Comparison of Simulated Precipitation over East Asia in Two Regional Models with Hydrostatic and Nonhydrostatic Dynamical Cores

JIHYEON JANG
Korea Institute of Atmospheric Prediction Systems, Seoul, South Korea
SONG-YOU HONG
Korea Institute of Atmospheric Prediction Systems, and Department of Atmospheric Sciences, Yonsei University, Seoul, South Korea

(Manuscript received 6 December 2015, in final form 19 June 2016)

ABSTRACT
This study examines the characteristics of a nonhydrostatic dynamical core compared to a corresponding hydrostatic dynamical core in the Regional Model Program (RMP) of the Global/Regional Integrated Model system (GRIMs), a spectral model for regional forecasts, focusing on simulated precipitation over Korea. This kind of comparison is also executed in the Weather Research and Forecasting (WRF) finite-difference model with the same physics package used in the RMP. Overall, it is found that the nonhydrostatic dynamical core experiment accurately reproduces the heavy rainfall near Seoul, South Korea, on a 3-km grid, relative to the results from the hydrostatic dynamical core in both models. However, the characteristics of nonhydrostatic effects on the simulated precipitation differ between the RMP and WRF Model. The RMP with the nonhydrostatic dynamical core improves the local maximum, which is exaggerated in the hydrostatic simulation. The hydrostatic simulation of the WRF Model displaces the major precipitation area toward the mountainous region along the east coast of the peninsula, which is shifted into the observed area in the nonhydrostatic simulation. In the simulation of a summer monsoonal rainfall, these nonhydrostatic effects are negligible in the RMP, but the simulated monsoonal rainfall is still influenced by the dynamical core in the WRF Model even at a 27-km grid spacing. One of the reasons for the smaller dynamical core effect in the RMP seems to be the relatively strong horizontal diffusion, resulting in a smaller grid size of the hydrostatic limit.

1. Introduction
Hydrostatic approximation has been used for numerical weather prediction models for several decades in order to allow a longer time step by filtering out vertically propagating sound waves. However, nonhydrostatic models have become necessary, as the resolvable grid spacing in numerical weather prediction increases with continuously improving computing resources. Advancement of new numerical treatments to handle the sound waves, such as the semi-implicit (Tapp and White 1976) and split-explicit techniques (Klemp and Wilhelmson 1978), has accelerated the development of nonhydrostatic models. Thus, nonhydrostatic mesoscale models have been actively used in research and operational communities over the last two decades.

Nonhydrostatic mesoscale models have been validated by idealized experiments, such as mountain waves over a bell-shaped mountain, density currents produced by a cold bubble, and rising thermal bubble cases (e.g., Bubnová et al. 1995; Skamarock and Klemp 2008; Jang and Hong 2016). Findings showed that the two-dimensional idealized cases are fairly well reproduced only by the nonhydrostatic dynamical core. In particular, Jang and Hong (2016) compared the ideal and trapped lee-wave cases simulated from two models: one with the spectral and the other with the finite-difference method. Their results depicted that the characteristics of the advection and numerical diffusion schemes are more influential than the discrepancies in the spatial discretization.

Real-case simulations with a full physics package also have been conducted to examine the advantage...
of the nonhydrostatic dynamical core in simulating high-impact weather events, such as heavy rainfall (e.g., Dudhia 1993; Kato 1996; Janjić et al. 2001; Saito et al. 2006). These studies revealed that the nonhydrostatic mesoscale model generally outperforms the hydrostatic model in the prediction of synoptic fields and quantitative precipitation forecasts at higher resolutions, with the grid spacing smaller than 10 km. Meanwhile, Dudhia (2014) mentioned that the dynamics has a “gray zone” in which it is unclear whether nonhydrostatic dynamics should be used. He mentioned that the gray-zone scale depends on the scales of weather features and would be in the range of 3580 MONTHLY WEATHER REVIEW VOLUME 144

FIG. 1. The 24-h accumulated precipitation (mm day$^{-1}$) at 1200 UTC 27 Jul 2011 obtained from (a) the Tropical Rainfall Measuring Mission (TRMM) Multisatellite Precipitation Analysis (TMPA) and (b) the Automatic Weather Station (AWS) observations.

FIG. 2. One-month averaged daily rainfall (mm day$^{-1}$) from 0000 UTC 1 Jul to 0000 UTC 1 Aug 2006, obtained from (a) TMPA and (b) AWS observations.
grid size less than 5 km. Dudhia (1993) showed that the nonhydrostatic effects start to appear for the horizontal grid spacing less than 5 km in the simulation of a cold front. Kato (1996) pointed out that the hydrostatic simulation tends to overestimate and overexpand precipitation at a 5-km grid spacing. Janjić et al. (2001) showed that the impacts of nonhydrostatic dynamics are generally weak at an 8-km grid spacing, but visible differences are found in simulated orographic precipitation. Saito et al. (2006) found that the nonhydrostatic mesoscale model outperforms the hydrostatic model in the prediction of synoptic fields and precipitation forecasts at a 10-km grid spacing. Recently, Wedi et al. (2012) presented high-resolution simulations at a 2.5-km grid spacing with a nonhydrostatic global spectral model and briefly discussed the importance of physics parameterization for the representation of features at convection-permitting scales.

In this study, we aim to evaluate the effects of the nonhydrostatic dynamical core with a full physics package, focusing on severe weather over East Asia, relative to the work in Jang and Hong (2016) that investigated the nonhydrostatic effects in a dry atmosphere. As in Jang and Hong (2016), the Regional Model Program (RMP) of the Global/Regional Integrated Model system (GRIMs; Hong et al. 2013b) and the Weather Research and Forecasting (WRF) Model (Skamarock et al. 2008), which are spectral and grid-point models, respectively, are employed. There are several differences in the numerical techniques between the two models, such as numerical diffusion scheme, as summarized in Jang and Hong (2016). To isolate the effects of the dynamical core, including numerics, an identical physics package is set up for both models. To the authors’ knowledge, no study has examined the dynamical core effects in two different models, focusing on precipitating convection. A heavy rainfall case over Korea on 26–28 July 2011 is selected to identify the grid-size dependency of the nonhydrostatic effects in both models, with the horizontal grid spacings of 27, 9, and 3 km. A regional climate simulation for July 2006 is designed to examine the effects of dynamical cores on the simulated climate.

This paper is organized as follows. In section 2, the case description and experimental design are provided. Results for a heavy rainfall event and further 1-month regional climate simulations are discussed in sections 3 and 4, respectively, and conclusions are given in section 5.

2. Case description and experimental design

a. Case description

A flash-flooding heavy rainfall event that occurred from 26 to 28 July 2011 over Seoul, South Korea (Fig. 1), was selected as a case study to examine the impacts of nonhydrostatic dynamics on simulated precipitation. The daily precipitation on 27 July 2011, 301.5 mm, set a record for maximum rainfall over Seoul in July, and most of the rainfall was observed from 1200 UTC 26 July to 1200 UTC 27 July 2011. Thus, this 24-h accumulated precipitation was evaluated in this study. The related strong convection was induced by a supply of abundant
warm and humid air directed to the midwestern region of the Korean Peninsula transported from the Yellow Sea. It persisted within a quasi-stationary synoptic environment: the western Pacific subtropical high over the southeast to Korea and Japan and a cutoff blocking high over 500 hPa near the Sea of Okhotsk (Jang and Hong 2014).

For the monsoonal regional climate simulation, July of 2006 was selected. A major rainband is located over Korea and Japan (Fig. 2). This month has been used for the evaluation of the capability of the WRF Model and hydrostatic RMP at a larger grid spacing (Koo and Hong 2010) and the comparison of the single- and double-moment microphysics schemes (Hong et al. 2010).

b. Experimental design

Four simulations with nonhydrostatic (NH) and hydrostatic (HY) dynamics for the RMP and WRF version 3.5.1 are conducted: \(R_{NH}, R_{HY}, W_{NH}, \) and \(W_{HY}\) experiments. For the RMP, the nonhydrostatic dynamical core was implemented from the mesoscale spectral model (Juang 2000) to the RMP by Jang and Hong (2016), and the WRF Model has continuously provided the hydrostatic and nonhydrostatic options (Skamarock et al. 2008). The main difference in the dynamics between the RMP and WRF Models is the horizontal discretization method, a spectral method for the RMP and a finite-difference method for the WRF Model. Another important difference between the two models is numerical diffusion: the WRF Model uses the inherent diffusion that is possessed in the advection scheme, while the RMP uses explicit spectral diffusion with stronger magnitude due to the possibility of Gibbs phenomena in the spectral representation. Details of the differences of the dynamical cores in the WRF Model and RMP are described in Jang and Hong (2016). Experiments are designed with the same physics package in the two models. The physics for both models include the Noah land surface and soil physics scheme (Chen and Dudhia 2001; Ek et al. 2003), the Yonsei University (YSU) planetary boundary layer.
(PBL) vertical diffusion scheme (Hong et al. 2006), the Kain–Fritsch (KF) new eta deep convection scheme (Kain 2004), the GRIMs shallow convection scheme (Hong et al. 2013a), the WRF single-moment 3-class (WSM3) microphysics scheme (Hong et al. 2004), and the shortwave (Chou and Suarez 1994) and longwave (Chou and Suarez 1999) radiation scheme. Note that deep convection parameterization is not used in the 3-km grid domain where convective rainfall is assumed to be explicitly resolved.

All experiments for heavy rainfall are performed for 48 h, from 0000 UTC 26 July to 0000 UTC 28 July 2011. The integration time step is set as 60 s for domain 1, 10 s for domain 2, and 6 s for domain 3. The initial condition of the experiments utilizes the National Centers for Environmental Prediction (NCEP) Final Analysis (FNL) data on 1° × 1° global grids every 6 h, without specific assimilation of observational data. All experiments consist of one-way nested domains with a Lambert conformal map projection (Fig. 3). The horizontal domain configuration for domains 1–3 is identical to the setup for the real-case simulation in Jang and Hong (2016). RMP uses 64 terrain-following sigma coordinate vertical layers and WRF Model uses 56. The vertical domain in the RMP extends from the surface to 0 hPa, since sigma (σ) in the RMP is defined as \( σ = p/p_s \), where \( p \) and \( p_s \) are pressure and surface pressure, respectively. On the other hand, the model top pressure in the WRF simulation is set as 10 hPa, since the top pressure in the WRF Model is recommended to be or equal to the highest level of the initial condition. Thus, we prespecify the sigma spacings (\( Δσ \)) in the WRF simulation such that they are the same pressure spacings as those in the RMP simulation up to the 56th layer. In addition, the topography in the WRF simulation is replaced with the smoothed topography in the RMP simulation in order to use the identical topography data. The data are taken from the U.S. Geological Survey (USGS) Global 30 arc s elevation data (GTOPO30), interpolated to the model grid, and smoothed by the Lanczos algorithm in the preprocessing of the RMP.

For reference, the wall-clock time of the nonhydrostatic run over the corresponding hydrostatic run is increased by about 20% in the RMP experiments, whereas the increase...
of the computing time is not distinct in the WRF experiments. Addition of computer time in the case of the RMP experiments is partly related to transformation between spectral and grid spaces for additional prognostic variables.

For a regional climate simulation, identical nested domains are used for the 1-month integration of July 2006, the summer monsoon season in East Asia. The integration is performed from 0000 UTC 29 June 2006. The entire vertical grid system has 28 layers. In this simulation, we also prescribe the sigma spacings ($\Delta \sigma$) in the WRF simulation such that they are the same pressure spacings as those in the RMP simulation up to the 26th layer and then slightly decreasing spacings for the remaining two layers. Initial and boundary conditions are generated every 6 h by the NCEP reanalysis II data on T62 horizontal resolution and 28 vertical layers. Thus, no vertical interpolation is needed for the experiments by the RMP.

The spatial pattern of precipitation over and around the Korean Peninsula is evaluated by the Tropical Rainfall Measuring Mission (TRMM) Multisatellite Precipitation Analysis (TMPA; Huffman et al. 2007) and the Automatic Weather Station (AWS) data. To evaluate the simulated precipitation for the heavy rainfall event quantitatively, the pattern correlation (PC) and root-mean-square error (RMSE) of the surface precipitation are calculated against the AWS data observed over South Korea. The skill scores, local maximum, and areal average of precipitation over the observed precipitation core are summarized in Table 1. For the quantitative evaluation of the simulated monsoonal rainfall, the equitable threat score (ETS) was computed at various intensity categories based on a 2x2 contingency table [$a$: simulation yes, observation yes; $b$: simulation yes, observation no; $c$: simulation no, observation yes; $d$: simulation no, observation no; Wilks (1995); Su et al. (2008)]. The ETS is defined as
\[
\text{ETS} = \frac{(a - H_c)/(a + b + c - H_c)}{H_c},
\]
where $H_c$ is $(a + b)(a + c)/N$, where $N$ is the total number of estimates. That is, the ETS measures the fraction of observed and/or simulated rain that were correctly simulated, adjusted for the frequency ($H_c$) of hits that could be expected due purely to random chance. The perfect score for the ETS is 1 (Su et al. 2008). It is commonly used as a skill measure for precipitation forecasts. Frequency and intensity of the precipitation are also computed at various intensity categories.

3. A heavy rainfall event over the Korean Peninsula

The overall distribution of the simulated precipitation between the nonhydrostatic and hydrostatic experiments
from both models does not reveal discernible differences in the experiments at a 27-km grid spacing, with more precipitation in the WRF runs (Table 1, figures not shown here). It is, however, apparent that the amount of precipitation over the observed precipitation core is greater in the hydrostatic run than in the nonhydrostatic run of both the WRF Model and RMP. At a 9-km grid spacing, the overall distribution of the 24-h accumulated precipitation is similar irrespective of the selected dynamical core (Fig. 4). Although the tabulated skill scores of the simulated precipitation are better in the hydrostatic experiments than in the nonhydrostatic experiments in both models (Table 1), the pattern of major precipitation is nearly unchanged (Fig. 4). To confirm the similarities in the precipitation patterns between the hydrostatic and nonhydrostatic simulations, the correlation coefficient of the simulated precipitation between the hydrostatic and nonhydrostatic runs over South Korea is calculated. The correlation coefficients at the 27-km grid spacing are 0.99 and 0.98 for the RMP and WRF simulations, respectively, and they are 0.92 and 0.93 at the 9-km grid spacing, respectively. It seems that the hydrostatic approximation used in the dynamical core does not cause unrealistically spurious simulation at the 9-km grid spacing. As in the sensitivity to the dynamical core at the 27-km grid spacing, the amount of precipitation over the heavy rainfall region is greater when the hydrostatic dynamical core is used, in both models, but the magnitude of sensitivity is greater in the WRF Model than in the RMP. The maximum amounts in the W_HY and W_NH runs are 169.09 and 177.53 mm, respectively, whereas they are 140.70 and 144.62 mm, in the case of the R_NH and R_HY experiments, respectively. Similarly, distribution of differences in precipitation between the two dynamical cores reveal a similar response in both models, but the magnitude of the differences is greater in the WRF Model than in the RMP (cf. Figs. 4c and 4f).

The sensitivity of the simulated precipitation to the two dynamical cores becomes large at smaller grid spacings (Table 1). For both the WRF Model and RMP, the amount of precipitation over the observed
precipitation core is greater in the nonhydrostatic dynamical core runs than in the hydrostatic dynamical core runs at a 3-km grid spacing, an opposite response to that found at larger grid spacings. The alleviation of excessive rainfall peaks at the rainfall core is commonly observed in both models when the nonhydrostatic dynamical core is employed. It is apparent that the precipitation from the W_HY run is concentrated over the eastern part of the Korean Peninsula (Fig. 5a), whereas the W_NH run reproduces the precipitation over the central part of the peninsula (Fig. 5b). The difference field (Fig. 5c) confirms the displacement of major rainfall toward the northeast when the hydrostatic dynamical core is used. For the RMP, the effect of the dynamical core on the simulated precipitation is similar to that in the WRF runs (cf. Figs. 5c and 5f) but with a weakened sensitivity in the case of the RMP runs. Although the northeast displacement of the simulated precipitation in the hydrostatic dynamical core is evident in both models, the location of the local maximum is about the same in the R_HY and R_NH runs. In addition, the correlation coefficient of the simulated precipitation between the W_HY and W_NH runs, 0.61, is smaller than that between the R_HY and R_NH runs, 0.72. Further analyses of the 24-h accumulated precipitation depending on the altitude confirmed that the overestimation of the precipitation at altitudes higher than 1000 m is prominent in the W_HY run (not shown). Time series of the 3-h accumulated precipitation show that the intensity of the rainfall peaks depends more upon the dynamical core than upon the model itself (Fig. 6). For example, the duration of precipitation over the second peak from the R_NH and W_NH runs is longer than that from the R_HY and W_HY runs, with a stronger intensity, which is closer to what was observed.

In Fig. 7, the kinetic energy spectra of the 200-hPa winds at 24-h forecasts are compared. The kinetic energy simulated from the WRF Model faithfully follows the slope of mesoscales with a $-5/3$ slope, whereas the small-scale features from the RMP are damped due to a stronger numerical diffusion than in the WRF Model, in order to ensure the numerical stability [see Jang and Hong (2016) for details]. The energy spectra are similar for both dynamical cores in the WRF Model, whereas the nonhydrostatic dynamical core shows greater amounts of energy in mesoscale ranges in the case of RMP runs. Meanwhile, additional experiments at the 3-km grid spacing with a higher-order diffusion in the RMP, that is, the sixth-order diffusion, were conducted for both dynamical cores. It is found that the spectra for the wavelengths between 10 and 100 km are increased in the hydrostatic run with the sixth-order diffusion, whereas the spectra are not altered by the order of diffusion in the case of nonhydrostatic dynamical core run. Thus, the lower sensitivity of the simulated precipitation to the dynamical core can be due to a relatively strong horizontal diffusion in the RMP.

It is unclear how the dynamical core affects simulated precipitation through physical processes. A stronger sensitivity of the dynamical core at smaller grid spacing in both models assures us that prognostic vertical velocity reflecting nonhydrostatic features can provide realistic dynamical motion so that deep convection breaks out with the onset of precipitation at the right locations.

### 4. Monsoonal rainfall in July 2006

It is seen that both models reproduce the major monsoonal rainfall over Korea and Japan at the 27-km grid spacing, but with greater amounts over land in the WRF runs and smaller amounts in the RMP runs (cf. Figs. 2 and 8). The result from the W_HY run shows a distinct difference from the W_NH experiment, with noticeable over-estimation of the rainfall over the high-altitude region over the Korean Peninsula and Japan (Fig. 8c). On the other hand, the results from the RMP show overall similarities between the R_HY and R_NH runs (cf. Figs. 8c and 8f), even though the R_NH run slightly increases the precipitation over the central part of the peninsula, which is closer to the observed precipitation. In the comparison of skill scores over South Korea, differences of RMSE and PC between the W_HY and W_NH experiments are larger than that between the R_HY and R_NH experiments (Table 2).

Figure 9 depicts the 1-month precipitation simulated with the 3-km grid spacing. It is clear that the dynamical core effects are larger at smaller grid spacings, as seen in the previous section. In addition, the sensitivity to the

### Table 2. RMSE and PC against AWS observations, and local maximum over South Korea for daily precipitation (mm day$^{-1}$) averaged for July 2006 over three domains. Best scores for each domain are highlighted in bold.

<table>
<thead>
<tr>
<th>Domain</th>
<th>Expt</th>
<th>RMSE</th>
<th>PC</th>
<th>Max</th>
</tr>
</thead>
<tbody>
<tr>
<td>Domain 1 (27 km)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>R_NH</td>
<td>8.78</td>
<td>0.41</td>
<td>25.11</td>
<td></td>
</tr>
<tr>
<td>R_HY</td>
<td><strong>8.52</strong></td>
<td><strong>0.42</strong></td>
<td><strong>23.89</strong></td>
<td></td>
</tr>
<tr>
<td>W_NH</td>
<td>9.27</td>
<td>0.34</td>
<td><strong>35.34</strong></td>
<td></td>
</tr>
<tr>
<td>W_HY</td>
<td>8.87</td>
<td><strong>0.43</strong></td>
<td>35.13</td>
<td></td>
</tr>
<tr>
<td>R_NH</td>
<td>8.86</td>
<td>0.41</td>
<td>37.50</td>
<td></td>
</tr>
<tr>
<td>R_HY</td>
<td><strong>8.22</strong></td>
<td>0.46</td>
<td><strong>38.09</strong></td>
<td></td>
</tr>
<tr>
<td>W_NH</td>
<td>8.72</td>
<td><strong>0.49</strong></td>
<td>44.38</td>
<td></td>
</tr>
<tr>
<td>W_HY</td>
<td>9.58</td>
<td>0.48</td>
<td>48.55</td>
<td></td>
</tr>
<tr>
<td>Domain 2 (9 km)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>R_NH</td>
<td><strong>8.74</strong></td>
<td><strong>0.48</strong></td>
<td>45.40</td>
<td></td>
</tr>
<tr>
<td>R_HY</td>
<td>9.25</td>
<td>0.44</td>
<td><strong>37.97</strong></td>
<td></td>
</tr>
<tr>
<td>W_NH</td>
<td>9.04</td>
<td>0.47</td>
<td>33.97</td>
<td></td>
</tr>
<tr>
<td>W_HY</td>
<td>11.30</td>
<td>0.28</td>
<td>90.82</td>
<td></td>
</tr>
<tr>
<td>AWS</td>
<td>40.1</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*Note: Bold values indicate the best scores for each domain.*
The dynamical core in the WRF Model is larger than that in the RMP (cf. Figs. 9c and 9f). In particular, the overestimation in the W_HY experiment is exaggerated over the mountain region at this grid spacing (Figs. 9a, 9c, and 10a). This systematic bias is highly alleviated by the nonhydrostatic dynamical core. The W_NH run produces a realistic amount of monsoonal rainfall over the Korean Peninsula, even though the major rainband is shifted southward, as compared to the observed (Figs. 9b and 10b). In the RMP, the amount of precipitation is closer to the observed than at the 27-km grid spacing (cf. Figs. 8 and 9). In addition, the rainband simulated from the R_HY run is shifted southward, whereas the R_NH run captures the location of the major rainband over the peninsula and the East Sea of Korea (cf. Figs. 9d and 9e; Figs. 10c and 10d). In the tabulated skill scores over domain 3 in Table 2, the degradation of the precipitation simulated by the W_HY run is significant, whereas the precipitation from the R_HY run is not significantly different from that in the R_NH experiment. It is difficult to determine the physical mechanism for excessive rainfall over high altitudes in the W_HY run, but simulated updrafts from the W_HY run are dominant over the mountain region of North Korea with greater amounts of cloud and rainfall, relative to other experiments (figures not shown).

Figure 11 shows the frequency, amount, and ETS of the simulated precipitation with the 3-km grid spacing. At the 27-km grid spacing, the computed precipitation statistics generally followed the comparison results as seen in Fig. 11, but with overall degradation of the skill at higher precipitation categories (figures not shown). In Fig. 11a, it is seen that the nonhydrostatic dynamical core suppresses the rainfall activity in both models in the heavy rainfall category larger than 16 mm h\(^{-1}\). In terms of the amount of the precipitation, the W_NH run simulates a smaller amount of precipitation overall categories than the W_HY run, whereas the R_NH run increases the precipitation in the weak category (0.01–8 mm h\(^{-1}\)) and reduces the precipitation in the heavy category (8–64 mm h\(^{-1}\)) (Fig. 11b). In addition, a quantitative evaluation of the simulated precipitation over South Korea.
in July 2006 is also conducted (Fig. 11c). The ETS apparently confirms that the nonhydrostatic runs simulate precipitation more accurately in general than the hydrostatic runs in both models. It is also seen that the ETS from the RMP runs is better than that from the WRF runs, except in the heavy precipitation category. This can be explained by the fact that the RMP predicts the perturbation to base fields from a coarser resolution and has effects of nudging the larger-scale information continuously over the entire domain, which is beneficial to long-term simulations (Juang et al. 1997).

5. Conclusions

The impact of the dynamical core (hydrostatic vs nonhydrostatic) is investigated, focusing on the simulated precipitation over Korea in two regional models: the RMP and WRF Model. Overall, it is found that the nonhydrostatic dynamical core experiment accurately reproduces the heavy rainfall near Seoul in terms of the maximum and distribution of major precipitation at a 3-km grid spacing, relative to the results from the hydrostatic dynamical core in both models. It is found that the RMP with the nonhydrostatic dynamical core improves the local maximum, which is exaggerated in the hydrostatic simulation. The hydrostatic simulation of the WRF Model displaces the major precipitation area toward the mountainous region along the east coast of the peninsula, which is shifted into the observed area in the nonhydrostatic simulation. At larger grid spacing, these nonhydrostatic effects are negligible in the RMP, but the simulated monsoonal rainfall is still influenced by the dynamical core in the WRF Model even at a 27-km grid spacing.

In Jang and Hong (2016), the difference of simulated trapped lee waves between the hydrostatic and nonhydrostatic simulations becomes noticeable at a 1-km grid spacing for both models, although more extended
propagation of the lee waves is found in the WRF simulation. On the other hand, in this paper, differences in the simulated precipitation are prominent at the 3-km grid spacing in both models, which indicates that the gray-zone scale of the dynamics seems to be dependent on the scale and characteristics of target phenomena. This finding also suggests that the impacts of the physics forcing, depending on the dynamical core, become uncertain for the simulation of high-impact weather, such as heavy rainfall in the summertime.

It is not clear why the nonhydrostatic effect in the WRF simulation is relatively large at larger grid spacings, where the hydrostatic approximation is known to be valid. In the comparison of kinetic energy spectra from both models, the WRF Model tends to reproduce the energy in the mesoscale range, whereas the spectra are damped in the RMP. This indicates that precipitation processes can be more sensitive to the dynamical core in the WRF Model than in the RMP. As seen in Jang and Hong (2016), the magnitude of horizontal diffusion is greater in the RMP than in the WRF Model. In other words, the smaller dynamical core effect in the RMP seems to be due to the relatively strong horizontal diffusion, resulting in a smaller grid size of the hydrostatic limit.

Our study indicates that the hydrostatic limit can be larger for a moist atmosphere than a dry atmosphere. However, it is difficult to generalize these findings to other mesoscale models with hydrostatic and nonhydrostatic dynamical cores, since this study is limited by the fact that it focused on precipitation over Korea in the summertime. Further, this limit can depend upon precipitation processes over geographically different regions.

**Acknowledgments.** The authors would like to express their gratitude to the three anonymous reviewers and editor for their valuable comments on our study. This work has been carried out through the R&D project on...
the development of global numerical weather prediction systems of Korea Institute of Atmospheric Prediction Systems (KIAPS) funded by Korea Meteorological Administration (KMA).

REFERENCES


