

CHAPTER 4 RESULTS AND DISCUSSION

4.1 Performance of SILEPE Model

The experiment cases for testing SILEPE model are shown in Table 4.1.

Table 4.1 The experiment setting for testing the performance of SILEPE model.

Model Domain	lat: 40°S to 80°N, long: 180°W to 180°E
Model Resolution	$\Delta x = \Delta y = 1^\circ$, $\Delta t = 60 s$.
Initial Condition	NCEP data reanalysis (follow the cases in Table 3.1), 500 hPa Case A 08 Dec 2002 00UTC Case B 07 Dec 2002 00UTC Case C 14 Dec 2002 00UTC Case D 13 Dec 2002 00UTC
Boundary Condition	Cyclic in the west-east boundary Open in the north-south boundary
Forecast Time	4 days

Since SILEPE has a problem at the north boundary of the domain due to strong gradient of geopotential height, in order to avoid this problem the domain is extended to 40°S - 80°N, 180°W - 180°E. However, the domain for testing the performance of the domain is between 20°S - 60°N and 60°E - 140°E.

The results in Figure 4.1 show that Case A has the pattern closes to NCEP than that of Case B. The acceptable forecast time is about 3-4 days. Similarly, Case C is better than Case D (not shown).

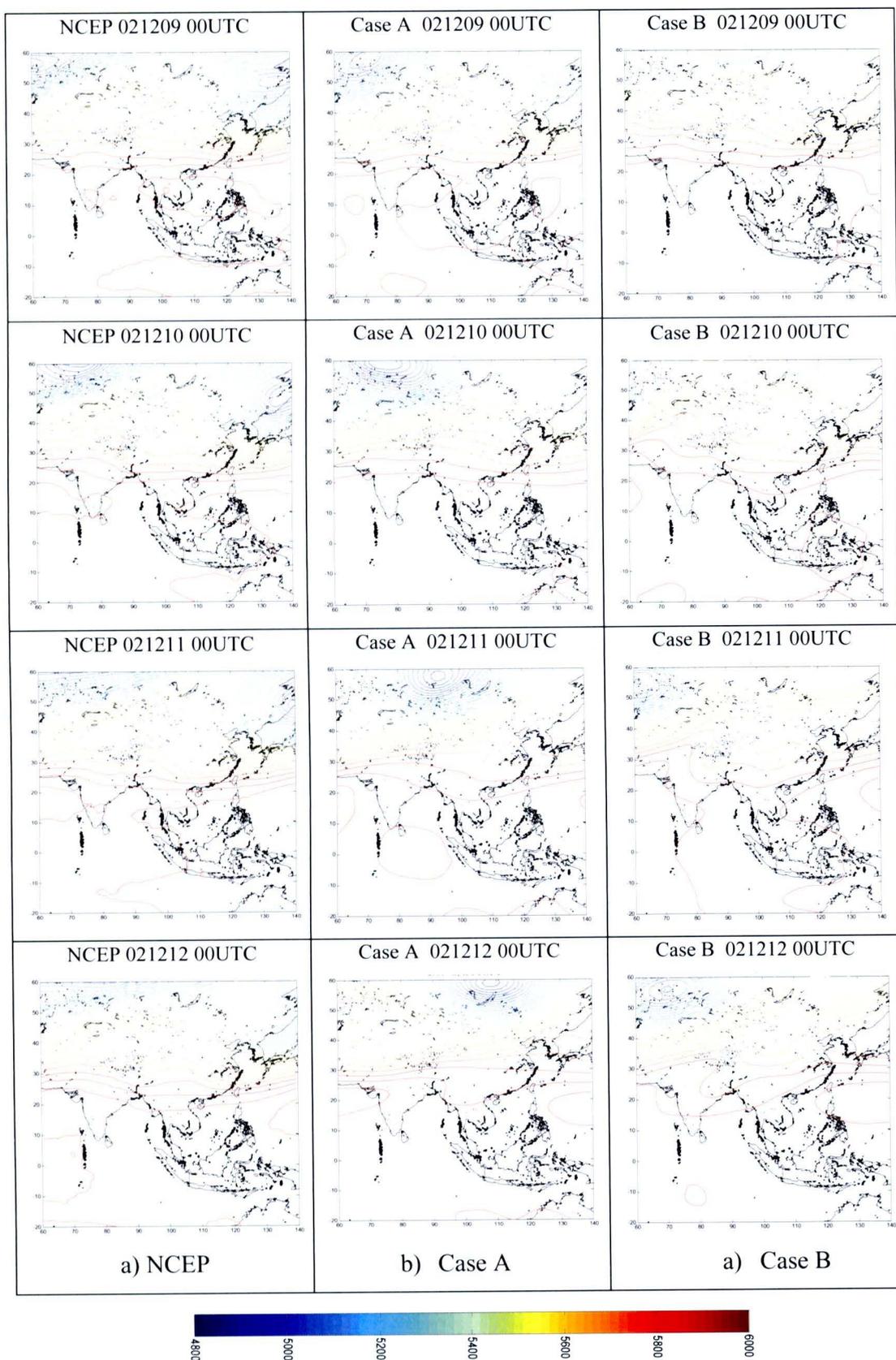


Figure 4.1 Daily geopotential height (m) from a) NCEP b) Case A and c) Case B.

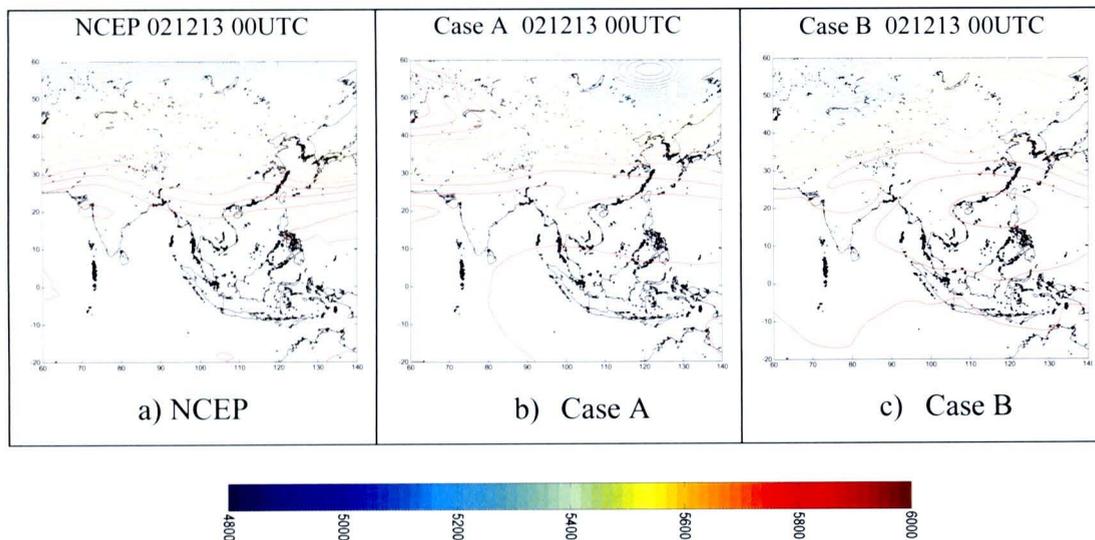


Figure 4.1 (Continued).

4.2 Bred Vector

The result for Case 4 in Table 3.3 is discussed as an example. The steps to generate the initial perturbation by breeding method of Case 4 12Z 07 DEC 2059 are as follows.

- 1) Perform the control run (CTL)

In the control run, initial condition is obtained from IPCC data 12Z 07 DEC 2059 of A2 scenario. The forecast interval is 12 hours and the forecast time is 14 days. Examples of CTL for geopotential height plot every 24 hr are shown in Figure 4.2.

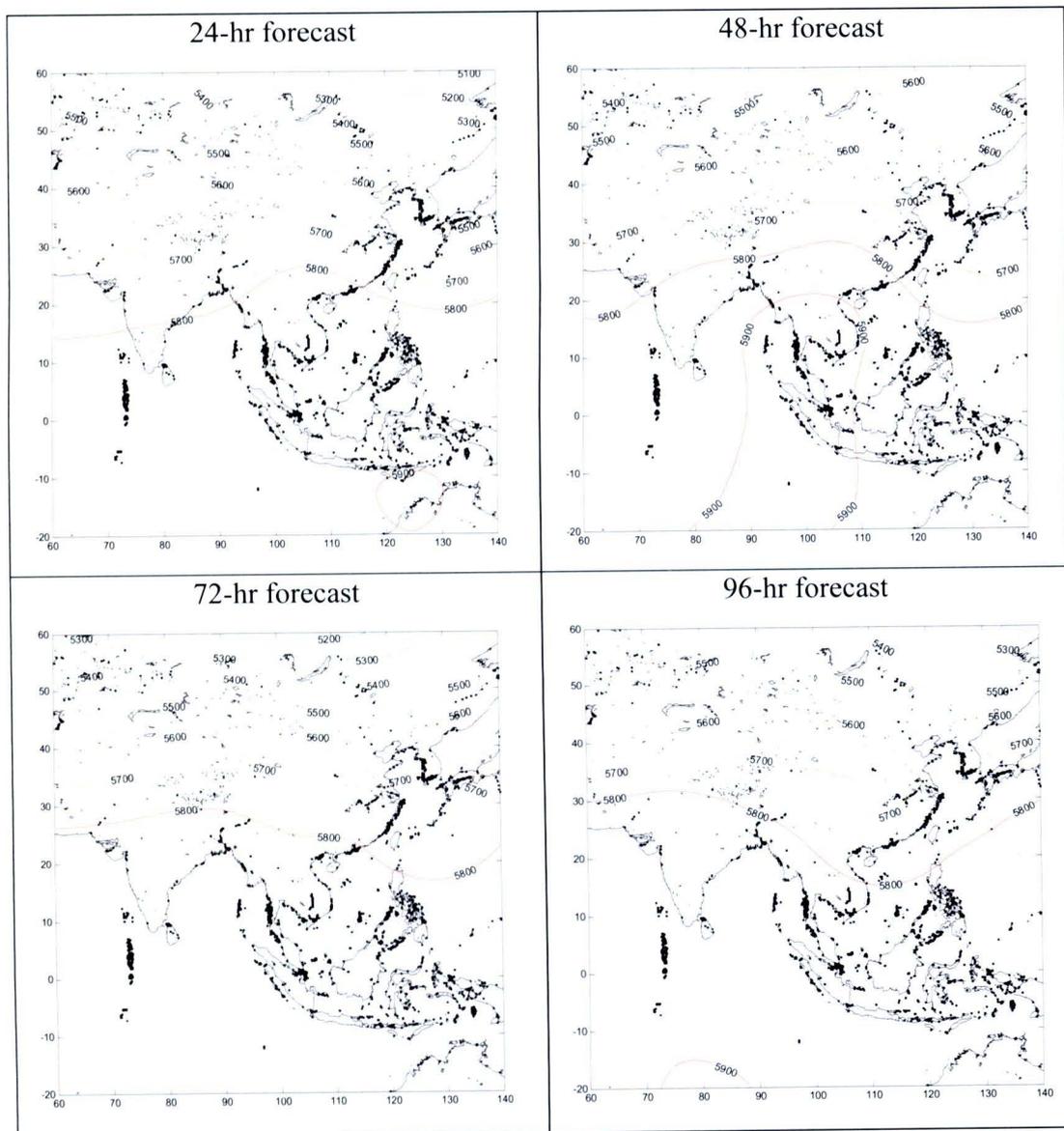


Figure 4.2 The 500 hPa geopotential height for every of 24 hr of the control run of Case 4.

2) Find the initial value for generation initial perturbation

Figure 4.3 shows the initial value of 500 hPa geopotential height at $t = 0$ (00 hr) after model initialization.

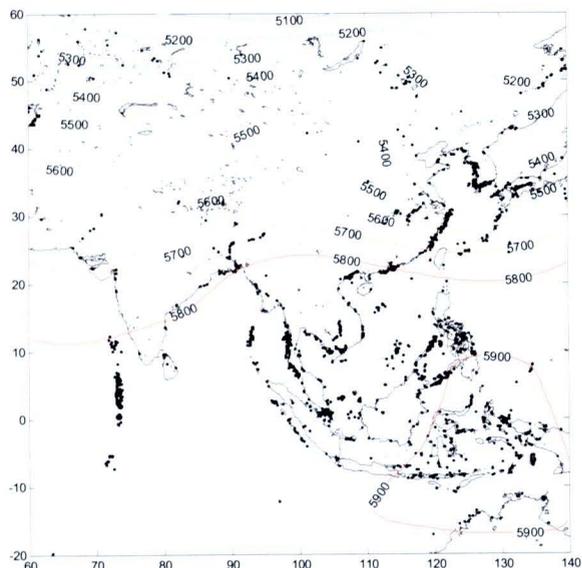


Figure 4.3 The 500 hPa geopotential height at $t = 0$ (00 hr) after model initialization.

3) Find the initial perturbation

The initial perturbation is calculated from the 500 hPa geopotential height difference between the initial value and A2 scenario. There are plus perturbation (+PRT) and minus perturbation (-PRT). The +PRT and -PRT are shown as an example in Figure 4.4.

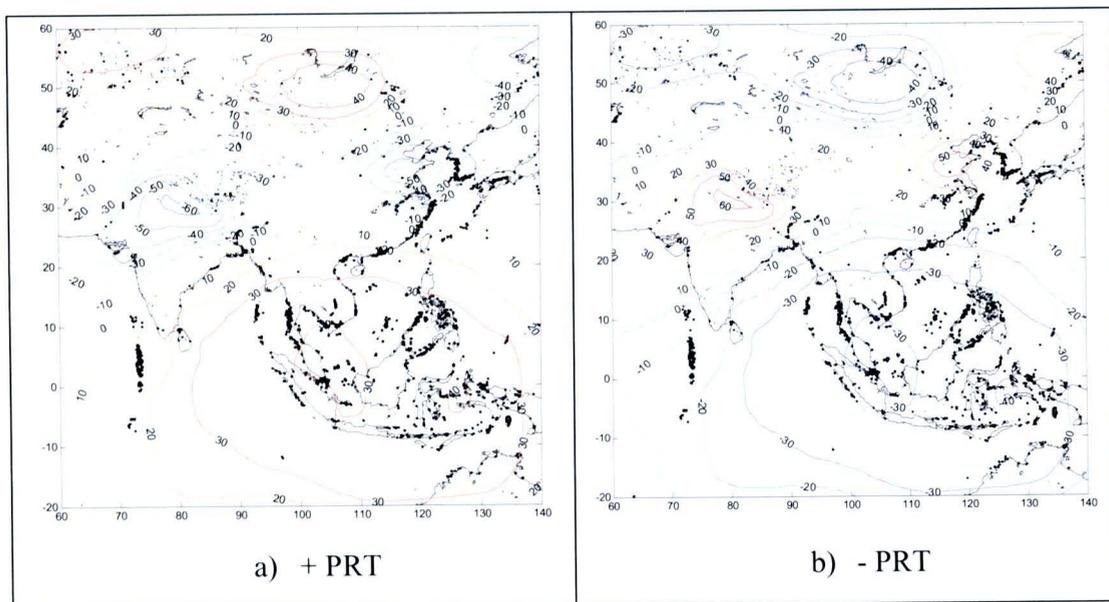


Figure 4.4 The initial perturbation at $t = 0$.

In order to see the differences among CTL that come from A2 scenario, plus perturbation (+PRT) and minus (-PRT), spaghetti plot of geopotential height at 5700 m is shown. This 5700 m value of geopotential height is selected because it has the largest change during the forecast. The contours of 5700 m geopotential height from A2, +PRT and -PRT are shown in Figure 4.5.

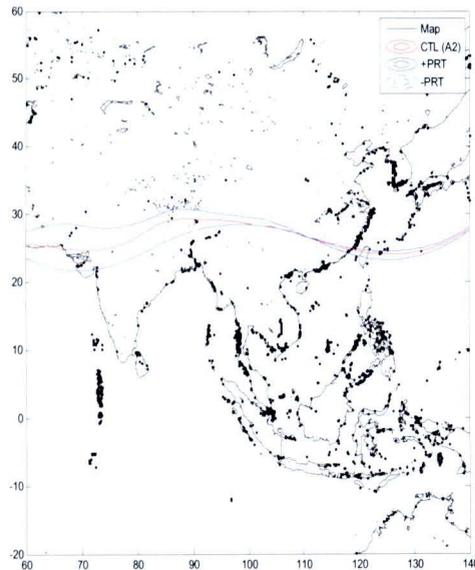


Figure 4.5 Spaghetti plot of 5700 m geopotential height for CTL (A2), +PRT, and -PRT at $t = 0$.

- 4) Find the Euclidean norm of the initial perturbation

The Euclidean norm of initial perturbation at $t = 0$ is 1.7931×10^3 m.

- 5) Perform the perturbation run (PRT)

The perturbation run is started from the perturbed initial condition of geopotential height (in step 3), integrate the perturbed initial condition with the SILEPE model forward for $\delta t = 6$ hr (in the first step). Then subtract the original unperturbed solution (CTL) from the perturbed run (PRT). The difference between CTL and PRT is called initial perturbation at $\delta t = 6$ hr and is shown in Figure 4.6.

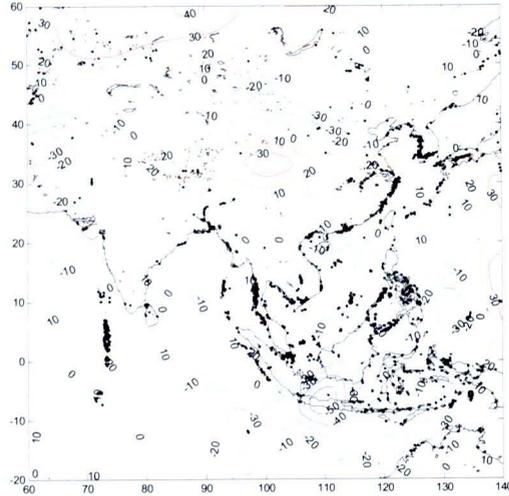


Figure 4.6 The perturbation at $\delta t = 6$ hr.

- 6) Find the norm of the difference in step 3

The Euclidean norm of initial perturbation $\delta t = 6$ hr. is 908.961311754447 m.

- 7) Calculate the rescaling factor

Adjust the norm of the difference between CTL and PRT to the initial norm by using the rescaling factor

$$R(x, t + \delta t) = \frac{\|\delta Z(x, 0)\|}{\|\delta Z(x, t + \delta t)\|} = \frac{908.961311754447}{1.7931 \times 10^3} = 1.97265168519740$$

- 8) Generate the new perturbation (bred vector) using the rescaling factor

The new perturbation or bred vector is calculated by rescaling factor follows Equation (3.11). The results are shown in Figure 4.7.

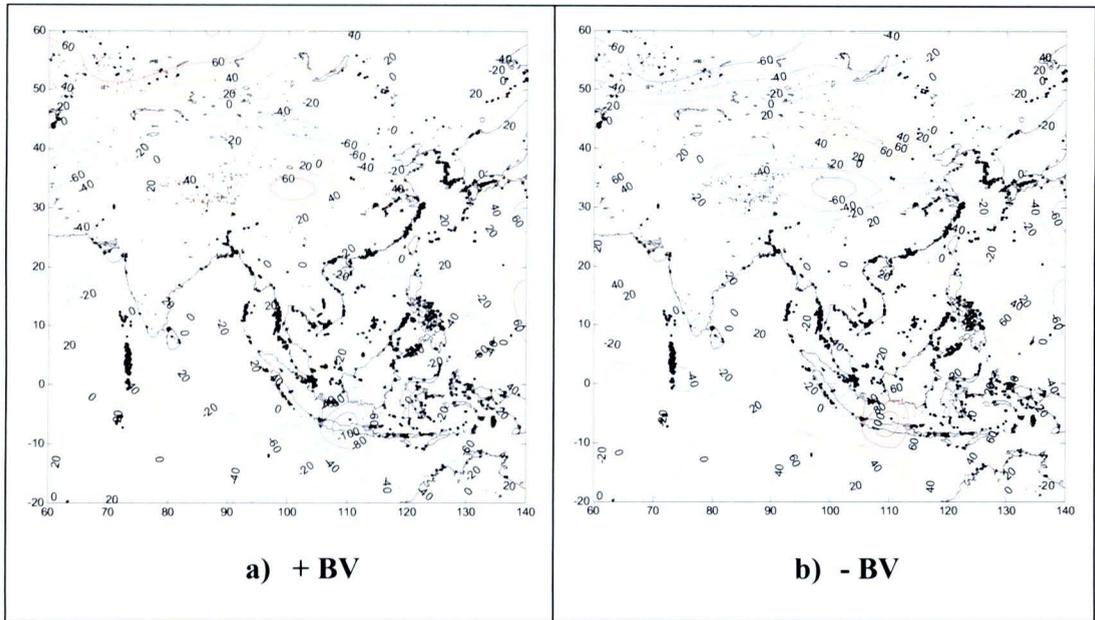


Figure 4.7 The new perturbations or bred vectors for a) the plus bred vector (+BV) and b) the minus bred vector (-BV).

9) Repeat for the next time interval

The steps are repeated by rescaling every 12 hr until 14 days. The bred vector or the perturbation will consist of 50 values which are 25 plus bred vectors (+BV) and 25 minus bred vectors (-BV).

4.3 Ensemble Forecast

Table 4.2 shows the outline of experiment setting for the ensemble forecasts.

Table 4.2 The outline of experiment setting for the ensemble forecasts using bred vector.

Model Domain	lat: 40°S to 80°N, long: 180°W to 180°E
Resolution	$\Delta x = \Delta y = 1^\circ$, $\Delta t = 60 s$.
Initial Condition	50 values of + BV and – BV
Boundary Condition	Cyclic in the west-east boundary Open in the north-south boundary
Forecast Time	4 days

The ensemble members are generated by ensemble forecasts from the SILEPE model with 50 perturbed initial conditions. To demonstrate the distribution of all ensemble members, geopotential height at altitude of interest can be expressed as a spaghetti plot. Examples of spaghetti plots of the 5800 m contour of the 500 hPa pressure surface over Southeast Asia, based on day-1 ensemble forecast with IPCC data of 12Z 07 DEC 2059, for 24-hr, 48-hr, 72-hr, until 96-hr lead times, are shown in Figure 4.8.

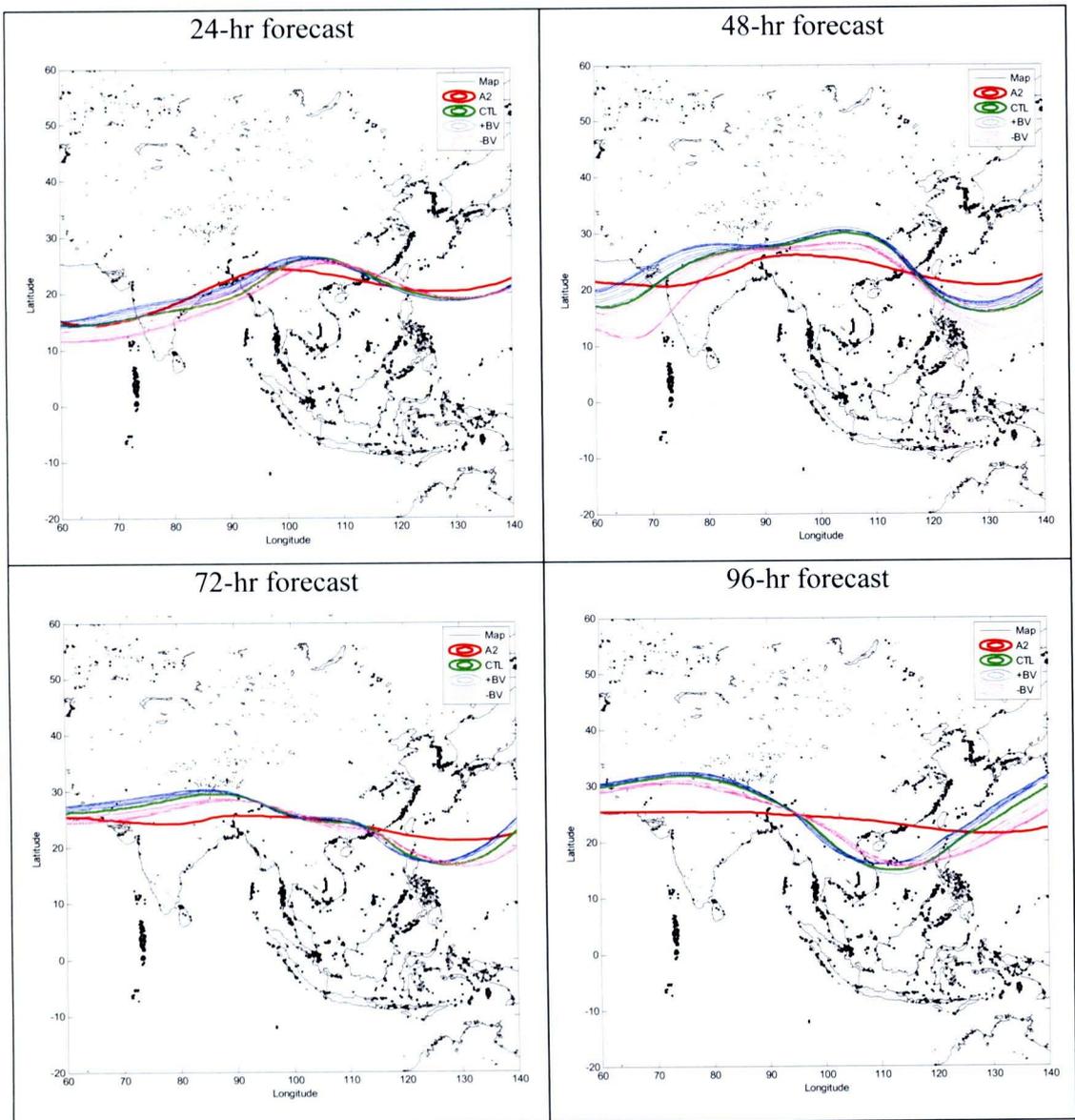


Figure 4.8 Spaghetti plots of 5800 m geopotential height for Case 4.

In Figure 4.8, the blue lines are the contours associated with the 25 positive ensemble members or plus bred vectors, the pink lines are the contours associated with the 25

negative ensemble members or minus bred vectors, the red heavy lines are based on the A2 data, and the green heavy lines show the control forecast. The geopotential height contours of ensemble members spread over India and cover the control run and A2 in 24-hr forecast. In 48-hr forecast, the ensemble members spread more than in 24-hr forecast especially over India and Papua New Guinea but cover control run and A2 only in some regions. The ensemble members cover the region that control run is close to A2. In 96-hr forecast, the ensemble members spreading decrease when compare with the other forecast times.

Results for other experiment cases are shown in Figures 4.9 – 4.12.

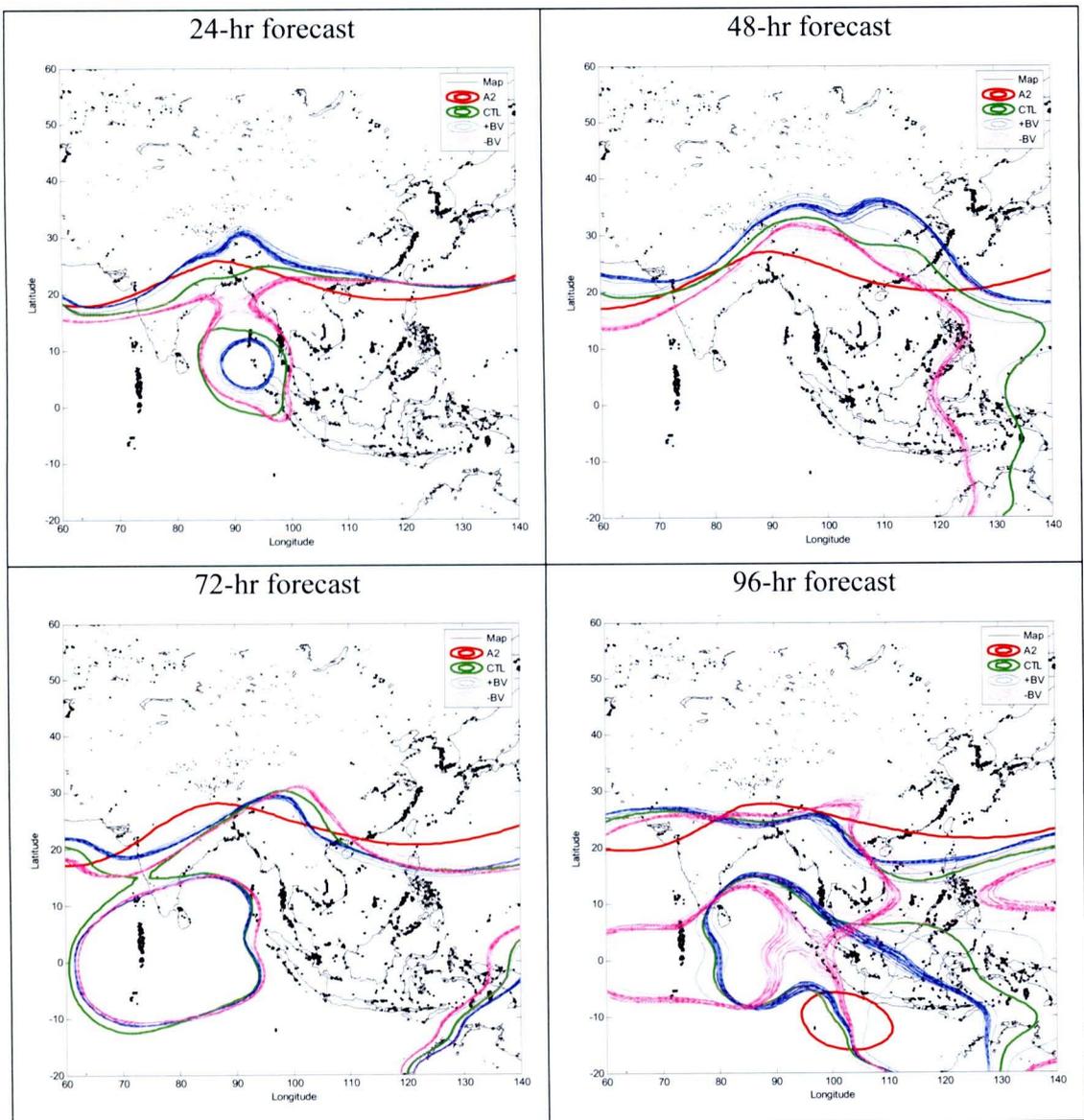


Figure 4.9 Spaghetti plot of geopotential height at 5800 m for Case 1.

In Figure 4.9, the geopotential height contour of ensemble members show maximum spread over Andaman Sea in 24-hr, 72-hr and 96-hr forecasts. It covers the control run and A2 only in 24-hr and 48-hr forecasts. In 48-hr forecast, the ensemble members spread well over South China Sea.

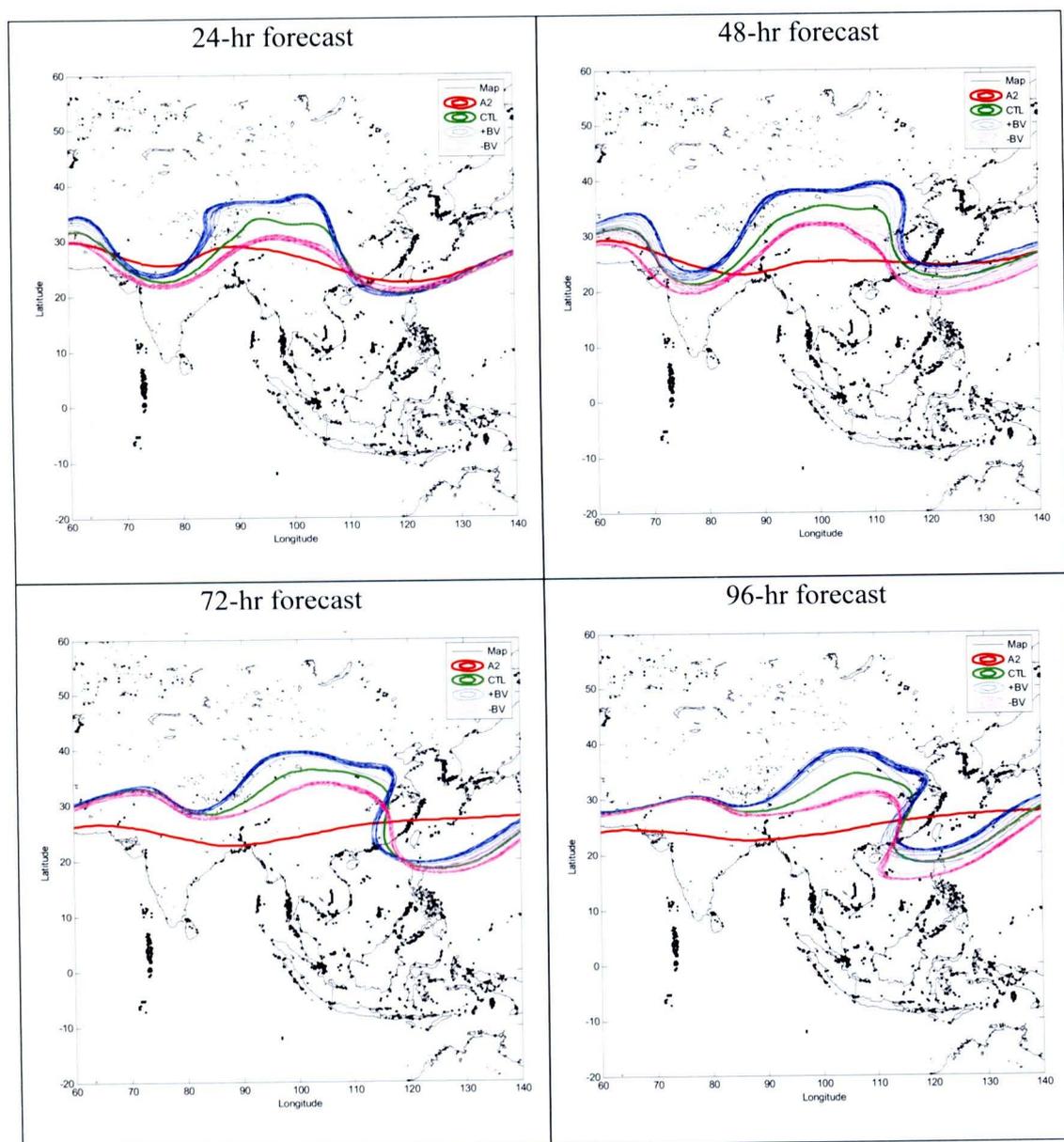


Figure 4.10 Spaghetti plot of geopotential height at 5800 m for Case 2.

The geopotential height contours of ensemble members cover the control run and A2 in 24-hr and 48-hr forecasts over some regions for Case 2 in Figure 4.10. In 48-hr forecast, the ensemble members spread more than in 24-hr forecast over Pakistan and Taiwan but

cover control run and A2 scenario only in some regions. In 72-hr and 96-hr forecasts, the ensemble members spreading decrease when compare with the other forecast times but still cover control run and the maximum spread is over Philippines.

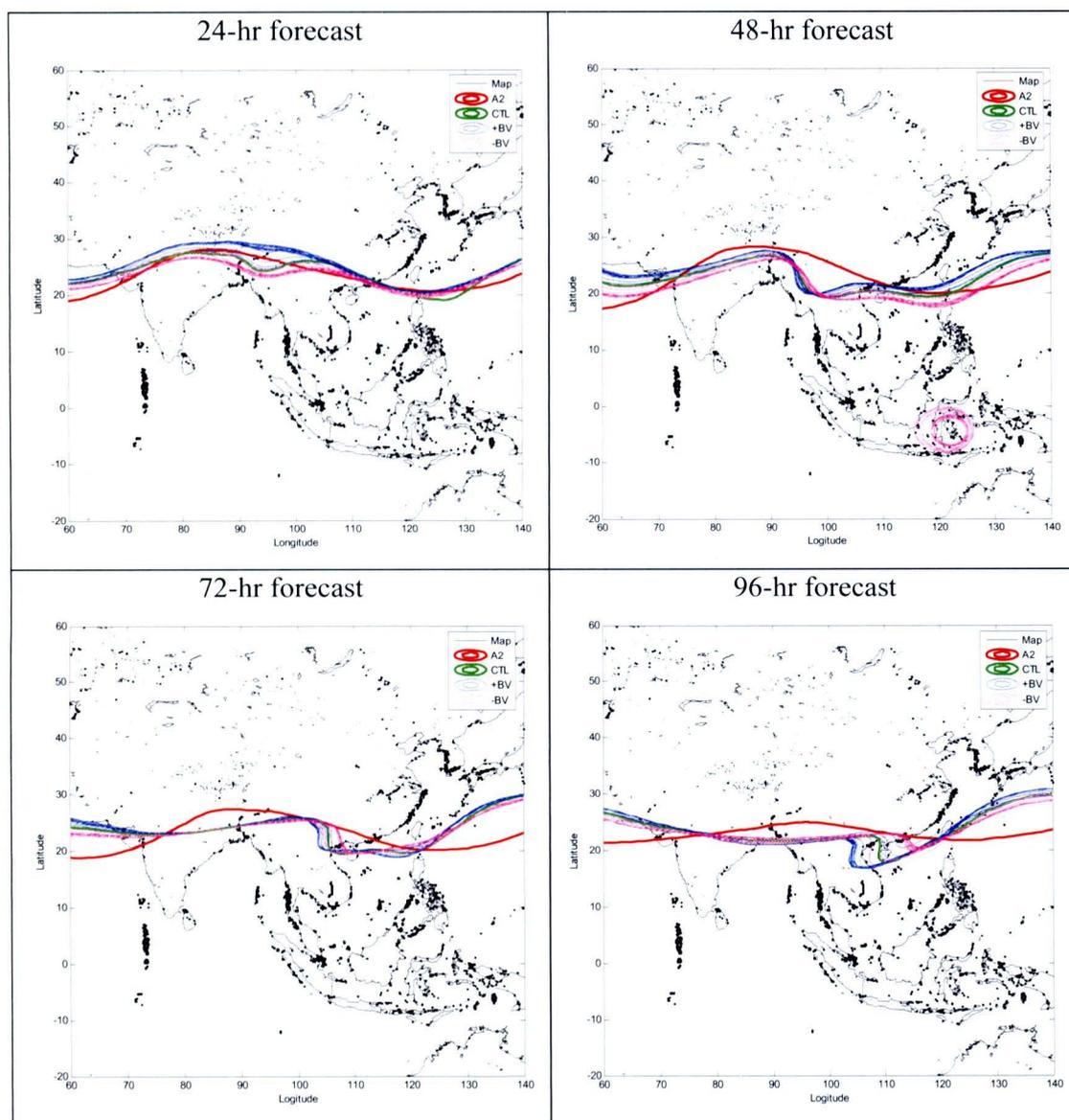


Figure 4.11 Spaghetti plot of geopotential height at 5800 m for Case 3.

For Case 3 in Figure 4.11, the geopotential height contours of ensemble members spread over Myanmar and cover the control run and A2 in 24-hr forecast. In 48-hr forecast, geopotential height contours of ensemble members spreading increase over Arabian Sea, Philippines, and Indonesia and cover the control run but cover only some

regions of A2 where the control run is close to A2. In 72-hr and 96-hr forecasts, the ensemble members do not cover A2 but still cover the control run. The geopotential height contours of ensemble members show the maximum spread over South China Sea in 96-hr forecast.

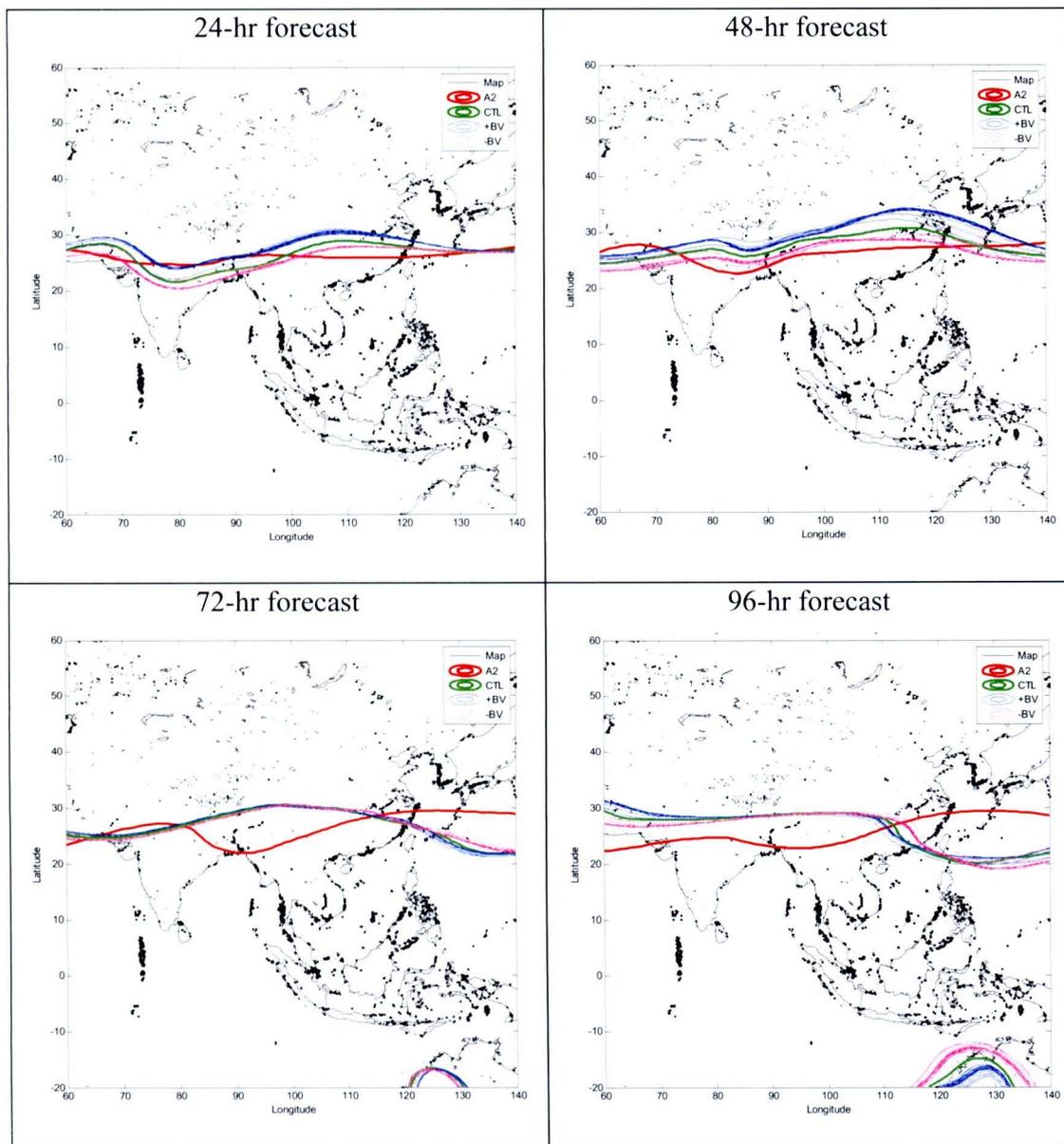


Figure 4.12 Spaghetti plot of geopotential height at 5800 m for Case 5.

For Case 5, the geopotential height contour of ensemble members spread over China and India and cover the control run and A2 in 24-hr and 48-hr forecasts as shown in Figure 4.12. In 72-hr forecast, the contour of ensemble members spreading decrease.

The contour of ensemble members and cover only the control run over Australia but do not cover A2 in 96-hr forecast.

4.4 Domain Invariant of Ensemble Forecast

A domain invariant is a property of a class of mathematical objects that remains unchanged when transformations of a certain type are applied to the objects on the domain. The domain invariants of ensemble members obtained from the mean potential vorticity, the mean geopotential height, and the mean total energy of the control run (CTL) and the mean of 50 ensemble members (mean EM) are shown in Table 4.3.

Table 4.3 Domain invariants of the control run (CTL) and the mean of 50 ensemble members (mean EM).

Time (hr)	Mean Potential Vorticity ($\text{km}^2/\text{kg.s}$)			Mean Geopotential Height (m)			Mean Total Energy (m^3/s^2)		
	CTL	Mean EM	Abs Error	CTL	Mean EM	Abs Error	CTL	Mean EM	Abs Error
0	8.001E-09	8.0015E-09	5.00E-13	5.633E+03	5.6332E+03	0.20	1.567E+08	1.567E+08	25490.20
6	7.996E-09	7.9963E-09	2.80E-13	5.630E+03	5.6300E+03	0.02	1.565E+08	1.565E+08	5882.35
12	8.020E-09	8.0195E-09	5.00E-13	5.630E+03	5.6303E+03	0.34	1.565E+08	1.565E+08	7843.14
18	8.038E-09	8.0375E-09	4.60E-13	5.629E+03	5.6295E+03	0.48	1.564E+08	1.564E+08	49019.61
24	8.044E-09	8.0431E-09	9.40E-13	5.629E+03	5.6287E+03	0.34	1.564E+08	1.564E+08	0.00
30	8.044E-09	8.0428E-09	1.24E-12	5.631E+03	5.6308E+03	0.22	1.565E+08	1.565E+08	27450.98
36	8.034E-09	8.0331E-09	9.20E-13	5.632E+03	5.6320E+03	0.02	1.566E+08	1.566E+08	7843.14
42	8.015E-09	8.0136E-09	1.42E-12	5.634E+03	5.6340E+03	0.00	1.567E+08	1.567E+08	13725.49
48	7.986E-09	7.9852E-09	7.60E-13	5.636E+03	5.6360E+03	0.04	1.568E+08	1.568E+08	13725.49
54	7.960E-09	7.9590E-09	1.04E-12	5.639E+03	5.6386E+03	0.44	1.569E+08	1.569E+08	0.00
60	7.948E-09	7.9467E-09	1.28E-12	5.640E+03	5.6406E+03	0.56	1.570E+08	1.570E+08	0.00
66	7.944E-09	7.9434E-09	5.60E-13	5.642E+03	5.6423E+03	0.28	1.571E+08	1.571E+08	13725.49
72	7.942E-09	7.9405E-09	1.46E-12	5.644E+03	5.6440E+03	0.02	1.571E+08	1.571E+08	37254.90
78	7.941E-09	7.9392E-09	1.84E-12	5.645E+03	5.6457E+03	0.68	1.572E+08	1.572E+08	5882.35
84	7.942E-09	7.9398E-09	2.18E-12	5.647E+03	5.6467E+03	0.30	1.573E+08	1.573E+08	33333.33
90	7.944E-09	7.9404E-09	3.64E-12	5.648E+03	5.6479E+03	0.10	1.573E+08	1.573E+08	45098.04
96	7.941E-09	7.9375E-09	3.54E-12	5.649E+03	5.6490E+03	0.00	1.574E+08	1.574E+08	41176.47
	Correlation = 0.9997			Correlation = 0.9990			Correlation = 0.9972		

Table 4.3 shows the values of mean potential vorticity, mean geopotential height, and mean total energy of CTL and mean EM, and also absolute error (Abs Error) from the selected case of IPCC data at 12Z 08 DEC 2049 (Case 1), for every 6 hr until 96 hr or 4 days. The table also shows a correlation between domain invariant of CTL and mean EM. In order to see more clearly, the behavior of the domain invariant is presented in Figures 4.13-4.15.

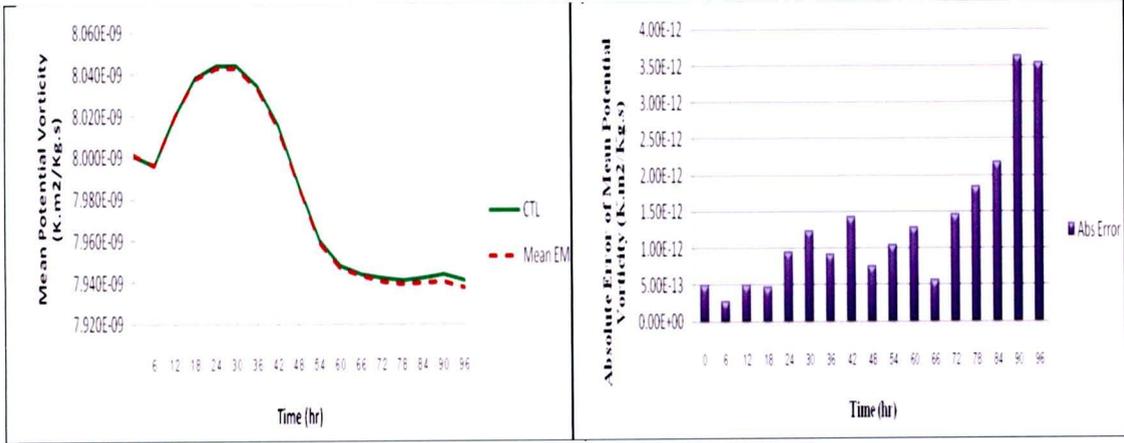


Figure 4.13a Mean potential vorticity for CTL and mean EM.

Figure 4.13b Absolute error of mean potential vorticity between CTL and mean EM.

Figure 4.13a shows that the mean potential vorticity ($\text{km}^2/\text{kg.s}$) for CTL (solid line) and mean EM (dash line) are very close from the beginning until 66 hr. The correlation between the CTL and mean EM is very high (0.9997). The maximum absolute error for mean potential vorticity between CTL and mean EM is $3.64 \times 10^{-10} \text{ km}^2/\text{kg.s}$ at 90-hr forecast, and the minimum value is $2.8 \times 10^{-13} \text{ km}^2/\text{kg.s}$ at 6-hr forecast.

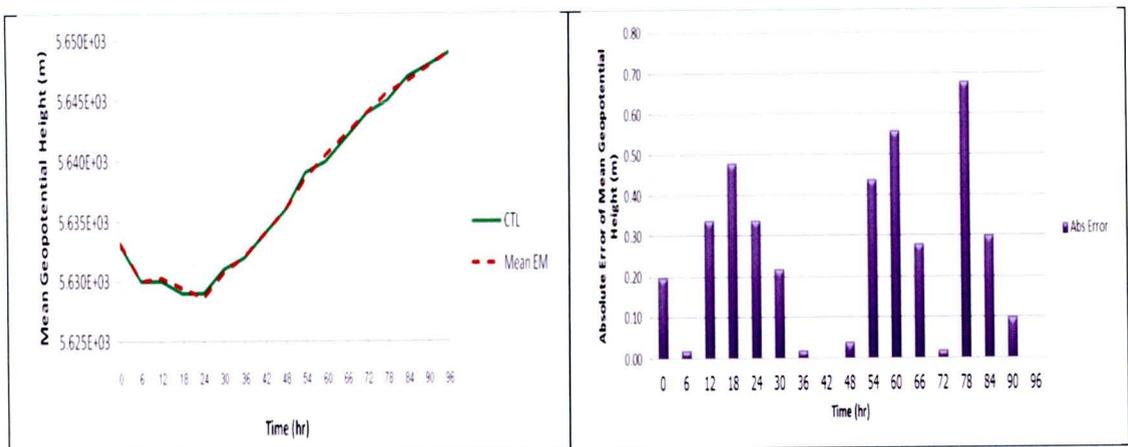


Figure 4.14a Mean geopotential height for CTL and mean EM.

Figure 4.14b Absolute error of mean geopotential height between CTL and mean EM.

The mean geopotential height (m) for CTL (solid line) and mean EM (dash line) in Figure 4.14a are decreased from the beginning until 24 hr, after that the values are

increased linearly. Based on the graph in Figure 4.14b, it is found that the absolute error of mean geopotential height between CTL and mean EM is small. This is because the initial condition is perturbed by breeding technique over Southeast Asia only, which is a very small area compared to the entire forecast domain.

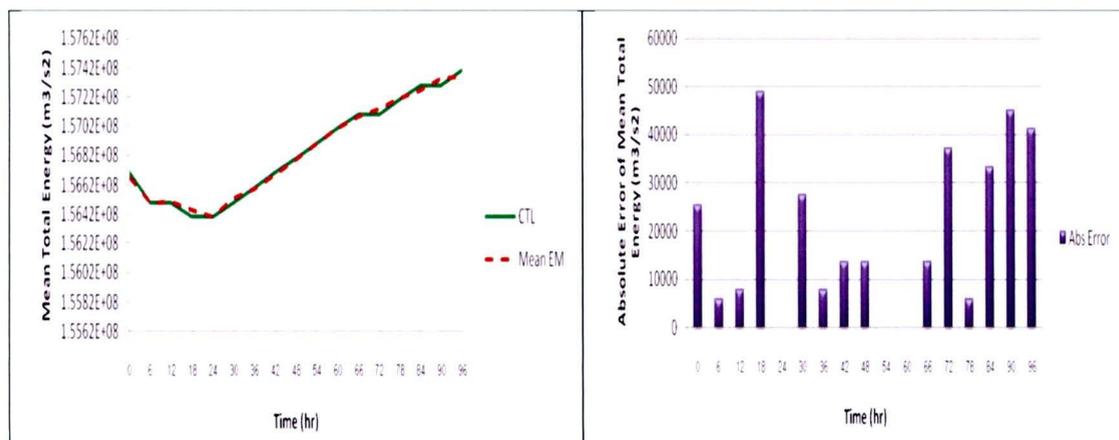


Figure 4.15a Mean total energy for CTL and mean EM.

Figure 4.15b Absolute error of mean total energy between CTL and mean EM.

In Figure 4.15a, the values of mean total energy (m^3/s^2) for CTL (green solid line) and mean EM (red dash line) show the same pattern, with the correlation 0.9972. At 18-hr forecast, absolute error of mean total energy between CTL and mean EM has the maximum value of $49019.61 \text{ m}^3/\text{s}^2$ and no error at 24-hr, 54-hr, and 60-hr forecasts.

The results of the experiments to determine the domain invariant from the calculated values of mean potential vorticity, mean geopotential height, and mean total energy of CTL and mean EM by SILEPE model show that the pattern of the domain invariant of CTL and mean EM are similar. It is consistent with the correlation which is very close to 1. It can be concluded that the 50 ensemble members are good samples in cold surge simulation over Southeast Asia under A2 global warming scenario.

4.5 Ensemble Forecast Probability

From Section 4.2, there appears to be a significant amount of uncertainty in the initial condition and forecast of the 5800 m height contour in most of the 24-hr and 48-hr forecasts which are considered as “good ensemble”. After that, the ensemble members

are smoothed and not cover A2 which are considered as “bad ensemble”. The smoothing occurs from the balance law in SILEPE model (Equations (2.11) - (2.13)). Because the spaghetti plots are shown only one value of geopotential height, in order to know where cold surge under global warming (A2 scenario) will likely to occur over Southeast Asia. The proximity of ensemble forecasts to A2 over Southeast Asia can also be expressed in terms of ensemble probability. The ensemble probability is calculated as the fraction of the number of ensemble members that have error in a specified range, with all ensemble members. It can be written as,

$$P_i(E) = \frac{n_i(E)}{n(T)} \times 100 \quad (4.1)$$

where E is the error range (difference between ensemble member and A2).

$P_i(E)$ is the probability of E at point i .

$n_i(E)$ is the number of ensemble member that satisfies the event E at the grid point i .

$n(T)$ is the total number of ensemble number.

For example, in Case 1 the number of ensemble member that correspond to the error range (E) is shown in Table 4.4.

Table 4.4 Example of the number of ensemble member that corresponds to the event at each grid point in Case 1 for 24-hr forecast.

Grid Point	Error Range (E)	n(E)	n(T)	P(E) (%)
lat: 54° N lon: 92° E	± 2.5%	0	50	0
	± 5%	27	50	54
	± 7.5%	50	50	100
lat: 55° N lon: 85° E	± 2.5%	19	50	38
	± 5%	50	50	100
	± 7.5%	50	50	100

In Table 4.4, the grid point 54° N, 92° E has probability 0%, that is no ensemble member is in the range of error ± 2.5%, probability 54% means that 27 out of 50

ensemble members is in the range of error $\pm 5\%$, and probability 100% has all ensemble members in the range of error 5%.

The results of the ensemble forecast probability to Case 1 are shown in Figures 4.16 - 4.18. The results for Cases 2 - 4 are shown in Appendix A.

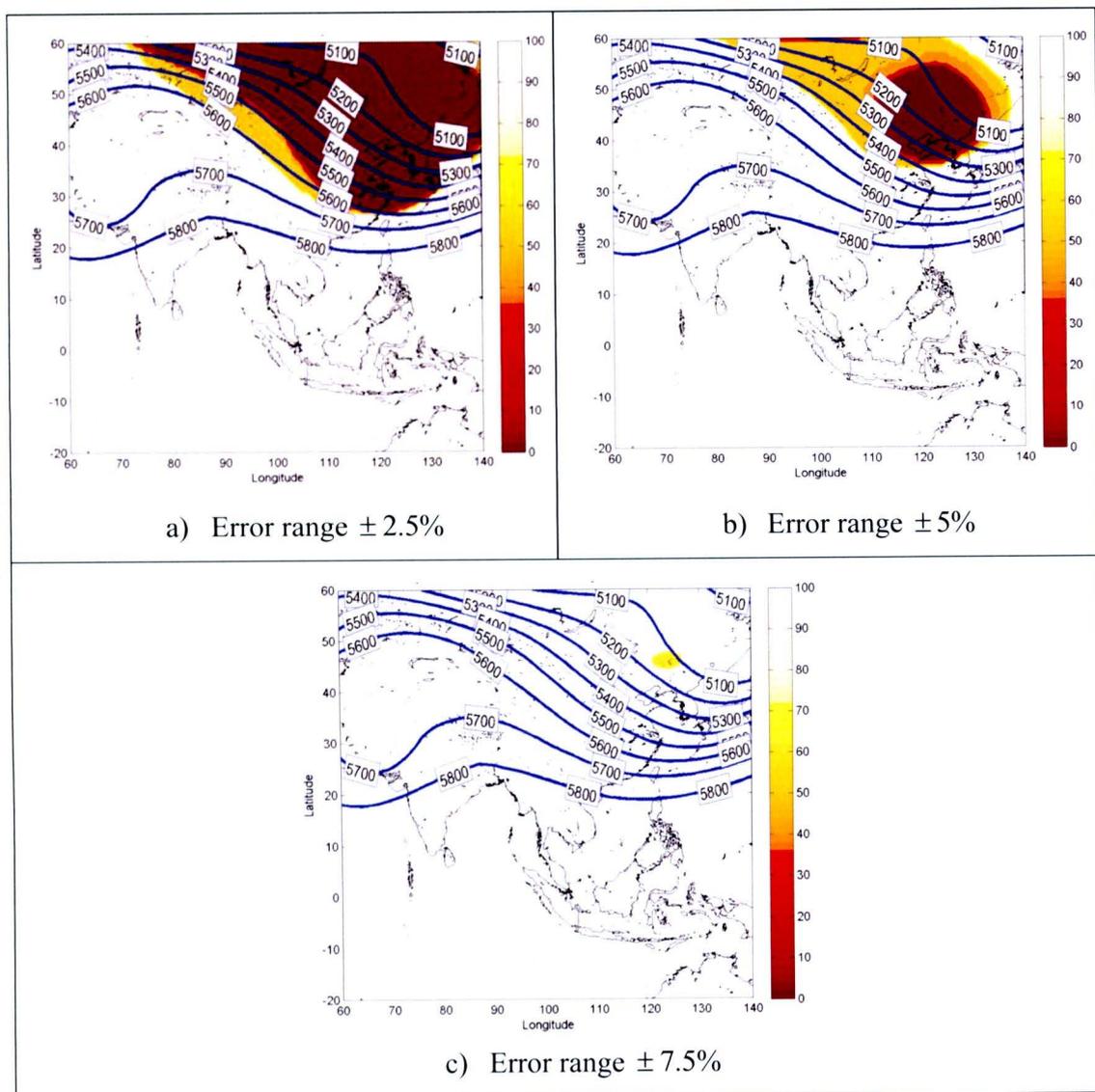


Figure 4.16 Ensemble forecast probability of geopotential height at 500 hPa for Case 1 at 24-hr forecast.

In Figure 4.16, the dark red is the maximum of ensemble probability, the white is zero ensemble probability, and the dark yellow is the medium ensemble probability. For additional information, the contour lines also show the geopotential height of A2 at 500

hPa. For 24-hr forecast, the maximum uncertainty with ensemble forecast probability of 0% is in the upper right quadrant. This area of maximum uncertainty decreases when the error range increases as shown in Figures 4.16b - c.

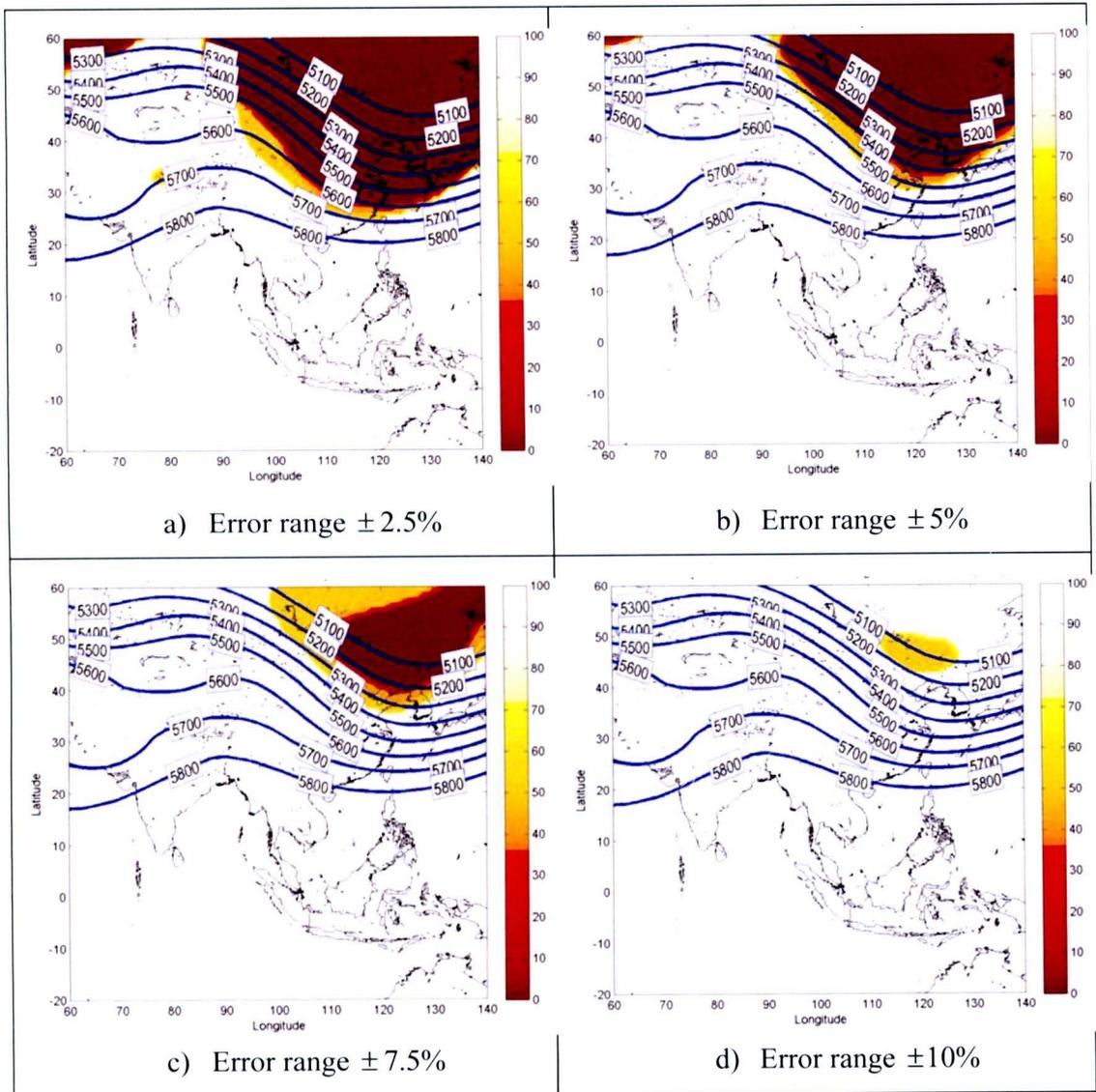


Figure 4.17 Ensemble forecast probability of geopotential height at 500 hPa for Case 1 at 48-hr forecast.

At 48-hr forecast, the area of maximum uncertainty has similar pattern as in 24-hr forecast but with larger areas for the same ensemble forecast probability (Figure 4.17).

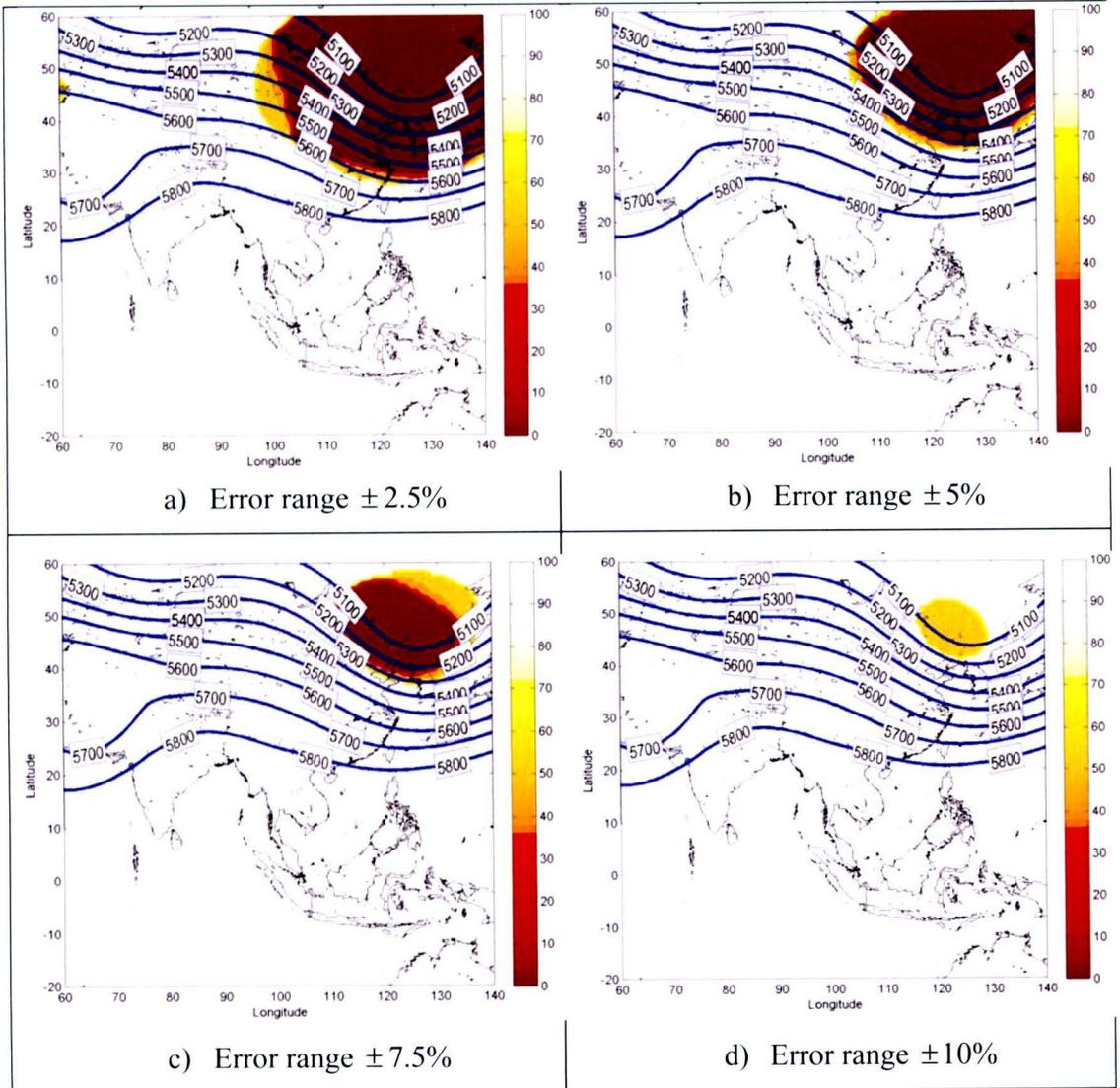


Figure 4.18 Ensemble forecast probability of geopotential height at 500 hPa for Case 1 at 72-hr forecast.

However, at 72-hr forecast the areas of maximum uncertainty are smaller than those of 48-hr forecast for the error ranges of $\pm 2.5\%$, $\pm 5\%$ and $\pm 7.5\%$ (Figure 4.18). The areas of maximum uncertainty for the error range of $\pm 10\%$ is slightly larger than that of 48-hr forecast.

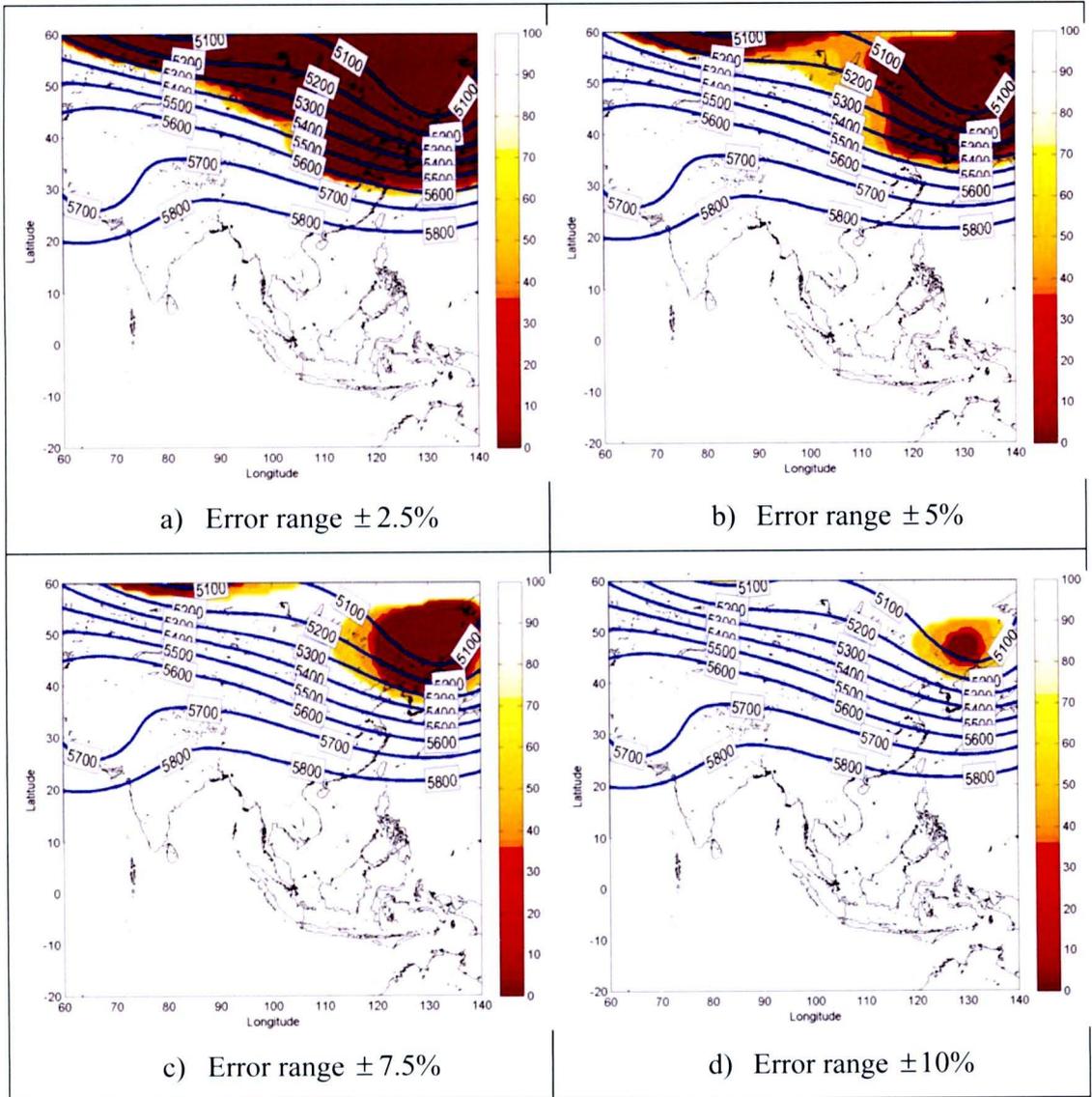


Figure 4.19 Ensemble forecast probability of geopotential height at 500 hPa for Case 1 at 96-hr forecast.

The areas of maximum uncertainty at 96-hr forecast are larger than those of 72-hr forecast for the same error ranges, as shown in Figure 4.19.

The results of ensemble forecast probability of geopotential height at 500 hPa for every cases can be summarized in terms of the pattern of cold surge as shown in Table 4.5.

Table 4.5 The pattern of cold surge from the ensemble forecast probability of geopotential height at 500 hPa.

Forecast Time	Cold Surge Pattern
24 hr	There is a longwave trough at the upper right quadrant of the domain which has the strongest gradient of geopotential height. The maximum uncertainty of ensemble forecasts is located around latitude $45^{\circ} N$ which is outside Southeast Asia. Thus, the ensemble forecasts indicate that the pattern of geopotential height can be a representative of the cold surge over Southeast Asia under A2.
48 hr	The pattern of geopotential height is similar to that of 24-hr forecast with a small eastward movement of the longwave trough over Southeast Asia. The areas of maximum uncertainty are larger than those of 24-hr forecast. However, the ensemble forecasts still indicate that the pattern of geopotential height represents the cold surge over Southeast Asia.
72 hr	The overall pattern of geopotential height is similar to the 48-hr pattern with a smaller eastward movement of the longwave trough. The pattern of geopotential height is still a representative of the cold surge.
96 hr	There is a small damping of the longwave trough which continue to move eastward. The ensemble forecasts still show that the pattern of geopotential height is a representative of the cold surge over Southeast Asia.

Similar patterns of geopotential height are also obtained from Cases 2 – 4 (Appendix A). The position and strength of each case is slightly different from other cases. However, all cases indicate the existence of longwave trough in the upper right quadrant of the domain during the cold surge period over Southeast Asia.