［共同研究成果］

Reproduction of diurnal variability of Meiyu precipitation in the Yangtze River Valley using non-hydrostatic model

Guixing Chen, Weiming Sha and Toshiki Iwasaki
Department of Geophysics, Graduate School of Science, Tohoku University

Meiyu precipitation in the Yangtze River Valley (YRV) tends to reach its maximum in the morning. The middle and lower reaches of YRV are identified as two preferred regions of morning heavy rainfalls. To clarify the underlying physics responsible for this diurnal variability, a series of high-resolution simulations are conducted to examine nocturnal convection systems for a 5-day period of repeatedly occurring heavy rainfalls. Both the rainfall amount and its diurnal cycle in the vicinity of Meiyu front are well reproduced; so are the associated low-level processes that vary diurnally and regionally. It is found that the formation and evolution of nocturnal convections exhibit strong association with the nighttime intensification of the low-level jet (LLJ) over south China and the arrival of warm/moist air pool to the Meiyu frontal zone in the YRV. Overnight they strengthen the Meiyu front from its south sector. To the south of the Meiyu front and the north terminus of LLJ, the moisture convergence and convective instability are distinctly enhanced, triggering the nocturnal growth of convection and producing the strong morning rainfall.

1. Introduction

During the warm season, East Asia is featured distinctly by the march of the summer rainband, which is well known as the Meiyu in China and the Baiu in Japan. It brings plenty of rainfall for the East Asian countries; it sometimes causes heavy rainfalls and severe disasters. Along with this seasonal change, diurnal cycle in cloudiness and precipitation is found to be another key aspect of the weather and climate. Diurnal variability of Meiyu/Baiu precipitation is studied to expand our understanding and predicting on the precipitation systems and their underlying physical processes.

Observation and numerical analyses on Meiyu precipitation systems have been conducted for decades [1]. The rain-bearing systems in Yangtze River Valley (YRV) come from the mesoscale ones that are generally embedded in the synoptic/large-scale Meiyu frontal zone. Recent works make use of the high-resolution rainfall data and reveal that the Meiyu precipitation tends to reach its maximum during the late night and morning [2, 3]. This morning signature of precipitation is attributed to the long-lived organized convection such the mesoscale convection systems [4-6]. Furthermore, the diurnal cycle varies in regions of the YRV. The precipitation in the middle reach of YRV (MYRV, 105−112°E, 25−30°N) is attributed to the migrating episodes that initial at the east slope of the plateau since midnight and move eastward during late night and morning. However, the precipitation in the lower reach of YRV (LYRV, 112−120°E, 25−30°N) results from the local eruption of moist convections driven by the enhanced monsoon flow during the early morning.

There have been some difficulties in reproducing the diurnal cycle of Meiyu precipitation in the YRV. The Meiyu precipitation results mainly from the heavy rainfall events whose location and timing are difficult to predict in numerical models. On the other hand, the high-resolution model is necessary for resolving the mesoscale features of rain-bearing systems, while a large domain of simulation is needed for capturing the associated synoptic or large-scale environment and topographical impacts of the Tibetan Plateau.

The need of the high spatio-temporal resolution over a large model domain highlights the importance of the huge computation resource and parallel computation efficiency. In this brief report, we take the advantage of supercomputer systems to conduct a series of simulation to reproduce the diurnal variability of Meiyu precipitation in the YRV. Technical supports for speeding up of the simulation are given through the collaborative work with Cyberscience Center, Tohoku University.

2. Model setting and numerical experiment

The model used in this study is a non-hydrostatic model developed by the Japan Meteorological Agency and Meteorological Research Institute (JMA-NHM). A detailed description of JMA-NHM is provided by Saito et al. [7]. The basic equations in the model are fully compressible equations. The semi-implicit time-integration scheme [horizontally implicit–vertically implicit (HI-VI) scheme] is employed for treating the gravity wave. The advection scheme (4-order flux type horizontally and 2-order center difference vertically), atmospheric radiation schemes, mixed-phased cloud physics, etc., are also incorporated into the model. The modified Kain–Fritsch convection scheme and the improved Mellor–Yamada level-3 closure model are chosen for the parameterization of atmospheric processes.

The simulation targets are the heavy rainfall events that occurred repeatedly during 11−16 June 1998; their diurnal cycles are highly similar to the climatological ones. The model domain contains 504×364 horizontal grid points with 10-km grid, which covers East Asia and the Tibetan Plateau (Fig. 1). 38 vertical levels with variable grid intervals from $\Delta z = 40$ to $\Delta z = 1060\,\mathrm{m}$ are used, where the lowest level and the model top are located at 20 and 19270 m. To reproduce the timing and locations of heavy rainfalls more reliable, five integrations rather than a successive one are conducted. Each initiates at every 00UTC of 11−15 June for daytime spin-up and lasts for 36 h; time step is 30 s. Diurnal cycles of 9-33 h are examined with emphasis on the nocturnal evolution of precipitation systems.

The elevation in the model is given by GTOPO30, which is derived by the U.S. Geological Survey's Center. Initial and lateral boundary conditions for horizontal wind, pressure, temperature, and water vapor are given by 6-hourly 0.5° GEWEX Asian Monsoon Experiment (GAME) reanalysis data. The initial conditions of cloud microphysical quantities are provided by the corresponding 6-h forecasts of JMA-NHM from 18UTC. The 3-hourly rainfall data of the Tropical Rainfall Measuring Mission (TRMM) are used to validate the simulation of rainfall amount and diurnal cycle.

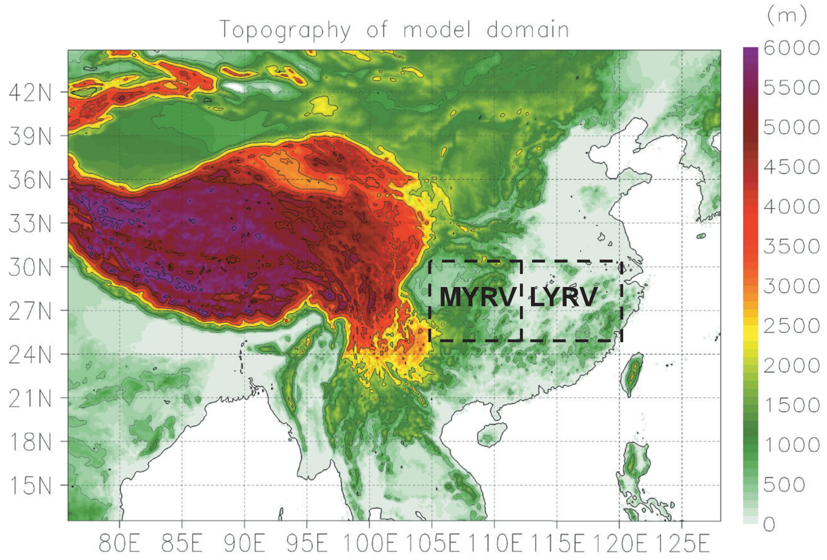

Figure 1. The Model domain and smoothed elevation of GTOPO30 (shaded). Dashed rectangles mark the MYRV and LYRV.

3. Rainfall validation

For rainfall validation, the rainfall amount during 11–16 June is compared between the TRMM-3B42 observation (fig. 2a) and the simulated one (fig. 2c). Both the observations and simulation show that heavy rainfalls appear in the MYRV along the east periphery of the Yun-gui Plateau and in the west-east oriented frontal zone in the LYRV, where the flood took place. Along the Meiyu rainband at 27–30°N, there are a number of precipitation centers at 110°E, 114°E, 116–118°E and 125°E, respectively. The extreme amount in the LYRV exceeds 300 mm in 5-day period. The simulated Meiyu rainband is narrower and more intense than that in TRMM measurements, partially due to its high resolution. Overall, the simulations reproduce well the overall distribution, mesoscale feature, and magnitude of the Meiyu heavy rainfalls in the YRV.

Time-longitude diagrams of hourly rainrate along the latitude of 25–30°N are used to evaluate the modelling on the individual event of heavy rainfall and mean diurnal cycle. Figures 3a and 3b show that three intense events in the MYRV at the mornings of 13, 14 and 16 June are captured by simulation. They are associated with the eastward propagating convections that develop at 105–106°E at late night and strengthen at ~110°E at morning. The rainfall becomes evanescent at the daytime of 14 June, partly returns at the morning of 15

June, and fully recovers at the morning of 16 June. The simulations reproduce the relative weak morning rainfalls on 12 and 15 June, although the rainy area is slightly overestimated. In the LYRV, both the observation and simulation show that the extensive rainfall takes place in the morning hours of 12–16 June. Note that, the eastward migrating signal from the MYRV becomes obscure when arriving at the LYRV. More likely, the Meiyu precipitation systems develop explosively within hours at one same morning in both the MYRV and LYRV. For example, strong rainfall takes place 105–111°E from the late night of 15 June to next morning; meanwhile intense rainfall appears at 114–115°E and 118–120°E. It seems clear that the diurnal cycles in the MYRV and LYRV are independent to each other.

Figures 3c and 3d show the 5-day composite diurnal cycle of rainfall. Both the observation and simulation show that the diurnal cycle of rainfall has two preferred regions: MYRV and LYRV. A gap is readily identified at 112°E that divides these two regimes. Rainfall tends to develop at the east periphery of the Yun-gui Plateau at 15UTC, and then moves to 110°E where it attains its maximum at 21–03UTC. This eastward propagation has a slow phase speed of 9–13 m/s, i.e., traveling across ~4° longitude within 8–12 h. This migrating signal is thus confined in the MYRV. It accounts only for the local eastward-shifted diurnal phase. Instead, another kind of diurnal cycle can be distinguished in the LYRV. Precipitation systems have a rapid local development at 18UTC and produce the extensive rainfall in the morning hours. These regional features in the LYRV and MYRV are highly consistent to the climatological pattern of diurnal cycle, underscoring the fact that the heavy rainfall is a determining factor of the diurnal rainfall cycle and regional difference.

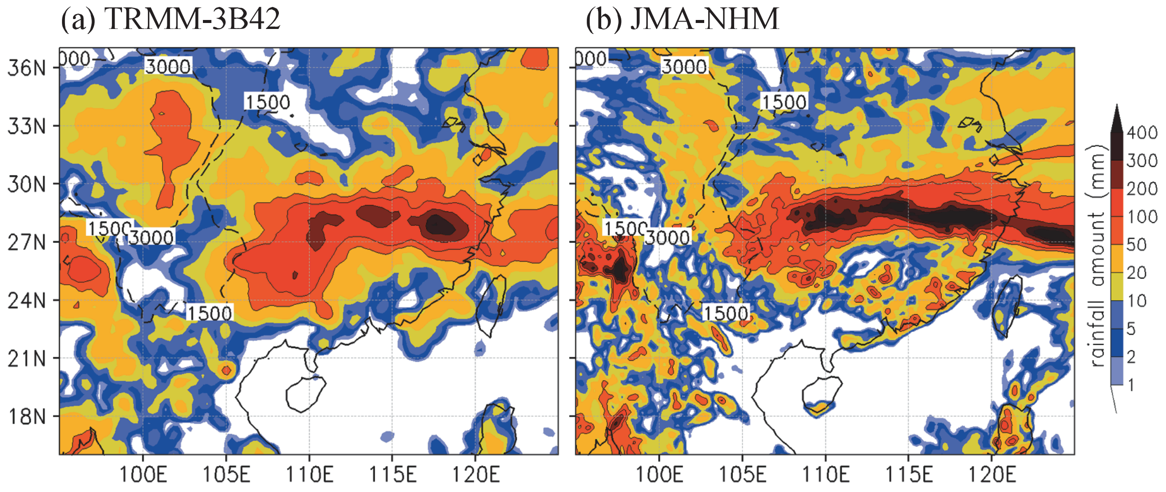

Figure 2. Accumulated rainfall amount from 09UTC June 11 to 09UTC June 16, 1998. (a) TRMM-3B42 observation; (b) JMA-NHM simulation.

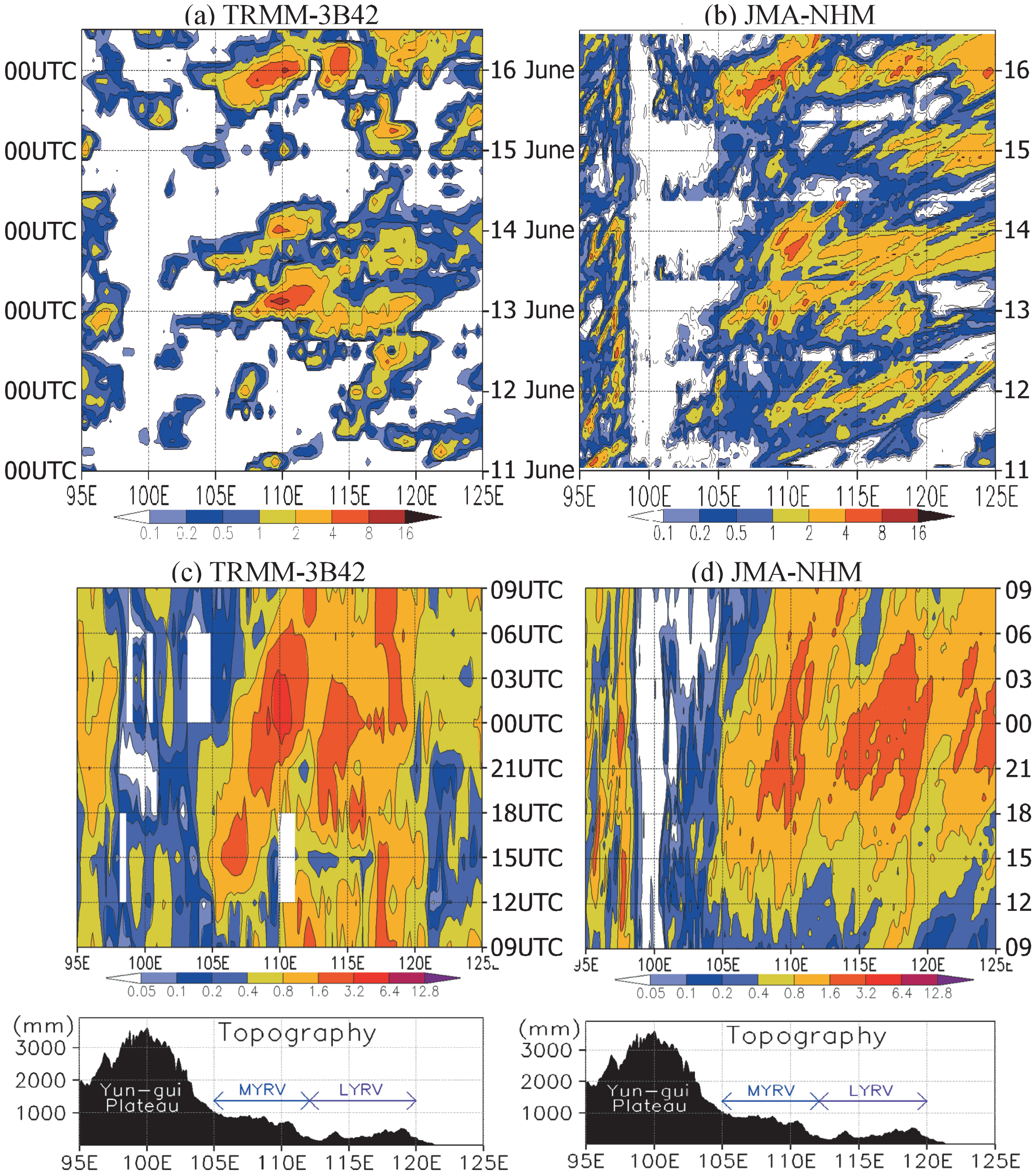

Figure 3. Time-longitude variation of rainfall averaged in the zone of 25~30°N by (a) TRMM-3B42 observation and (b) JMA-NHM simulation. (c) and (d) show the 5-day composite of diurnal cycle for the observation and simulation, respectively. The terrain elevation of 25~30°N is shown in the bottom panel.

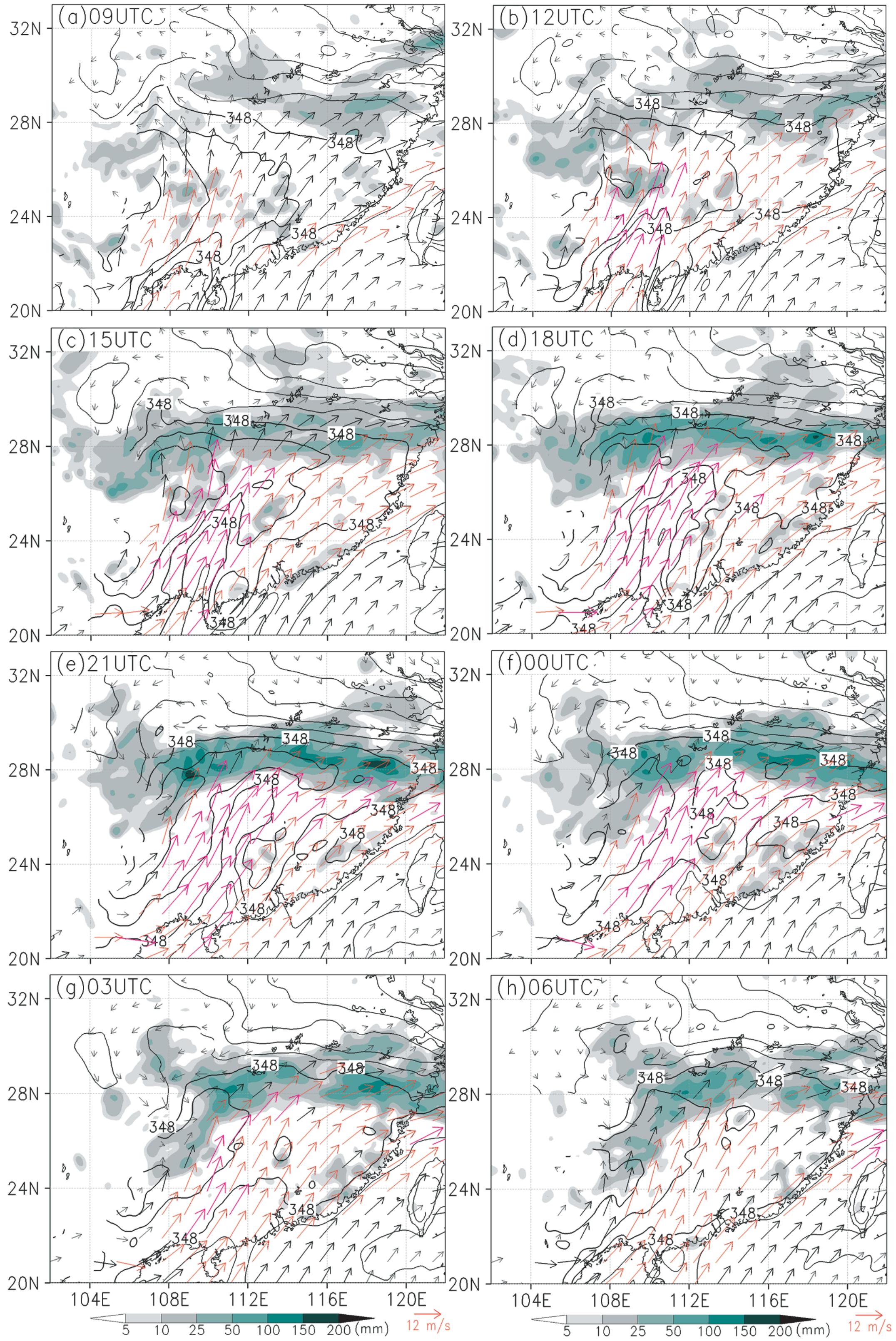

Figure 4. The 3-hourly simulated rainfall (shaded) 850 hPa horizontal winds (vector) and θe (contour) averaged during 11−16 June, 1998. The red vector shows the wind speed exceeding 12 m/s.

4. Diurnal varying low-level processes associated with nocturnal precipitation

Many studies have recognized that the lower-tropospheric conditions are crucial in allowing the organized convection to persist overnight [8, 9]. In the southeastern China, the organized convection can be reinforced by the nocturnal enhancement of monsoon flow in meso-α or synoptic scale [6]. However, the coarse observation data have limitation resolving the diurnal variation of mesoscale systems. Here, the high-resolution simulations are used to facilitate our studies on mesoscale/regional aspects of the thermodynamic and flow structure on a diurnal scale.

Figure 4 portrays the 3-hourly evolutions of simulated rainfall, 850 hPa horizontal wind and equivalent potential temperature (θ_e), averaged for a 5-day period. Through the period, the low-level anticyclone is situated at the northeastern part of South China Sea. The southwesterlies prevail over south China especially along the east periphery of the Yun-gui Plateau. Figures 4a shows that southwesterlies are relatively weak, ranging from 10 to 12 m/s at the afternoon. The warm/moist air with $\theta_e \geq 348$ K dominates the inland south China and develops particularly in the west. It may result from the daytime surface flux over the heated landmass, convective mixing and subsequent shallow convections [9]. The simulated rainfall is visible but weak in the YRV.

At evening and midnight (12–15UTC), the wind speed of southwesterlies increases to 16–20 m/s in the west of south China and 13–16 m/s in the east (figs. 4 b-c). A remarkable acceleration of 6–8 m/s (3–4 m/s) can be estimated for the west (east) region of south China. This nocturnal enhancement of low-level wind is in a good agreement with the sounding observation over south China (not shown). It highlights that the model has a good performance reproducing the diurnal variation of low-level processes as well. The intensified low-level wind exhibits as a converging southerly flow along the east periphery of the plateau, where convections become more vigorous. The high-θ_e air moves fast northward from south China to the YRV, while the low-θ_e air replaces the coastal region of south China.

Figures 4 d-f show that the southwesterly LLJ attains the strongest in strength (~20 m/s) through the late night and morning (18–00UTC). The wind speed maximum tends to extend northward or northeastward. This downstream extension of LLJ leads to the wind speed increasing by 4–5 m/s to the south of 28°N. The pool of warm/moist air ($\theta_e \geq 352$ K) arrives at the YRV. Consequently, the meridional gradient of θ_e value experiences a rapid increase, especially at the south sector of Meiyu front (28–30°N). It implies that the nighttime frontogenesis of Meiyu front is driven largely by the low-level forcing from the south. The arrival of warm/moist air pool also increases the convective instability to the south of the front. On the other hand, the confluent flow of LLJ enhances moisture convergence and mesoscale lifting. All these favorable conditions lead to a rapid growth of moist convections and hence the heavy rainfalls.

Figures 4 d-f also show that the southerlies are intensified over the west region of south China with an earlier and stronger phase than that in the east. It is found that this acceleration of low-level wind is driven by the large imbalance between the pressure gradient force and Coriolis force since evening when turbulent stress becomes decayed. This is responsible for the earlier initiation of convection in the MYRV (figs. 3 c-d). Meanwhile, the enhanced southerlies tend to veer to southwesterlies that steer away from the plateau; northerlies appear over the Sichuan Basin, a signature of mesoscale cyclone or vortex. Over there, the intense rainfall moves eastward or southeastward.

Figures 4 g-h show that southwesterlies over south China return to a suppressed phase at late morning and early afternoon; the wind speed declines to ~12 m/s. The warm/moist air pool in the YRV has been consumed and the value of θ_e becomes less than 348 K, while it begins to recover over south China. The heavy rainfalls to the south of Meiyu front begin to decay gradually as they continue migrating eastward.

5. Concluding remarks

To clarify the mechanism for the morning precipitation in the Meiyu regime, a series of high-resolution simulations are conducted to reproduce successfully the heavy rainfall events in the YRV. It is found that the two preferred regions of heavy rainfall in the MYRV and LYRV are attributed to the nocturnal intensification of monsoon flow and associated low-level moist processes. As a response, the low-level frontogenesis, moisture convergence, convective instability and mesoscale lifting are distinctly enhanced to the south of the Meiyu front, where the nighttime formation of convection and morning heavy rainfalls take place. Therefore, the timing of convection initiation is consistent with the arrival of warm/moist air pool, which is transported by the enhanced nocturnal LLJ. It highlights the importance of the diurnal-scale interactions among the monsoon flow, Meiyu front, boundary processes and topographic effects on the formation and evolution of Meiyu heavy rainfalls. We consider that the further investigation on the mechanism in regional and diurnal scales in the future is helpful to improve the predicting skill on the Meiyu precipitation system. The high-resolution simulations using the supercomputer systems will promote our understanding on the weather and climate over the East Asian countries.

Acknowledgements

Parts of the experimental results in this research were obtained using supercomputing resources at Cyberscience Center, Tohoku University. Technical supports were given through the collaborative work with Cyberscience Center.

References

[1] Ding, Y. H., 1992: Summer monsoon rainfalls in China, *J. Meteorol. Soc. Jpn.*, *70*(1B), 373-396.

[2] Yu, R., T. Zhou, A. Xiong, Y. Zhu, and J. Li, 2007a: Diurnal variations of summer precipitation over contiguous China, *Geophys. Res. Lett.*, *34*, L01704, doi:10.1029/2006GL028129.

[3] Chen, G., W. Sha, and T. Iwasaki, 2009a: Diurnal variation of precipitation over southeastern China: Spatial distribution and its seasonality, *J. Geophys. Res.*, 114, D13103, doi:10.1029/2008JD011103.

[4] Yu, R., Y. Xu, T. Zhou, and J. Li, 2007b: Relation between rainfall duration and diurnal variation in the warm season precipitation over central eastern China, *Geophys. Res. Lett.*, *34*, L13703, doi:10.1029/2007GL030315.

[5] Li Z., T. Takeda, K. Tsuboki, K. Kato, M. Kawashima, and Y. Fujiyoshi, 2007: Nocturnal evolution of cloud clusters over eastern China during the intensive observation periods of GAME/HUBEX in 1998 and 1999, *J. Meteorol. Soc. Jpn.*, *85*(1), 25-45.

[6] Chen, G., W. Sha, and T. Iwasaki, 2009b: Diurnal variation of precipitation over southeastern China: 2. Impact of the diurnal monsoon variability, *J. Geophys. Res.*, 114, D21105, doi:10.1029/2009JD012181.

[7] Saito, Kazuo, and Coauthors, 2006: The Operational JMA Nonhydrostatic Mesoscale Model. Mon. Wea. Rev., 134, 1266-1298.doi: 10.1175/MWR3120.1

[8] Trier, S. B., C. A. Davis, D. A. Ahijevych, M. L. Weisman, G. H. Bryan, 2006: Mechanisms supporting long-lived episodes of propagating nocturnal convection within a 7-Day WRF model simulation. *J. Atmos. Sci.*, 63, 2437-2461, doi: 10.1175/JAS3768.1

[9] Yamada, H., B. Geng, H. Uyeda, and K. Tsuboki, 2007: Role of the heated landmass on the evolution and duration of a heavy rain episode over a Meiyu-Baiu frontal zone, *J. Meteorol. Soc. Jpn.*, 85(5), 687-709, doi:10.2151/jmsj.85.687.