Ensemble Forecast of Rainfall over the Taiwan Area during the 2000-2002 Mei-Yu Seasons

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Outline

- Objectives
- Methodology
- Model and Experimental Design
- Evaluation Methods
- Rainfall Forecast Evaluation Results

Objectives

- How is the ability of the 15-km MM5 simulating rainfall over Taiwan during the 2000-2002 Mei-Yu seasons?
- How does the MM5 precipitation forecast evaluation change with rainfall thresholds and forecast periods?
- How does different combination of cumulus and microphysics scheme affect precipitation forecasts over Taiwan during the 2000-2002 Mei-Yu seasons?
- Can an ensemble forecast really provide a better precipitation forecast? If yes, how much is the gain?

Verification Data

- CWB's islandwide 343 automatic raingauge observations
- MM5 forecasted 12-h rainfalls during the 2000-2002 Mei-Yu seasons by six ensemble members (NTU, NCU, NTNU, CCU, CWB, CAA)

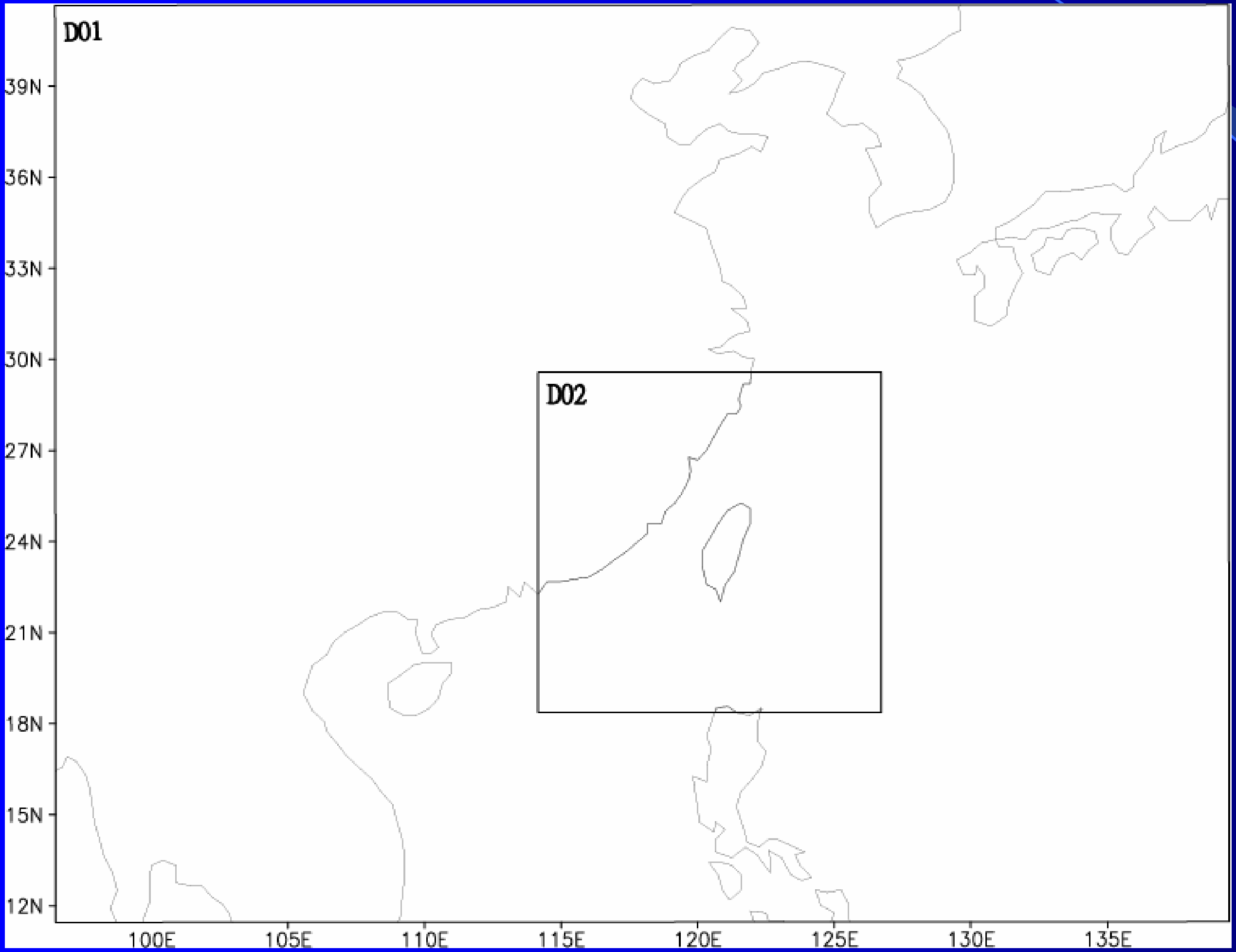
Precipitation Physics Combination of Ensemble Members

Member	Cumulus	Microphysics	Site
BM-R1	Betts-Miller	Reisner 1	NCU
KF-SI	Kain-Fritsch	Simple Ice	NTNU
KF-GD	Kain-Fritsch	Goddard	CCU
AK-SI	Anthes-Kuo	Simple Ice	CWB
GR-R1	Grell	Reisner 1	NTU
KF-R1	Kain-Fritsch	Reisner 1	CAA

Evaluation Method

- First, interpolate raingauge observations into the MM5 grid points using an arithmetic averaging.
- Then, construct a rainfall contingency table based on observed and forecasted rainfalls.
- Produce an ensemble forecast of rainfall using a multiple linear regression (MLR) method
- Evaluate rainfall forecasts of six members and the MLR ensemble mean

MM5 Configuration



- Grid Size

  D1：45 km

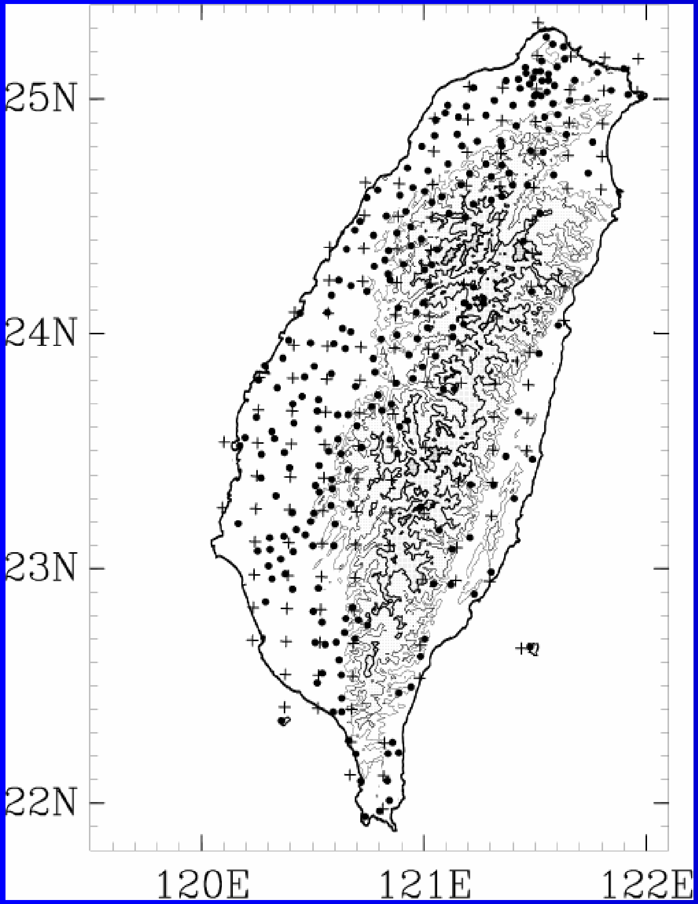
  D2：15 km

- Grid Points

  D1：71Ｘ81

  D2：79Ｘ79

Grid-Point Rainfall Analysis



- Arithmetic Averaging:

$$A_k^a = \frac{\sum_{i=1}^{N} (A_i^o)}{N}$$

N is number of raingauge stations inside a 15-km MM5 grid;

A_k^a is the analyzed rainfall on a MM5 grd;

A_i^o is the observed rainfall by raingauge.

•Raingauge (dot): 343 points

•MM5 grid (cross): 140 points on Taiwan

51 points for verification

(after data screening)

Ensemble rainfall forecast using a multiple linear regression (MLR) method: (Thanks to Dr. P.-J. Sheu)

Assume observed rainfall (***O***) can be expressed as a linear combination of MM5-forecasted rainfalls (***M***) as:

$$\begin{bmatrix} O_1 \\ O_2 \\ O_3 \\ \vdots \\ O_N \end{bmatrix} = \alpha \begin{bmatrix} (m_1)_1 \\ (m_1)_2 \\ (m_1)_3 \\ \vdots \\ (m_1)_N \end{bmatrix} + \beta \begin{bmatrix} (m_2)_1 \\ (m_2)_2 \\ (m_2)_3 \\ \vdots \\ (m_2)_N \end{bmatrix} + \gamma \begin{bmatrix} (m_3)_1 \\ (m_3)_2 \\ (m_3)_3 \\ \vdots \\ (m_3)_N \end{bmatrix} + \kappa \begin{bmatrix} (m_4)_1 \\ (m_4)_2 \\ (m_4)_3 \\ \vdots \\ (m_4)_N \end{bmatrix} + \delta \begin{bmatrix} (m_5)_1 \\ (m_5)_2 \\ (m_5)_3 \\ \vdots \\ (m_5)_N \end{bmatrix} + \varepsilon \begin{bmatrix} (m_6)_1 \\ (m_6)_2 \\ (m_6)_3 \\ \vdots \\ (m_6)_N \end{bmatrix} - \begin{bmatrix} r_1 \\ r_2 \\ r_3 \\ \vdots \\ r_N \end{bmatrix} \quad (1)$$

where m_1 is the first ensemble member, m_2 is the second ensemble member, and so on. ***N*** is the total number of forecast rainfall events (58 events) during a Mei-Yu season.

The above equation can be written in a vector form as:

$$\vec{O} = \alpha \vec{m}_1 + \beta \vec{m}_2 + \gamma \vec{m}_3 + \kappa \vec{m}_4 + \delta \vec{m}_5 + \varepsilon \vec{m}_6 - \vec{r} \quad (2)$$

Then the rainfall forecast error is

$$\vec{r} = \alpha \vec{m}_1 + \beta \vec{m}_2 + \gamma \vec{m}_3 + \kappa \vec{m}_4 + \delta \vec{m}_5 + \varepsilon \vec{m}_6 - \vec{O} \qquad (3)$$

where $\alpha, \beta, \gamma, \kappa, \delta, \varepsilon$ is the weighting coefficient for each member.

The square of forecast error is

$$r^2 = \vec{r} \cdot \vec{r} = (\alpha \vec{m}_1 + \beta \vec{m}_2 + \gamma \vec{m}_3 + \kappa \vec{m}_4 + \delta \vec{m}_5 + \varepsilon \vec{m}_6 - \vec{O})^2 \qquad (4)$$

Then a minimization of rainfall forecast error in a least square sense can be obtained by setting

$$\frac{\partial r^2}{\partial \alpha} = 0 = 2\vec{m}_1 \cdot (\alpha \vec{m}_1 + \beta \vec{m}_2 + \gamma \vec{m}_3 + \kappa \vec{m}_4 + \delta \vec{m}_5 + \varepsilon \vec{m}_6 - \vec{O}) \quad \text{(5a)}$$

$$\frac{\partial r^2}{\partial \beta} = 0 = 2\vec{m}_2 \cdot (\alpha \vec{m}_1 + \beta \vec{m}_2 + \gamma \vec{m}_3 + \kappa \vec{m}_4 + \delta \vec{m}_5 + \varepsilon \vec{m}_6 - \vec{O}) \quad \text{(5b)}$$

$$\frac{\partial r^2}{\partial \gamma} = 0 = 2\vec{m}_3 \cdot (\alpha \vec{m}_1 + \beta \vec{m}_2 + \gamma \vec{m}_3 + \kappa \vec{m}_4 + \delta \vec{m}_5 + \varepsilon \vec{m}_6 - \vec{O}) \quad \text{(5c)}$$

$$\frac{\partial r^2}{\partial \kappa} = 0 = 2\vec{m}_4 \cdot (\alpha \vec{m}_1 + \beta \vec{m}_2 + \gamma \vec{m}_3 + \kappa \vec{m}_4 + \delta \vec{m}_5 + \varepsilon \vec{m}_6 - \vec{O}) \quad \text{(5d)}$$

$$\frac{\partial r^2}{\partial \delta} = 0 = 2\vec{m}_5 \cdot (\alpha \vec{m}_1 + \beta \vec{m}_2 + \gamma \vec{m}_3 + \kappa \vec{m}_4 + \delta \vec{m}_5 + \varepsilon \vec{m}_6 - \vec{O}) \quad \text{(5e)}$$

$$\frac{\partial r^2}{\partial \varepsilon} = 0 = 2\vec{m}_6 \cdot (\alpha \vec{m}_1 + \beta \vec{m}_2 + \gamma \vec{m}_3 + \kappa \vec{m}_4 + \delta \vec{m}_5 + \varepsilon \vec{m}_6 - \vec{O}) \quad \text{(5f)}$$

After some arrangements, we can have

$$(\vec{m}_1\cdot\vec{m}_1)\alpha+(\vec{m}_1\cdot\vec{m}_2)\beta+(\vec{m}_1\cdot\vec{m}_3)\gamma+(\vec{m}_1\cdot\vec{m}_4)\kappa+(\vec{m}_1\cdot\vec{m}_5)\delta+(\vec{m}_1\cdot\vec{m}_6)\varepsilon=\vec{m}_1\cdot\vec{O} \tag{6a}$$

$$(\vec{m}_2\cdot\vec{m}_1)\alpha+(\vec{m}_2\cdot\vec{m}_2)\beta+(\vec{m}_2\cdot\vec{m}_3)\gamma+(\vec{m}_2\cdot\vec{m}_4)\kappa+(\vec{m}_2\cdot\vec{m}_5)\delta+(\vec{m}_2\cdot\vec{m}_6)\varepsilon=\vec{m}_2\cdot\vec{O} \tag{6b}$$

$$(\vec{m}_3\cdot\vec{m}_1)\alpha+(\vec{m}_3\cdot\vec{m}_2)\beta+(\vec{m}_3\cdot\vec{m}_3)\gamma+(\vec{m}_3\cdot\vec{m}_4)\kappa+(\vec{m}_3\cdot\vec{m}_5)\delta+(\vec{m}_3\cdot\vec{m}_6)\varepsilon=\vec{m}_3\cdot\vec{O} \tag{6c}$$

$$(\vec{m}_4\cdot\vec{m}_1)\alpha+(\vec{m}_4\cdot\vec{m}_2)\beta+(\vec{m}_4\cdot\vec{m}_3)\gamma+(\vec{m}_4\cdot\vec{m}_4)\kappa+(\vec{m}_4\cdot\vec{m}_5)\delta+(\vec{m}_4\cdot\vec{m}_6)\varepsilon=\vec{m}_4\cdot\vec{O} \tag{6d}$$

$$(\vec{m}_5\cdot\vec{m}_1)\alpha+(\vec{m}_5\cdot\vec{m}_2)\beta+(\vec{m}_5\cdot\vec{m}_3)\gamma+(\vec{m}_5\cdot\vec{m}_4)\kappa+(\vec{m}_5\cdot\vec{m}_5)\delta+(\vec{m}_5\cdot\vec{m}_6)\varepsilon=\vec{m}_5\cdot\vec{O} \tag{6e}$$

$$(\vec{m}_6\cdot\vec{m}_1)\alpha+(\vec{m}_6\cdot\vec{m}_2)\beta+(\vec{m}_6\cdot\vec{m}_3)\gamma+(\vec{m}_6\cdot\vec{m}_4)\kappa+(\vec{m}_6\cdot\vec{m}_5)\delta+(\vec{m}_6\cdot\vec{m}_6)\varepsilon=\vec{m}_6\cdot\vec{O} \tag{6f}$$

We can re-write the above system of equations in a matrix form,

$$\underbrace{\begin{bmatrix} \vec{m}_1\cdot\vec{m}_1 & \vec{m}_1\cdot\vec{m}_2 & \vec{m}_1\cdot\vec{m}_3 & \vec{m}_1\cdot\vec{m}_4 & \vec{m}_1\cdot\vec{m}_5 & \vec{m}_1\cdot\vec{m}_6 \\ \vec{m}_2\cdot\vec{m}_1 & \vec{m}_2\cdot\vec{m}_2 & \vec{m}_2\cdot\vec{m}_3 & \vec{m}_2\cdot\vec{m}_4 & \vec{m}_2\cdot\vec{m}_5 & \vec{m}_2\cdot\vec{m}_6 \\ \vec{m}_3\cdot\vec{m}_1 & \vec{m}_3\cdot\vec{m}_2 & \vec{m}_3\cdot\vec{m}_3 & \vec{m}_3\cdot\vec{m}_4 & \vec{m}_3\cdot\vec{m}_5 & \vec{m}_3\cdot\vec{m}_6 \\ \vec{m}_4\cdot\vec{m}_1 & \vec{m}_4\cdot\vec{m}_2 & \vec{m}_4\cdot\vec{m}_3 & \vec{m}_4\cdot\vec{m}_4 & \vec{m}_4\cdot\vec{m}_5 & \vec{m}_4\cdot\vec{m}_6 \\ \vec{m}_5\cdot\vec{m}_1 & \vec{m}_5\cdot\vec{m}_2 & \vec{m}_5\cdot\vec{m}_3 & \vec{m}_5\cdot\vec{m}_4 & \vec{m}_5\cdot\vec{m}_5 & \vec{m}_5\cdot\vec{m}_6 \\ \vec{m}_6\cdot\vec{m}_1 & \vec{m}_6\cdot\vec{m}_2 & \vec{m}_6\cdot\vec{m}_3 & \vec{m}_6\cdot\vec{m}_4 & \vec{m}_6\cdot\vec{m}_5 & \vec{m}_6\cdot\vec{m}_6 \end{bmatrix}_{6\times 6}}_{\mathbf{A}} \underbrace{\begin{bmatrix} \alpha \\ \beta \\ \gamma \\ \kappa \\ \delta \\ \varepsilon \end{bmatrix}_{6\times 1}}_{\mathbf{B}} = \underbrace{\begin{bmatrix} \vec{m}_1\cdot\vec{O} \\ \vec{m}_2\cdot\vec{O} \\ \vec{m}_3\cdot\vec{O} \\ \vec{m}_4\cdot\vec{O} \\ \vec{m}_5\cdot\vec{O} \\ \vec{m}_6\cdot\vec{O} \end{bmatrix}_{6\times 1}}_{\mathbf{C}} \tag{7}$$

Thus a minimization of square of forecast rainfall error can be written as

$$\mathbf{AB = C}$$

So

$$\mathbf{B = A^{-1}C}$$

where vector B whose element (α , β , γ , κ , δ , ε) is the weighting coefficient of each ensemble member.

Rainfall Contingency Table

Observed / Forecasted	Rain	No Rain
Rain	A	B
No Rain	C	D

Note: N is the total number of events (A+B+C+D)

Precipitation thresholds used in this study:
0.3, 2.5, 5, 10, 15, 25, 35, and 50.

Evaluation Scores

Based on A, B, C, D in the contingency table, several forecast evaluation scores can be defines as:

BS (Bias Score) = (A+B)/(A+C)

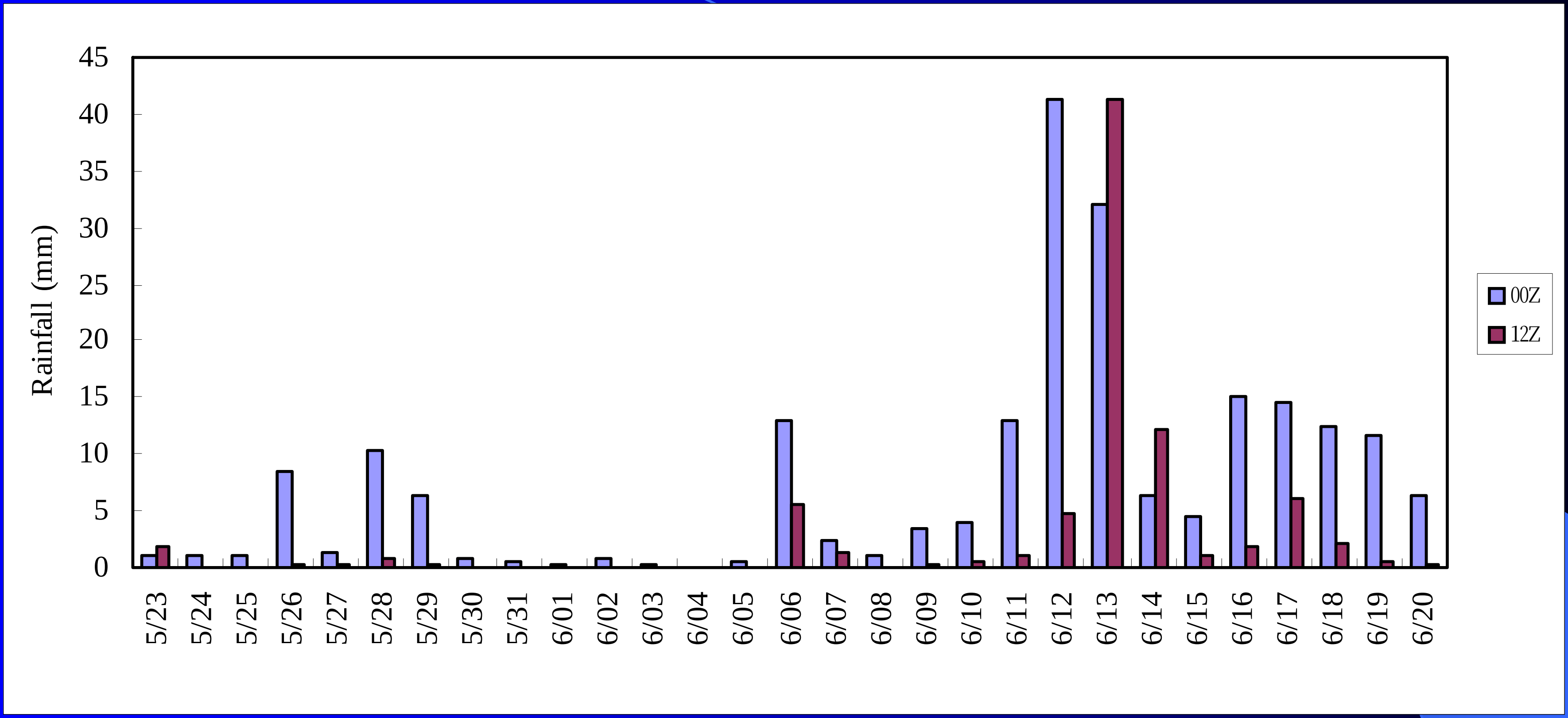
ETS (Equitable Threat Score) = (A-E)/(A+B+C-E)

E (Random Guess) = (A+B)*(A+C)/N

TS (Threat Score) = A/(A+B+C)

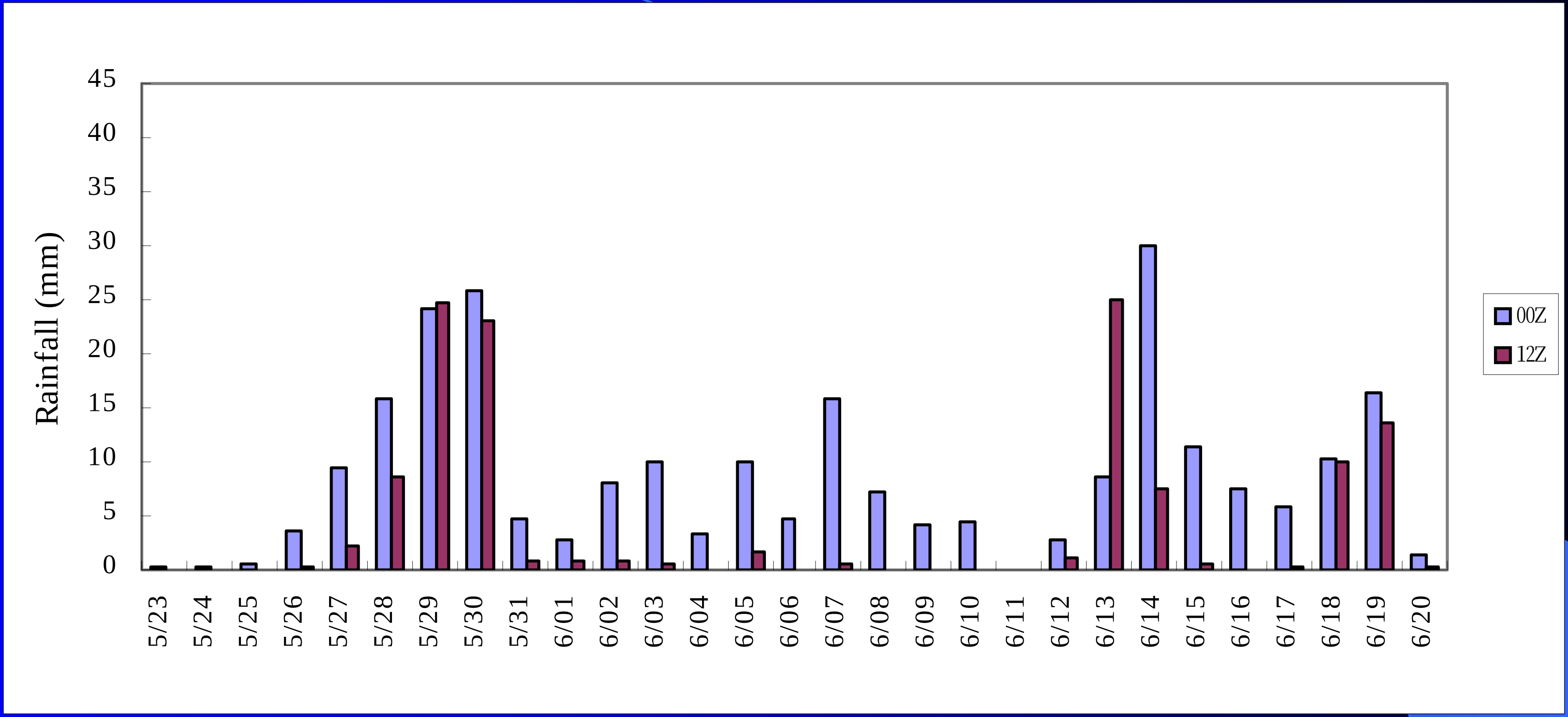
P.S. N is the total number of events (A+B+C+D)

2000 Mei-Yu Season



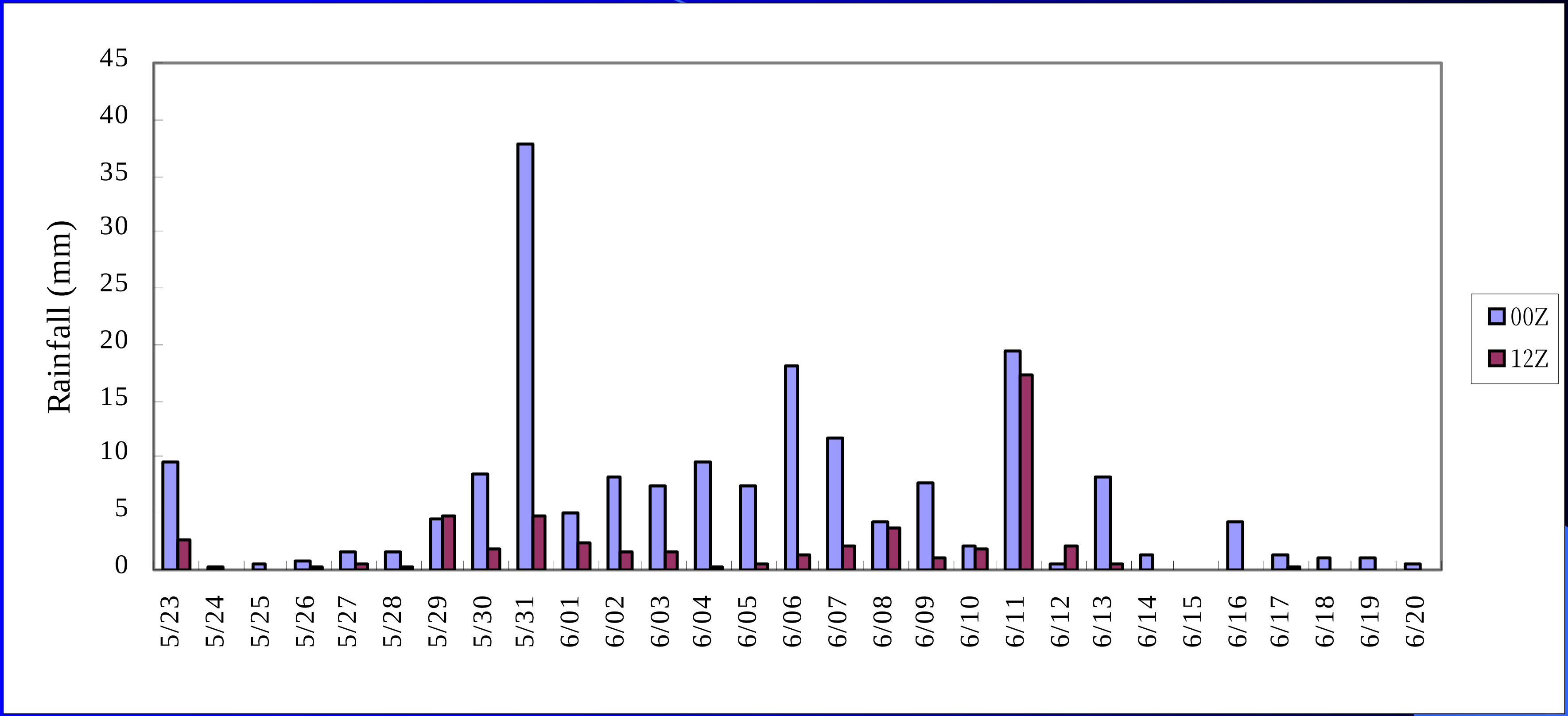
12-h accumulated rainfall averaged for all raingauge stations on the Taiwan island.

2001 Mei-Yu Season



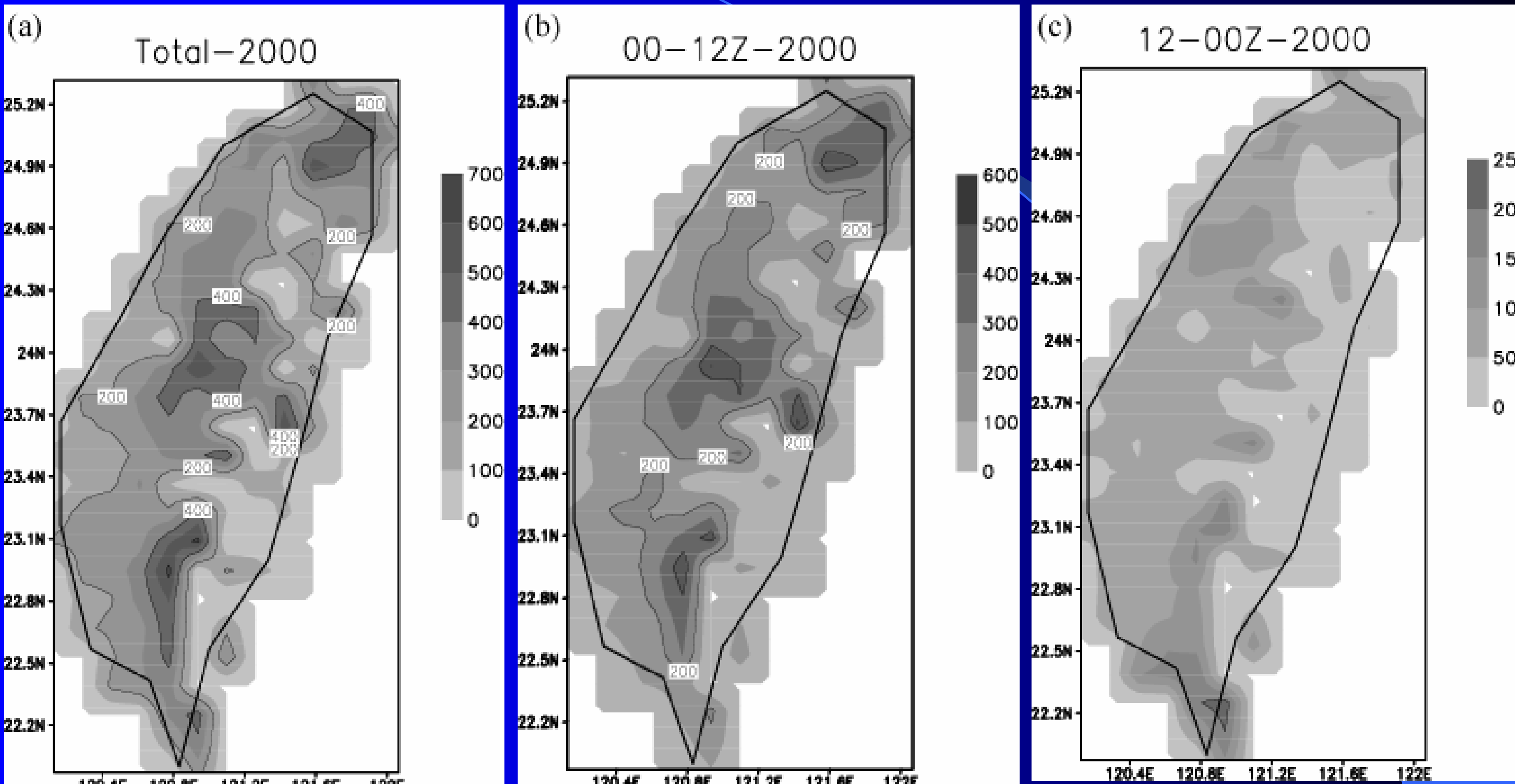
12-h accumulated rainfall averaged for all raingauge stations on the Taiwan island.

2002 Mei-Yu Season



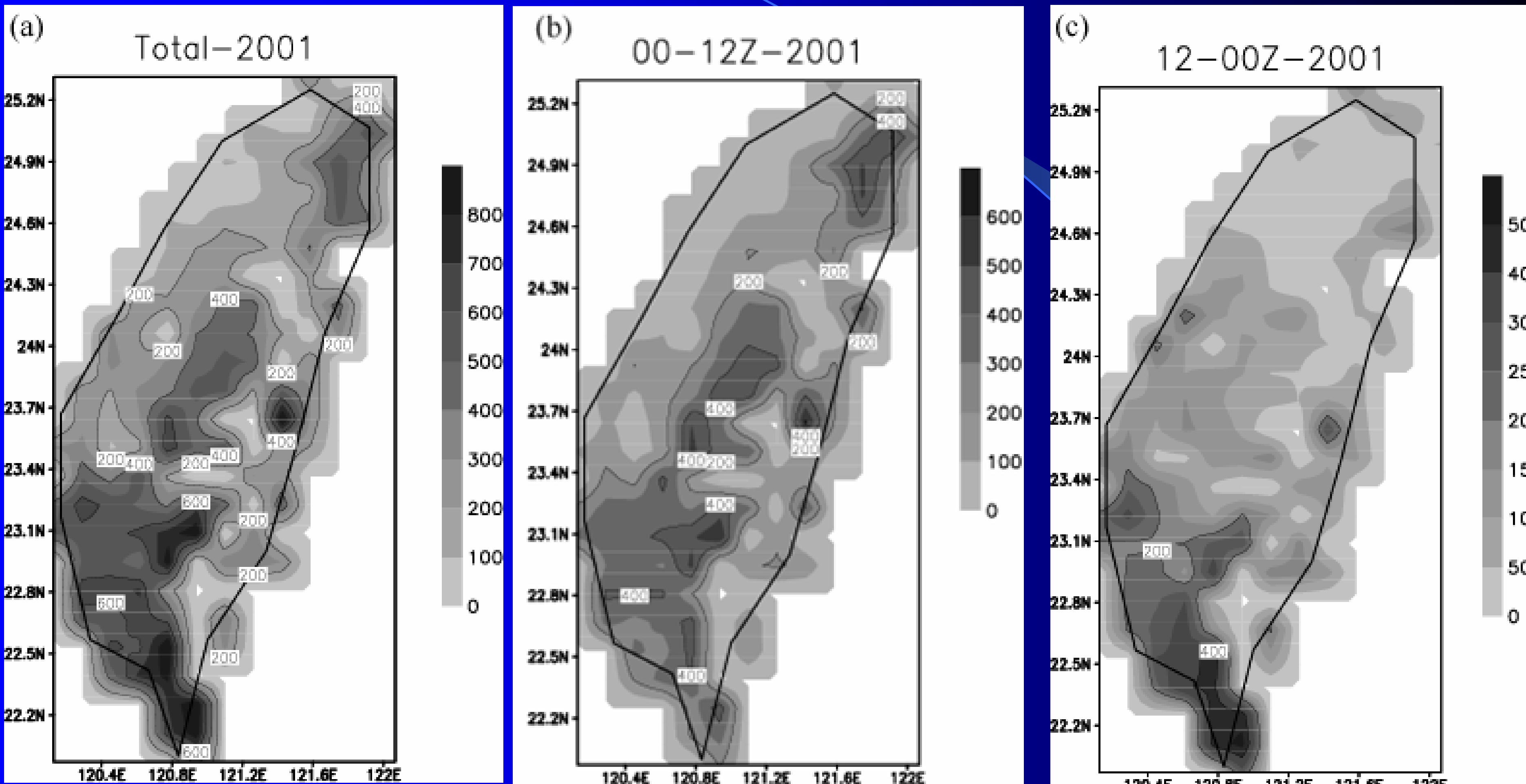
12-h accumulated rainfall averaged for all raingauge stations on the Taiwan island.

Rainfall Distribution during the 2000 Mei-Yu Season



Total Daytime Nighttime

Rainfall Distribution during the 2001 Mei-Yu Season

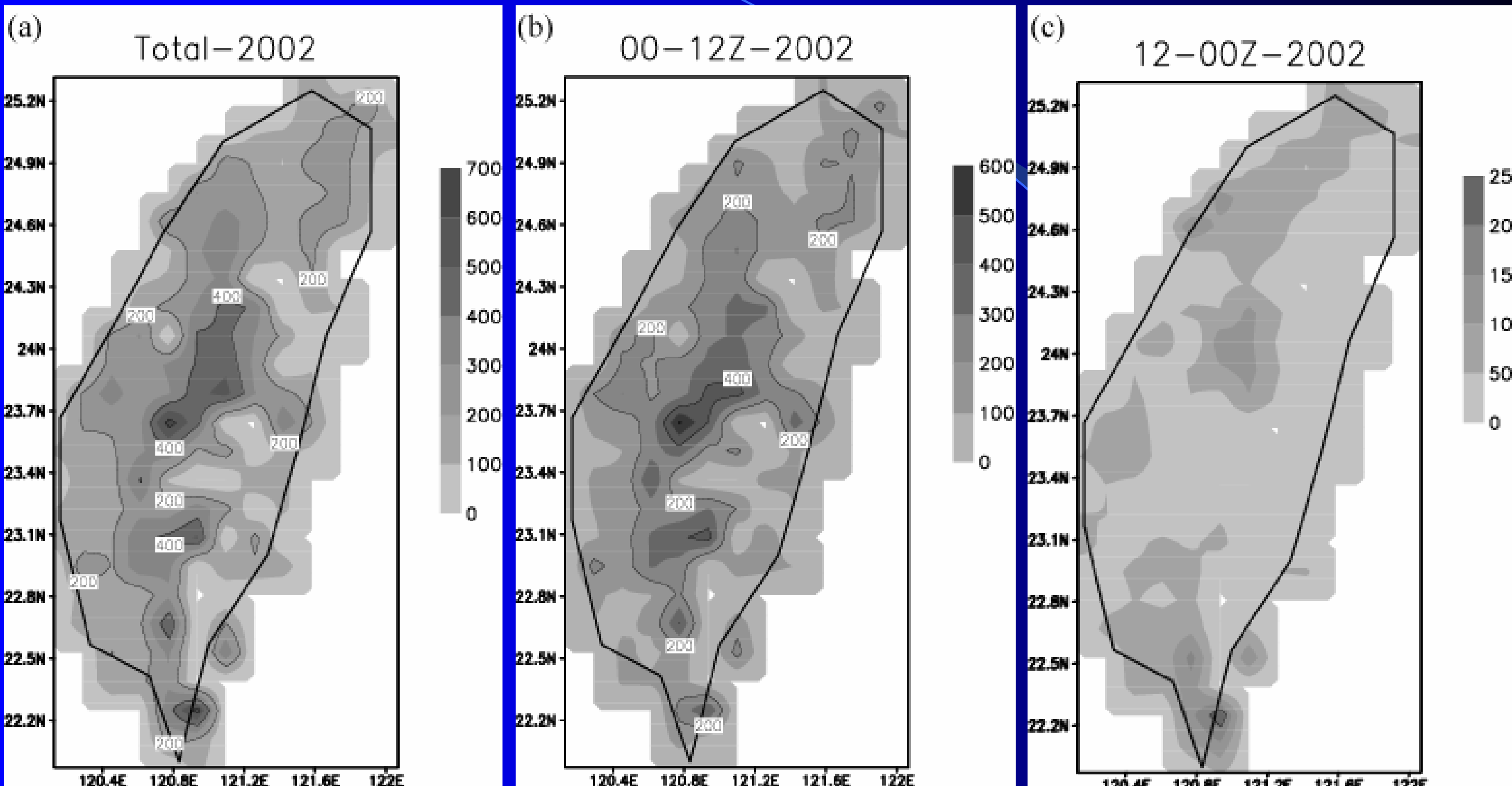


Total

Daytime

Nighttime

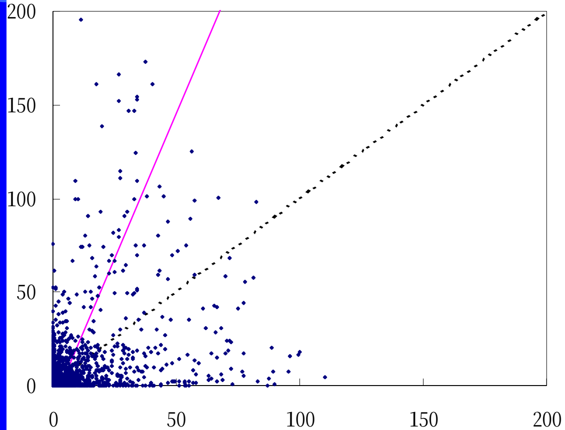
Rainfall Distribution during the 2002 Mei-Yu Season



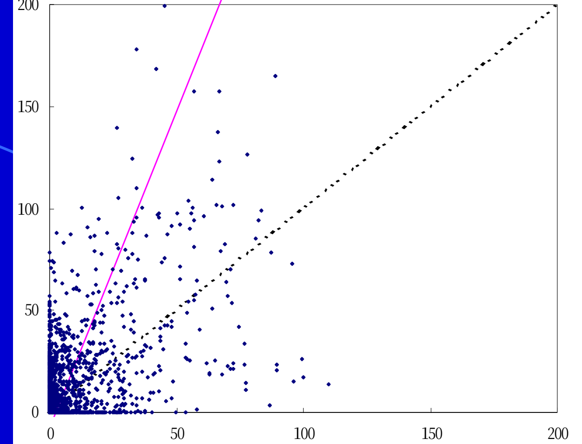
Total Daytime Nighttime

Observed vs. Forecasted Rainfall Amount for the 12-24 h Forecast

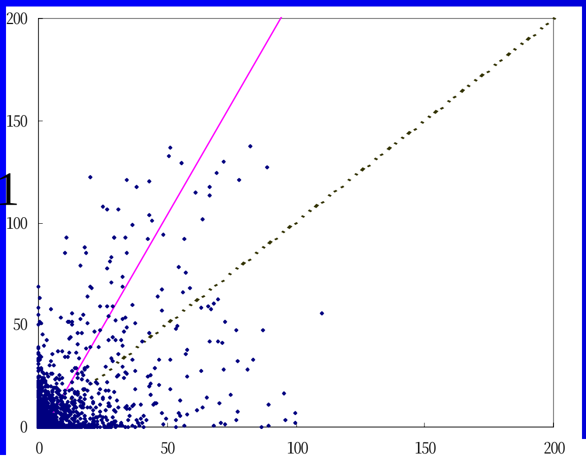
AK-SI



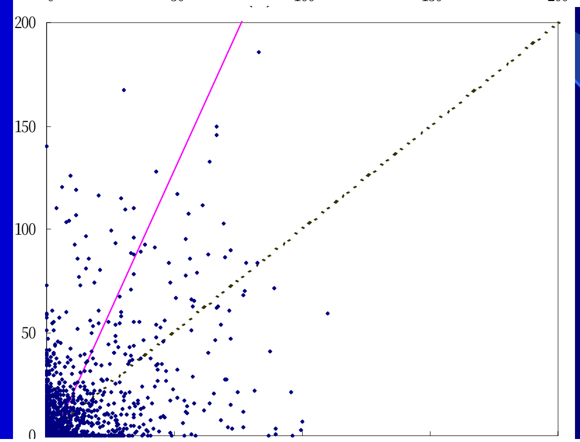
BM-R1



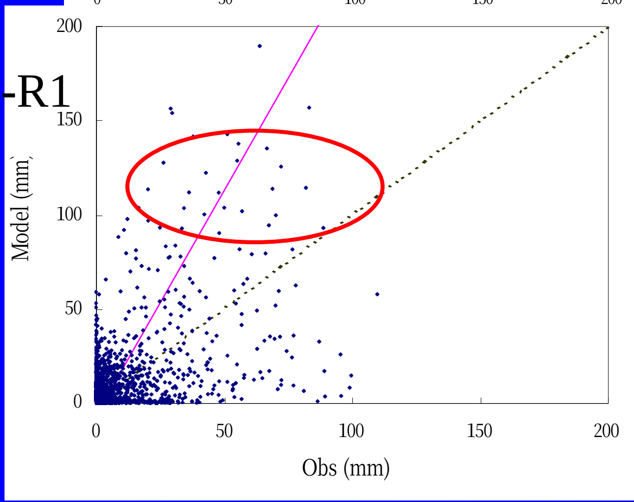
GR-R1



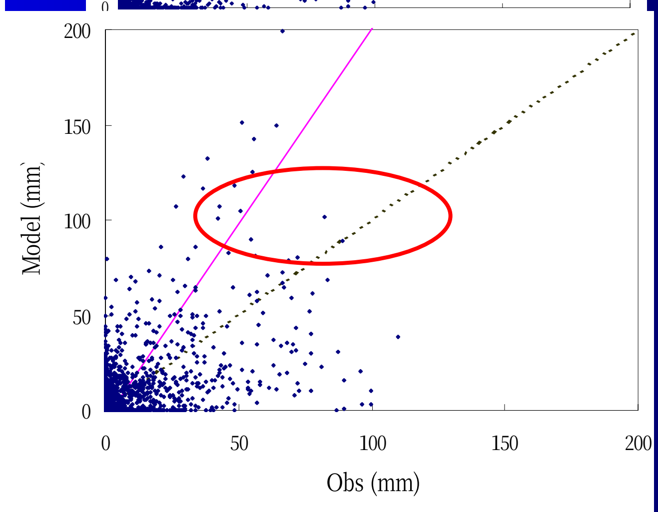
KF-GD



KF-R1



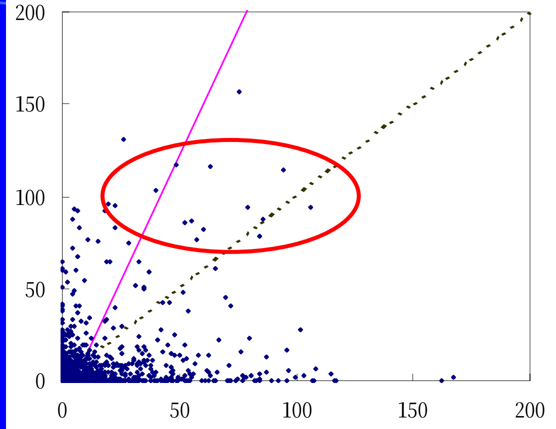
KF-SI



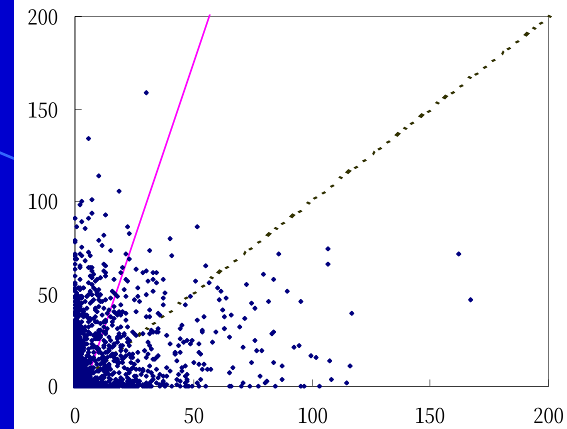
2000 Mei-Yu Season

Observed vs. Forecasted Rainfall Amount for the 12-24 h Forecast

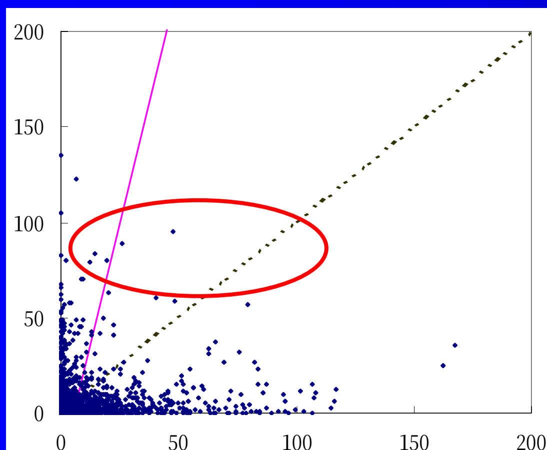
AK-SI



BM-R1



GR-R1



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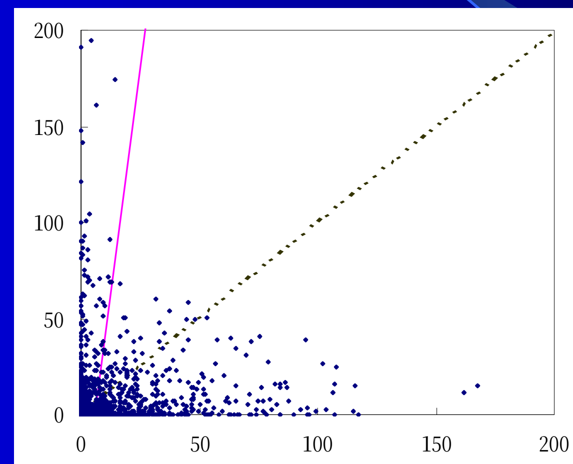

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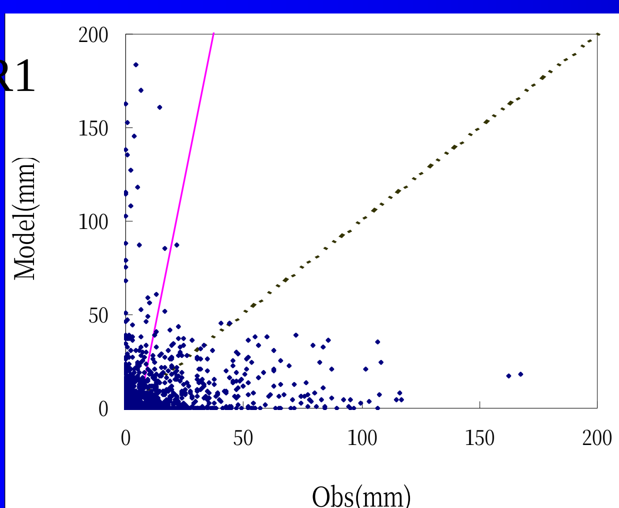

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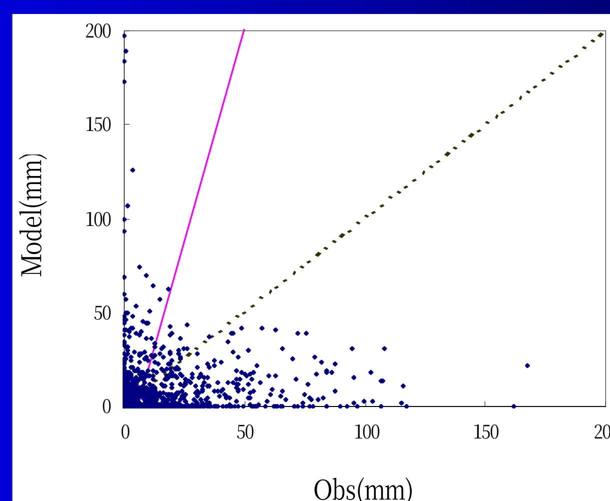
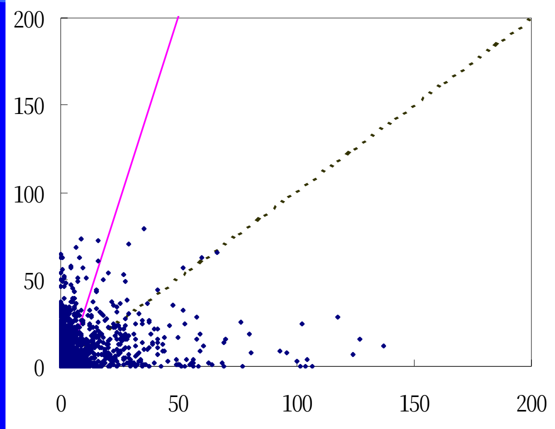


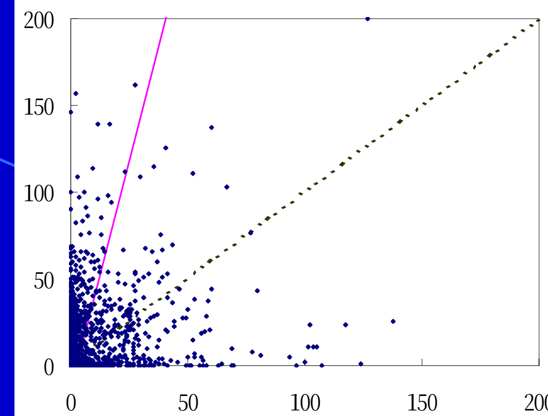
2001 Mei-Yu Season

Observed vs. Forecasted Rainfall Amount for the 12-24 h Forecast

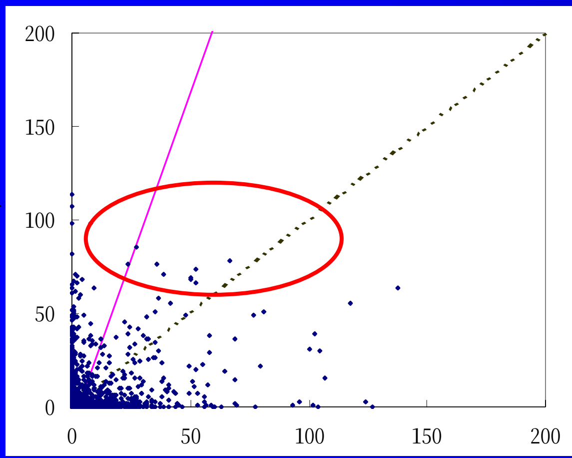
AK-SI



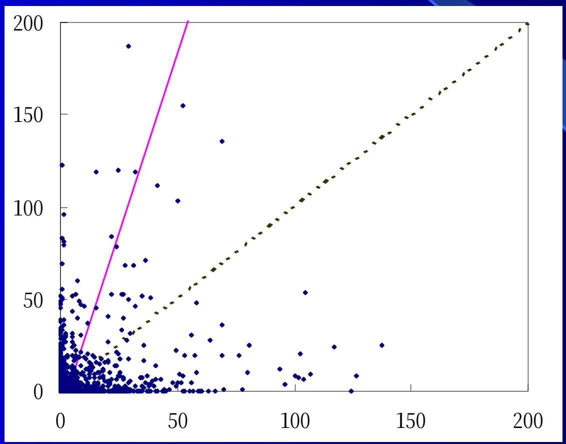
BM-R1



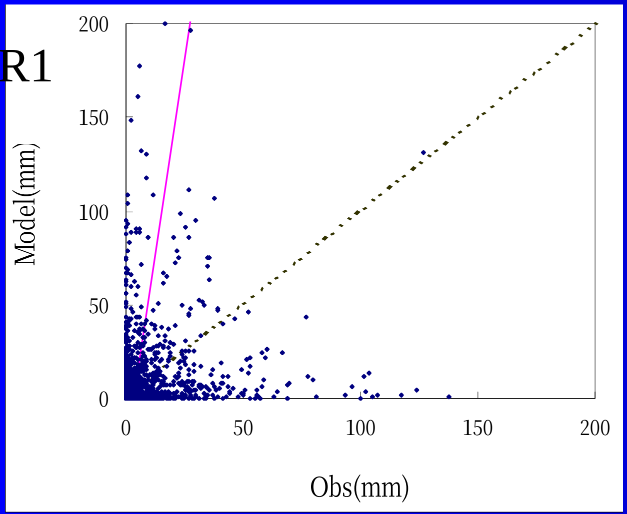
GR-R1



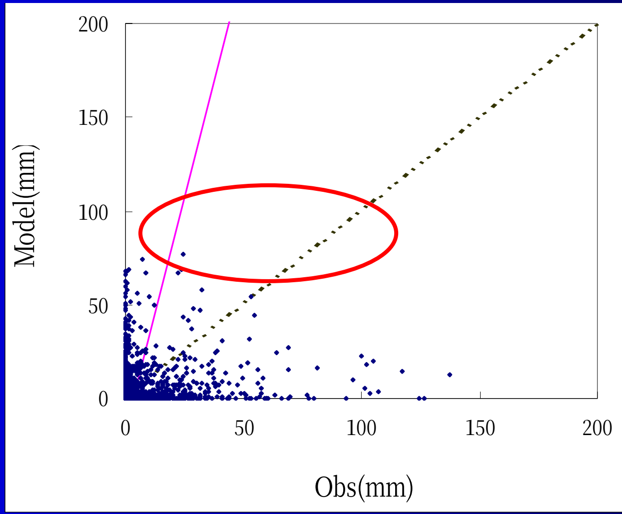
KF-GD



KF-R1



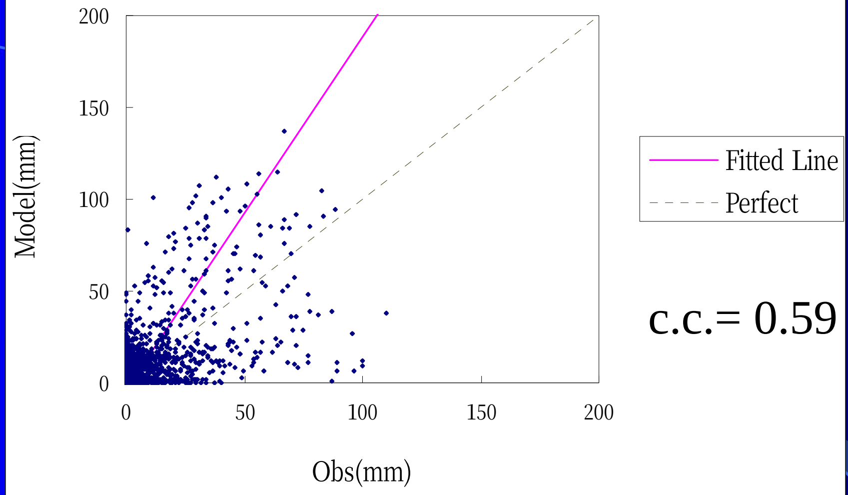
KF-SI



2002 Mei-Yu Season

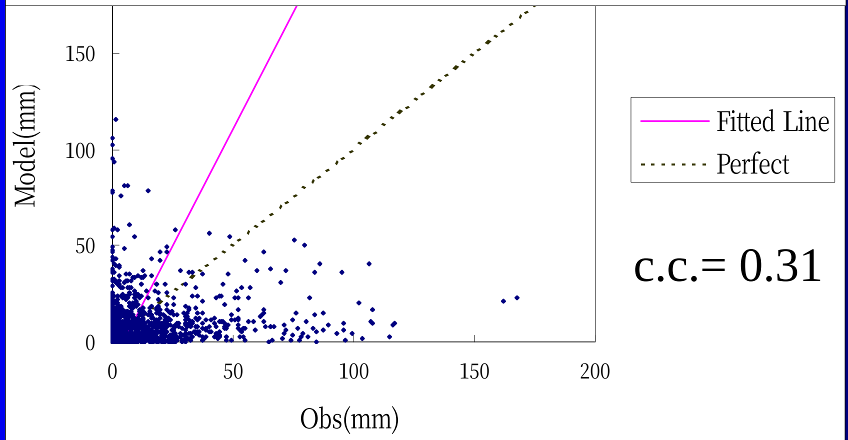
Observed vs. MLR Ensemble Forecasted Rainfall Amount for the 12-24 h Forecast

2000



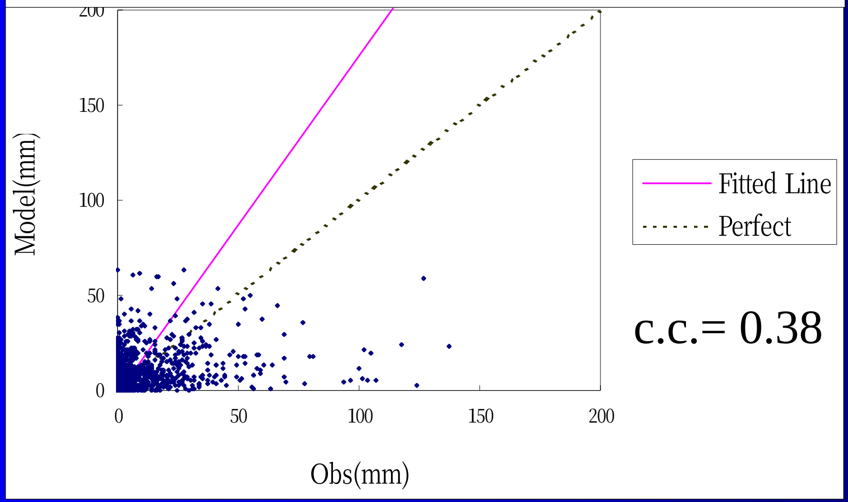
c.c.= 0.59

2001



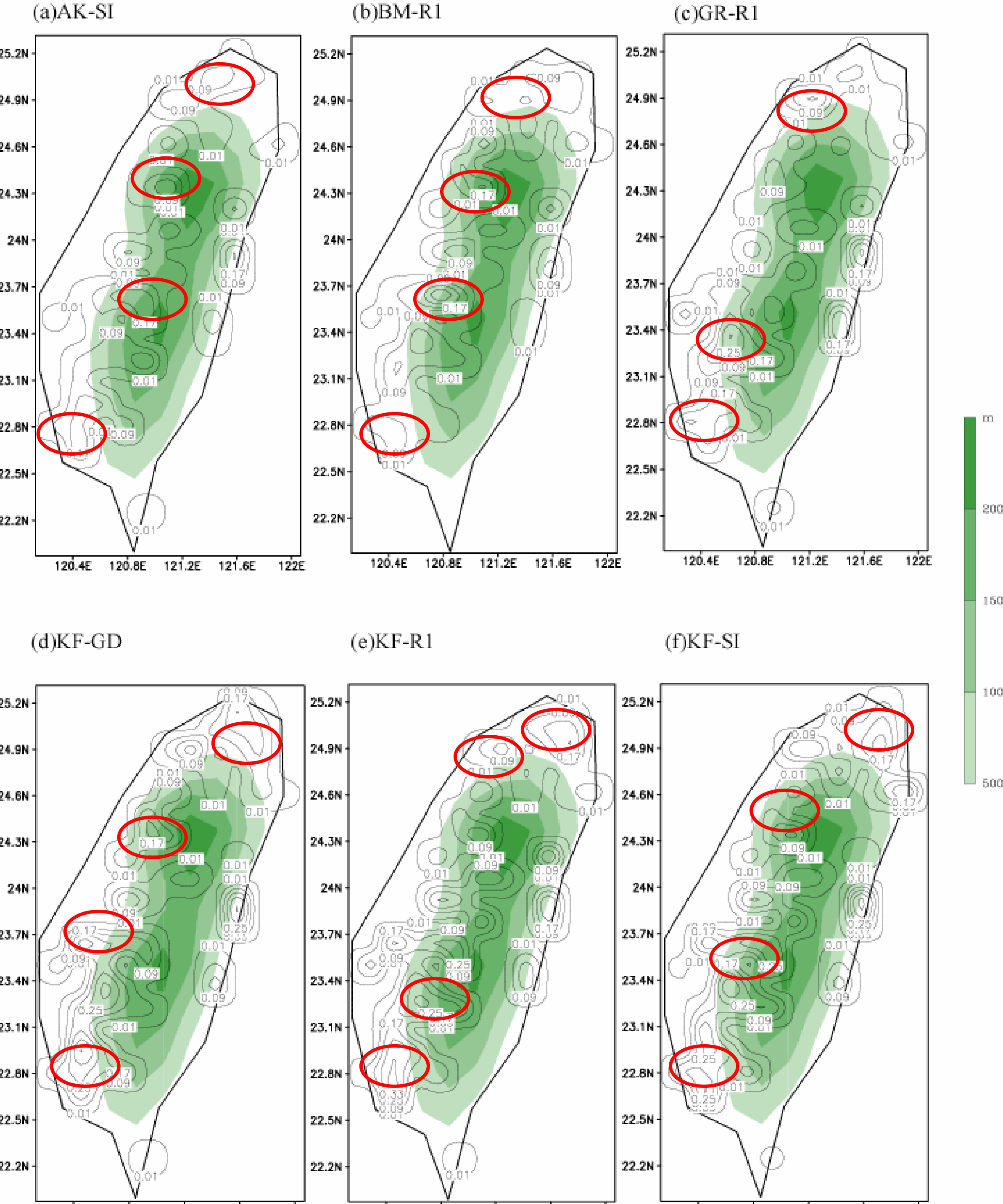
c.c.= 0.31

2002



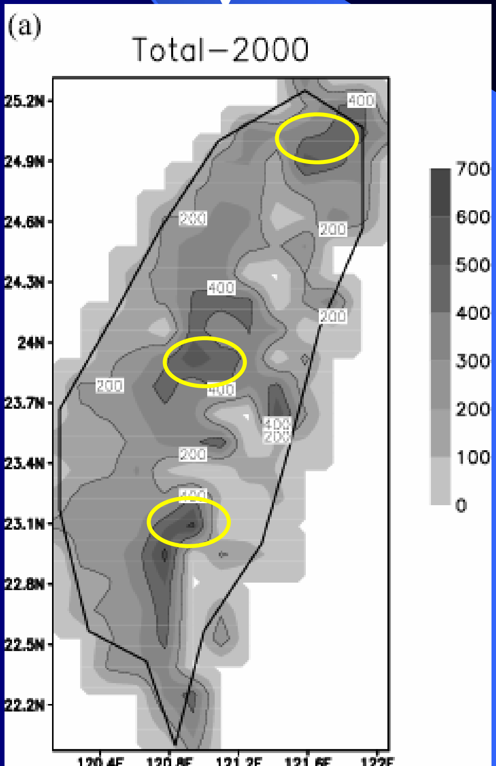
c.c.= 0.38

2000 Mei-Yu Season

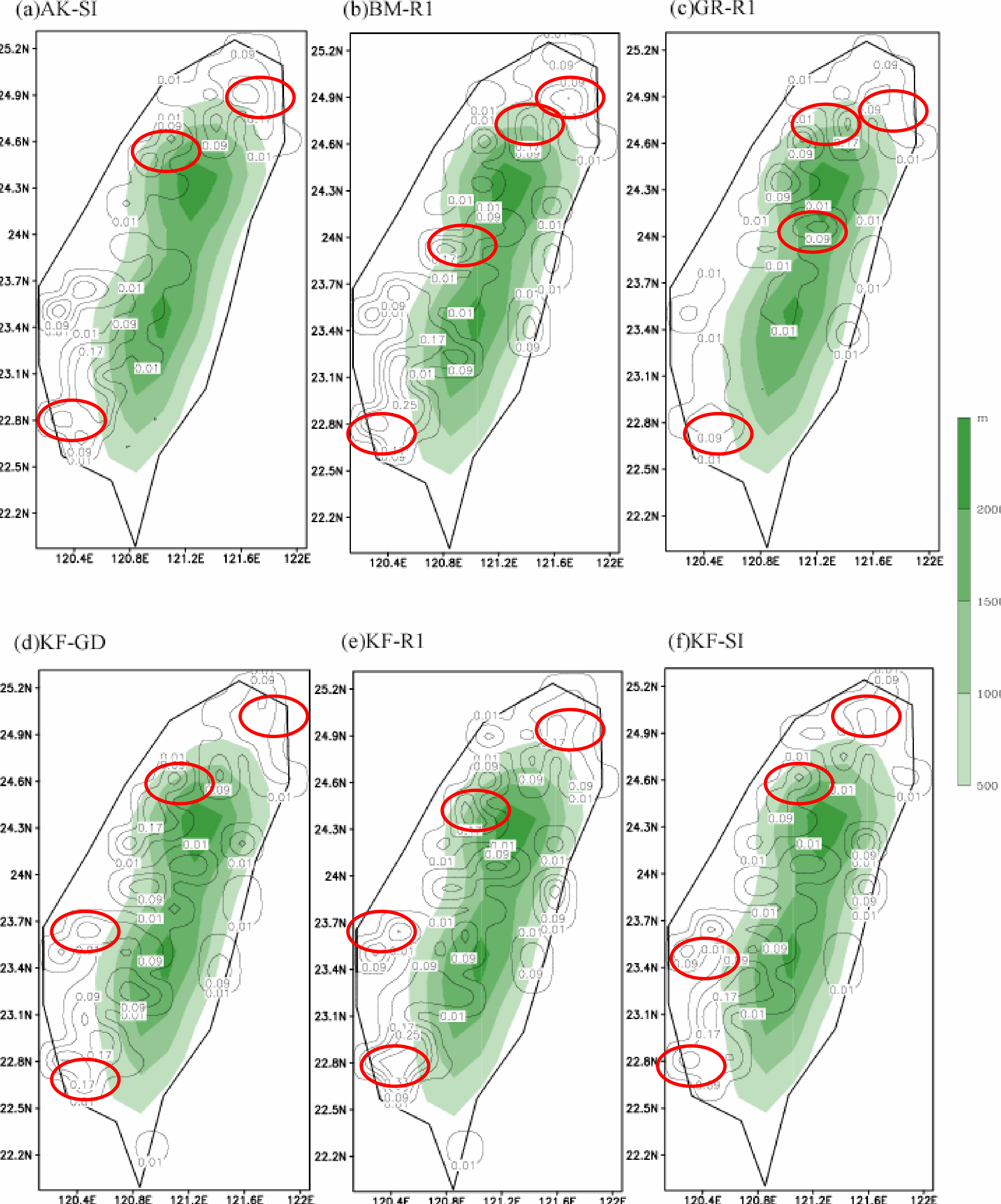


Horizontal ETS Distribution
For 12-24 h fcst

Observed Rainfall

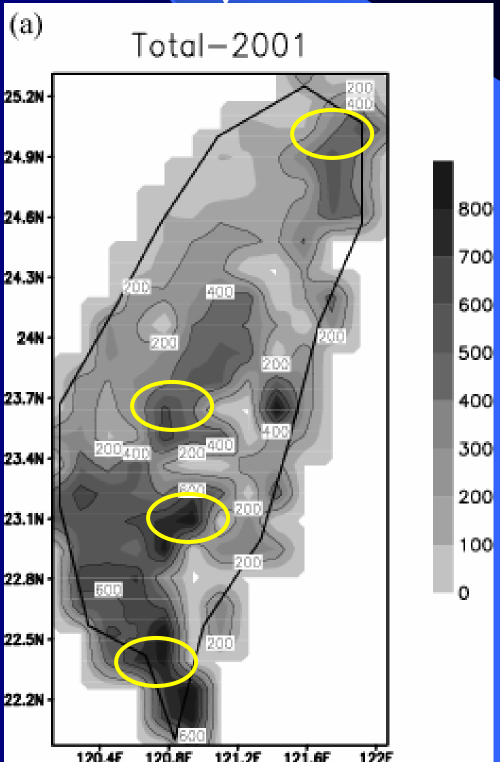


2001 Mei-Yu Season



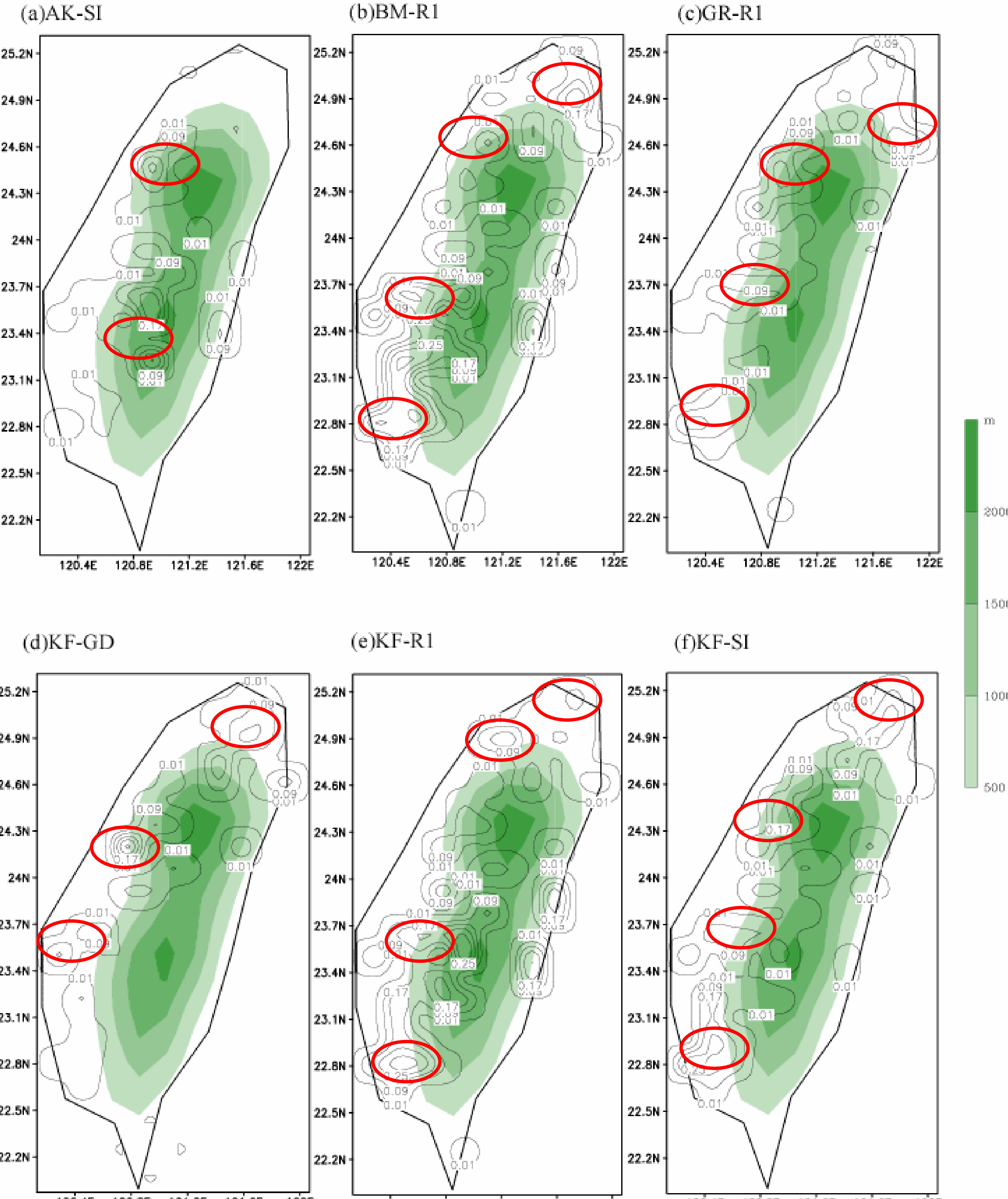
Horizontal ETS Distribution For 12-24 h fcst

Observed Rainfall

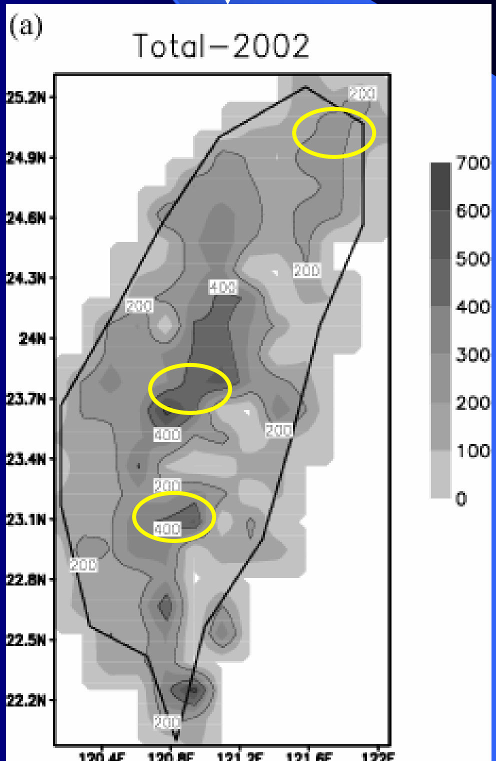


2002 Mei-Yu Season

Horizontal ETS Distribution
For 12-24 h fcst

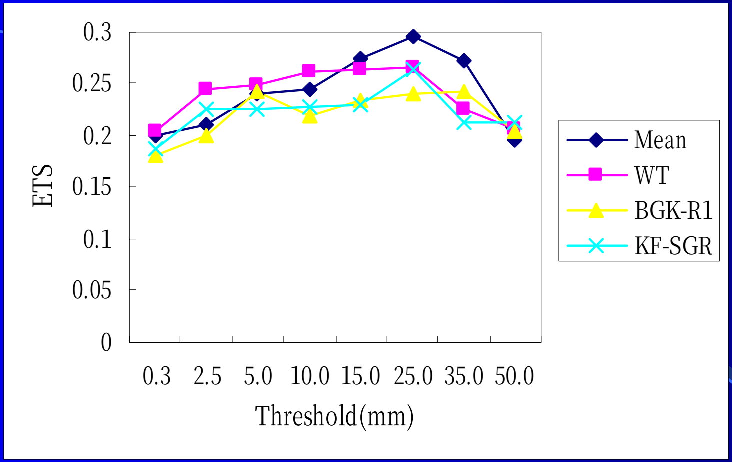


Observed Rainfall

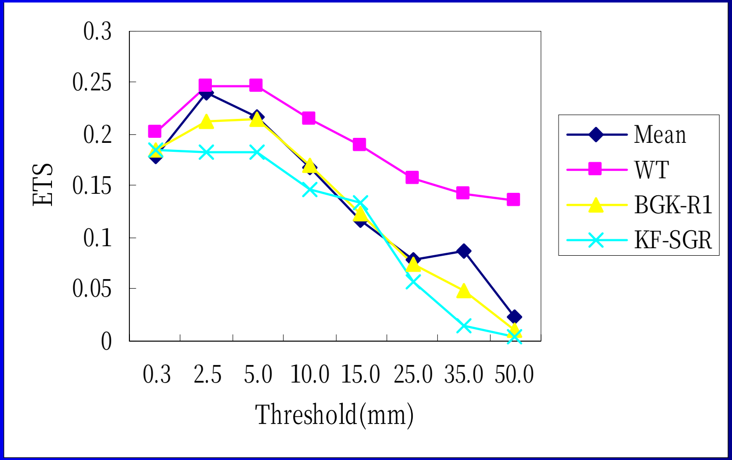


ETS Scores for Four Ensemble 12-24 h Forecasts

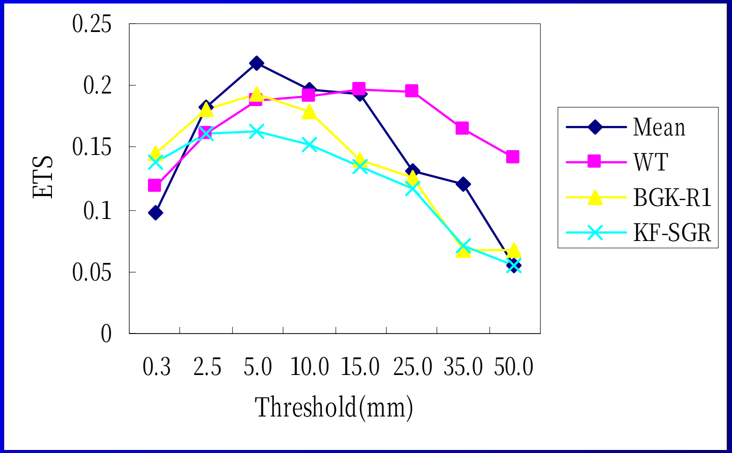
2000



2001



2002



Mean: Same weighting for Six members

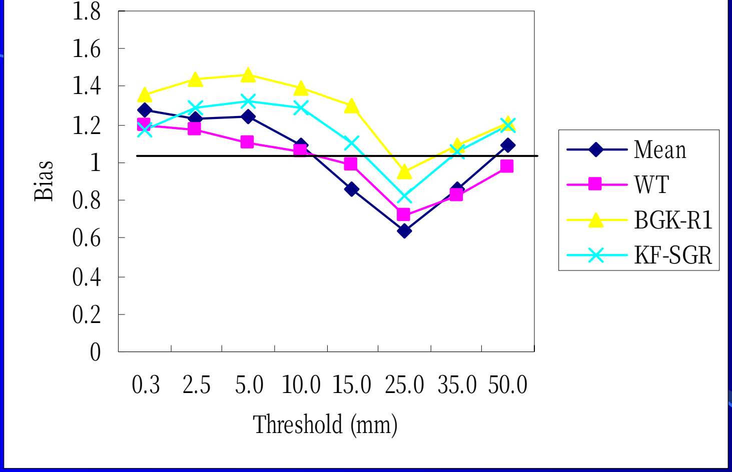
WT: multiple linear regression (MLR) method

BKG-R1: Same weighting for Three CPS members

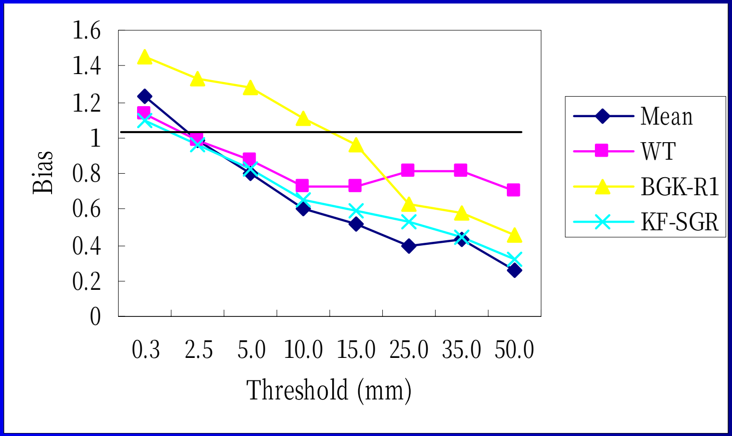
KF-SGR: Same weighting for Three Microphysics members

BS Scores for Four Ensemble 12-24 h Forecasts

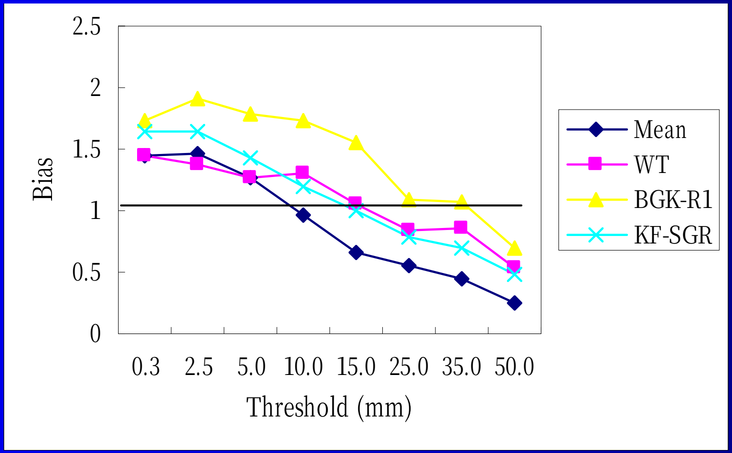
2000



2001



2002



Mean: Same weighting for Six members

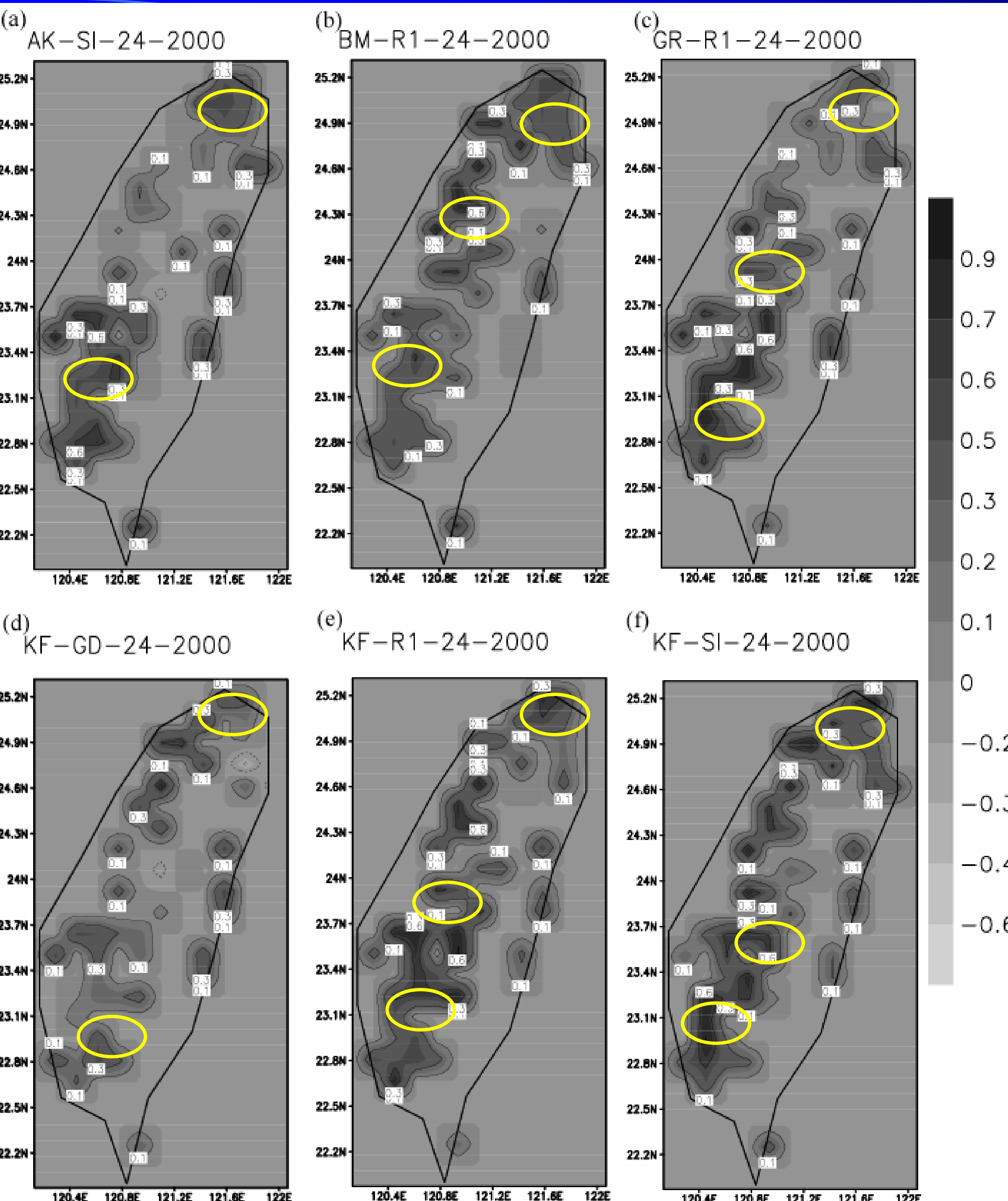
WT: multiple linear regression (MLR) method

BKG-R1: Same weighting for Three CPS members

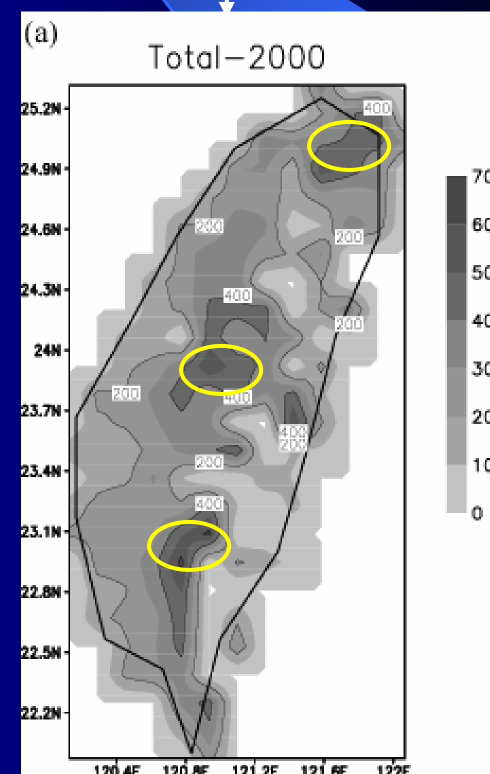
KF-SGR: Same weighting for Three Microphysics members

2000 Mei-Yu Season

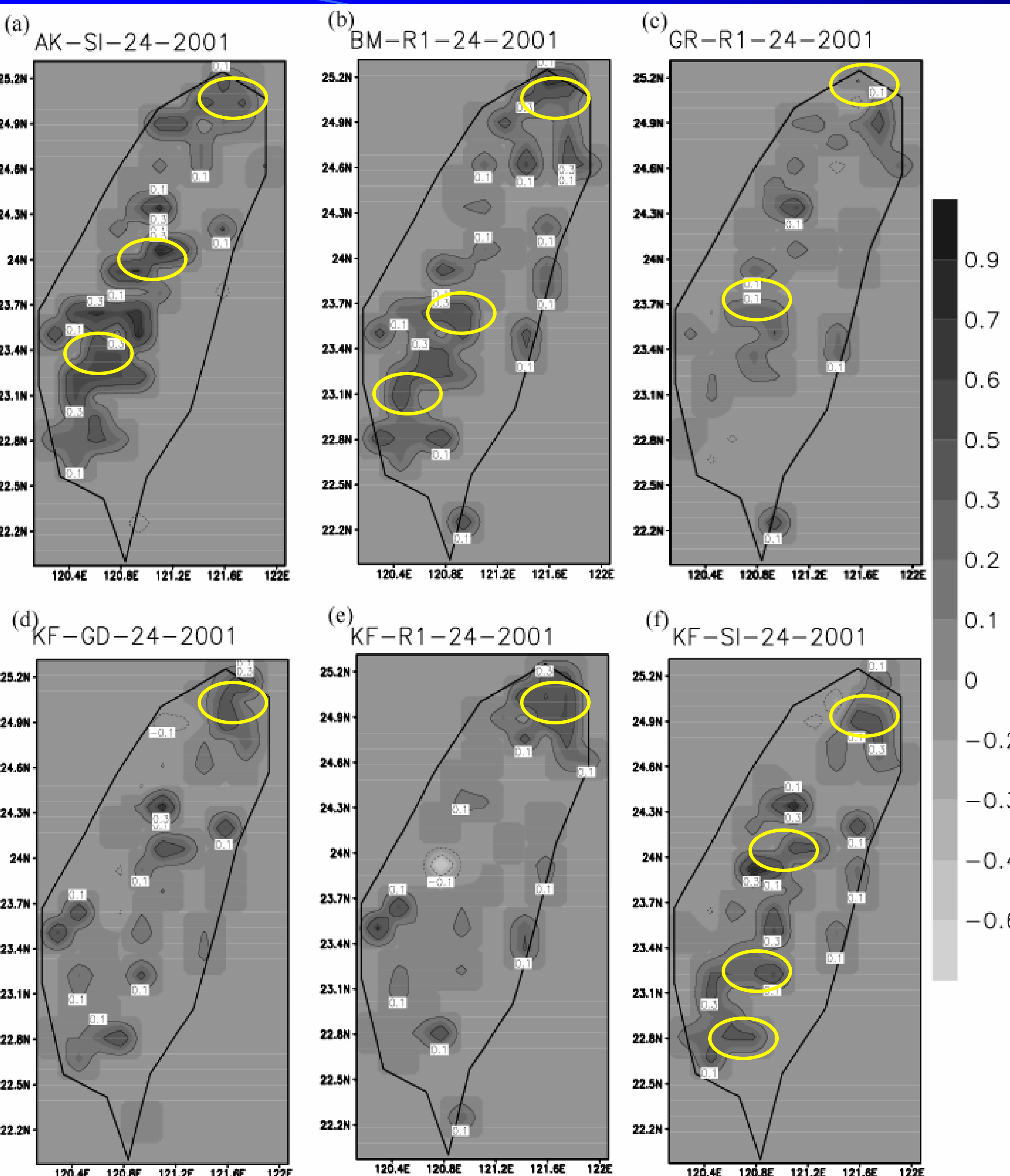
Distribution of Weighting Coefficient for 12-24 h fcst



Observed Rainfall

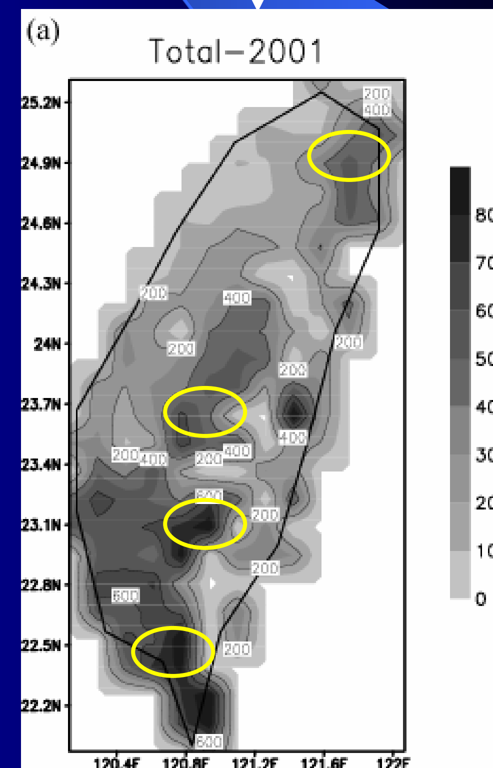


2001 Mei-Yu Season

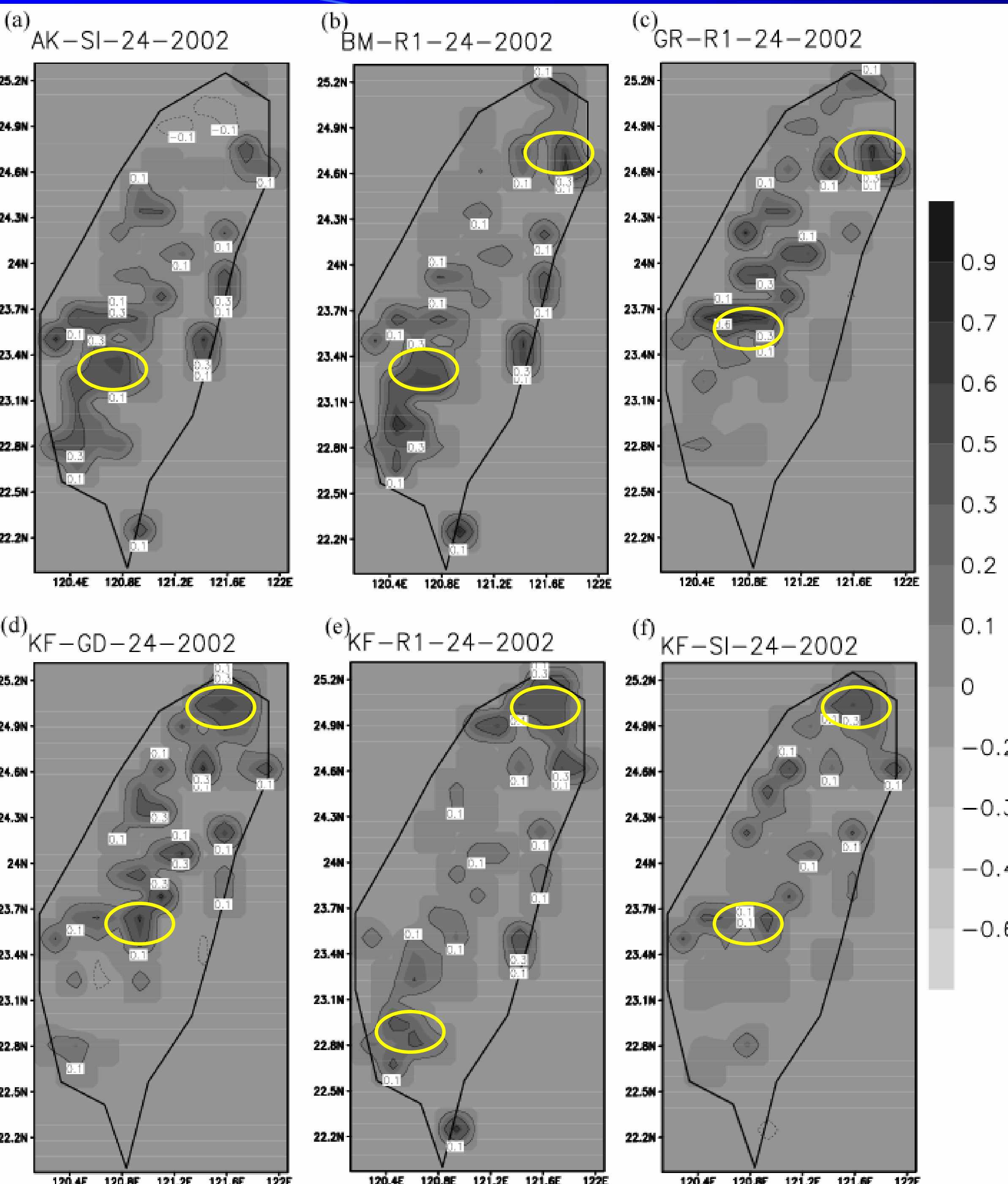


Distribution of Weighting Coefficien
for 12-24 h fcst

Observed Rainfall

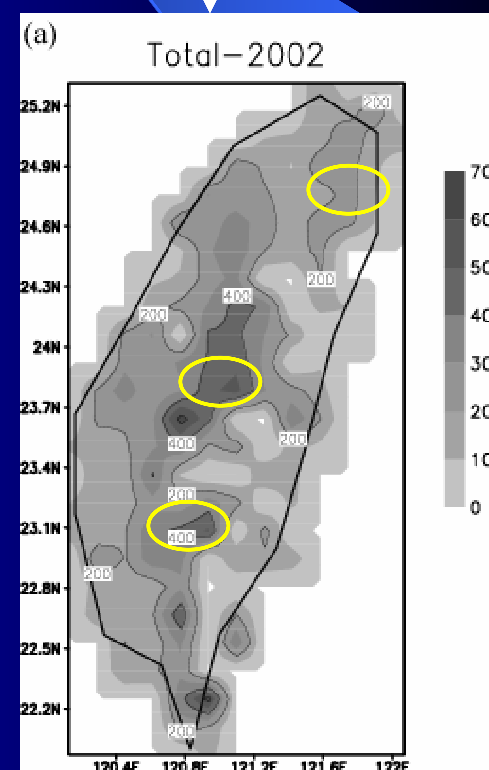


2002 Mei-Yu Season



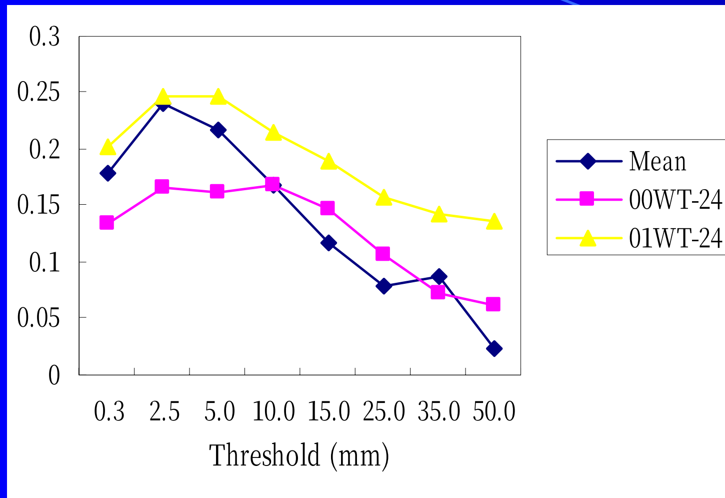
Distribution of Weighting Coefficient for 12-24 h fcst

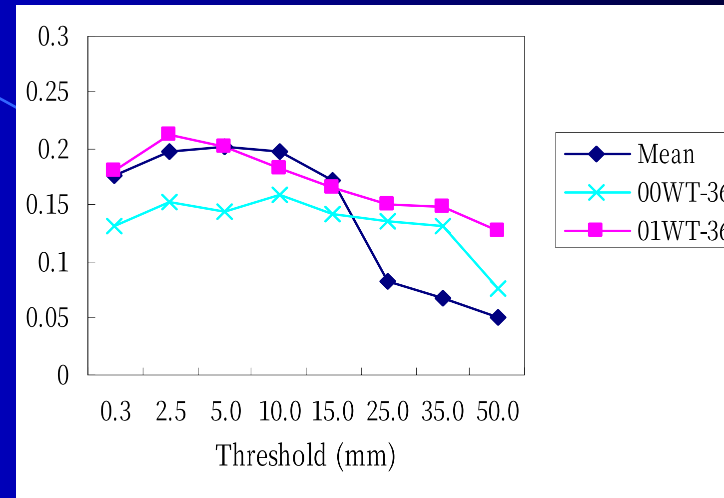
Observed Rainfall



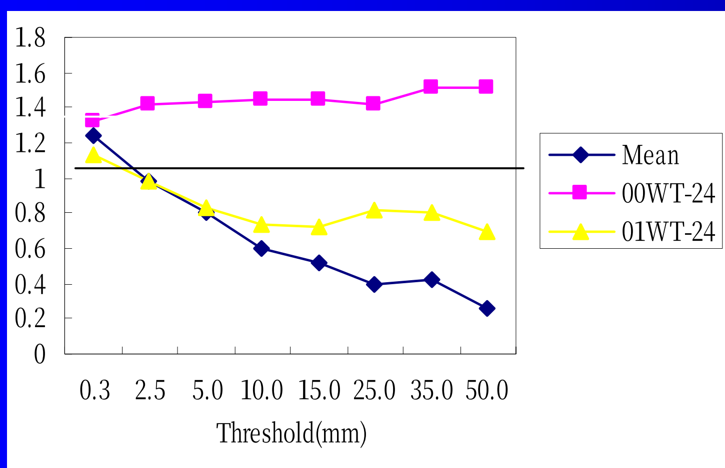
12-24 h 2001 / 24-36 h 2001

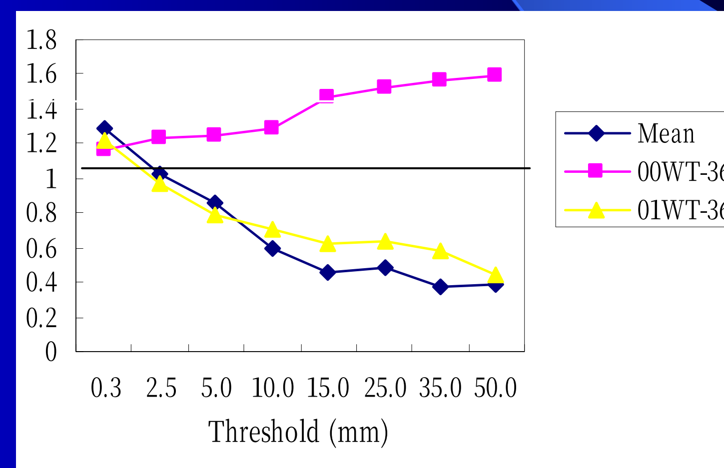
ETS





Bias

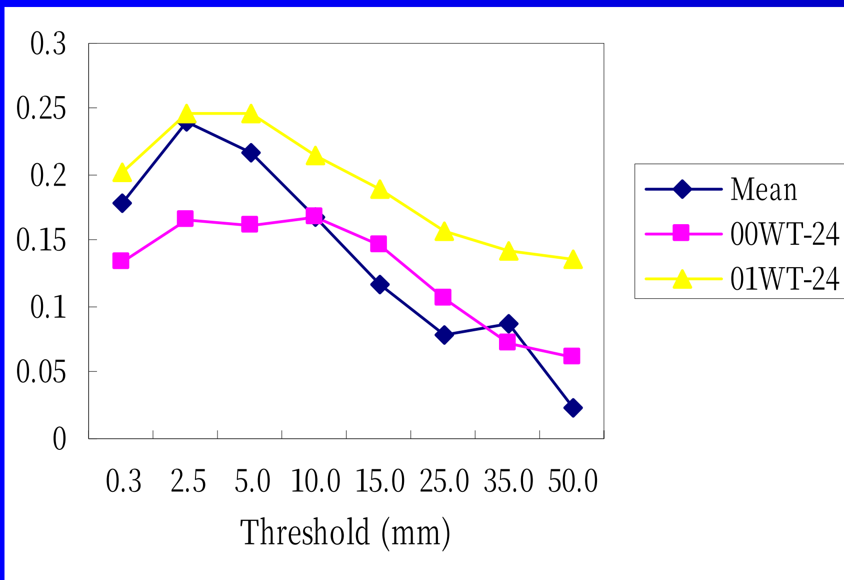




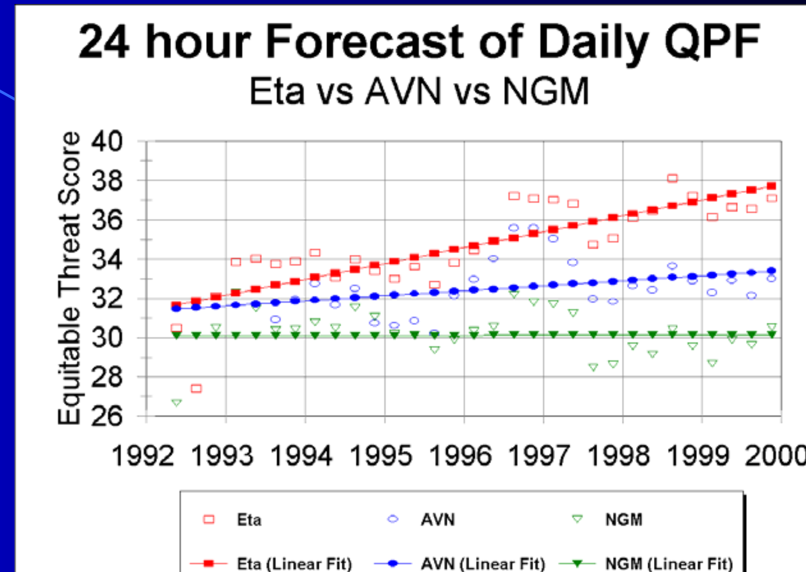
Mean: Same Weighting for Six Members
00WT: Use the MLR Weighting from Year 2000
01WT: Use the MLR Weighting from Year 2001 (Current Year)

Taiwan's Mei-Yu Season
MLR Ensemble Forecasting

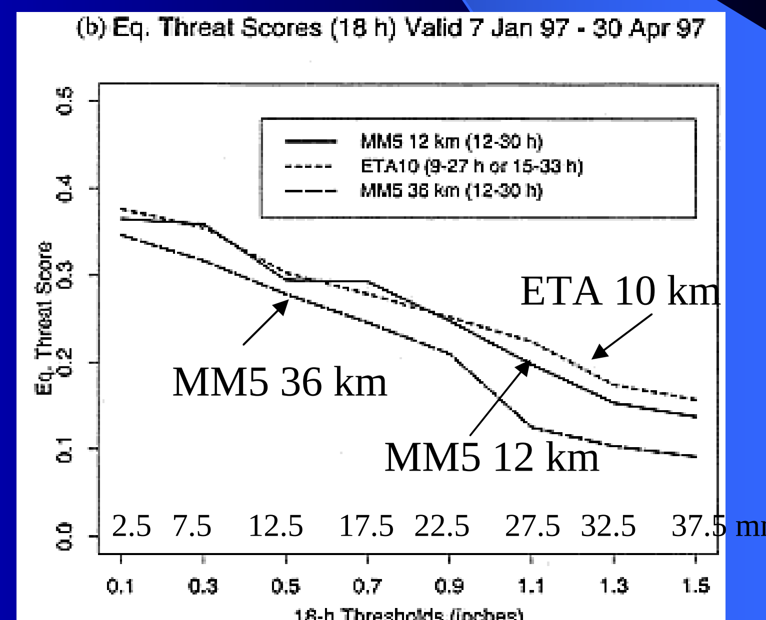
12-24 h 2001 (MM5 15 km)



NCEP Model Forecast
for Threshold = 2.5 mm



Washington's Cold Season (Colle et al. 1999)

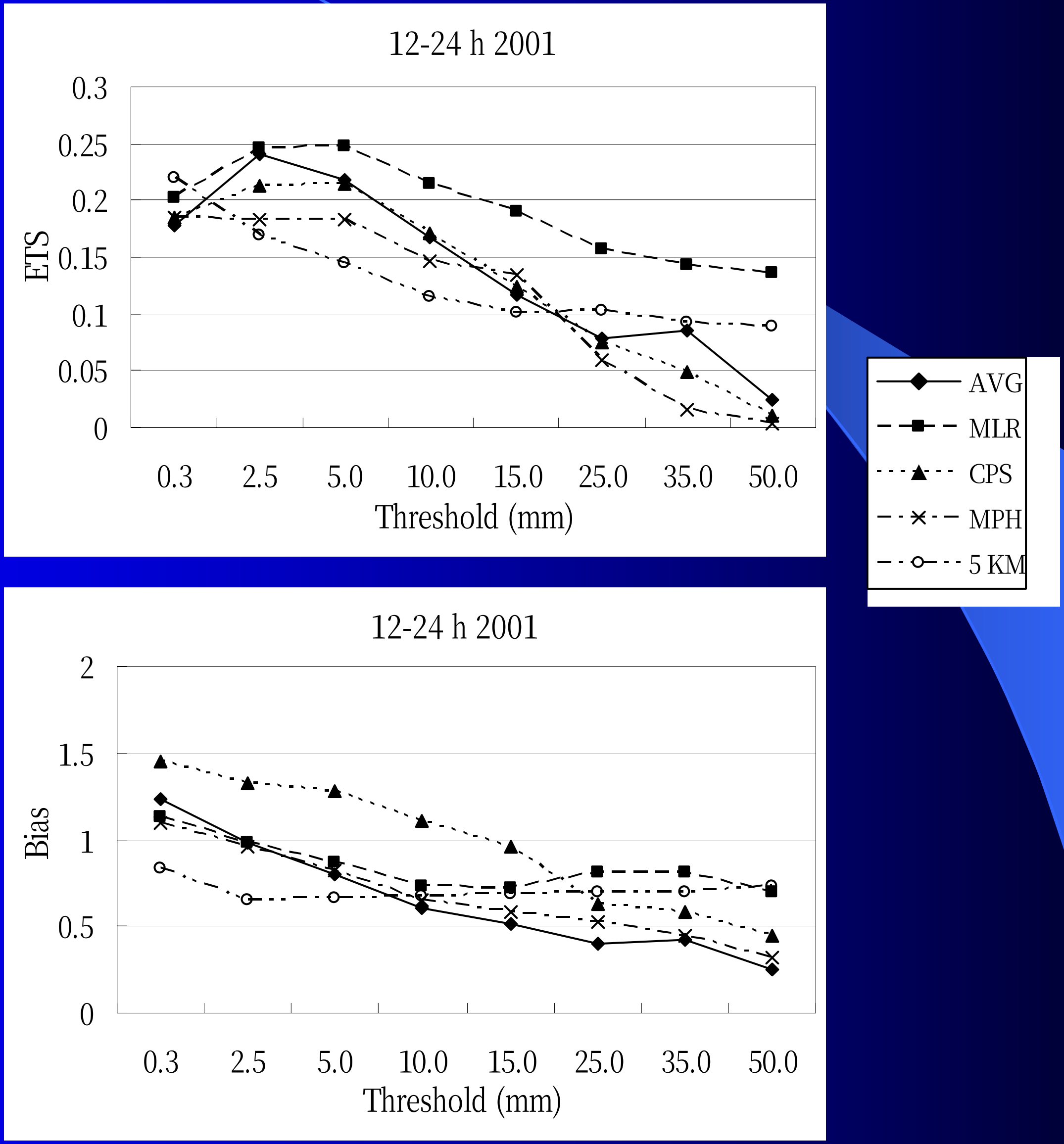


18 h fcst

A Comparison of Ensemble Forecasting with High-Resolution (5-km) Forecasting

ETS

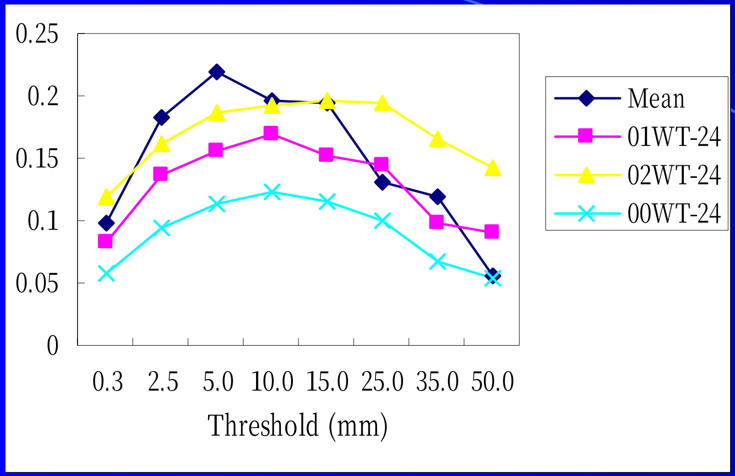
Bias

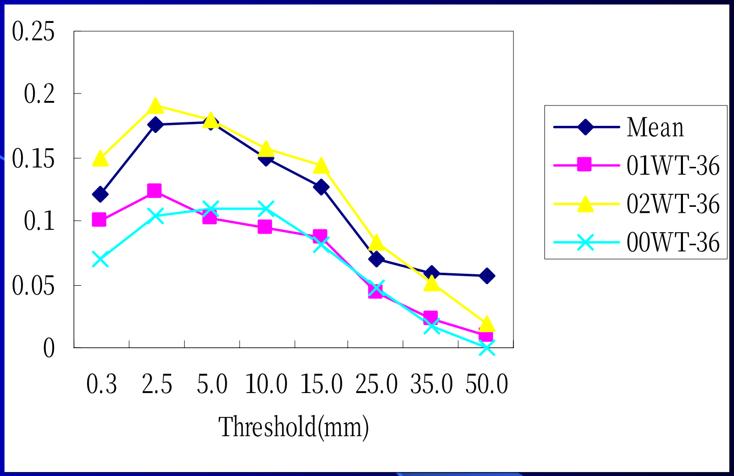


P.S. High-Resolution Forecasting is provided by Hong (2003)

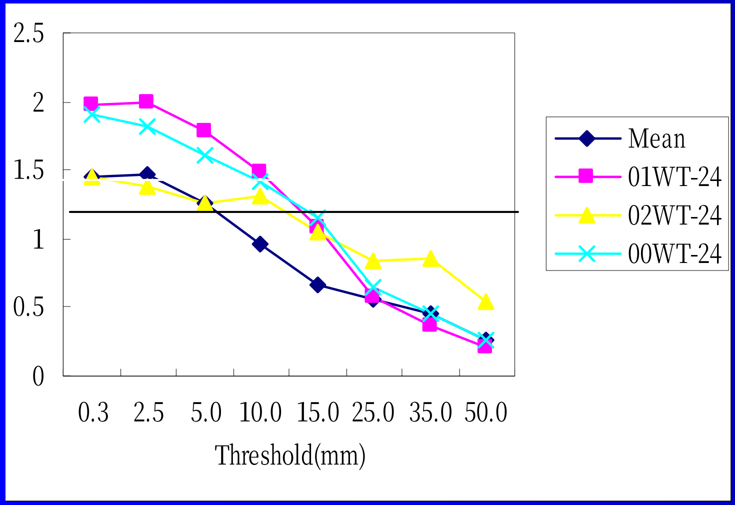
12-24 h 2002 | 24-36 h 2002

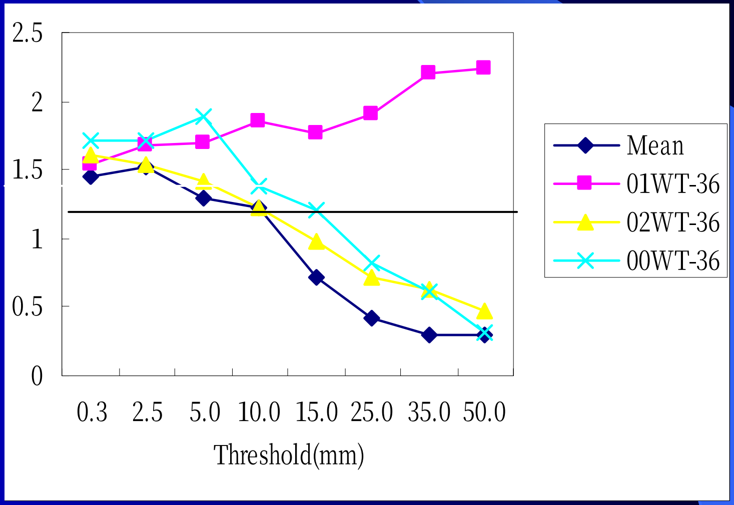
ETS





Bias





Mean: Same Weighting for Six Members

00WT: Use the MLR Weighting from Year 2000

01WT: Use the MLR Weighting from Year 2001

02WT: Use the MLR Weighting from Year 2002 (Current Year)

Conclusions (1/3)

(1) A combination of Grell CPS with Reisner-1 microphysics provided the best QPF over Taiwan during the 2000-2002 Mei-Yu seasons, and the second best was Kain-Fritsch CPS with Simple-Ice microphysics.

(2) For rainfall occurrence forecast, most members had better skill over the NE mountain area, NW coastal plan, central mountain cascade, SW coastal plain, and SW mountain area. These areas were also regions of more accumulated rainfalls during the Mei-Yu seasons.

(3) An ensemble forecast of rainfall using the MLR method had the best ETS and BS performance for all rainfall thresholds, and it persistently outperformed the MEAN forecast with 6 members having the same weighting.

Conclusions (2/3)

(4) The ETS scores for the MLR ensemble forecasting:

• Year 2000: for 12-24 fcst, the ETS score is 0.15~0.35 for all precip. thresholds; for 24-36 h fcst, the ETS score is 0.18~0.24 for mid-to-heavy rainfalls (15~50 mm).

• Year 2001 (most rainfall): the ETS score is 0.15~0.25 for all precip. thresholds.

• Year 2002 (least rainfall): the ETS score is 0.12~0.2 for all precip. thresholds.

(5) The MLR ensemble forecasting applies more weighting over regions of higher ETS scores, thus producing a better predictive skill for all (*particularly for high*) precip. thresholds.

Conclusions (3/3)

(6) The MLR ensemble forecasting with weighting from previous years still had similar trends of ETS and BS to those determined from current-year weighting, albeit with less skill.

→ Taiwan's rainfalls during the Mei-Yu seasons may have some climatological characteristics, and the MLR ensemble forecasting may be able to capture this climatological attribute.