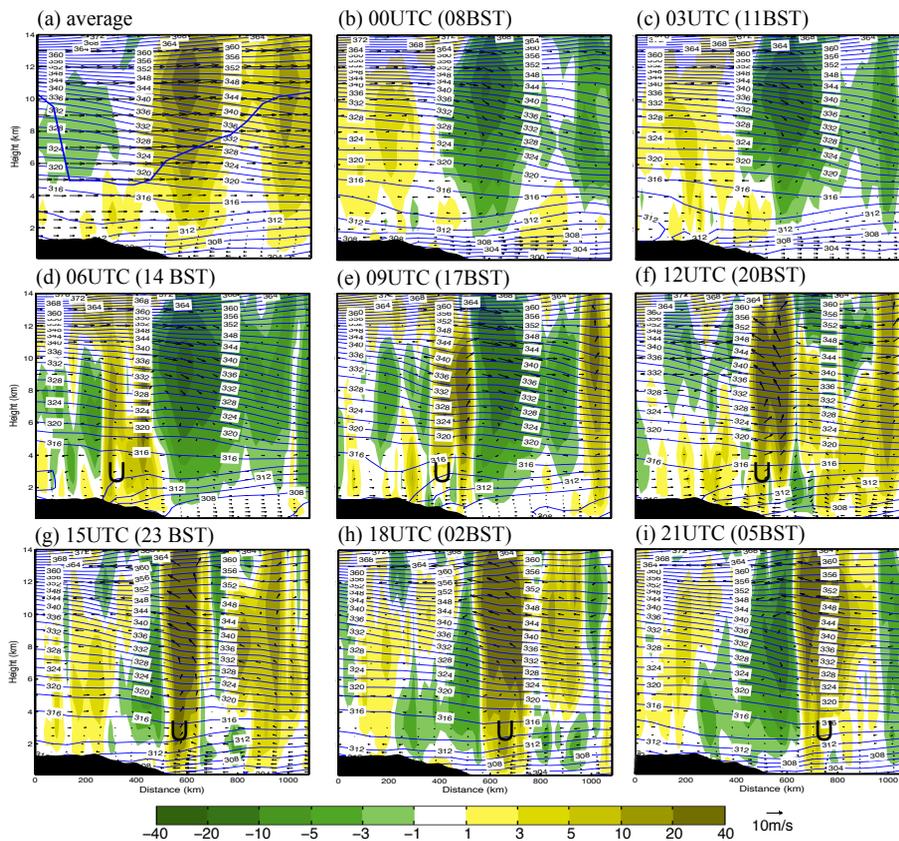


Fig. 11. As in Fig. 10, but for NOVAP experiment.