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Assessment of a Regional-Scale Weather Model for Hydrological Applications in South Korea

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Abstract

In this study, a regional numerical weather prediction (NWP) model known as the Weather Research Forescasting (WRF) model was adopted to improve the quantitative precipitation forecasts (QPF) by optimizing combined microphysics and cumulus parameterization schemes. Four locations in two regions (plain region for Sangkeug and Imsil; mountainous region for Dongchun and Bunchun) in Korean Peninsula were examined for QPF for two heavy rainfall events 2006 and 2008. The maximum Index of Agreement (IOA) was 0.96 at Bunchun in 2006 using the combined Thompson microphysics and the Grell cumulus parameterization schemes. Sensitivity of QPF on domain size at Sangkeug indicated that the localized smaller domain had 55% (from 0.35 to 0.90) improved precipitation accuracy based on IOA of 2008. For the July 2006 Sangkeug event, the sensitivity to cumulus parameterization schemes for precipitation prediction cannot be ignored with finer resolutions. In mountainous region, the combined Thompson microphysics and Grell cumulus parameterization schemes make a better quantitative precipitation forecast, while in plain region, the combined Thompson microphysics and Kain-Frisch cumulus parameterization schemes are the best.

Keywords: regional numerical weather prediction model, quantitative precipitation forecast, localized conditions, mountainous region, hydrology

1. Introduction

Flooding is one of the major natural hazards associated with extreme weather events, such as tropical cyclones and snowstorms, because it accounts for a large proportion (30% in Asia from 1990 to 2011; EM-DAT 2014) of total disasters (Dolcine et al., 2001; Hudson & Colditz, 2003). In the past decade, flood modeling prediction has been improved through the application of various technologies. Having been implemented in the U.S. and other countries, an advanced next generation Doppler weather radar system known as NEXRAD (WSR-88D) has become a popular way of monitoring weather systems. In terms of lead time for QPF, Bedient et al. (2003) asserted that two or three hours were gained when NEXRAD was adopted in the flood warning system. These lead times can be used in the conversion process from the NEXRAD rainfall time series to a flood inundation map, especially for extreme flood events (Knebl et al., 2005). Unfortunately, the lead time of QPF by including NEXRAD in the flood warning system does not apply to mountainous watershed regions due to shorter flow travel times (Anderson et al., 2002; Yoshitani et al., 2009).

As a result, some researchers have adopted numerical weather prediction (NWP) models to extend the lead time to one or two days for flood forecasting at small mountainous watersheds (Anderson et al., 2002; Yoshitani et al., 2009). For example, the Penn State-NCAR fifth generation Mesoscale Model (MM5, see Grell et al., 1995) and the Weather Research Forecast (WRF, see Skamarock et al., 2008) model have been used for QPF in flood prediction. Yu et al. (1999) used MM5 with fixed parameterizations (multi-level Blackadar type planetary boundary layer and Grell cumulus parameterizations) for the Upper West Branch of the Susquehanna River Basin at Williamsport, Pennsylvania. In addition, Westrick et al. (2002) and Anderson et al. (2002) utilized MM5 for rainfall predictions in the western U.S., specifically along the western flanks of the Washington Cascade Mountains and the Calaveras River Basin in central California. These types of NWP models have also been used in Korea (Hong & Lee, 2009) and Japan (Yoshitani et al., 2009).

In regionalized NWP model applications, high spatial and temporal variability in QPF for different regions with diverse climate conditions make a regional-scale NWP model very sensitive to model configurations (Giorgi & Mearns, 1999) such as cumulus and microphysics parameter schemes. In applying the WRF model in a hydrological model, Lowrey and Yang (2008) evaluated both physical parameterization schemes for QPF using a 2002 central Texas storm event in the San Antonio River Basin. Sensitivity tests for combinations of physics parameterization schemes have also been performed for rainfall estimation (Evans et al., 2012) and winter precipitation estimation (Yuan et al., 2012). Both studies found deficiencies in applying the best physics scheme combinations for rainfall estimation (Ji et al., 2013). Based on previous studies, a regional-scale NWP model with selected model configurations can provide acceptable lead time with reasonable accuracy for QPF. However, there have been few applications of regional-scale NWP models, such as WRF, to hydrological aspects of the Korean Peninsula. The major purpose of this study is to investigate the applicability of the WRF model (Skamarock et al., 2008) to the Korean Peninsula using two July storms for years 2006 and 2008 and to present better options for diverse terrain conditions. In addition, comparisons with diverse grid sizes are presented to provide the most favorable resolution for the central Korean Peninsula.

2. Description of the WRF model

In this study, the WRF model v3.1, which is also called the Advanced Research WRF (ARW) model, was used to predict regional-scale precipitation for hydrological applications. WRF v3.1 has been updated for satellite imagery-based land use categories instead of USGS categories, generalized soil moisture and temperature arrays in three dimensions, and fixed interpolation schemes from previous versions. The WRF models have various options in numerical schemes, physics representations and parameterizations, and data assimilation packages for real-time NWP, thus allow parameterization sensitivity tests and idealized numerical simulations to be conducted. In addition, the WRF model conserves mass, momentum, and entropy in prognostic equations to generate spurious oscillations and numerical smoothing, whereas MM5 has no conservational property (Pattanayak & Mohanty, 2008). In various model evaluations, Sousounis et al. (2004) performed NWP model intercomparisons among MM5, WRF, RUC, and ETA models to simulate heavy rainfall events in 2003 and concluded that WRF and MM5 provided the greatest number of configurations and were more applicable than other models. Furthermore, they indicated that the WRF model generated finer-scale structures closer to realistic conditions than those in other models. In the comparison between WRF and MM5 performances for cyclones in 2006 over the Indian Ocean, the WRF model makes better prediction in terms of their track and intensity (Pattanayak & Mohanty, 2008).

There are two substantial physical parameterization schemes of the WRF model that deal with atmospheric heat and moisture flux tendencies thus have direct impacts on QPF: cumulus parameterization and microphysics parameterization. Generally, cumulus parameterization is not necessary for a grid size (grid scale) less than 3 or 4 km because mesoscale processes and motion can be approximately resolved by the grid size (Gilliland & Rowe, 2007). However, in order to avoid the energy accumulation at grid points, cumulus parameterization is commonly activated simultaneously with microphysics parameterization for rainfall prediction for simulations with grid size of 4 km or even smaller, especially when the grid size falls in the so-called "no-man's land" or "gray zone" (1 – 10 km, based on Gerard, 2007).. On the other hand, Clark et al. (2007) demonstrated that the diurnal precipitation cycle was better simulated using convection resolving microphysics schemes than non-convection-resolving cumulus parameterization scheme. Thus, in this study, we will test both approaches for finer-scale grid intervals, namely activating cumulus and microphysics parameterizations or using microphysics parameterization alone. The cumulus parameterization scheme will be chosen from Betts-Miller-Janjic (BMJ) scheme (Betts and Miller, 1993; Janjic, 1994), Grell 3D ensemble scheme (Grell & Devenyi, 2002), or Kain-Fritsch (new Eta) scheme (Kain & Fritsch, 1990; Kain, 2004). The BMJ scheme is a column moisture adjustment scheme with relaxation to a well-mixed profile in an operational Eta structure. The Grell 3D ensemble scheme includes subsidence in neighboring column thus is more appropriate for higher resolution simulations. The Kain-Frisch scheme is a sub-grid scheme with deep and shallow convection, a maximum flux approach in applications of downdrafts, and the Convective Available Potential Energy (CAPE) removal time scale (Lin, 2007).

Regarding microphysical parameterizations, we applied either Purdue Lin scheme (Lin et al., 1983 – Lin-Farley-Orville scheme; Chen and Sun, 2002), Thompson scheme (Thompson et al., 2004), or the Single-Moment 6-class microphysics scheme (WSM-6, Hong & Lim, 2006). All of the selected schemes include ice phase, i.e. ice, snow, and graupel/hail hydrometers in the microphysical processes thus are appropriate for simulating mid latitude deep convective clouds and smaller grid simulations. Microphysics parameterization schemes dictate properties and structures of cloud within meso- and cloud-scale models and thus dominate the evolution (e.g. generation, growth, decay, and fall) of precipitation using different categories (cloud ice, graupel/hail, and snow) of the ice phase.

The National Center for Environmental Prediction (NCEP) FNL (Final) Operational Global Analysis Data prepared every six hours with 1.0 by 1.0 degree grids was used to initialize and update the boundary conditions of the WRF model. These data were obtained from the Global Data Assimilation System (GDAS) using data from diverse sources such as the Global Telecommunication System (GTS). These FNL data consist of surface pressure, sea level pressure, sea surface temperature, geopotential height, temperature, soil moisture, ice cover, relative humidity, and *u*- and *v*-winds, at 26 mandatory stretching levels between 10mb and 1000mb.

3. Experimental Design

3.1 Regions of Study

To assess the capability of WRF applications for hydrological aspects, four specific locations, i.e. Sangkeug, Dongchun, Imsil and Bunchun, were selected (Figure 1). These four selected locations have the following geographical characteristics: plain area located in middle of Korean Peninsula (Sangkeug), surrounded by mountains (Dongchun), plain area (Imsim), and high mountains area near the east coast (Bunchun). These diverse characteristics may require different combinations of physical parameterization schemes including ensemble approaches in the WRF model for QPF targeted for hydrological applications. Table 1 summarizes the characteristics of the four selected rainfall sites. In fact, these four locations can be categorized in two regions, namely the plain region for Sangkeug and Imsil, and the mountainous region for Dongchun and Bunchun.

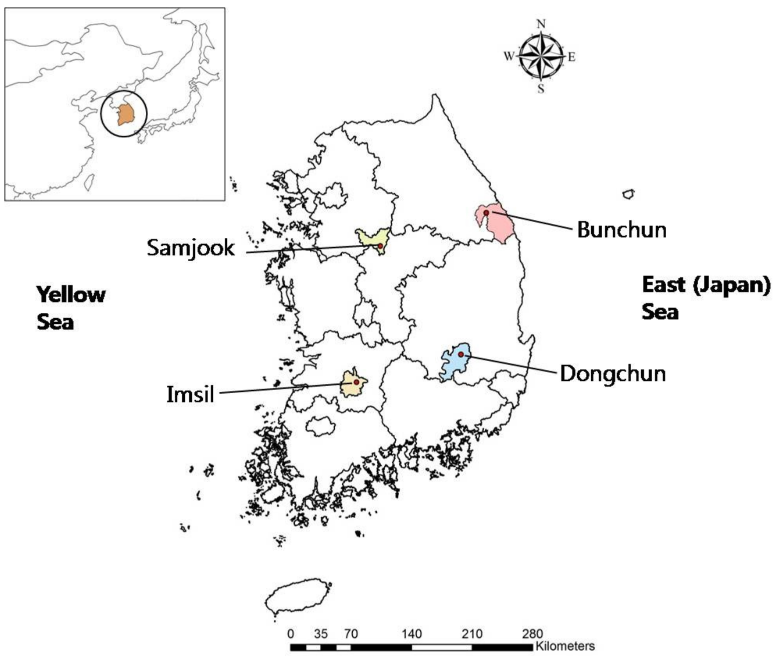

Figure 1. Four locations in two regions (plain region for Sangkeug and Imsil; mountainous region for Dongchun and Bunchun) in Korean Peninsula were selected for the evaluation of hydrological applications using WRF to make QPF for two heavy rainfall events 2006 and 2008

Table 1. Characteristics of four selected observatories

Observatory	Associated River Basin	Characteristic
Sangkeug	Chongmi River Basin (~600 km^2)	Plain Area located in the middle of Korean Peninsula
Dongchun	Kumho River Basin (~1000 km^2)	Surrounded by mountains
Imsil	Ohsoo River Basin (~370 km^2)	Plain Area
Bunchun	Colji River Basin (~560 km^2)	High mountain Area located near east side of Korean peninsula

For simulations using the WRF v3.1 model, three nested domains with two-way interactions (Figure 2) were selected to predict precipitation with relatively finer resolution. The grid sizes were 36 km, 12 km, and 4 km for the outer (D1), middle (D2), and inner (D3) domains, respectively. Domain D1 has 71x67 grid points in the south-north (SN) and west-east (WE) directions and is centered at (127.169°E, 37.561°N). Domain 2, which was embedded in D1, has 109 (SN) by 94 (WE) grid points. Domain 3, which was used for rainfall estimation as input data of hydrological models, has 97 (SN) by 157 (WE) grid points. Note that D3 covered the whole South Korea (Figure 2), including four selected locations and had a 4 km grid resolution (Figure 1). The map projections for these domains were Mercator.

3.2 Simulations

In order to predict precipitation for 2006 and 2008 storm events, 9 different combinations of physics parameterizations were examined to identify the better conditions for rainfall in a specific area because the accuracy of rainfall prediction is strongly influenced by regional and climate characteristics (Giorgi and Mearns, 1999). In addition, the planetary boundary layer (PBL) parameterization, domain and buffer zone, and initialization scheme are substantial components of regional climate models. PBL schemes calculate vertical fluxes of heat, moisture and momentum in the planetary boundary layer. In this study, the Yonsei University (YSU) PBL scheme (Hong et al., 2006), a non-local K-theory (eddy coefficient) scheme including explicit entrainment layer and parabolic K profile in the mixed layer, was selected for all tests. Table 2 shows different combinations of physics parameterizations in the WRF model chosen for testing in this study.

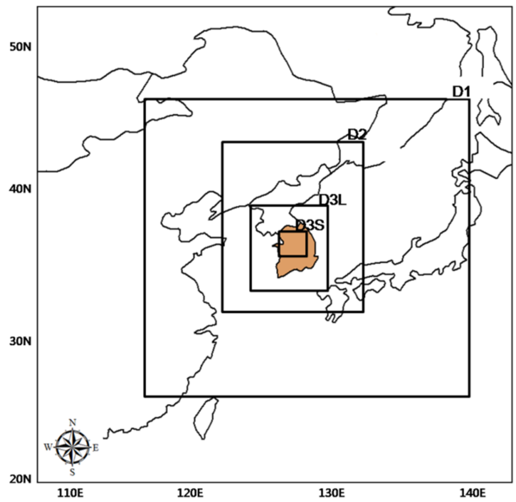

Figure 2. Three nested domains in Korean Peninsula designed for WRF simulations (D3L: Larger Domain 3, D3S: Smaller Domain 3)

Table 2. Combinations of microphysics and cumulus parameterizations for the regional scale weather model simulations for precipitation prediction

Acronym	Microphysics	Cumulus
LB	Purdue Lin scheme	Betts-Miller-Janjic scheme
LG	Purdue Lin scheme	Grell 3D ensemble scheme
LK	Purdue Lin scheme	Kain-Frisch scheme
TB	Thompson scheme	Betts-Miller-Janjic scheme
TG	Thompson scheme	Grell 3D ensemble scheme
TK	Thompson scheme	Kain-Frisch scheme
WB	WSM-6 scheme	Betts-Miller-Janjic scheme
WG	WSM-6 scheme	Grell 3D ensemble scheme
WK	WSM-6 scheme	Kain-Frisch scheme

Note. The YSU PBL scheme is used for all experiments listed above.

3.3 Storm Events

During the summer season from June to August in South Korea, most of heavy rainfall events are attributed to cloud clusters and local convection associated with summer monsoons. In this study, we considered two heavy rainfall events with the following simulation time periods, 00 UTC July 9 – 00 UTC July 22, 2006 (14 days) and 00 UTC July 10 – 00 UTC July 28, 2008 (19 days), including 3 days for spin-up time, to search for the optimal precipitation prediction at certain points using the WRF model with 6 hourly updates from NCEP FNL data. Although the selected 2006 and 2008 storm events were associated with typhoons, the heavy rainfall produced were not associated with typhoon rain bands directly (Lee et al., 1988). The predicted rainfall rates from the WRF model initialized by the FNL data required several conversion steps in the hydrologic models as one of the grid cell parameter files. The predicted rainfall rates have a format of network common data form (NetCDF). Observed rainfall rates are provided by the Water Management Information System (WAMIS) through Automated Weather Stations (AWS).

3.4 Hydrological Application

Once rainfall is predicted by the WRF model, its data was then used to start the simulations of the hydrologic model, i.e. the Hydrologic Engineering Center (HEC) – Hydrologic Modeling System (HMS) in this case. For applications of gridded rainfall data in the Modified Clark (also known as ModClark) unit hydrograph method, the distributed hydrologic model environment was provided by HEC-geoHMS prior to HMS operation for preprocessing of the data, and terrain and basin processing for HMS model setting. Terrain processing was based on the Digital Elevation Model (DEM) generated from numerical map by the National Geographic Information Institute in Korea. In addition, soil types and land cover information were obtained from the Water Management Information System (WAMIS, http://wamis.go.kr/eng/main.aspx) in the Ministry of Land and then converted to the United States Department of Agriculture Soil Conservation Service Curve Number System for rainfall-runoff. Before the hydrologic simulations, calibration processes of a hydrological model were required. For this process, observed rainfall data storage system (DSS) files were applied as gridded rainfall information. Using the optimization function such as univariate gradient procedure, time of concentration and the storage coefficient were obtained while minimizing the difference between observed and calculated discharge values. Based on the AMC-II of the Natural Resources Conservation Service (NRCS)'s standard antecedent moisture conditions, the initial abstraction rate and the potential abstraction scale factor were tweaked manually. AMC-II represents the average of antecedent moisture conditions. Finalized parameter values were adopted to make a calibrated model. For the four previously selected sites, the Chongmi River Basin was chosen for potential hydrological predictions. Figure 3 shows the watershed map file of the Chongmi River Basin. The predicted discharge values are then compared with the observed discharge values obtained from WAMIS.

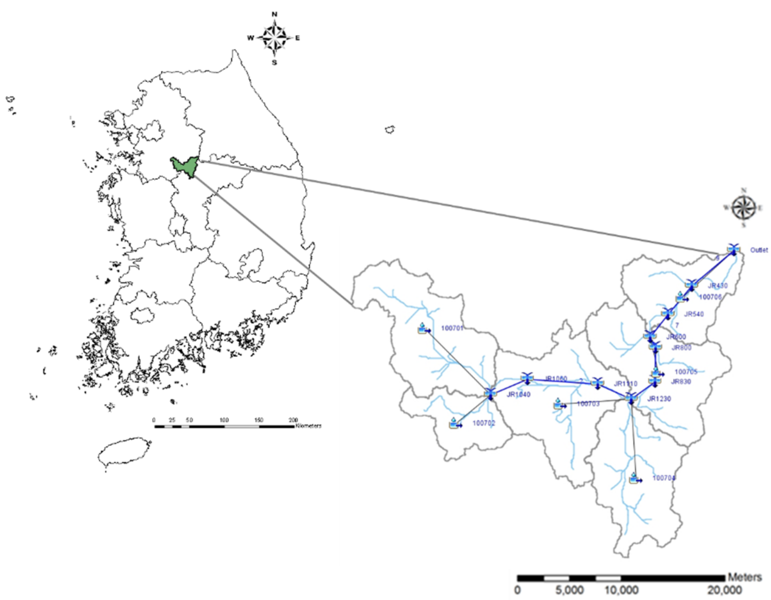

Figure 3. The watershed map of the Chongmi River Basin for hydrological applications

3.5 Error Metrics

For comparison, three numerical indicators were used; Root Mean Square Error (RMSE), Index of Agreement (IOA), and Mean Bias Deviation (MBD). RMSE and IOA represent the degree of agreement of the calculated and observed rainfall data, while MBD characterizes the bias of WRF simulations. Minimum RMSE values in terms of precipitation indicate better simulations in WRF applications. The IOA value is between 0 and 1, with a value closer to 1 indicating that the simulation is better matched to observations. A negative (positive) MBD value indicates that the simulations are under-predicted (over-predicted). In this study, the WRF predicted rainfall data were verified by the observational data (i.e. daily rainfall) from four selected sites. Since the grid points of rainfall prediction from the WRF model did not match exactly the locations of rainfall observation, they are averaged over the nine surrounding grid points for comparisons. There were a total of 44 (11 days/location × 4 locations) comparisons and 64 (16 days/location × 4 locations) rainfall data sets for 2006 and 2008, respectively. Note that to improve the accuracy, a test on nearest neighborhood or bilinear interpolation may be used. This will be considered in a follow-up study.

These numerical indicators are defined as follows:

$$IOA = 1 - \frac{\sum_{i=1}^{N} (Model_i - Obs_i)^2}{\sum_{i=1}^{N} (|Model_i - AVG(Obs)| + |Obs_i - AVG(Obs)|)^2} \quad (1)$$

$$MBD = \frac{\frac{1}{N}\sum_{i=1}^{N} (Model_i - Obs_i)}{\frac{1}{N}\sum_{i=1}^{N} Obs_i} \quad (2)$$

where

$Model_i$: WRF model predicted rainfall rate (mm/d) at location i

Obs_i: Observed rainfall rate (mm/d) at location i

AVG: Averaged value

N: Total number of observations or predictions

4. Results and Discussions

The rainfall rates predicted by WRF simulations using 9 combinations of microphysics and cumulus parameterization schemes were compared with observations (Figure 4). Note that the observed rainfall rates at Sangkeug, which is on a plain area near central Korean Peninsula, had two minor peaks of approximately 100 and 130 mm/d, respectively, on 14 and 16 July 2006. Note that none of the simulated results followed this observed trend. In particular, WB (WSM-6 - BMJ schemes; see Table 2 for acronyms hereafter) schemes showed an unusually high rainfall rate of approximately 470 mm/d on July 15. On the other hand, most of the other simulations provided better rainfall rate on July 15 comparable to the observed rainfall rate. The heavy rainfall rate on 16 July 2006 was attributed to the local orographic uplifting associated with the mountain range to the west of South Korea and the anti-cyclonic circulation associated with Gaema Heights in North Korea (Hong & Lee, 2009). However, precipitation in 2008 was not as intense as in 2006, in terms of the maximum daily rainfall. Maximum daily rainfalls were 66 mm/d on 19 July 2008 and 115 mm/d on 16 July 2006. In general, LB schemes followed this observed rainfall trend better than other scheme combinations, although the two peak rainfall rates did not match the observed rates. The first peak value was under-predicted, while the second peak was over-predicted by a rate of about 20 mm/d. In addition, the model-simulated time for these two rainfall peaks were delayed by one to two days.

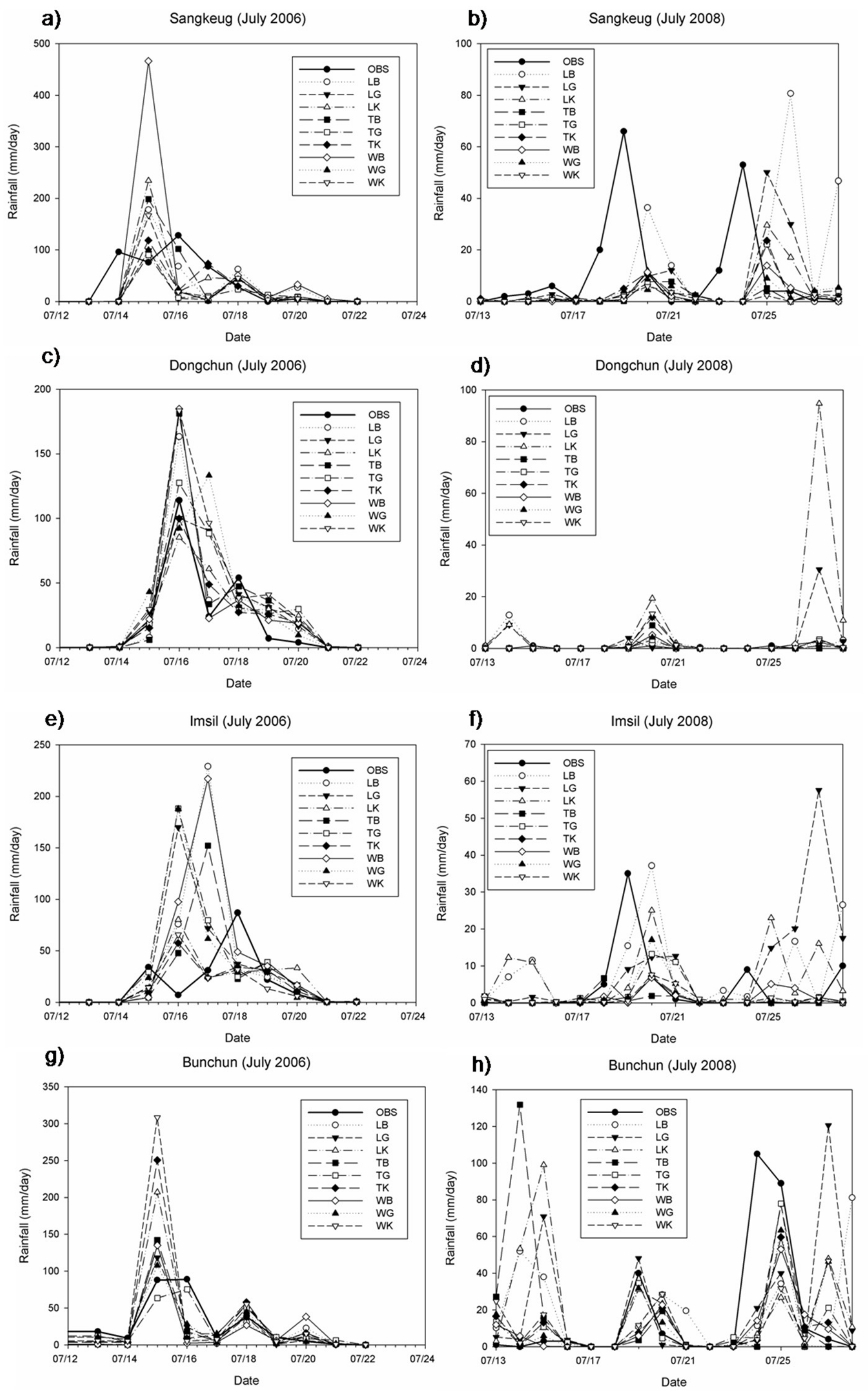

Figure 4. Comparison of observed daily rainfall rate with those predicted by WRF with various combinations of microphysics and cumulus parameterization schemes (See Table 2 for acronyms.)

For the second rainfall peak, LG simulated a mostly comparable daily rainfall rate with some delay. At Dongchun, which is surrounded by mountains, the 2006 prediction matched the observations closely, with two peaks occurring on July 16 and 18. Schemes TG appears to have best matched observations making it the better combination of physics parameterizations. Schemes WB followed the observation trend well with one higher and one lower rainfall peaks on July 18. In 2008, there was no substantial rate of rainfall observed at Dongchun; however, WRF predicted three different rainfall peaks on July 14, 20, and 27. In particular, on July 27, LK simulated a much higher precipitation (95 mm/d) than the observation (1 mm/d). Most of the 2006 predictions for Imsil, which is located in the plain area, significantly over-predicted the rainfall, especially on July 17. Schemes LB and schemes WB predicted a peak rainfall greater than 200 mm/d for July 17, which may cause false flood warning in reality. Schemes LG, TG, and WG simulated unreasonable peak rainfall (approximately 190 mm/d) for July 16. For the 2008 event, there were three rainfall peaks observed on July 19, 24, and 28. From observations, the maximum daily rainfall rate was 35 mm/d on July 19. Schemes LB simulated a peak rainfall rate very close to the observation, though with some date discrepancy (1 day delay). The date discrepancy might be due to the spin-up of the precipitating system by the model, but could also be caused by other factors, such as imperfections in initial and boundary conditions, and model numeric, and chaotic behavior of the atmosphere etc. On July 27, a maximum daily rainfall peak was predicted, but no rainfall was observed in reality. Optimal predictions following the trend of observations were obtained for Bunchun, located in Kangwon Province on the east side of Korean Peninsula, for both 2006 and 2008. In 2006, two equal rates of approximately 89 mm/d were obtained on July 15 and 16. Another daily rainfall peak was observed two days later on July 18. In this event, schemes TG matched the observed trend very closely except for July 20. However, the rainfall difference was insignificant. Schemes WK, TK, and LK predicted excessive rates of daily rainfall for 15 July 2008, which were two to three times higher than observations. In particular, the daily rainfall rate predicted by schemes WK may mislead decision makers to send false warning for flood evacuations because this high rainfall rate (over 300 mm/d) could be able to generate severe flooding. For 2008, the rainfall predicted by schemes TG matched closely the trend of rainfall observations. However, this prediction strongly underestimated the daily rainfall on July 24 because the difference in the rainfall rates between schemes TG and observations was greater than 100 mm/d.

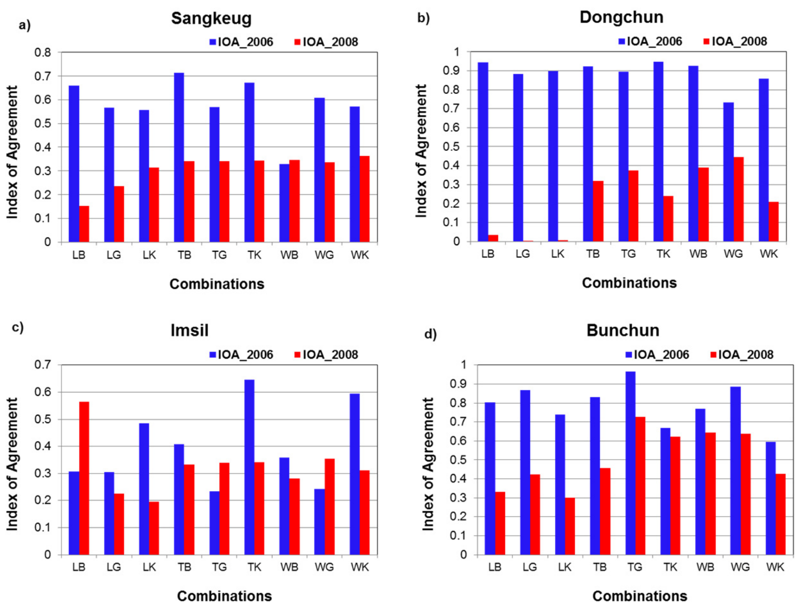

Figure 5. Index of Agreement (IOA) between observed and simulated rainfall rates

For more objective validations, index of agreement (IOA) were adopted for the comparisons (Figure 5). The selection of the better combinations of microphysics and cumulus parameterizations at each location was required to simultaneously determine data for both years 2006 and 2008. For Sangkeug, schemes TB and TK were selected as a better combination of schemes. Schemes LB was not selected because it had higher IOA in 2006 (~0.68), but a very low IOA in 2008 (~0.15). Schemes WB showed potential to be a better combination with the lowest IOA. Dongchun, a station surrounded by mountains, had both schemes TG and WB as a better combination for both years. In 2006, schemes LB, TK, and WB simulated an IOA greater than 0.9 at Dongchun, but LB and TK did not perform consistently in 2008. For Imsil, Kain-Frisch cumulus parameterization scheme had significant impacts on QPF. Schemes TK and WK combinations for 2006 showed the highest IOA (over 0.6). For Sangkeug, LB worked well in 2006 but not in 2008. For Bunchun, a station located on the east side of Korean Peninsula with high mountains, the Grell 3D ensemble cumulus parameterization scheme was a key physical option because it generated a precipitation rate closest to the observations for both years. In particular, TG showed a maximum IOA near 1 with a minimum RMSE for both 2006 and 2008. Combinations of WG and WB generated good IOA greater than 0.8 for 2006 and about 0.6 for 2008. Generally, the Purdue Lin scheme (Lin et al., 1983; Chen & Sun 2002) with diverse cumulus parameterization options did not make a precipitation prediction close to observations for any of the four locations in either year.

Figure 6 shows the mean bias deviations of WRF simulated rainfall rates using different combinations of microphysics and cumulus parameterization schemes. The mean bias deviation (MBD) values were produced by average of 2006 and 2008 MBDs at each category of locations (mountainous and plain areas). For mountainous area, all of combined schemes over predicted the rainfall, compared to the observed rainfall data. Especially, the combination of Kain-Miller-Janjic cumulus parameterization scheme and Lin et al. microphysics scheme predicted over 11 times larger difference to the observations. The minimum biased combinations in mountainous area were TG and WG (0.34). In plain area, rainfall values were estimated negatively at some combinations (LK, TB, TG, TK, WG, WK). Lin et al. microphysics and Kain-Miller-Janjic cumulus parameterization schemes especially generated the minimum biased estimation. The maximum biased rainfall values were found at WK combination with -0.52 MBD. In terms of the magnitude of mean bias, mountainous area presented some difficulties for rainfall prediction. Based on RMSE, IOA, and MBD, for mountainous regions (Dongchun and Bunchun), the Grell 3D ensemble cumulus parameterization and Thompson microphysics schemes performed best compared to other combined schemes; while for plain areas (Sangkeug, Imsil), the Kain-Frisch cumulus parameterization and Thompson microphysics schemes performed best compared to other combined schemes.

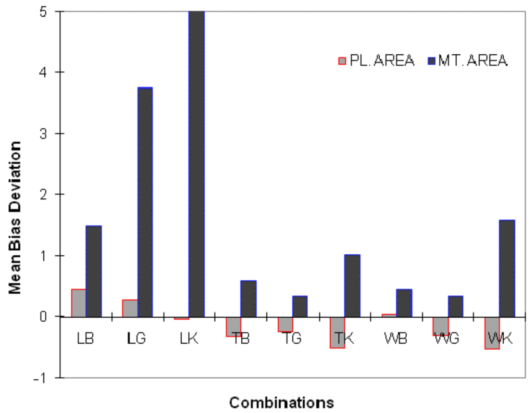

Figure 6. Mean bias deviation (MBD) for model simulated rainfall rates using nine combined microphysics-cumulus parameterization schemes

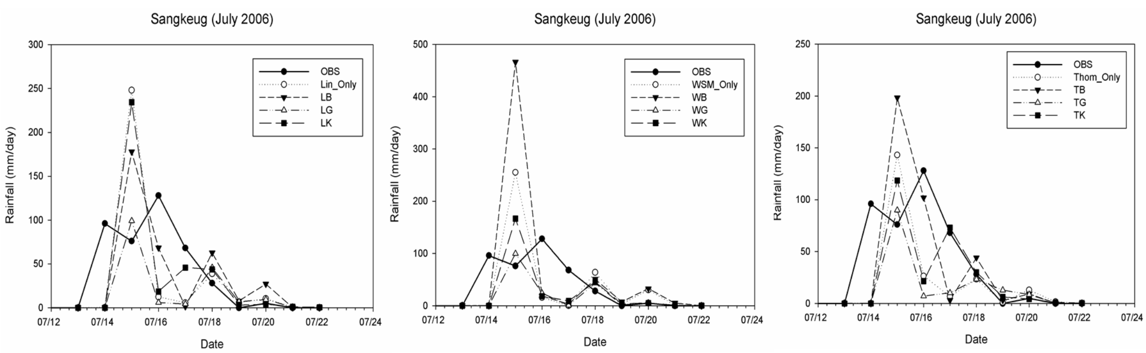

Figure 7. Sensitivity tests for cumulus parameterization functions at Sangkeug for the July 2006 storm event. (Lin_Only, Thom_Only, and WSM_Only indicate that results predicted by only include microphysics, but no cumulus, parameterization scheme.)

In simulations with finer resolutions (4 km), cumulus parameterizations played important roles in QPF, which are contrasted with comments, i.e. cumulus parameterization is not necessary for simulation with grid sizes finer than 4-5 km, made by some researchers (e.g. Gilliland & Rowe 2007). Figure 7 shows the sensitivity test for the cumulus parameterization scheme at Sangkeug for the July 2006 event. Based on these results, it appears that the cumulus parameterization schemes play considerable roles in the prediction of maximum rainfall rates. In particular, the

Betts-Miller-Janjic cumulus parameterization scheme coupled with the WSM microphysics scheme in the third panel produced two orders of magnitude difference in the maximum rainfall estimation on day 15. Furthermore, a cumulus parameterization scheme coupled with a PBL scheme is highly sensitive compared to the coupling with a microphysics scheme for warm season precipitation predictions (Lowrey & Yang 2008).

Hong and Lee (2009) proposed the possibility of highly localized rainfall events when 2006 storms were analyzed for Korean Peninsula. Based on their finding, a minimal domain size (45 by 45 with 4 km resolution, Figure 2) for the third nest near Sangkeug Station was applied to QPF. Figure 8 shows the results using a smaller inner domain compared with former simulations for Sangkeug Station for July 2006 and 2008. The smaller inner domain substantially improved the QPF. For the 2006 event, a smaller inner domain predicted precipitation rate over 0.8 IOA, which is approximately 0.2 units greater than that using the previous domain size. An appreciable improvement can be found in the 2008 results by using a smaller inner domain size. The IOA of 2008 simulated rainfall rates with a larger domain was between 0.3 and 0.4; however, an IOA greater than 0.9 was generated by TK_S using a smaller inner domain. The above results imply that a smaller inner domain can improve the ability of a regional-scale numerical weather model to predict precipitation rate for flood prediction. In the study of Lowery and Yang (2008), the relative domain size and locations are emphasized because these are the substantial factors in the localized rainfall estimation.

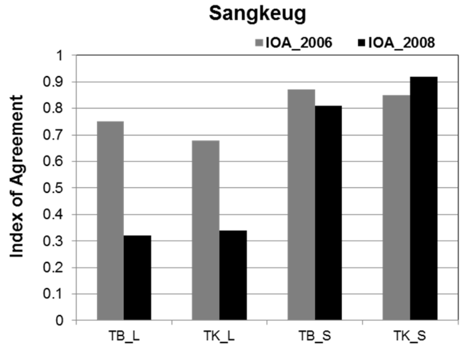

Figure 8. IOA comparisons between rainfall rates predicted by a larger domain and a smaller inner domain (TB_L, TK_L: combinations with large domain; TB_S, TK_S: combinations with localized smaller domain)

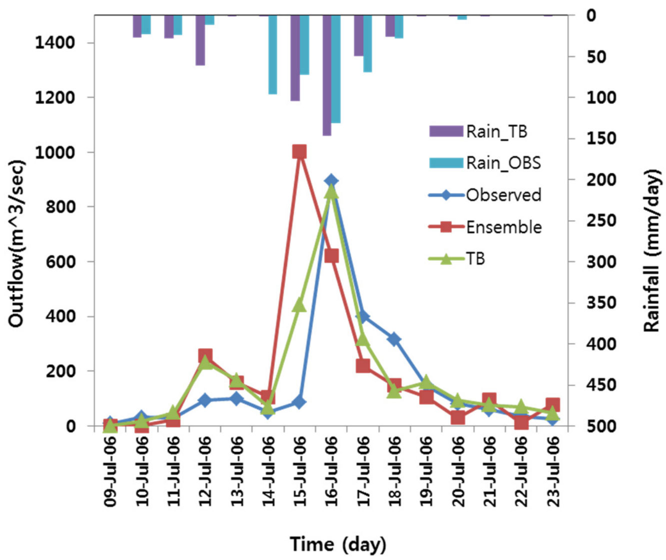

Figure 9. Comparison of discharge values for a 2006 rainfall event from the smaller domain at the Chongmi River Basin

The 2006 rainfall rates predicted by the smaller domain size in the combined Thompson-Betts-Miller-Janjic parameterization schemes were adopted to predict the rainfall-runoff response (Figure 9). Based on the optimized hydrological conditions, rainfall rates predicted by TB produced closely matched peak outflow at discharge point in the Chongmi River Basin on July 16. However, the discharge predicted from TB on July 15 was four times higher than the observed discharge. In addition, TB generated a larger discharge increase between July 11 and 12. Ensemble rainfall data (averaged rainfall amount) produced a greater than $100\, m^3 / \sec$ higher peak discharge with one day earlier than the observed peak discharge. The predicted discharge values matched closely with the trend of observed discharge in both cases, which indicate the possibility of rainfall prediction by the WRF model and the discharge trend for flood event could be obtained prior to the extreme flood event. For more precise flood event alert, hourly time interval might be required especially mountainous regions.

4. Conclusions and Recommendations

In the assessment of a regional-scale weather prediction (WRF) model for hydrological applications in South Korea, diverse model configurations have been tested. Nine combinations of microphysics and cumulus parameterization schemes were evaluated for four selected locations, Sangkeug, Dongchun, Imsil, and Buchun using two storm events occurred in 2006 and 2008. Both Index of Agreement (IOA) and Root Mean Square Error (RMSE) are adopted to make objective analysis of the accuracy of quantitative precipitation forecast (QPF).

It was found that the better cumulus-microphysics parameterization (cumulus parameterization-microphysics) schemes are sensitive to the locations. In the mountainous regions (Dongchun, Bunchun), Thompson microphysics and Grell 3D Ensemble cumulus parameterization schemes performed better than other scheme combination, while the Thompson microphysics and Kain-Frisch cumulus parameterization schemes were selected for plain regions (Sangkeug, Imsil) for given flood events (summer of 2006 and 2008). Most of the 2006 predicted rainfall rates closely matched the observations as measured by IOA. The model simulated maximum IOA of rainfall rates in 2006 and 2008 at Bunchun was generated using the Thompson microphysics and Grell 3D ensemble cumulus parameterization schemes. Both physics parameterizations were more relevant to rainfall prediction. Based on the results predicted by these combinations, a smaller inner domain size (third nested domain) at Sangkeug was used for sensitivity tests to determine the effects of domain size on precipitation prediction. A smaller inner domain was found to substantially improve precipitation prediction, especially for 2008 events. In terms of IOA, the rainfall rate prediction was improved by more than 50 percent using a smaller inner domain. These results demonstrated that a regional-scale numerical weather prediction model with the specific combination of physical parameterizations and a smaller inner domain may significantly improve QPF, even with a finer grid size (4 km). In using a regional-scale numerical weather model, a smaller inner domain appears to be necessary for more accurate precipitation prediction. In addition, localized rainfall estimation with a smaller domain size produced discharge values that were reasonably well matched with observed data in the rainfall-runoff simulation. For further investigation, diverse domain size and flood forecasting could be pursued in detail in these regions and hourly rainfall simulation might be required for more precise flood event alert.

Note that some physics parameterization schemes might be region and/or region dependent due to their original design and the synoptic forcing. Thus, the conclusions drawn from our simulations might be only limited to the Korean Peninsula. In order to make a more general conclusion, a more thorough and fundamental study is needed, which might be due to the designs of individual schemes. For example, our results with Grell cumulus parameterization scheme are consistent with those studied in Dodla et al. (2013), i.e. better QPF over the mountainous region. On the other hand, the Kain-Fritsch scheme predicted rainfall patterns over the mountainous areas of the south Asian region, and Grell scheme realistically captured the rainfall patterns over the southern plain area of the region (Sardar et al., 2012). Thus, Sarder et al.'s finding is completely opposite to ours. Some other studies (e.g., Ardie et al., 2012; Yang and Tung 2003) have even pointed toward the possibility of case dependent due to synoptic forcing. Due to their original design, Kain-Fritch cumulus scheme is heavily dependent on the CAPE, while the Grell cumulus scheme uses horizontal and vertical advection to compute the rate of destabilization, which could be sensitive to the updraft calculated at the top of the mixed layer (Cohen, 2012).

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