RAINFALL FORECAST OF CUMULUS PARAMETERIZATION SCHEMES IN THE TAIWAN AREA

Ming-Jen Yang

Department of Atmospheric Sciences
Chinese Culture University

1. INTRODUCTION

Many cumulus parameterization schemes (CPSs) have been developed and implemented into numerical weather prediction models. However, most of CPSs are developed in specific convective environments and are evaluated in a limited number of cases (Kuo et al. 1996; Wang and Seaman 1997; Gallus 1999; Yang et al. 2000). None of the CPSs are specifically designed for precipitation systems in a subtropical environment with pronounced orography, or the Taiwan area in particular. This paper presents a comparison study of rainfall forecasts by a few CPSs for precipitating events in the Taiwan area.

The research purposes of this study are fourfold. First, do CPSs have consistent and systematic performance in different synoptic environments? Second, what is the general applicability of CPSs when they are applied in the Taiwan area rather than in those original environments tested by the scheme developers? Third, can a precipitation prediction based on an ensemble of CPSs provide a better forecast than that by one single CPS? Fourth, for CPSs designed originally for large-scale models, what are the typical problems when they are applied in a mesoscale model?

This study follows Wang and Seaman (1997) and Yang et al. (2000) to evaluate the performance of four CPSs in fully prognostic tests, using six rainfall events in four seasons over the Taiwan area. The rainfall *predictive skill* over 6-h period is evaluated for each CPS experiment. The mesoscale model used is The Pennsylvania State University—National Center for Atmospheric Research (PSU-NCAR) mesoscale model MM5 at grid sizes of 45 and 15 km. These horizontal resolutions are the same as those of the operational Central Weather Bureau regional model recently. Each precipitation forecast is evaluated statistically over 15-km grid points over Taiwan using the conventional skill scores for different precipitation threshold values based on island-wide rain gauge observations.

Corresponding author address: Dr. Min-Jen Yang, Dept. of Atmospheric Sciences, Chinese Culture University, 55 Hwa Kang Road, Yang Ming Shan, Taipei, Taiwan, 111, ROC. Email: mingjen@twister.atmos.pccu.edu.tw

2. METHODOLOGY

The nonhydrostatic MM5 model (Version 2.11) is used as a common testing framework to investigate four CPSs. The MM5 is run for six cases at grid sizes of 45 km and 15 km. The rainfall forecast is then examined in terms of *accumulated amount* and *area coverage* of precipitation over the Taiwan area.

The four CPSs chosen for evaluation are the Anthes-Kuo scheme (AK; Anthes 1977), the Betts-Miller scheme (BM; Betts and Miller 1986), the Grell scheme (GR; Grell 1993), and the Kain-Fritsch scheme (KF; Kain and Fritsch 1993). Each simulation with a CPS represents one rainfall forecast experiment. In order to explore the potential of an ensemble forecast with a mixture of different CPSs, an average forecast (AG) is also made by arithmetically averaging the rainfall forecasts by the four CPSs. All parameters in the CPSs remain constant among simulations for different cases, in a manner similar to an operational setting.

The observations used to evaluate MM5 rainfall predictions are the rainfall data collected by the automatic rain gauge stations at the Central Weather Bureau in Taiwan. This data set consists of 343 rain gauge stations around the Taiwan island with an average distance less than 5 km (Figure 1). The observed rainfall data are then interpolated to the 15-km model grid points (155 points available totally), using the Cressman (1959) objective analysis method.

The model prognostic fields (rainfall distribution, sea level pressure, and wind) are first verified against satellite imagery and objective analyses to make sure that the model has adequate skill to reproduce the synoptic-scale features with embedded mesoscale precipitating systems. Then, the categorical statistics scores (Hamill 1999; McBride and Ebert 2000) such as threat score (TS), equitable threat score (ETS), bias score (BS), probability of detection (POD), and false alarm rate (FAR) are evaluated for several threshold values (0.25, 2.5, 10, 15, 20, and 25 mm), based on the 6-h rainfall forecast by each CPS experiment on the 15-km grid points. Note that total (parameterized and resolved) precipitation is evaluated. Because there are only few 45-km grid points (17 points) in Taiwan, categorical statistics scores with such a limited sampling points probably do not have much statistical meaning; thus the 45-km verification results are not discussed. For precipitation amount forecast, the following statistical parameters are examined:

mean error, mean error percentage, mean absolute error, mean absolute error percentage, precipitation summary percentage, and precipitation maximum percentage.

We select six cases that represent a variety of synoptic and mesoscale weather conditions producing rainfalls over the Taiwan area. Two cold-season cases, two warm-season cases, one Mei-Yu front case, and one typhoon case are selected. The synoptic-scale environments for the cold-season events were characterized by wintertime cold-air outbreak and autumn cold front. The synoptic-scale conditions for the warm-season cases were associated with spring-season frontal rainfall and summertime afternoon thunderstorms. A stationary front during the 1999 Mei-Yu season (28 May 1999) and Typhoon Otto (1999) were chosen to represent the typical Mei-Yu front and typhoon cases which climatologically produced the most severe heavy rainfalls over the Taiwan area.

In addition to the subgrid-scale CPSs tested, the MM5 physical parameterizations used in this study include the Blackadar (1979) planetary boundary layer scheme (Zhang and Anthes 1982), the radiation scheme with the interaction between clear sky and clouds (Dudhia 1989), and the grid-scale Simple Ice microphysics scheme (Dudhia 1989).

The MM5 configuration includes a coarse mesh of 45-km grid size and a fine mesh of 15-km grid size. The 45-km domain has 81×71 grid points and the 15-km domain has 91×91 grid points, with 27 σ levels in the vertical for both domains. Each MM5 run is 36 hours. In order to mimic the operational setting over Taiwan where the Central Weather Bureau has an operational global model (the Central Weather Bureau Global Forecast System; CWBGFS, Liou et al. 1997), the initial condition for each MM5 run is provided by the CWBGFS analysis field, and the boundary condition is provided by the CWBGFS forecast field. Routine surface observations and sounding data are included through the MM5 objective analysis package (RAWINS) to improve the initial condition field.

3. RESULTS

Verification of the simulated rainfall distribution, sea-level pressure, and wind fields of six rainfall cases with satellite pictures and observational analyses indicates that the MM5 model has a good skill at predicting the synoptic-scale features. Principal findings of this comparison of precipitation predictions by cumulus parameterization schemes over the Taiwan area are summarized below.

For a given synoptic environment, performance of each CPS is quite similar; these CPSs behave very differently under different synoptic forcings. This implies that the synoptic and/or mesoscale environment provides the primary control on model's rainfall forecast skill, and the CPSs used in the model only modify forecasts slightly.

Except for two warm-season events (spring rainfall and summertime thunderstorm cases), the 15-km MM5 using four CPSs shows good predictive skill for coverage of measureable 6-h rainfall for four rainfall cases over the Taiwan area, with TSs greater than 0.4 at the precipitation threshold of 0.25 mm.

For rainfall predictions (TSs and ETSs) in Taiwan, the MM5 model performs better in cold-season events than in warm-season events (Figure 2), in agreement with many previous studies (Wang and Seaman 1997; Gallus 1999).

None of these CPSs consistently outperforms the others in all measurements of forecast skill, and each CPS has very different performance of rainfall forecast under different synoptic conditions (Wang and Seaman 1997).

For the wettest 3 out of six cases, the ensemble forecast (AG experiment) with an arithmetic average of rainfall predictions by four CPSs has the best skill in predicting the occurrence of rainfall (i.e., the best TS at 0.25-mm threshold). However, due to its inherent smoothing nature, the ensemble forecast only has moderate predictive skill in total precipitation amount and the peak rainfall intensity.

In general, the 15-km MM5 tends to overpredict the area of light rainfall and underpredict the area of heavy rainfall (Gallus 1999). For the false alarm rates by four CPSs over six cases over Taiwan, AK has the largest degree of false rainfall warning and BM has the least degree of false warning. This is different from the fact that the BMJ scheme in the NCEP Eta model has a relatively large false rainfall area, and it may be due to the different geographical setting tested in this study (midlatitude continental environment versus subtropical oceanic environment).

Except for the spring rainfall case, all CPSs underestimate precipitation amount, especially for heavy rainfall cases (Mei-Yu front and Typhoon Otto), consistent with Spencer and Stensrud (1998) and Gallus (1999). For total rainfall amount prediction, GR has the best skill in four out of six cases. On the other hand, for the rainfall maximum forecast, BM has the best performance in three out of six events.

The characteristic responses and systematic behaviors of four CPSs are listed here. AK tends to overpredict the rainfall area, especially for light precipitation events. BM is inclined to produce heavy precipitation in a localized area, so it underpredicts the rainfall area. KF has the best skill in rainfall-area prediction for the winter cold-air outbreak case. GR has the best predictive skill for the heavy-rainfall events of the Mei-Yu front and Typhoon Otto cases.

Finally, the skill of the precipitation forecast changes markedly under different synoptic-scale environments, even for the same CPS. The large rainfall-forecast variability in these events raises concerns of relying upon one CPS for forecasting guidance. An approach to reduce this case dependency of CPS performance is to run several

CPSs to create an ensemble, as we did in the AG experiment which had the best skill in predicting the occurrence of rainfall in three out of six cases. Other studies (Mullen and Buizza 2001; Grimit and Mass 2002) also show positive impacts to precipitation prediction by ensemble forecasting. Thus, there may be some potential to improve rainfall-area prediction in the Taiwan area in the long term by using an ensemble forecast with a mixture of several CPSs, as we did in the Ensemble Forecast Experiment during the Mei-Yu season (May and June) in 2000 and 2001.

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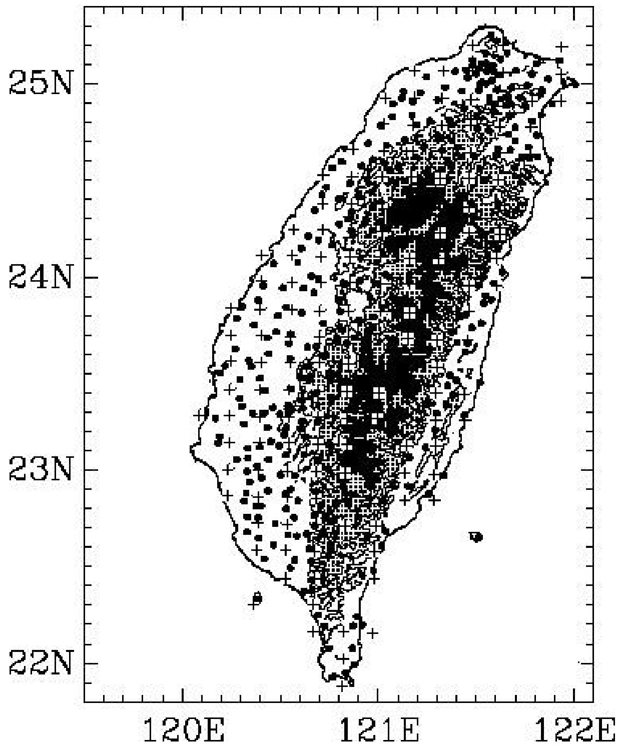

Figure 1: Rain gauge stations (small dots) and the 15-km model grid points (crosses) over the Taiwan area used in the evaluation of the cumulus schemes. Topographic contours are at 500, 1500, 2500, and 3500 m.

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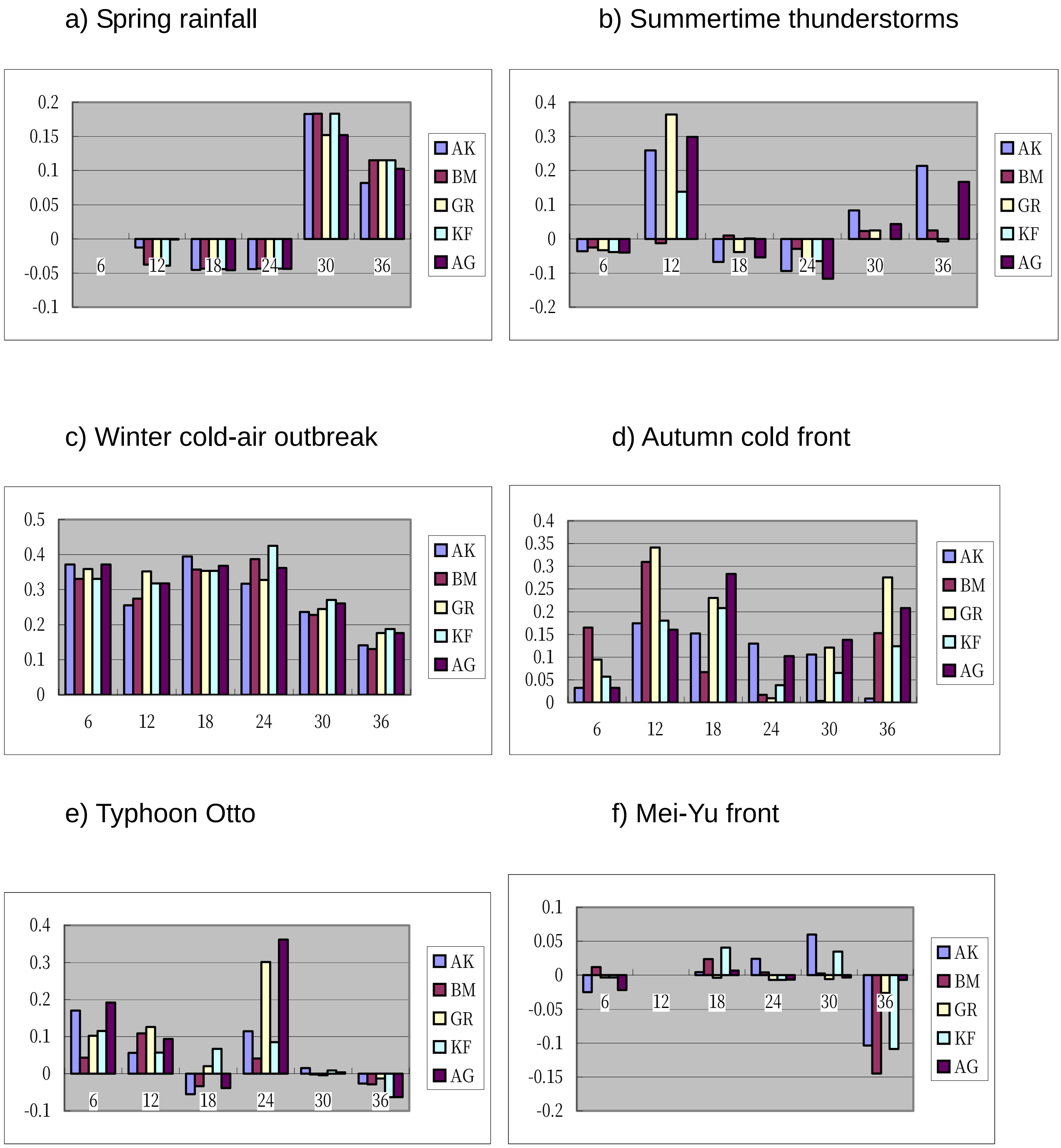

Figure 2: Equitable threat scores (ETSs) at the 0.25 mm threshold for 6-h rainfall predictions from 15-km MM5 runs for the a) spring rainfall, b) summer-time thunderstorm, c) winter cold-air outbreak, d) autumn cold front, e) Typhoon Otto, and e) Mei-Yu front case. The times on the abscissa are relative to the model initial time.