Ensemble prediction of rainfall during the 2000–2002 Mei-Yu seasons: Evaluation over the Taiwan area

Ming-Jen Yang,[1] Ben J.-D. Jou,[2] Shi-Chieh Wang,[3] Jing-Shan Hong,[4] Pay-Liam Lin,[5] Jen-Hsin Teng,[4] and Hui-Chuan Lin[6]

Received 18 November 2003; revised 31 March 2004; accepted 22 June 2004; published 18 September 2004.

[1] This paper reports the first effort on real-time ensemble predictions of precipitation during the 2000–2002 Mei-Yu seasons (May to June) over the Taiwan area. Six members were included, each using the fifth-generation Pennsylvania State University-National Center for Atmospheric Research Mesoscale Model (MM5) nesting down to 15-km grid size, with different combinations of cumulus and microphysics parameterizations. Rainfall forecasts were evaluated with the equitable threat score (ETS) and bias score (BS). On the basis of verifications on 15-km grid points over three Mei-Yu seasons, it was found that no one member persistently had the least root mean square error of 12–24 hours and 24–36 hours accumulated rainfalls. For rainfall occurrence, most members had better predictions over the northeastern mountainous area, the northwestern coastal plain, the central mountain slope, the southwestern coastal plan, and the southwestern mountainous area. These regions also corresponded to areas of more accumulated rainfalls during three Mei-Yu seasons. An ensemble prediction, using a multiple linear regression (MLR) method which performed a least-square fit between the predicted and observed rainfalls in postseason analysis, had the best ETS and BS skill. The MLR ensemble forecast outperformed the average forecast (for all six members), the average forecasts of cumulus (four-member) and microphysics (three-member) ensembles, and also a high-resolution (5-km) forecast; however, a high-resolution forecast still had better skill for heavy rainfall events. The MLR ensemble forecast, using the weightings determined from previous Mei-Yu seasons, still had similar ETS trend to that with weightings determined by current-year Mei-Yu season, albeit with less skill. *INDEX TERMS:* 0320 Atmospheric Composition and Structure: Cloud physics and chemistry; 0325 Atmospheric Composition and Structure: Evolution of the atmosphere; *KEYWORDS:* Mei-Yu season, ensemble rainfall forecast, Taiwan, MM5

Citation: Yang, M.-J., B. J.-D. Jou, S.-C. Wang, J.-S. Hong, P.-L. Lin, J.-H. Teng, and H.-C. Lin (2004), Ensemble prediction of rainfall during the 2000–2002 Mei-Yu seasons: Evaluation over the Taiwan area, *J. Geophys. Res.*, *109*, D18203, doi:10.1029/2003JD004368.

1. Introduction

[2] The Mei-Yu season is a climate regime characterized by the frequent occurrence of mesoscale convective systems during the seasonal transition period when summer monsoon advances stepwise northwardly through southeast Asia. The climatological and synoptic characteristics of Mei-Yu fronts have been extensively examined by many studies [*Chen*, 1983; *Chen and Yu*, 1988; *Chen and Li*, 1995]. The climatological Mei-Yu season over the Taiwan area lasts from mid May to mid June and coincides with a local maximum in seasonal precipitation distribution [*Chen and Chi*, 1980; *Chen and Chen*, 2003]. Vigorous convection and organized mesoscale convective systems, producing heavy rainfall, are often embedded with a Mei-Yu front [*Kuo and Chen*, 1990; *Yeh and Chen*, 1998; *Chen et al.*, 2003].

[3] The concept of ensemble forecasting was first introduced by *Lorenz* [1963], where he examined the initial state uncertainties in the atmosphere and discussed the well-known "butterfly" or chaos effect. Much progress has been made in ensemble forecasts using numerical weather prediction (NWP) models, especially for global NWP application [*Molteni et al.*, 1996; *Krishnamurti et al.*, 1999, 2000]. With the increase of computational power, now is the time to attempt the ensemble forecasting on the mesoscale [*Stensrud et al.*, 2000; *Grimit and Mass*, 2002; *Colle et al.*, 2003].

[4] *Wang and Seaman* [1997] performed a comparison study of four cumulus parameterization schemes (CPSs) using the fifth-generation Pennsylvania State University-

[1]Institute of Hydrological Sciences, National Central University, Chung-Li, Taiwan.
[2]Department of Atmospheric Sciences, National Taiwan University, Taipei, Taiwan.
[3]Department of Atmospheric Sciences, Chinese Culture University, Taipei, Taiwan.
[4]Central Weather Bureau, Taipei, Taiwan.
[5]Department of Atmospheric Sciences, National Central University, Chung-Li, Taiwan.
[6]Civil Aeronautics Administration, Taipei, Taiwan.

0148-0227/04/2003JD004368$09.00

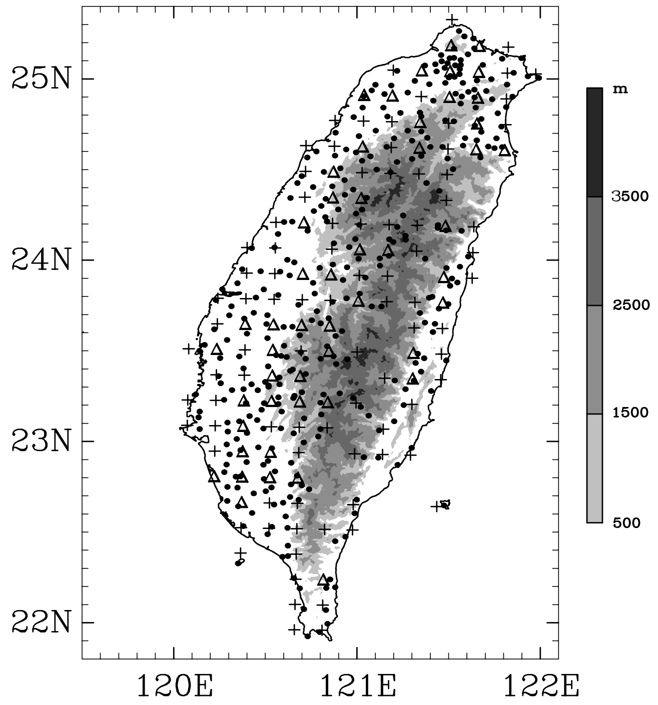

Figure 1. ARMTS rainfall stations (small dots) over the Taiwan area and the corresponding 15-km MM5 grid points used (triangles) and not used (crosses) in forecast evaluation. Taiwan topography is in gray scale at 500, 1500, 2500, and 3500 m.

National Center for Atmospheric Research (Penn State/NCAR) Mesoscale Model (MM5). Performance of these CPSs was examined for six precipitation events over the continental United States in both cold and warm seasons. They found that no one CPS always outperformed the others. The forecast skill was generally higher for cold-season events than for warm-season events. There was an increase in the forecast skill with the increase of horizontal resolution, and the gain was most obvious in predicting heavier rainfall amounts.

[5] *Mullen et al.* [1999] investigated the impact of differences in analysis-forecast systems on dispersion of an ensemble forecast for a cyclogenesis case. It was found that quantitative precipitation forecasts (QPFs) and probabilistic QPFs were extremely sensitive to the choice of precipitation parameterization in the model. The combined effect of uncertainties in precipitation physics and the initial conditions thus provided a means to increase the dispersion of QPF ensemble forecast system.

[6] *Yang et al.* [2000] evaluated the performance of subgrid-scale cumulus schemes and resolvable-scale microphysics schemes in the simulation of a Mei-Yu frontal system at grid sizes of 45 km and 15 km, using the MM5 model. They found that the horizontal extent and intensity of simulated precipitation and the embedded mesoscale structure were very sensitive to the choice of cumulus schemes. At grid sizes of 45 km and 15 km, variations in the subgrid-scale cumulus scheme have a much larger impact on the distribution and amount of Mei-Yu frontal precipitation than variations in the resolvable-scale microphysics scheme.

[7] *Yang and Tung* [2003] evaluated rainfall predictions of four CPSs in fully prognostic tests, using six rainfall events in four seasons over the Taiwan area. The ensemble prediction with an arithmetic average of rainfall forecasts by four CPSs has the best threat score at 0.25-mm threshold for the wettest 3 of 6 cases (including a Mei-Yu front case).

[8] This study follows *Yang et al.* [2000] and *Yang and Tung* [2003] to investigate the performance of subgrid-scale cumulus schemes and resolvable-scale microphysics schemes in a double-nested MM5 (with grid sizes of 45 km and 15 km), by evaluating the real-time ensemble forecasts of precipitation over Taiwan during the Mei-Yu season (May and June) in 2000, 2001, and 2002. Six members were included in the MM5 ensemble with different combinations of cumulus and microphysics parameterization schemes as a means to examine the impact of precipitation parameterization upon rainfall forecast. The initial condition uncertainty is also important, but its influence on rainfall prediction is not discussed in this study. Following *Krishnamurti et al.* [1999, 2000], an ensemble forecast of precipitation was made in postseason analysis using a multiple linear regression (MLR) method which performed a least square fit between the predicted rainfall and observed rainfall for all forecast events during a Mei-Yu season.

[9] By analyzing many ensemble rainfall forecasts during three consecutive Mei-Yu seasons, this paper addresses several important questions:

[10] 1. How is the ability of the 15-km MM5 to simulate precipitation during the Mei-Yu season over the Taiwan area?

[11] 2. How does the MM5 precipitation verification change as a function of precipitation threshold and forecast duration?

[12] 3. What is the influence of using different combinations of cumulus and microphysics schemes on the simulated rainfall during Taiwan's Mei-Yu season?

[13] 4. What is the spatial distribution of ETS and BS of each member and the ensemble mean with respect to Taiwan's topography for Mei-Yu season rainfall?

[14] 5. Can an ensemble rainfall forecast provide a better prediction compared to a single high-resolution forecast? If yes, how much is the gain?

[15] The data set, MM5 model setup, and evaluation methods used in the rainfall prediction are described in section 2. Section 3 presents the forecast verification of each of six 15-km MM5 ensembles during the 2000–2002 Mei-Yu seasons. The ensemble rainfall predictions are shown in section 4. Conclusions and discussion are presented in the final section.

2. Data Set and Method

2.1. Rainfall Characteristics in Three Mei-Yu Seasons

[16] The rainfall data used to verify MM5 ensemble predictions are collected by 343 Automatic Rainfall and Meteorological Telemetry System (ARMTS) stations at the Central Weather Bureau in Taiwan. Figure 1 shows the horizontal distribution of this rainfall data set, with one of the highest-density networks in the world. The analyzed rainfall on a 15-km grid point are determined by averaging ARMTS data arithmetically inside a 15 km $\times$ 15 km grid

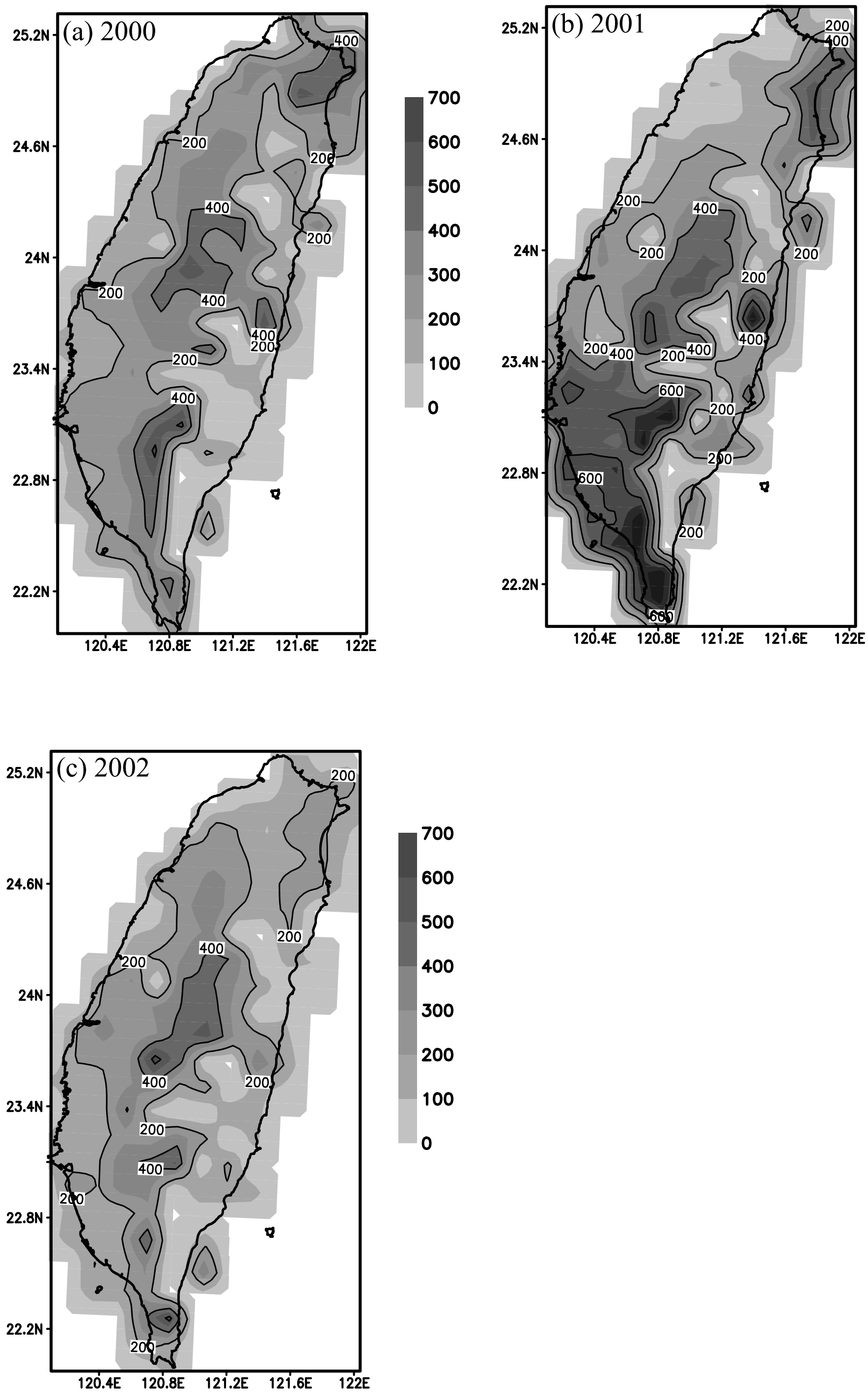

Figure 2. Total observed rainfall (mm) during the (a) 2000, (b) 2001, and (c) 2002 Mei-Yu season periods (0000 UTC 23 May to 0000 UTC 21 June).

box centered on that grid point. If there are less than three ARMTS stations inside a 15 km × 15 km grid box, that grid point is not used for rainfall verification because of too few rainfall sampling points. After this data screening, there are only 51 (originally 140) grid points over Taiwan on the 15-km MM5 grid used for verification.

[17] The horizontal distributions of total accumulated rainfalls during three Mei-Yu seasons are shown in Figure 2. The time period from 0000 UTC 23 May to 0000 UTC 21 June is used in this study as the period of Mei-Yu season in 2000, 2001, and 2002. It is clear from Figure 2 that most of rainfall occurred on the central mountain ridge, northeastern mountainous area, and southwestern mountainous area. The 2001 Mei-Yu season (Figure 2b) is the wettest season in three Mei-Yu seasons, with accumulated rainfall maximum more than 800 mm;

Table 1. Precipitation Physics Schemes Used by Each Ensemble Member

Member	Cumulus Scheme	Microphysics Scheme
BR	Betts-Miller	Resiner 1
KS	Kain-Fritsch	simple ice
KG	Kain-Fritsch	Goddard Graupel
AR	Anthes-Kuo	Reisner 1
GR	Grell	Reisner 1
KR	Kain-Fritsch	Reisner 1

on the other hand, the 2002 Mei-Yu season (Figure 2c) is the driest season with rainfall maximum only slightly more than 600 mm.

2.2. MM5 Ensemble Forecasts

[18] Four universities and two government agencies in Taiwan have jointed together to conduct the Ensemble Forecast Experiment during the Mei-Yu season (May and June) since 2000. The participating sites included the National Taiwan University, National Central University, National Taiwan Normal University, Chinese Culture University, Central Weather Bureau, and Civil Aeronautics Administration. Each site used the MM5 model (version 3.3; *Grell et al.* [1994]) as a common framework with different combination of cumulus and microphysics parameterizations. Table 1 lists the six combinations of four cumulus schemes with three microphysics schemes. Cumulus parameterizations tested were the Anthes-Kuo [*Kuo*, 1974; *Anthes*, 1977], Betts-Miller [*Betts and Miller*, 1986], Grell [*Grell*, 1993], and Kain-Fritsch scheme [*Kain and Fritsch*, 1993]. Microphysics parameterizations tested were the Simple Ice [*Dudhia*, 1989], Reisner 1 [*Reisner et al.*, 1998], and Goddard Graupel scheme [*Tao and Simpson*, 1993]. Notice that the three members of KS, KG, and KR can be considered as a ‘‘microphysics’’ ensemble because all three use the same cumulus (Kain-Fritsch) but different microphysics schemes. Similarly, the four members of BR, AR, GR, and KR are considered as a ‘‘cumulus’’ ensemble because all four use the same microphysics (Reisner 1) but different cumulus schemes. Adjusting parameters in the same precipitation parameterization could have similar influence on rainfall forecast as using different precipitation parameterization, but this impact is not discussed in this study.

[19] The model configuration for the MM5 ensemble includes a coarse mesh of 45-km grid size and a fine mesh of 15-km grid size (Figure 3). Domain size is 81 × 71

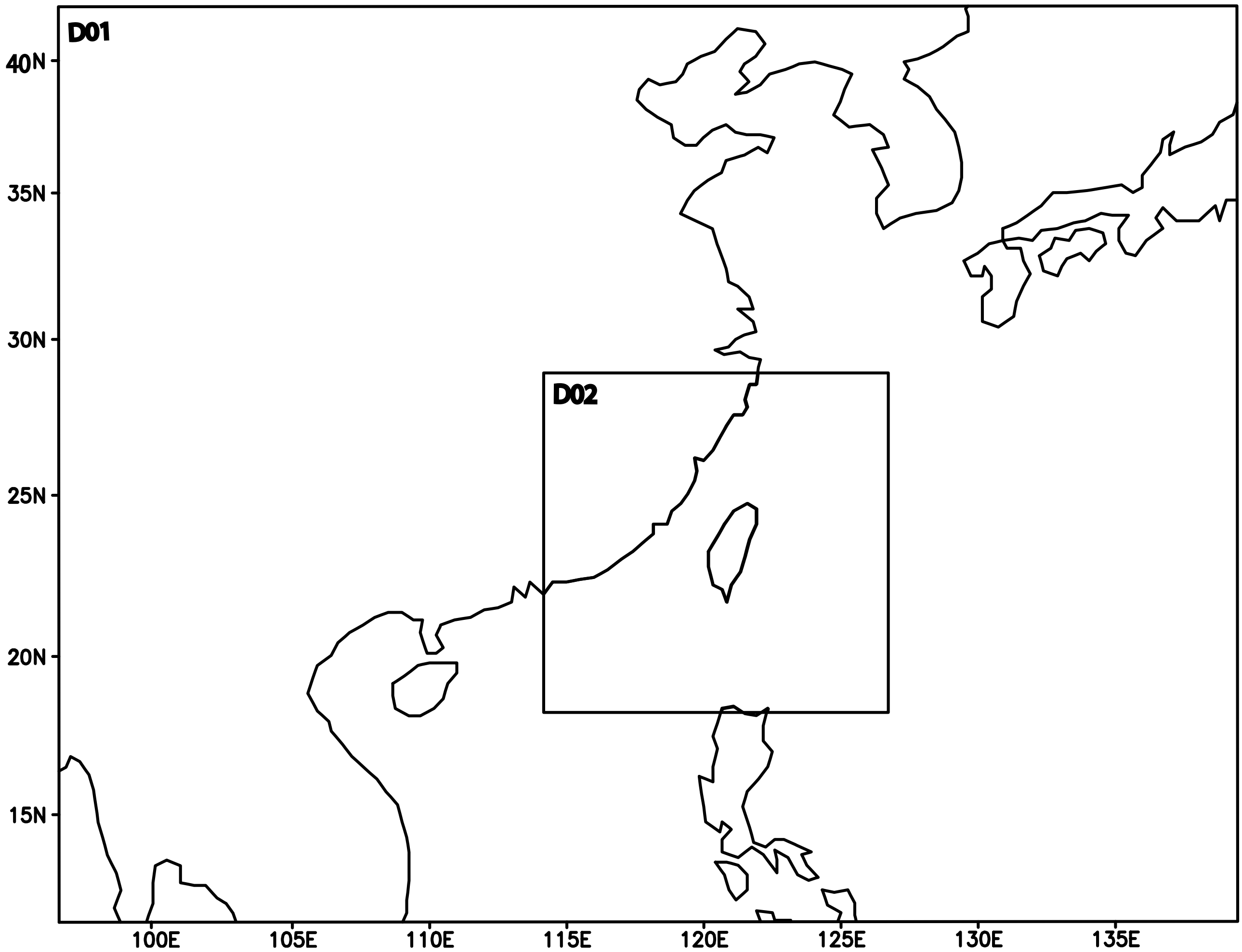

Figure 3. Computation domains of the MM5 ensemble.

for coarse mesh and 79 × 79 for fine mesh. Only twenty-three σ levels are used in the vertical on both grids to save memory and CPU time in this real-time configuration. Except for different combination of precipitation schemes, all ensemble members used the same physical parameterizations which included the Medium-Range Forecast (MRF) model planetary boundary layer scheme [*Hong and Pan*, 1996], and a radiation scheme with interaction between clear sky and clouds [*Dudhia*, 1989]. Each MM5 forecast was 36 hours, produced twice a day (for 0000 and 1200 UTC initializations), and there were 58 forecasts in a Mei-Yu season. The initial condition for the MM5 ensemble was provided by the analysis field of the Central Weather Bureau Global Forecast System (CWBGFS; *Liou et al.* [1997]) as the first-guess field, and the boundary condition was provided by the CWBGFS forecast field through the MM5 "regrid" package. Surface observations and sounding data were included to improve the first-guess field through the MM5 "little-r" objective analysis package.

2.3. Verification Methods

[20] The statistics scores of equitable threat score (ETS) and bias score (BS) [*Hamill*, 1999; *McBride and Ebert*, 2000; *Yang and Tung*, 2003] are evaluated for eight precipitation thresholds (0.3, 2.5, 5, 10, 15, 20, 35, and 50 mm), based on the 12-hour rainfall forecast by each member on the 15-km grid points. The reason for evaluation of the rainfall forecast over the 15-km model grid points in this study, not over the rain gauge stations as presented by F. Mesinger (preprint, 1998) and *Colle et al.* [1999], is because the simulated rainfall by a 15-km MM5 mainly represents the precipitation processes resolved on that grid and our purpose is to verify the rainfall predictive skill of "15-km" ensembles. Rainfall observations on ARMTS stations, on the other hand, represent the very small-scale precipitation processes (recall Figure 1 for Taiwan's high-density rain gauge network).

3. Verification of Each Ensemble Member

3.1. Twelve-Hour Rainfall Amount

[21] Figure 4 shows the scatter plot of observed 12-hour rainfall versus forecasted 12-hour rainfall by six members for the 12–24 hour forecasts during the 2000 Mei-Yu season. Each point on this scatter plot represents the observed versus forecasted rainfall pair on a 15-km grid point over Taiwan for each forecast event (2958 pairs totally in one Mei-Yu season). Most points (about 90%) are over the lower left corner of the scatter plots with both forecasted and observed 12-hour rainfall less than 25 mm, although there are still substantial number of outlier points. These outlier points represent poor rainfall forecasts on these grid points, resulting from bad timing of a Mei-Yu front, improper precipitation parameterization over these areas, and not enough resolution to resolve the complex interaction of environmental airflows with local topography. Figure 4 basically illustrates that the 15-km member sometimes overestimated the 12-hour accumulated rainfall amounts (mainly for the lowland grid points), and sometimes underestimeated 12-hour rainfalls (mainly for the mountain grid points). In summation of all (51) 15-km grid points over Taiwan and for all (58) forecast events in a Mei-Yu season, all members generally overestimated 12-hour rainfall amounts. This overestimation of 12-hour rainfall amount by all members is because after gauge data screening, there are more sampling of 15-km grid points over the lower land than over the mountainous area in Taiwan, and a 15-km MM5 tends to overestimate rainfall over the lowland area and underestimate rainfall over the mountainous region [see *Yang and Tung*, 2003, Figures 11 and 12].

[22] Table 2 lists the root mean square error (RMSE) of two 12-hour rainfall forecasts calculated for all 15-km grid points over Taiwan during the 2000–2002 Mei-Yu seasons. The student's *t* test is used to measure its statistical significance. For example, the RMSE of the KS member for the 12–24 hour rainfall forecast in 2000 Mei-Yu season is statistically significant at the 95% confidence level because its value (13.02 mm) is greater than 5.23 mm. All the statistics in Table 2 are significant at 95% level as a result of large number of sampling points (2958 points for each member in one season). With the increase of forecast duration, the predictive skill tends to decrease [*Chien et al.*, 2002], so most members generally have better skill (lower RMSE) in 12–24 hours than in 24–36 hours. It is clear from Table 2 that no one member persistently outperformed others (had the least RMSE) in both 12-hour periods for three consecutive Mei-Yu seasons.

3.2. Horizontal Distribution of ETS and BS

[23] Figure 5 displays the horizontal distribution of ETS at the 0.3-mm threshold for 12–24 hour rainfall forecasts of six members during the 2000 Mei-Yu season. It is consistent with the RMSE comparison in Table 2 that the precipitation-physics combination of Kain-Fritsch cumulus with simple-ice microphysics (the KS member) had best predictive skill in the 2000 Mei-Yu season with highest ETS more than 0.4. Most members had high ETS scores (greater than 0.2) over the northeastern mountainous area, northwestern coastal plain, central mountain slope, southwestern coastal plan, and southwestern mountainous area. These regions were also areas of local accumulated rainfall maxima for the 2000 Mei-Yu season (see Figure 2a). Similar results are found for the 2001 and 2002 Mei-Yu seasons. High ETS skill over the northeast mountain area is due to the frequent frontal rainfalls. The central and southwestern mountain slope areas with terrain heights of 500–1500 m are the upwind slopes for the climatologically prevailing southwesterly flow during a Mei-Yu season (see *Chen and Chen* [2003, Figure 12] for the southwesterly flow). These terrain heights of 500–1500 m are not very high (compared to the highest terrain (>3500 m) shown in Figure 1), and the 15-km MM5 is capable to resolve and predict the precipitation produced by the moisture-laden southwesterly flow impinging on these mountain slopes during a Mei-Yu season [*Yang et al.*, 2000; *Chien et al.*, 2002; *Chen and Chen*, 2003].

[24] Figure 6 shows the horizontal distribution of BS for the 2000 Mei-Yu season. Basically all members had good BS scores (BS ∼ 1) over areas with high ETS

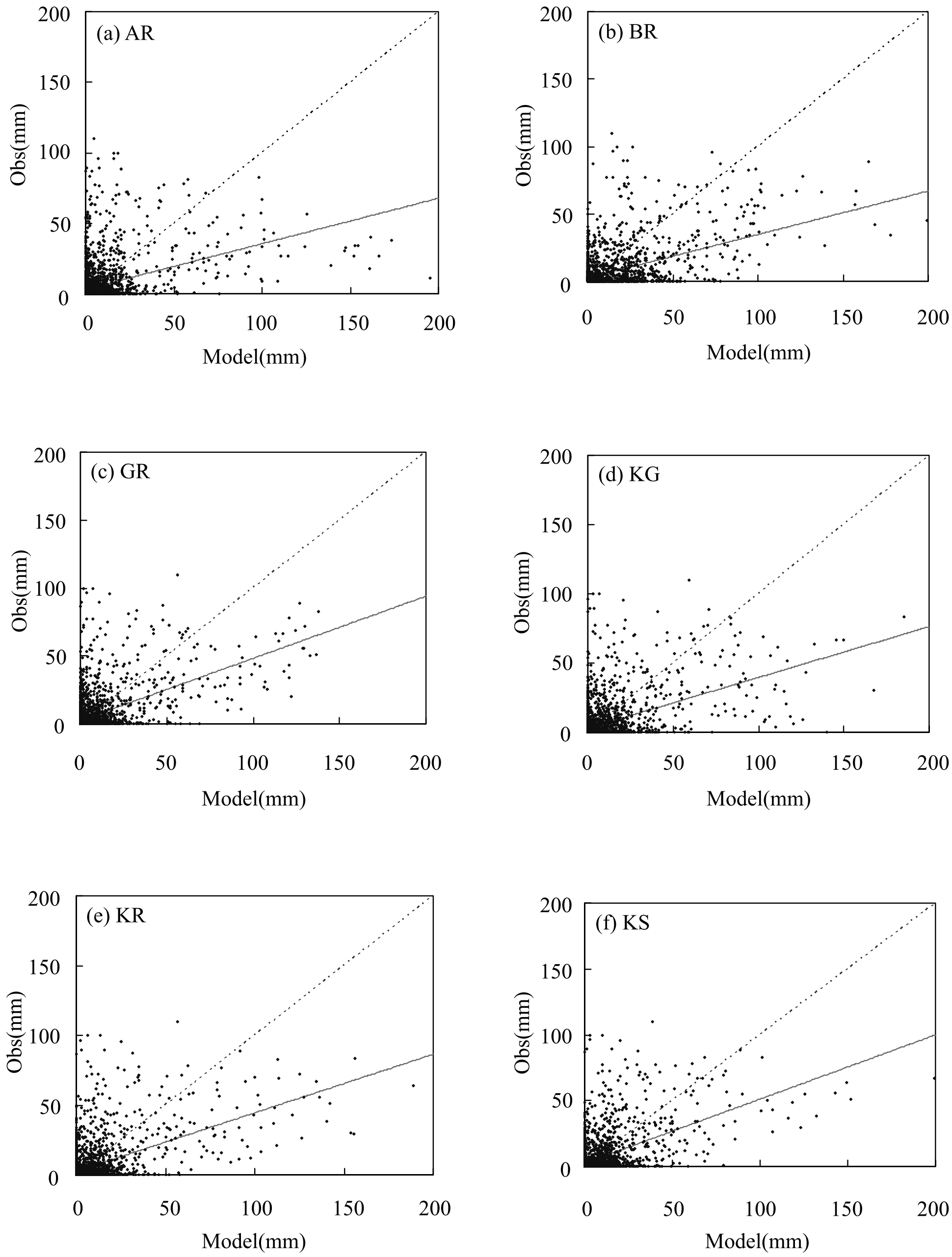

Figure 4. Scatter plots of observed 12-hour rainfall versus forecasted 12-hour rainfall by the (a) AR, (b) BR, (c) GR, (d) KG, (e) KR, and (f) KS member for the 12–24 hour forecasts during the 2000 Mei-Yu season. The solid line is the best fit line, and the dash line is the perfect-fit line.

Table 2. Root Mean Square Error (RMSE; in Millimeters) of 12-Hour Rainfall Forecasts Calculated for All 15-km MM5 Grid Points Over Taiwan During the 2000–2002 Mei-Yu Seasons[a]

Year	Forecast, hours	AR	BR	GR	KG	KR	KS
2000	12–24	16.07 (7.00)	18.61 (9.62)	13.60 (5.22)	15.65 (7.29)	14.48 (5.88)	13.02 (5.23)
	24–36	15.65 (6.80)	15.81 (6.04)	15.46 (6.08)	18.63 (8.92)	13.56 (7.79)	13.77 (5.30)
2001	12–24	16.37 (6.67)	19.12 (6.51)	17.01 (6.54)	20.42 (9.66)	19.04 (8.84)	17.43 (7.89)
	24–36	15.67 (6.91)	19.28 (7.12)	16.79 (6.65)	17.22 (6.84)	15.38 (6.31)	16.32 (6.69)
2002	12–24	13.84 (5.38)	18.34 (8.64)	13.50 (5.54)	14.15 (6.49)	19.87 (10.22)	13.30 (5.53)
	24–36	13.97 (5.55)	18.80 (6.91)	14.38 (5.82)	16.03 (7.03)	20.67 (8.43)	16.39 (6.80)
2000–2002	12–24	15.47 (4.91)	18.69 (6.48)	14.79 (4.44)	16.95 (6.20)	17.96 (6.71)	14.72 (4.99)
	24–36	15.12 (4.86)	18.03 (5.12)	15.57 (4.72)	17.32 (5.91)	16.81 (5.82)	15.54 (4.84)
2000–2002	Two 12	15.29 (4.10)	18.36 (4.98)	15.19 (3.86)	17.14 (5.10)	17.39 (5.31)	15.14 (4.13)

[a]The numbers in parenthesis are the RMSE with a 95% statistical significance level.

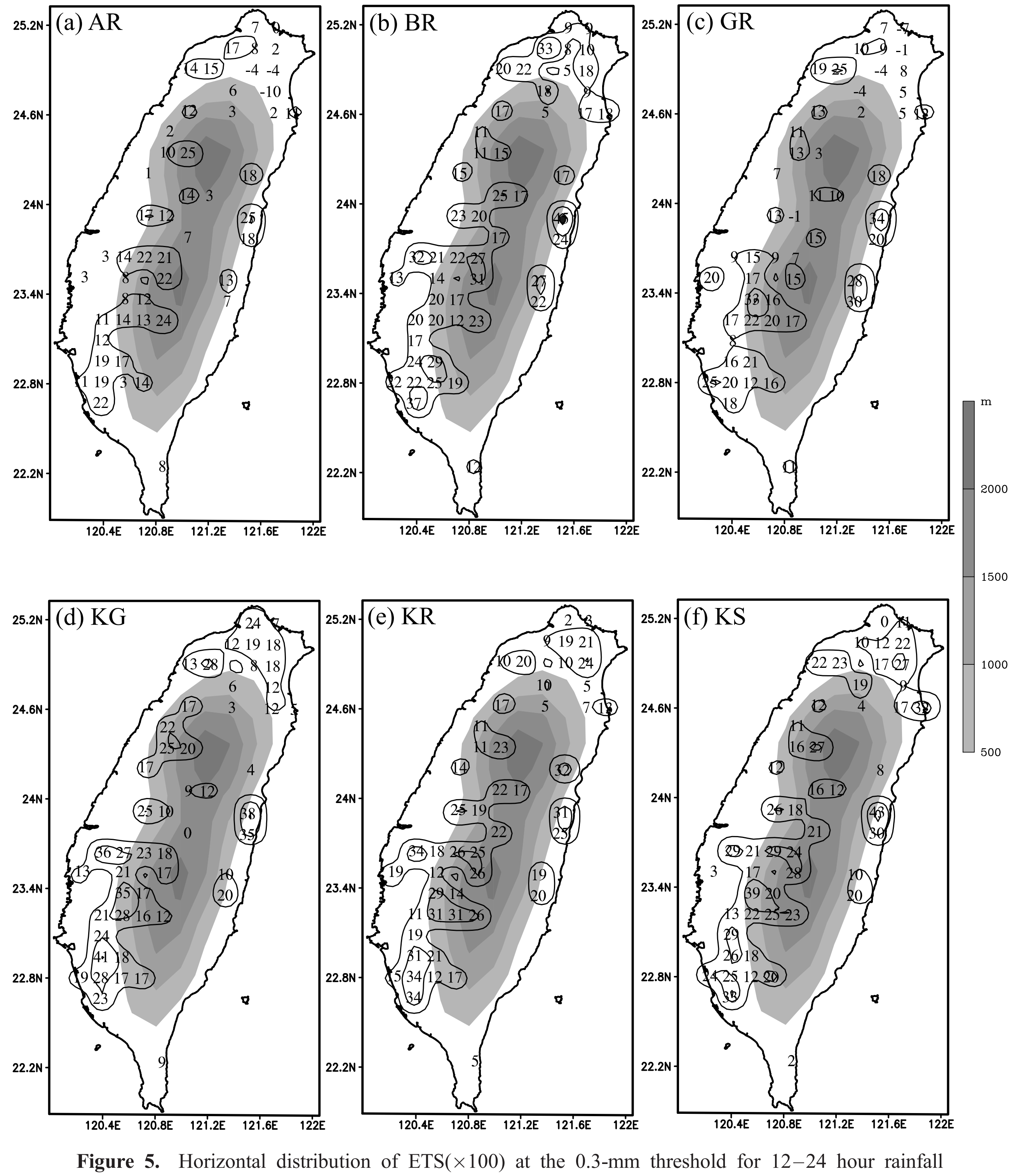

Figure 5. Horizontal distribution of ETS(×100) at the 0.3-mm threshold for 12–24 hour rainfall forecast during the 2000 Mei-Yu season for the (a) AR, (b) BR, (c) GR, (d) KG, (e) KR, and (f) KS ensemble member. The 9 and 25 ETS isopleths are contoured with solid lines. Terrain from the 15-km MM5 is shaded. See color version of this figure in the HTML.

scores, the northeastern mountainous area, northwestern coastal plain, central mountain slope, southwestern coastal plan, and southwestern mountainous area. This indicates that regardless of different precipitation physics used in each member, the 15-km MM5 can forecast the occurrence of rainfall over coastal plains and mountain slopes over Taiwan during a Mei-Yu season reasonably well. Again similar findings are also found for the 2001 and 2002 Mei-Yu seasons.

3.3. Performance of ETS and BS Over Different Precipitation Threshold

[25] Figure 7 shows the ETSs of 12–24 hour precipitation forecasts of each ensemble member versus various

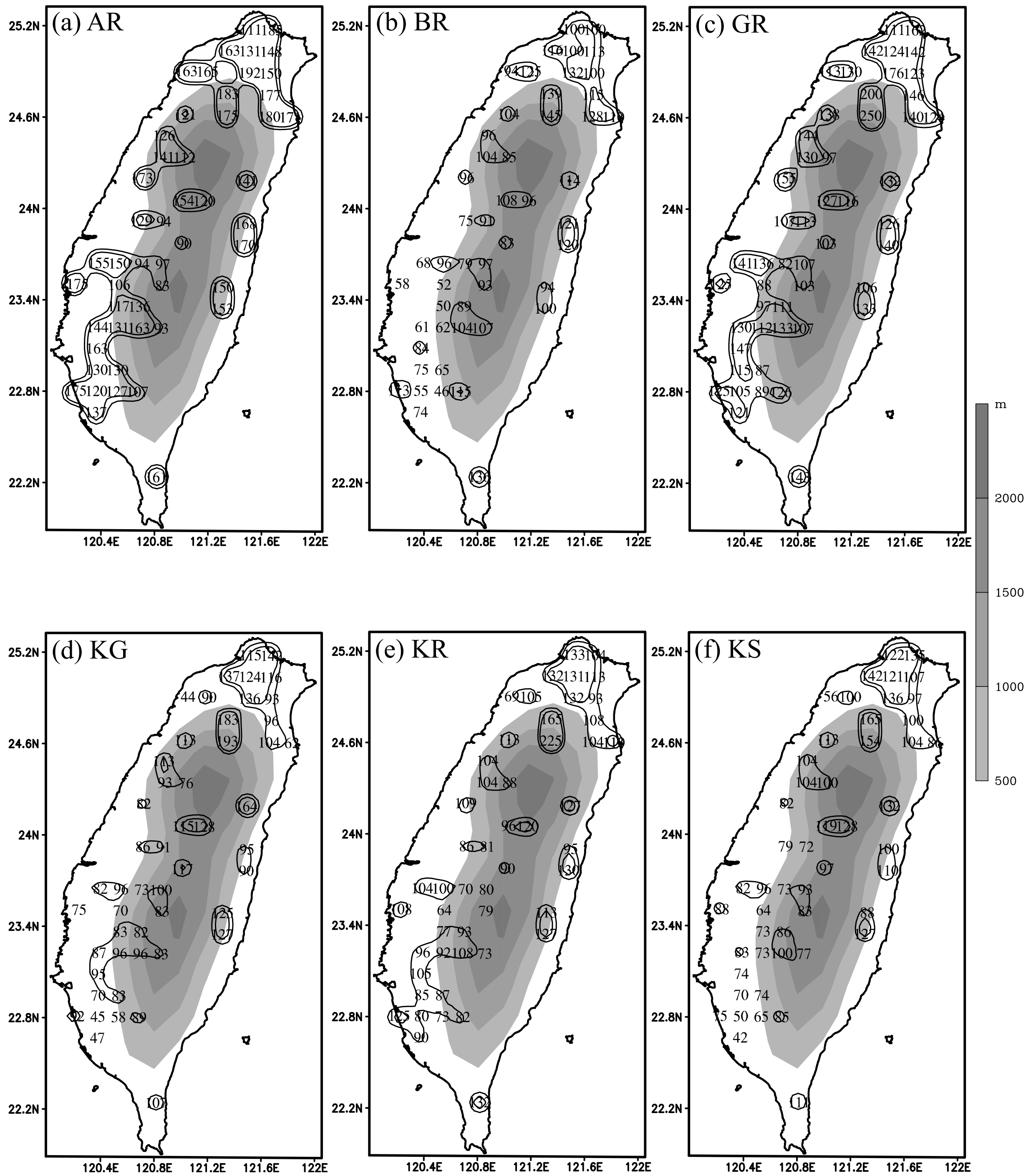

Figure 6. As in Figure 5 but for the BS. The 80% and 110% BS lines are contoured. See color version of this figure in the HTML.

thresholds for three Mei-Yu seasons. Curve AVG denotes the ETS of ensemble average forecast with each of six members having the same weighting coefficient (1/6), which was conducted in real time during these three Mei-Yu seasons. The corresponding BS result is in Figure 8. Most of ensemble members had high ETS skill for the precipitation thresholds of 15–35 mm (Figure 7a), which corresponded well to the observed averaged 12–24 hour rainfall accumulation during the 2000 Mei-Yu season. The ETS score for the average forecast was not the highest, compared to six individual members; however, this average forecast had the second- or third-best ETS score for all rainfall thresholds, consistent with *Chien and Jou* [2004]. Figure 8a further shows that for the 2000 Mei-Yu season, all members had reasonable BS performance (BS = 0.8–1.3), except for the BR experiment which had overestimation (BS > 1.5) of 12-hour rainfalls at moderate to heavy thresholds (10–50 mm).

[26] For the 2001 Mei-Yu season, most members had highest ETS performance of 12–24 hour rainfall at 2.5-mm

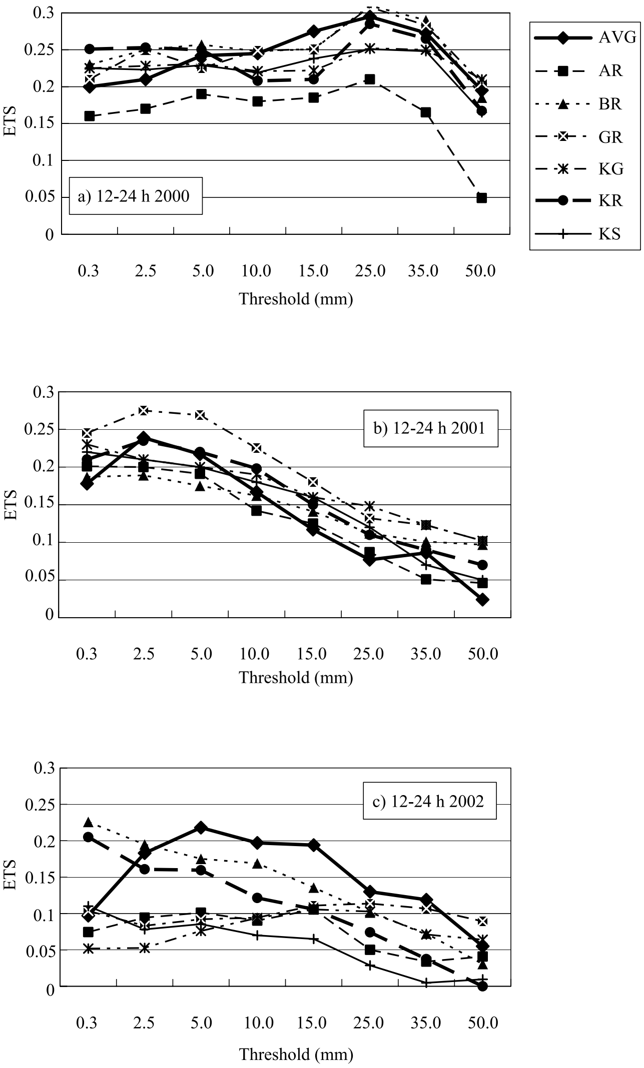

Figure 7. The ETS of 12–24 hour precipitation forecasts of each ensemble member versus various thresholds (mm) for the (a) 2000, (b) 2001, and (c) 2002 Mei-Yu season.

threshold (Figure 7b); the GR member had the best ETS skill in most rainfall thresholds, compared to other members. It is evident in Figure 7b that the skill of ETS of all six members decreased with the increase of precipitation thresholds, in agreement with other studies [*Colle et al.*, 1999; *Chien et al.*, 2002]. For the BS performance (Figure 8b), both GR and KG member had good BS skill (BS = 0.95–1.02) for all precipitation thresholds.

[27] For Year 2002 which had the least and sporadic Mei-Yu rainfalls among three consecutive Mei-Yu seasons, all MM5 members had poor ETS and BS performance compared to two previous Mei-Yu seasons. Figure 7c illustrates that during the 2002 Mei-Yu season, the members with relatively good ETS skill for the 12–24 hour rainfall forecast were BR (ETS = 0.02–0.21) and KR (ETS = 0.01–0.2), and other four members had very poor performance (ETS< 0.1). However, the average forecast had a better predictive skill by combing the advantages of all six members, and it obtained the best ETS score (ETS = 0.13–0.23) for 12-hour rainfall thresholds of 5–35 mm. Figure 8c also indicates persistent overestimation behavior (BS > 1) by four members (except for KG and GR member) for all thresholds in the 2002 Mei-Yu season.

4. Ensemble Rainfall Predictions

4.1. Ensemble Forecast by a Multiple Linear Regression

[28] Besides a real-time average ensemble forecast, an ensemble rainfall hindcast with each member having temporally and spatially varying weighting coefficient is done after each Mei-Yu season using the MLR method described in Appendix A. Weighting coefficients are determined by a minimization of the forecasted rainfall error in a least square sense for summation of all 15-km grid points over Taiwan and all forecast events in a Mei-Yu season. Note that there is no constraint for the summation of all weighting coefficients to be unity. The MLR ensemble "forecasted" rainfall is then a linear combination of forecasted rainfalls by six members.

[29] Figure 9 displays the scatter plot of observed 12-hour rainfall versus MLR forecasted 12-hour rainfall for the 12–24 hour forecast during the 2000 Mei-Yu season. Comparing with individual member's forecast (in Figure 4), it is evident that this MLR ensemble forecast significantly improves the prediction of 12–24 hour rainfall amount,

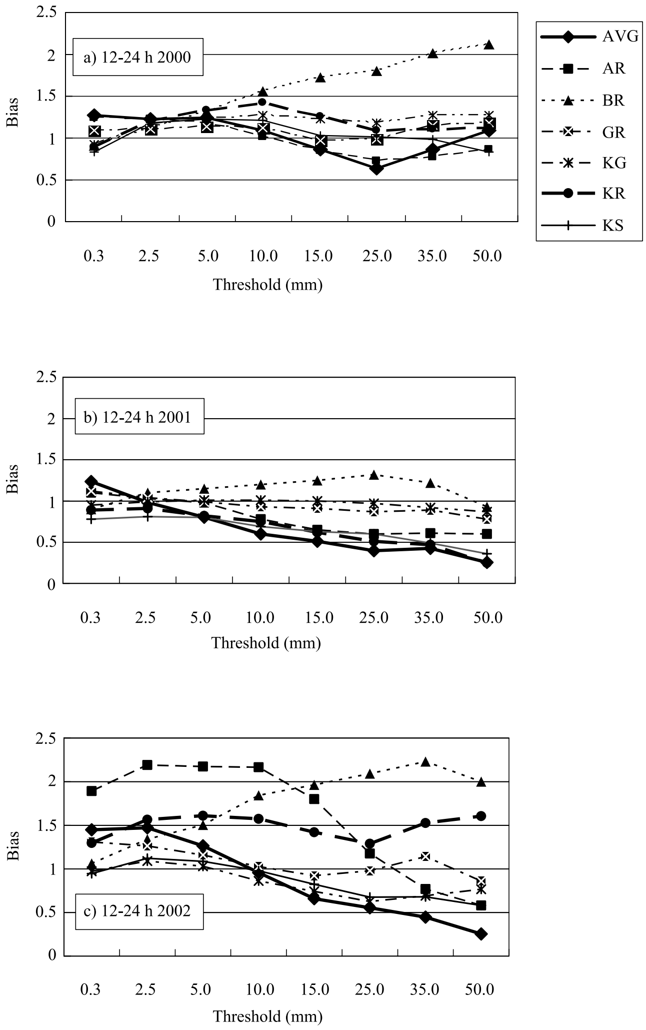

Figure 8. As in Figure 7 but for the BS.

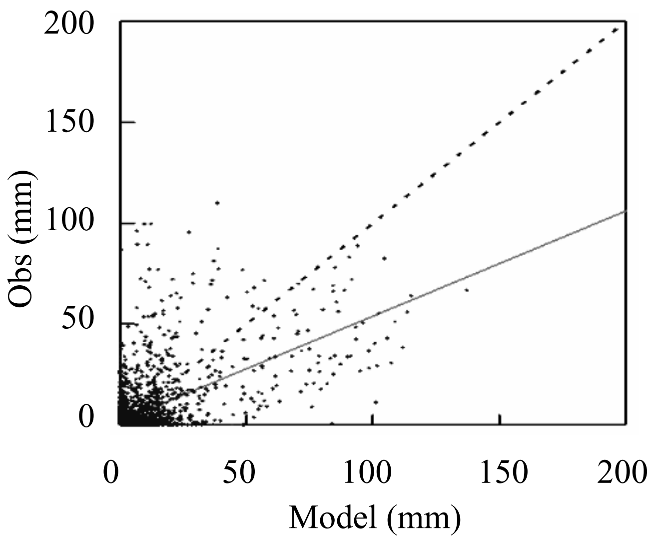

Figure 9. As in Figure 4 but for the MLR ensemble forecast.

with a correlation coefficient as high as 0.59. Similar improvements by the MLR ensemble forecasting technique are also found in the 2001 and 2002 Mei-Yu seasons, despite with lower correlation coefficients.

4.2. Rainfall Forecasts by Different Numbers of Ensemble Members

[30] Figure 10 shows the ETS and BS performance of 12–24 hour precipitation forecast of four ensembles during the 2000 Mei-Yu season. The average forecast (curve AVG) is the forecast with the same weighting coefficient (1/6) for each six member. The MLR ensemble forecast (curve MLR) is the one using the MLR method. The "cumulus" ensemble forecast (curve CPS) is the one with the same weighting coefficient (1/4) for each of four members having the same microphysics (Reisner 1) but different cumulus scheme. The "microphysics" ensemble forecast (curve MPH) is the one with the same weighting coefficient (1/3) for each of three members having the same cumulus (Kain-Fritsch) but different microphysics scheme. It is clear from Figure 10a that among four ensembles, the MLR ensemble forecasting had the best ETS predictive skill (ETS = 0.2–0.26), with the exception for medium to heavy rainfalls (12-hour rainfalls of 15–

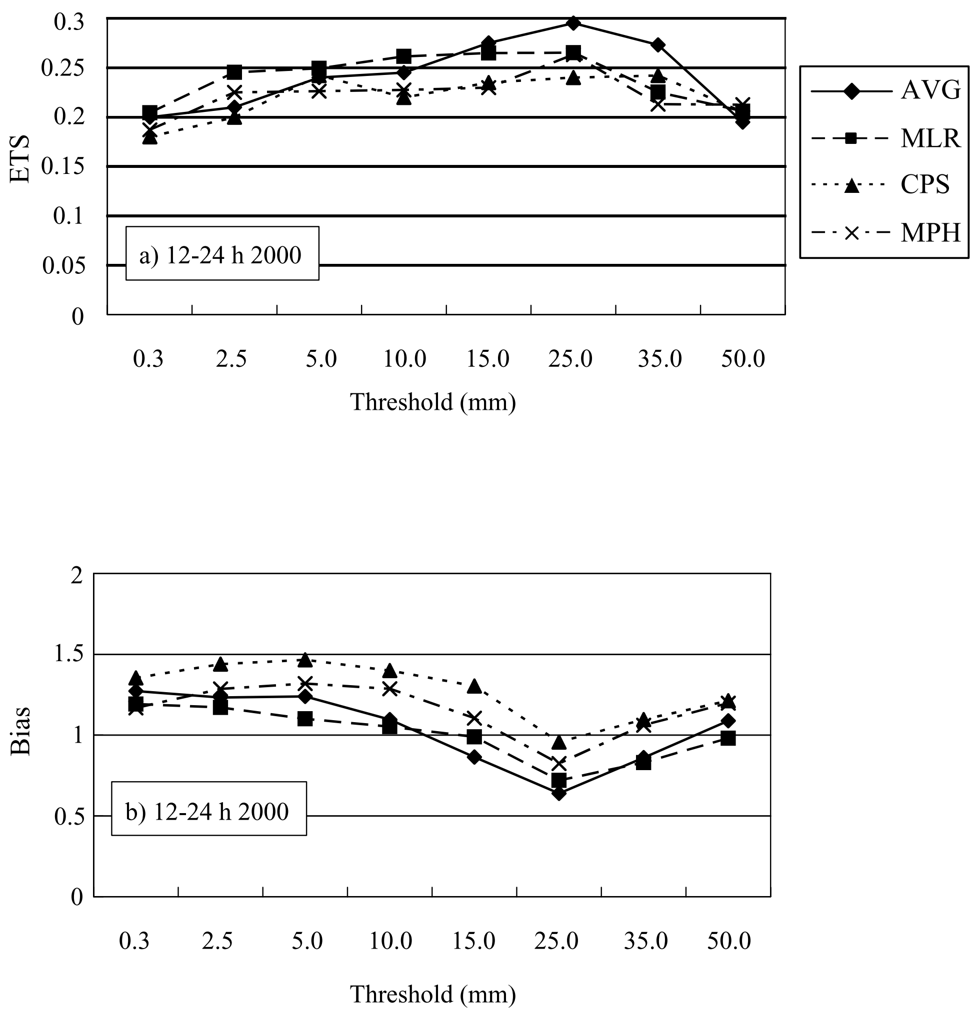

Figure 10. The (a) ETS and (b) BS of 12–24 hour precipitation forecasts of four ensemble forecasts versus various thresholds (mm) during the 2000 Mei-Yu season.

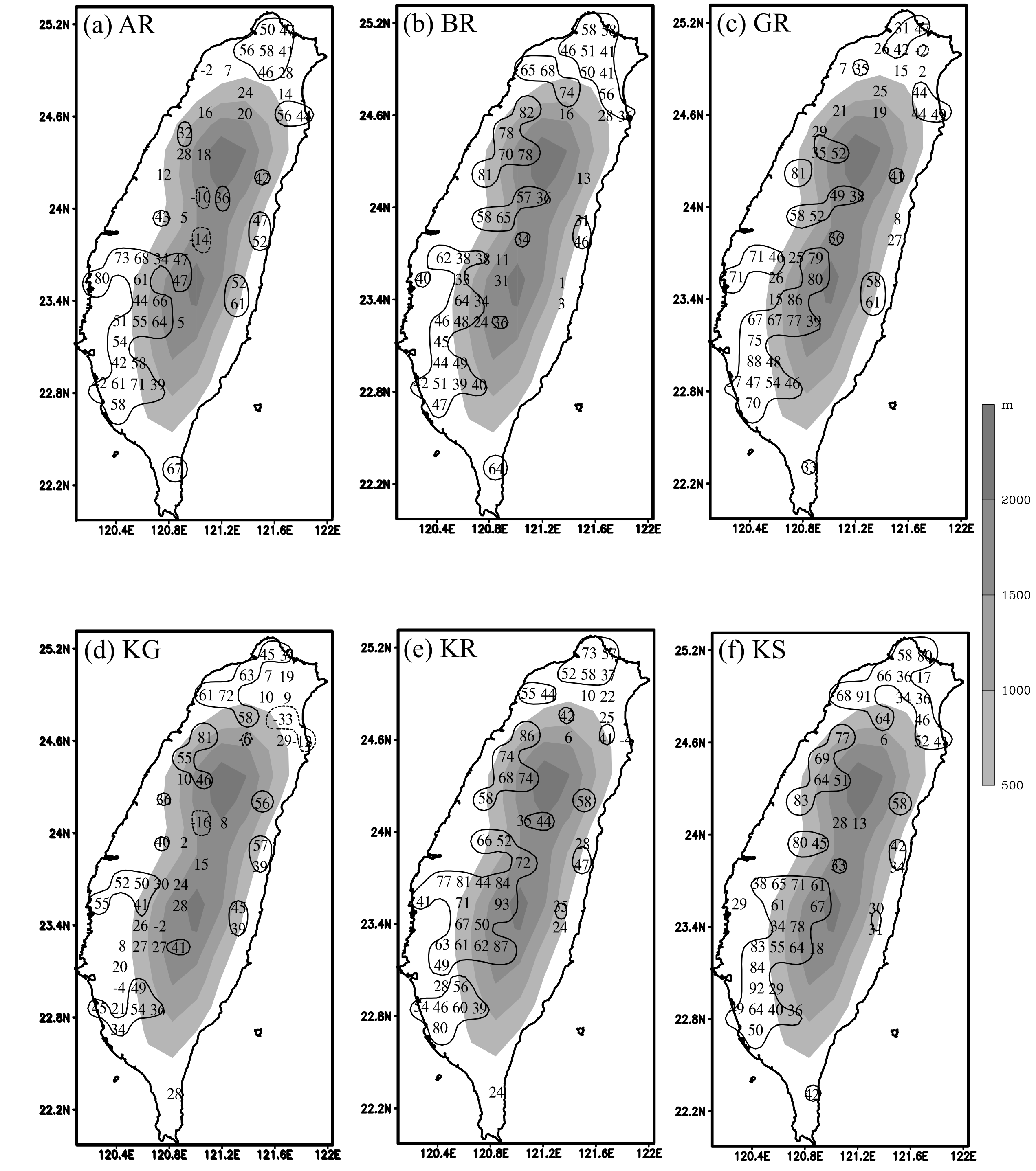

Figure 11. Horizontal distribution of weighting coefficient($\times$100) for the (a) AR, (b) BR, (c) GR, (d) KG, (e) KR, and (f) KS member in the calculation of MLR ensemble forecasted 12–24 hour rainfall during the 2000 Mei-Yu season. The 30% and -5% lines are contoured with solid and dotted lines, respectively. Terrain from the 15-km MM5 is shaded. See color version of this figure in the HTML.

35 mm) where the average forecast had the best ETS performance (ETS = 0.26–0.3). The ETS skill of either cumulus ensemble (four members) or microphysics ensemble (three members) is lower than that (AVG or MLR) of six-member ensembles. This indicates that a six-member ensemble has a better ETS skill than a four/three-member ensemble for Taiwan's Mei-Yu season rainfall.

[31] The corresponding BS skill of four ensembles during the 2000 Mei-Yu season is in Figure 10b. For all precipitation thresholds, the MLR ensemble forecasting again had the best BS predictive skill (with BS much closer to 1), and the simple average had the second best BS performance. Both four-member (CPS) and three-member (MPH) ensembles had evident overestimation for all precipitation thresh-

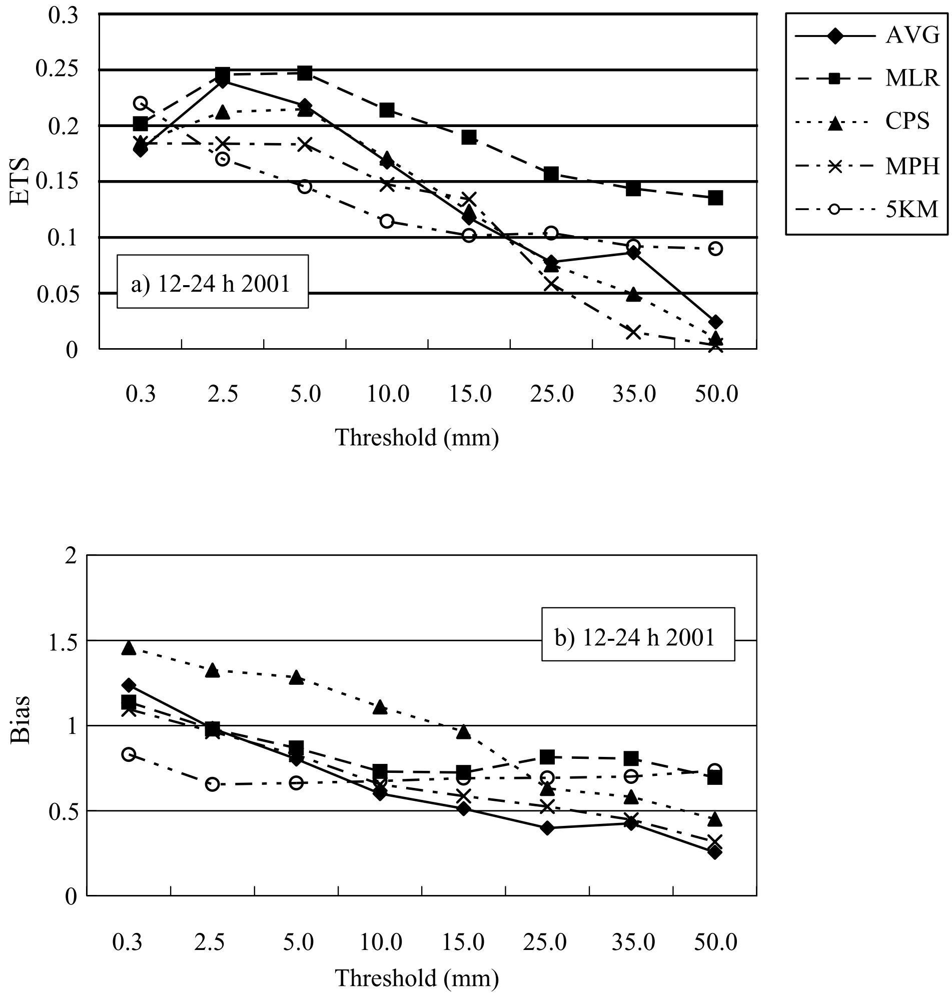

Figure 12. The (a) ETS and (b) BS of 12–24 hour rainfall forecasts of the average ensemble forecast (AVG), MLR ensemble forecast (MLR), cumulus ensemble (CPS), microphysics ensemble (MPH), and a high-resolution forecast (5KM) versus various precipitation thresholds during the 2001 Mei-Yu season.

olds. Similar results are also found for the 2001 and 2002 Mei-Yu seasons.

[32] Horizontal distribution of weighting coefficients of each member in the MLR ensemble forecasting for the 12–24 hour rainfalls during the 2000 Mei-Yu season is shown in Figure 11. All members had high weighting coefficients (greater than 0.3; sometimes even greater than 0.6) over the northeastern mountain area, central mountain slope, and southwestern mountain area; summation of all weighting coefficients is greater than one over these regions. These areas of high weighting coefficients corresponded well to areas of high ETS and BS skill (Figures 5 and 6) and were also geographical locations of more accumulated rainfalls during this Mei-Yu season (Figure 2a). Because the MLR ensemble forecasting can apply more weighting over areas where all members have higher rainfall predictive skill (in both ETS and BS), it can thus provide a better precipitation prediction than a simple average forecast.

4.3. Comparison With High-Resolution Rainfall Forecasts

[33] In order to verify the operational advantage of ensemble forecasting, a high-resolution MM5 forecast [*Hong*, 2003] with horizontal grid size nesting down to 5 km (four nested grids totally) was conducted in parallel with 15-km ensembles during the 2001 Mei-Yu season. The 45-km and 15-km domains of the fourfold-nested MM5 [see *Hong*, 2003, Figure 1] were similar to those of the double-nested MM5 (Figure 3) used by in our 15-km ensemble, and a 5-km grid with vertically 31 σ levels was further implemented on the Taiwan island. Physics options for this fourfold-nested MM5 was the same as those used by the double-nested MM5 in the ensemble, except that both the Kain-Fritch cumulus and Goddard microphysics schemes were used on the 135-km, 45-km, and 15-km grids but only Goddard microphysics scheme was used on the 5-km grid. Details of the 5-km forecasts over Taiwan during the 2001 Mei-Yu season are given in the work of *Hong* [2003]. For 5-km result shown in Figure 12, its rainfall forecast is verified on the same gird points as the 15-km ensemble.

[34] Figure 12a displays the ETS comparison of this 5-km forecast with four ensemble forecasts for 12–24 hour rainfall forecast during the 2001 Mei-Yu season, and Figure 12b is the corresponding BS comparison. It is clear from Figure 12a that the 15-km MLR ensemble rainfall forecast obviously outperformed the high-resolution (5-km)

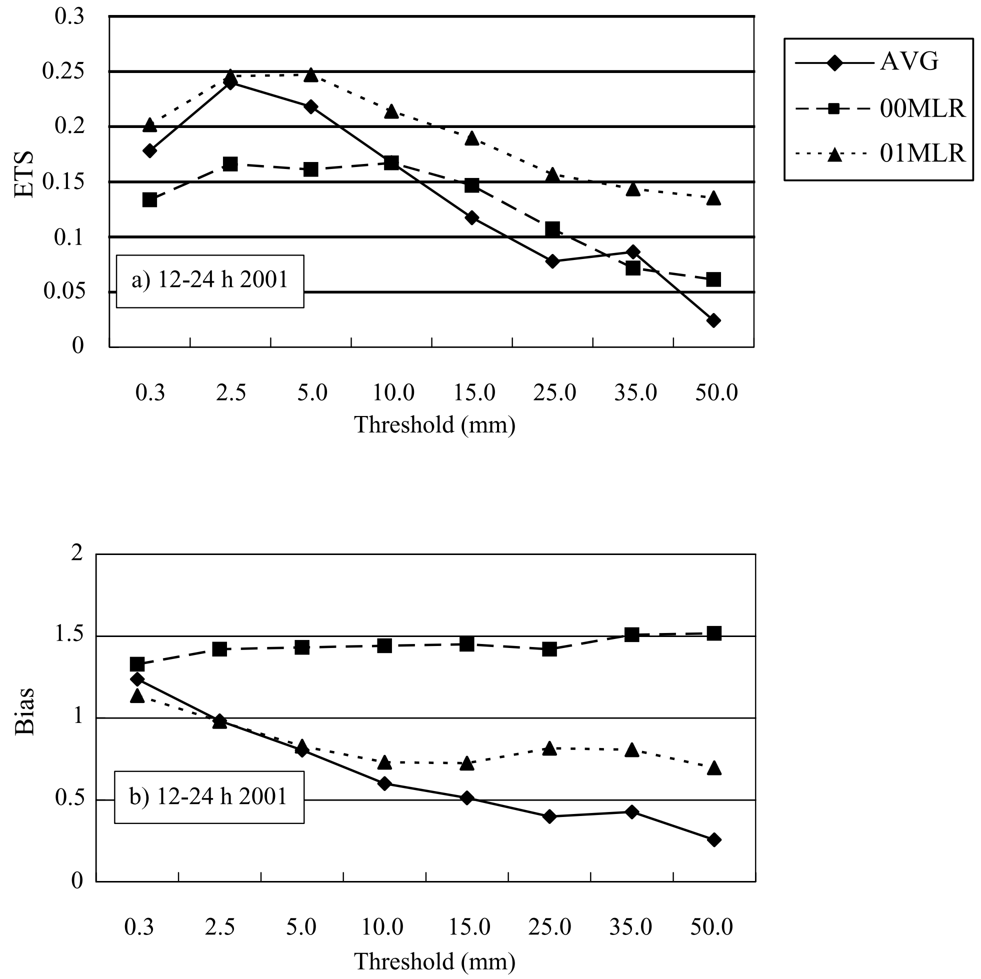

Figure 13. The (a) ETS and (b) BS of 12–24 hour rainfall forecasts of three ensemble forecasts versus different precipitation thresholds for the 2001 Mei-Yu season. See text for explanation of three ensemble forecasts.

rainfall forecast in ETS skill, except at the least precipitation threshold (0.3 mm/12 hours). For light to moderate thresholds (2.5–15 mm in 12 hours), both the six-member average forecast and four/three-member cumulus/microphysics forecasts had better ETS performance than the 5-km forecast. The 5-km forecast had better ETS skill at heavy-rainfall thresholds (25–50 mm in 12 hours). Figure 12b again shows that the 15-km MLR ensemble forecast had better BS skill compared to the single 5-km forecast. All three ensemble forecasts have overestimation at the least threshold (0.3 mm/12 hours) and underestimation for other thresholds; on the other hand, the single 5-km forecast has a persistent underestimation for all rainfall thresholds. The poor performance of 5-km forecasts may suffer from the feedbacks from the outer domains through boundary forcings, as indicated by *Warner and Hsu* [2000]. A high-resolution run, however, still has valuable information even when its ETS/BS statistical score is lower than the coarse-resolution counterparts [*Mass et al.*, 2002].

[35] The CPU time for one 5-km run was similar to that for four/three 15-km ensemble runs of the cumulus/microphysics ensembles (exact difference depended on the complexity of physics schemes), and the four/three-member ensemble had better ETS and BS skill than a single 5-km forecast for light to moderate thresholds (Figure 13). This indicates that it might be more operationally effective to perform several (at least three) low-resolution ensemble runs than one single high-resolution run, but more studies are needed to clarify this issue.

4.4. Ensemble Rainfall Forecasts Using Previous-Year Weighting Coefficients

[36] Although the MLR ensemble forecast may have the best rainfall predictive skill compared to either the average forecast or a single high-resolution forecast, the implementation of spatially and temporally varying weighting coefficients on model grid points is complicated and is done in a hindcast mode. One possible way to apply this MLR forecasting technique operationally is to use the weightings determined from previous Mei-Yu seasons or previous weeks during the same Mei-Yu season, and its result is shown in Figure 13.

[37] Figure 13a indicates that the MLR ensemble forecast using the current-year weightings (curve 01MLR) had the best ETS skill of 12–24 hour forecast for all thresholds. The MLR ensemble forecast using previous-year weightings (curve 00MLR) had similar ETS trends

for different thresholds to that of current-year MLR ensemble, albeit with less skill, and it still outperformed the average forecast for moderate to high rainfalls (10 mm or more in 12 hours). The MLR forecast using the current-year weightings (curve 01MLR) also had the best BS skill of 12–24 hour forecast for all precipitation thresholds (Figure 13b); however, the MLR forecast using previous-year weightings (curve 00MLR) had obvious overestimation for all rainfall thresholds with BS persistently greater than one.

5. Conclusions and Discussion

[38] This paper reports the first effort on real-time ensemble forecasting of rainfall during the 2000–2002 Mei-Yu seasons over the Taiwan area. Six members were included in the ensemble, using the Penn State/NCAR MM5 with a double-nested grid (45 km/15 km). Each member had the same model setting but with different combinations of subgrid-scale cumulus and grid-scale microphysics schemes. Forecast period for each member was 36 hours and 58 forecasts were performed by each member in a Mei-Yu season. Rainfall predictions were verified against high-density rain gauge observations, and the predictive skill of each member was compared using the ETS and BS scores. Impacts on rainfall forecasts due to initial condition uncertainties are not addressed in this study.

[39] Comparing the RMSEs of forecasted 12–24 and 24–36 hour rainfalls over three Mei-Yu seasons, it was found that no one member persistently outperformed others (had the least RMSE) in both 12-hour periods. For the rainfall occurrence prediction (i.e., for the 12-hour rainfall threshold of 0.3 mm), most members had better ETS performance over the northeastern mountainous area, northwestern coastal plain, central mountain slope, southwestern coastal plan, and southwestern mountainous area. These regions also corresponded well to areas of more accumulated rainfalls in the Mei-Yu seasons.

[40] Through detailed examination of precipitation predictions by four kinds of ensemble forecasts, it is found that the ensemble forecast using a multiple linear regression (MLR) technique had the best ETS and BS skill. Two six-member ensembles (MLR and average) persistently outperformed the four-member cumulus and three-member microphysics ensembles for all rainfall thresholds. A simple bias correction to a given model setting could also improve rainfall performance, compared to the MLR and average ensemble forecasts, but many years of simulations are required to have enough data to perform bias correction.

[41] During the 2001 Mei-Yu season, a single high-resolution (5-km grid size) forecast was performed in parallel with 15-km ensemble forecasts. The MLR ensemble rainfall forecast had a persistently higher ETS/BS skill than that of the single 5-km forecast for all precipitation thresholds, except at the least threshold (0.3 mm). The CPU time for a single 5-km forecast was similar to that of four/three-member 15-km average forecast, and the 15-km four/three-member average forecast had better ETS/BS performance than the single 5-km forecast for light to medium rainfalls. This implies that it might be more effective to perform several low-resolution ensemble runs than one high-resolution run, but more studies are needed before reaching a generalized conclusion.

[42] The MLR ensemble rainfall forecast, using the weighting coefficients determined from previous Mei-Yu seasons, still had similar ETS trend to the ensemble forecast with weightings determined by current-year Mei-Yu season, despite with a less skill. This implies that rainfalls during Taiwan's Mei-Yu season may have certain climatological characteristics associated with topography and prevailing wind, and an ensemble forecast using the MLR method could capture this climatological attribute. Therefore one way to apply this MLR ensemble forecasting technique operationally is to use the spatially and temporally varying weightings determined from previous Mei-Yu seasons or previous weeks in the same Mei-Yu season.

[43] Finally, the rainfall forecast of a NWP model has inherent limitation associated with the uncertainties of precipitation (cumulus and microphysics) parameterizations, as well as uncertainty of initial conditions and deficiency of other physical parameterizations and numerical schemes. Taiwan's steep terrain and rich weather phenomena make the limitation of model's rainfall forecast more severe. More work is needed to investigate the application of ensemble forecasting technique to other types of weather systems and to other geographical locations with different large- and synoptic-scale forcings.

Appendix A: Ensemble Rainfall Forecast Using the Multiple Linear Regression Method

[44] Assume the observed rainfall (O) on a model grid point can be fitted by forecasted rainfalls of ensemble members (m) in a multiple linear regression analysis as

$$\begin{bmatrix} O_1 \\ O_2 \\ O_3 \\ \vdots \\ \vdots \\ O_N \end{bmatrix} = \alpha \begin{bmatrix} (m_1)_1 \\ (m_1)_2 \\ (m_1)_3 \\ \vdots \\ \vdots \\ (m_1)_N \end{bmatrix} + \beta \begin{bmatrix} (m_2)_1 \\ (m_2)_2 \\ (m_2)_3 \\ \vdots \\ \vdots \\ (m_2)_N \end{bmatrix} + \gamma \begin{bmatrix} (m_3)_1 \\ (m_3)_2 \\ (m_3)_3 \\ \vdots \\ \vdots \\ (m_3)_N \end{bmatrix} + \kappa \begin{bmatrix} (m_4)_1 \\ (m_4)_2 \\ (m_4)_3 \\ \vdots \\ \vdots \\ (m_4)_N \end{bmatrix} + \delta \begin{bmatrix} (m_5)_1 \\ (m_5)_2 \\ (m_5)_3 \\ \vdots \\ \vdots \\ (m_5)_N \end{bmatrix} + \varepsilon \begin{bmatrix} (m_6)_1 \\ (m_6)_2 \\ (m_6)_3 \\ \vdots \\ \vdots \\ (m_6)_N \end{bmatrix} - \begin{bmatrix} r_1 \\ r_2 \\ r_3 \\ \vdots \\ \vdots \\ r_N \end{bmatrix}, \quad \text{(A1)}$$

where m_1 represents the forecasted rainfall of the first ensemble member, m_2 represents forecasted rainfall of the second member, and so on (six members totally). α, β, γ, κ, δ, ε are weighting coefficients for ensemble members. N is the total sampling size (58 forecast events in a Mei-Yu season), and r is the forecast difference. Note that there is no constraint for the summation of all weighting coefficients to be unity.

[45] One can rewrite (A1) in a vector form as

$$\vec{O} = \alpha\vec{m}_1 + \beta\vec{m}_2 + \gamma\vec{m}_3 + \kappa\vec{m}_4 + \delta\vec{m}_5 + \varepsilon\vec{m}_6 - \vec{r}, \tag{A2}$$

then the forecasted rainfall difference can be expressed as

$$\vec{r} = \alpha\vec{m}_1 + \beta\vec{m}_2 + \gamma\vec{m}_3 + \kappa\vec{m}_4 + \delta\vec{m}_5 + \varepsilon\vec{m}_6 - \vec{O}, \tag{A3}$$

so the square of difference is

$$r^2 = \left(\alpha\vec{m}_1 + \beta\vec{m}_2 + \gamma\vec{m}_3 + \kappa\vec{m}_4 + \delta\vec{m}_5 + \varepsilon\vec{m}_6 - \vec{O}\right)^2. \tag{A4}$$

In order to minimize the square of difference in a least-square sense, we let

$$\frac{\partial r^2}{\partial\alpha} = 0 = 2\vec{m}_1 \cdot \left(\alpha\vec{m}_1 + \beta\vec{m}_2 + \gamma\vec{m}_3 + \kappa\vec{m}_4 + \delta\vec{m}_5 + \varepsilon\vec{m}_6 - \vec{O}\right),$$
$$\frac{\partial r^2}{\partial\beta} = 0 = 2\vec{m}_2 \cdot \left(\alpha\vec{m}_1 + \beta\vec{m}_2 + \gamma\vec{m}_3 + \kappa\vec{m}_4 + \delta\vec{m}_5 + \varepsilon\vec{m}_6 - \vec{O}\right),$$
$$\frac{\partial r^2}{\partial\gamma} = 0 = 2\vec{m}_3 \cdot \left(\alpha\vec{m}_1 + \beta\vec{m}_2 + \gamma\vec{m}_3 + \kappa\vec{m}_4 + \delta\vec{m}_5 + \varepsilon\vec{m}_6 - \vec{O}\right),$$
$$\frac{\partial r^2}{\partial\kappa} = 0 = 2\vec{m}_4 \cdot \left(\alpha\vec{m}_1 + \beta\vec{m}_2 + \gamma\vec{m}_3 + \kappa\vec{m}_4 + \delta\vec{m}_5 + \varepsilon\vec{m}_6 - \vec{O}\right),$$
$$\frac{\partial r^2}{\partial\delta} = 0 = 2\vec{m}_5 \cdot \left(\alpha\vec{m}_1 + \beta\vec{m}_2 + \gamma\vec{m}_3 + \kappa\vec{m}_4 + \delta\vec{m}_5 + \varepsilon\vec{m}_6 - \vec{O}\right),$$
$$\frac{\partial r^2}{\partial\varepsilon} = 0 = 2\vec{m}_6 \cdot \left(\alpha\vec{m}_1 + \beta\vec{m}_2 + \gamma\vec{m}_3 + \kappa\vec{m}_4 + \delta\vec{m}_5 + \varepsilon\vec{m}_6 - \vec{O}\right),$$

and then the above six equations can be rewritten in a matrix form as

$$\underbrace{\begin{bmatrix} \vec{m}_1\cdot\vec{m}_1 & \vec{m}_1\cdot\vec{m}_2 & \vec{m}_1\cdot\vec{m}_3 & \vec{m}_1\cdot\vec{m}_4 & \vec{m}_1\cdot\vec{m}_5 & \vec{m}_1\cdot\vec{m}_6 \\ \vec{m}_2\cdot\vec{m}_1 & \vec{m}_2\cdot\vec{m}_2 & \vec{m}_2\cdot\vec{m}_3 & \vec{m}_2\cdot\vec{m}_4 & \vec{m}_2\cdot\vec{m}_5 & \vec{m}_2\cdot\vec{m}_6 \\ \vec{m}_3\cdot\vec{m}_1 & \vec{m}_3\cdot\vec{m}_2 & \vec{m}_3\cdot\vec{m} & \vec{m}_3\cdot\vec{m}_4 & \vec{m}_3\cdot\vec{m}_5 & \vec{m}_3\cdot\vec{m}_6 \\ \vec{m}_4\cdot\vec{m}_1 & \vec{m}_4\cdot\vec{m} & \vec{m}_4\cdot\vec{m}_3 & \vec{m}_4\cdot\vec{m}_4 & \vec{m}_4\cdot\vec{m}_5 & \vec{m}_4\cdot\vec{m}_6 \\ \vec{m}_5\cdot\vec{m}_1 & \vec{m}_5\cdot\vec{m} & \vec{m}_5\cdot\vec{m}_3 & \vec{m}_5\cdot\vec{m}_4 & \vec{m}_5\cdot\vec{m}_5 & \vec{m}_5\cdot\vec{m}_6 \\ \vec{m}_6\cdot\vec{m}_1 & \vec{m}_6\cdot\vec{m}_2 & \vec{m}_6\cdot\vec{m}_3 & \vec{m}_6\cdot\vec{m}_4 & \vec{m}_6\cdot\vec{m}_5 & \vec{m}_6\cdot\vec{m}_6 \end{bmatrix}}_{\mathbf{A}} \underbrace{\begin{bmatrix} \alpha \\ \beta \\ \gamma \\ \kappa \\ \delta \\ \varepsilon \end{bmatrix}}_{\mathbf{B}} = \underbrace{\begin{bmatrix} \vec{m}_1\cdot\vec{O} \\ \vec{m}_2\cdot\vec{O} \\ \vec{m}_3\cdot\vec{O} \\ \vec{m}_4\cdot\vec{O} \\ \vec{m}_5\cdot\vec{O} \\ \vec{m}_6\cdot\vec{O} \end{bmatrix}}_{\mathbf{C}}. \tag{A5}$$

Therefore the minimization relationship in (A5) can be expressed as

$$\mathbf{AB} = \mathbf{C}, \tag{A6}$$

and the element of the matrix $\mathbf{B}(= \mathbf{A}^{-1}\mathbf{C})$ is the weighting coefficient of each member to be used to determine the ensemble forecasted rainfall in (A1).

[46] **Acknowledgments.** The authors would like to thank the Central Weather Bureau and Civil Aeronautics Administration in Taiwan for their supports of the Mei-Yu season Ensemble Forecast Experiment which has been conducted since 2000. Thanks also go to Fang-Ching Chien for his cooperation during the experiment, P.-J. Sheu for his help on the multiple linear regression technique, and Quen-Chi Tung for graphics assistance. Constructive comments and suggestions of reviewers improve this paper substantially. Use of the MM5 was made possible by the Mesoscale and Microscale Meteorological Division of the National Center for Atmospheric Research. This research was supported by the National Science Council in Taiwan under grants NSC 92-2119-M-008-006-AP1, NSC 92-2111-M-002-020-AP2, NSC 92-2625-Z-008-006, and NSC 92-2625-Z-008-007 (IHS Publication Series 18).

References

Anthes, R. A. (1977), A cumulus parameterization scheme utilizing a one-dimensional cloud model, *Mon. Weather Rev.*, *105*, 270–286.

Betts, A. K., and M. J. Miller (1986), A new convective adjustment scheme. Part II: Single column tests using GATE wave, BOMEX, ATEX, and Arctic air-mass data sets, *Q. J. R. Meteorol. Soc.*, *112*, 693–709.

Chen, C.-S., and Y.-L. Chen (2003), The rainfall characteristics of Taiwan, *Mon. Weather Rev.*, *131*, 1323–1341.

Chen, G. T.-J. (1983), Observational aspects of the Mei-Yu phenomena in subtropical China, *J. Meteorol. Soc. Jpn.*, *61*, 306–312.

Chen, G. T.-J., and S. S. Chi (1980), On the frequency and speed of Mei-Yu front over southern China and the adjacent areas, *Pap. Meteorol. Res.*, *3*, 31–42.

Chen, G. T.-J., and C.-C. Yu (1988), Study of low-level jet and extremely heavy rainfall over northern Taiwan in the Mei-Yu season, *Mon. Weather Rev.*, *116*, 884–891.

Chen, G. T.-J., C.-H. Wang, and S. C.-S. Liu (2003), Potential vorticity diagnosis of a Mei-Yu front case, *Mon. Weather Rev.*, *131*, 2680–2696.

Chen, Y.-L., and J. Li (1995), Large-scale conditions favorable for the development of heavy rainfall during TAMEX, *Mon. Weather Rev.*, *123*, 2978–3002.

Chien, F.-C., and B. J.-D. Jou (2004), MM5 ensemble precipitation forecasts in the Taiwan area for three early-summer convective (Mei-yu) seasons, *Weather Forecast*, in press.

Chien, F.-C., Y.-H. Kuo, and M.-J. Yang (2002), Precipitation forecast of the MM5 in Taiwan area during the 1998 Mei-Yu season, *Weather Forecast.*, *17*, 739–754.

Colle, B. A., K. J. Westrick, and C. F. Mass (1999), Evaluation of MM5 Eta-10 precipitation forecasts over the Pacific Northwest during the cool season, *Weather Forecast.*, *14*, 137–154.

Colle, B. A., J. B. Olson, and J. S. Tongue (2003), Multiseason verification of the MM5. Part II: Evaluation of high-resolution precipitation forecasts over the northeastern United States, *Weather Forecast.*, *18*, 458–480.

Dudhia, J. (1989), Numerical study of convection observed during the winter monsoon experiment using a mesoscale two-dimensional model, *J. Atmos. Sci.*, *46*, 3077–3107.

Grell, G. A. (1993), Prognostic evaluation of assumptions used by cumulus parameterizations, *Mon. Weather Rev.*, *121*, 764–787.

Grell, G. A., J. Dudhia, and D. R. Stauffer (1994), A description of the fifth-generation Penn State/NCAR mesoscale model (MM5), *NCAR Tech. Note NCAR/TN-398+STR*, 117 pp., Boulder, Colo.

Grimit, E. P., and C. F. Mass (2002), Initial results of a mesoscale short-range ensemble forecasting system over the Pacific northwest, *Weather Forecast.*, *17*, 192–205.

Hamill, T. M. (1999), Hypothesis tests for evaluating numerical precipitation forecasts, *Weather Forecast.*, *14*, 155–167.

Hong, J.-S. (2003), Evaluation of the high-resolution model forecasts over the Taiwan area during GIMEX, *Weather Forecast.*, *18*, 836–846.

Hong, S.-Y., and H.-L. Pan (1996), Nonlocal boundary layer vertical diffusion in a medium-range forecast model, *Mon. Weather Rev.*, *124*, 2322–2339.

Kain, J. S., and J. M. Fritsch (1993), Convective parameterization for mesoscale models: The Kain-Fritsch scheme, in *The Representation of Cumulus Convection in Numerical Models*, *Meteorol. Monogr.*, vol. 46, edited by K. A. Emanuel and D. J. Raymond, pp. 165–170, Am. Meteorol. Soc., Boston, Mass.

Krishnamurti, T. N., C. M. Kishtawal, T. E. LaRow, D. R. Bachiochi, Z. Zhang, C. E. Williford, S. Gadgil, and S. Surendran (1999), Improved weather and seasonal climate forecasts from multimodel superensemble, *Science*, *285*, 1548–1550.

Krishnamurti, T. N., C. M. Kishtawal, Z. Zhang, T. Larow, D. Bachiochi, and E. Williford (2000), Multimodel ensemble forecasts for weather and seasonal climate, *J. Clim.*, *13*, 4196–4216.

Kuo, H.-L. (1974), Further studies of the parameterization of the influence of cumulus convection on large-scale flow, *J. Atmos. Sci.*, *31*, 1232–1240.

Kuo, Y.-H., and G. T.-J. Chen (1990), The Taiwan Area Mesoscale Experiment (TAMEX): An overview, *Bull. Am. Meteorol. Soc.*, *71*, 488–503.

Liou, C.-S., J.-H. Chen, C.-T. Terng, F.-J. Wang, C.-T. Fong, T. E. Rosmond, H.-C. Kuo, C.-H. Shiao, and M.-D. Cheng (1997), The second generation global forecast system at the Central Weather Bureau in Taiwan, *Weather Forecast.*, *12*, 653–663.

Lorenz, E. N. (1963), Deterministic nonperiodic flow, *J. Atmos. Sci.*, *20*, 130–141.

Mass, C. F., D. Ovens, K. Westrick, and B. A. Colle (2002), Does increasing horizontal resolution produce more skillful forecasts?, *Bull. Am. Meteorol. Soc.*, *83*, 407–430.

McBride, J. L., and E. E. Ebert (2000), Verification of quantitative precipitation forecasts from operational numerical weather prediction models over Australia, *Weather Forecast.*, *15*, 103–121.

Molteni, F., R. Buizza, T. N. Palmer, and T. Petroliagis (1996), The ECMWF ensemble prediction system: Methodology and validation, *Q. J. R. Meteorol. Soc.*, *122*, 73–119.

Mullen, S. L., J. Du, and F. Sanders (1999), The dependence of ensemble dispersion on analysis-forecast systems: Implications to short-range ensemble forecasting of precipitation, *Mon. Weather Rev.*, *127*, 1674–1686.

Reisner, J., R. T. Bruintjes, and R. J. Rasmussen (1998), Explicit forecasting of supercooled water in winter storms using the MM5 mesoscale model, *Q. J. R. Meteorol. Soc.*, *124B*, 1071–1107.

Stensrud, D. J., J.-W. Bao, and T. T. Warner (2000), Using initial condition and model physics perturbations in short-range ensemble simulations of mesoscale convective systems, *Mon. Weather Rev.*, *128*, 2077–2107.

Tao, W.-K., and J. Simpson (1993), The Goddard cumulus ensemble model. Part I: Model description, *Terr. Atmos. Oceanic Sci.*, *4*, 35–72.

Wang, W., and N. L. Seaman (1997), A comparison study of convective parameterization schemes in a mesoscale model, *Mon. Weather Rev.*, *125*, 252–278.

Warner, T. T., and H. M. Hsu (2000), Nested-model simulation of moist convection: The impact of coarse-grid parameterized convection on fine-grid resolved convection, *Mon. Weather Rev.*, *128*, 2211–2231.

Yang, M.-J., and Q.-C. Tung (2003), Evaluation of rainfall forecasts over Taiwan by four cumulus parameterization schemes, *J. Meteorol. Soc. Jpn.*, *81*, 1163–1183.

Yang, M.-J., F.-C. Chien, and M.-D. Cheng (2000), Precipitation parameterization in a simulated Mei-Yu front, *Terr. Atmos. Oceanic Sci.*, *11*, 393–422.

Yeh, H.-C., and Y.-L. Chen (1998), Characteristics of rainfall distribution over Taiwan during TAMEX, *J. Appl. Meteorol.*, *37*, 1457–1469.

J.-S. Hong and J.-H. Teng, Central Weather Bureau, Taipei 100, Taiwan.

B. J.-D. Jou, Department of Atmospheric Sciences, National Taiwan University, Taipei 106, Taiwan.

H.-C. Lin, Civil Aeronautics Administration, Taipei 105, Taiwan.

P.-L. Lin, Department of Atmospheric Sciences, National Central University, Chung-Li 320, Taiwan.

S.-C. Wang, Department of Atmospheric Sciences, Chinese Culture University, Taipei 111, Taiwan.

M.-J. Yang, Institute of Hydrological Sciences, National Central University, 300 Chung-Da Road, Chung-Li, 320 Taiwan. (mingjen@cc.ncu.edu.tw)