CLIMATE CHANGE DUE TO GREENHOUSE EFFECTS IN CHINA AS SIMULATED BY A REGIONAL CLIMATE MODEL—PART II: CLIMATE CHANGE*

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ABSTRACT

Impacts of greenhouse effects ($2\times CO_2$) on climate change over China as simulated by a regional climate model have been investigated. The model was based on RegCM2 and is nested in one-way mode within a global coupled atmosphere-ocean model (CSIRO R21L9 AOGCM). Two multi-year simulations, the control run with normal CO_2 concentration and sensitivity run with doubled CO_2 concentration are conducted.

As Part II of the publications, with a brief analysis of the $2\times CO_2$ experiment by CSIRO R21L9, results of the $2\times CO_2$ simulation by RegCM2 are analyzed in detail.

Results of the RegCM show a remarkably warming over China with an increment ranging from 2.2℃ in southern China to 2.8℃ in northern due to greenhouse effect. The regional averaged annual temperature increase is 2.5℃. The warming is greater in winter and spring. Daily maximum and minimum temperatures increase also over China which lead to much more hot spell days in summer and less cold spell days in winter.

Precipitation increases in all seasons of the year, with the greatest found in summer. Annual mean precipitation increases significantly in western China, parts of the area in south of the Yangtze River and northern part of the Northeast, while a decrease in the area from southern part of the Northeast to North China is simulated. The regional averaged annual increase of precipitation is 12%. More heavy rain events are found noticeably in southern China. The simulated tropical storms affecting and landing over China tend to increase. Analysis on the simulation of circulation pattern showed that the 500 hPa height in East Asia might rise significantly.

Key words: greenhouse effect, regional climate model, sensitivity run

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I. INTRODUCTION

The earth climate is formed under the energy balance of the incoming solar shortwave radiation and outgoing longwave thermal radiation emitted from the earth. Either absorption or emission of the radiation has its close relationship with the atmospheric components and their concentration. Changes of them consequently lead to the change of climate. Human-induced changes of atmospheric composition and concentration are an important way to cause anthropogenic climate change.

Carbon dioxide (CO_2) is an important greenhouse gas in the atmosphere. It can both absorb solar shortwave radiation and absorb/emit terrestrial longwave radiation. The amount of CO_2 has increased by more than 30% since pre-industrial times and is still increasing, mainly due to the human combustion of fossil fuels and deforestation. The increased concentration of CO_2 and other greenhouse gases in the atmosphere enhances the absorption and emission of infrared radiation. It has big influence on the climate system. From the observation, the global average surface air temperature has increased 0.4—0.8℃ since the late 19th century (Folland et al. 2001). There are many reasons for causing this, but more and more scientific evidence shows that human induced greenhouse effects play an important role.

Study of the effects of CO_2 concentration on climate dates back long time ago. The means to quantify the climate response to the increasing greenhouse gas is by using numerical models of different complexity. Energy balance model was widely used in the early studies. Then the general circulation model (GCM) began to be used (e.g. Manabe et al. 1967; 1975; 1980; Sellers 1974). Following its development and improvement, the coupled atmosphere-ocean general circulation model (AOGCM) became one of the most important and widely used tools in the study since 1980s.

Many research work has been carried out in China on the study of greenhouse effects on climate. Wang et al. (1993), Chen Keming et al. (1996), Chen Qiying et al. (1996) studied the climate response of greenhouse gases in the globe and in China by using GCMs. Song and Chen (1996), Li and Gong (1996), Chen and Fu (1997) studied the greenhouse effects in China by using of regional climate model (RCM). While much was learned from their work, further research is still needed, since the resolutions of the GCMs used are coarse, the RCMs were nested in AGCM, not AOGCM as well as the duration time was not long enough because of the limitation of computer resources. Finally more advanced models are available nowadays which can be used in the study to get hopefully better simulations.

We used a regional climate model (RegCM) through multiyear simulations, and studied the climate change in East Asia with focus on China region due to greenhouse effects (doubled CO_2 concentration).

The RegCM is driven by lateral boundary conditions provided by the Australia CSIRO AOGCM (Gordon and O'Farrell 1997). As mentioned in Part I of the publications (Gao et al. 2003), its 10-year simulation of 1981—1990 was used as control run of the CSIRO, and the 5-year simulation of 1986—1990 was used to drive the RegCM control run. Then the 10-year simulation of 2061 — 2070 and the 5-year simulation of 2066 — 2070 (corresponding to doubling of CO_2 concentration compared to 1990) are now used as sensitivity runs of the two models representing their future ($2\times CO_2$) climate conditions.

For the convenience of data analysis, the model output was interpolated to 160 stations throughout China as done in Gao et al. (2003).

II. CHANGES OF SURFACE AIR TEMPERATURE IN CHINA

As one of the most important greenhouse gases, CO_2 in increasing concentration has direct effects on the surface air temperature. Thus the change of temperature is firstly analyzed.

1. *Change of Mean Temperature*

Figure 1 shows the difference in temperature between $2\times CO_2$ and control runs produced by the CSIRO and RegCM for each month averaged over the China region. For brevity, we hereafter refer to these differences as "change due to $2\times CO_2$".

The temperature change simulated by CSIRO (dashed line in Fig. 1) shows the warming in each month of the year. The maximum is found in December (4.1℃) of winter, followed by May (3.7℃) in spring. The minimum is simulated in September in autumn season with a value of only 1.7℃.

Temperature change simulated by RegCM (solid line in Fig. 1) shows similar warming. The warming is found in all the months, the temperature rise in December and May is great, but with less values (3.2℃ and 3.1℃, respectively) than those by CSIRO. The minimum is also in September, but slightly higher (2.1℃) than CSIRO.

Table 1 shows temperature changes in the four seasons. Both models simulated a greater temperature rise in winter and spring than in summer and autumn. However, the simulated rising by RegCM in the former two seasons is lower than, while the rise in the latter two seasons is greater than CSIRO.

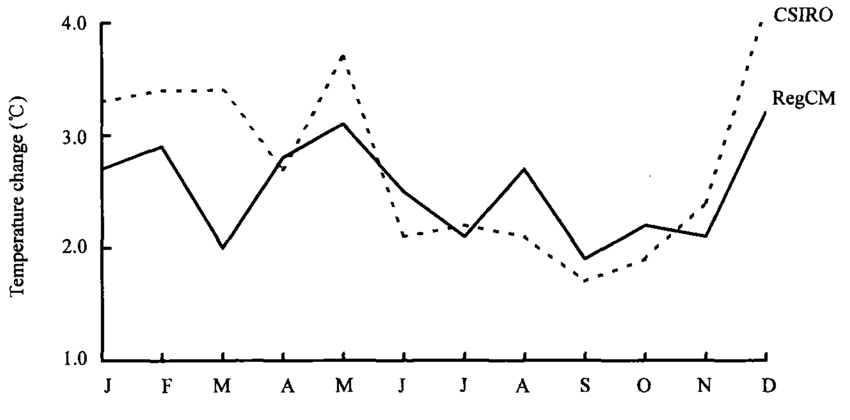

Fig. 1. Changes of monthly mean temperature due to $2\times CO_2$ (dashed line: simulation by CSIRO; solid line: simulation by RegCM).

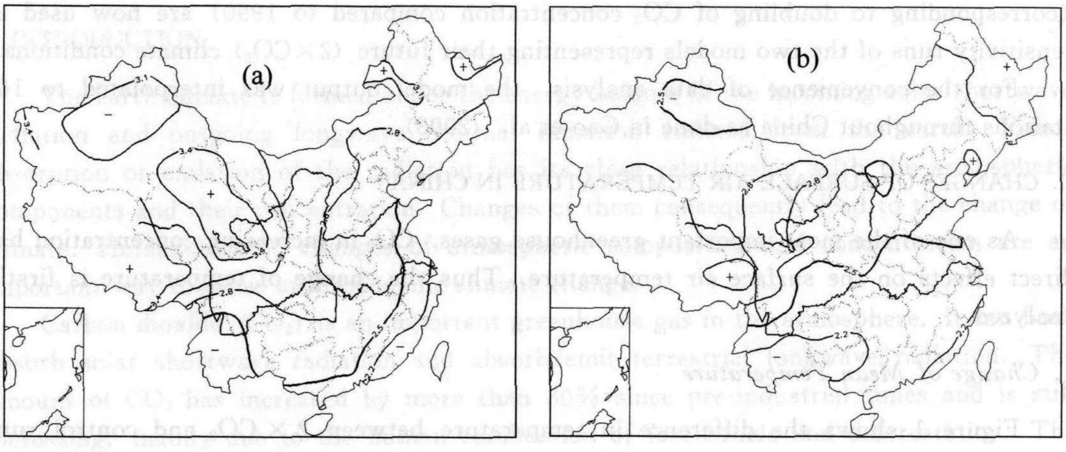

Fig. 2. Annual mean temperature changes in China due to $2\times CO_2$: (a) simulation by CSIRO; and (b) simulation by RegCM.

Table 1. Temperature Changes in Different Seasons of the Year in China due to $2\times CO_2$ (unit ℃)

	Winter	Spring	Summer	Autumn
CSIRO	3.6	3.3	2.1	2.0
RegCM	3.0	2.6	2.4	2.1

Annual mean temperature changes in China simulated by the two models are shown in Fig. 2. The CSIRO simulation shows (Fig. 2a) a general warming over China with a range from 2.2℃ in southeastern China to more than 3.0℃ in northern China. The averaged temperature rise is 2.8℃.

From Fig. 2b, the temperature change simulated by RegCM shows also a general warming over the region, but less pronounced than the CSIRO. The warming is lower in southern China, usually in the range between 2.0 to 2.5℃. The weak warming below 2.2℃ is simulated in Yunnan, portions of Guangxi and Guizhou in Southwest China, and in coastal areas of Southeast China. The RegCM simulation also shows a different spatial pattern from CSIRO. The warming shows a basically south (lower)-north (higher) increase pattern, while by use of CSIRO simulations it is in a southeast-northwest tilting direction.

2. *Changes of Daily Maximum and Minimum Temperatures and Diurnal Temperature Range*

Figure 3 shows the regional mean change of the daily maximum temperature (T_{max}) and daily minimum temperature (T_{min}), and the diurnal temperature range simulated by RegCM for each month. It can be seen that following the mean temperature rise in China, an increase in both T_{max} and T_{min} of the order of 0.5 to 4℃ is simulated in all months except November, when a small decrease in T_{max} is found. They show similar changes, but the increase of T_{max} is lower than that of T_{min} in most months, which causes a decrease in diurnal temperature range of a few tenths to 1℃. When annually averaged, the mean

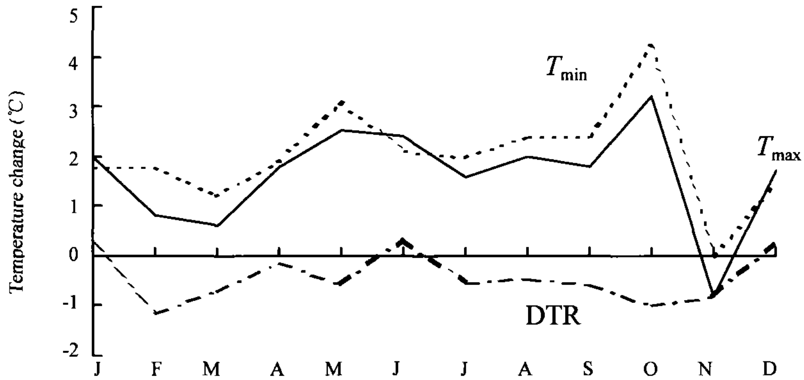

Fig. 3. Regional mean changes of T_{max} (solid line), T_{min} (dashed line), and diurnal temperature range (DTR, dot-dashed line) over China due to $2\times CO_2$.

changes of T_{max}, T_{min} and diurnal range over China are about 1.6℃, 2.0℃ and −0.4℃, respectively.

Changes in T_{max} and T_{min} should produce corresponding changes in the occurrence of hot and cold spells. As an example, Table 2 shows the change of number of cold days in winter at some stations in China (different criteria are used in defining the day numbers according to their geographical locations). It shows that there will be much less cold days in most areas of China due to $2\times CO_2$.

Table 2. Changes of Number of Cold Days in Winter at Some Stations in China due to $2\times CO_2$

	Harbin	Beijing	Shanghai	Guangzhou	Wuhan	Chongqing	Lanzhou	Urumqi
Criteria (℃)	−30	−20	−10	0	−8	−5	−20	−25
Days in CTL	24	30	30	9	35	29	26	24
Days in $2\times CO_2$	6	11	13	3	10	10	5	17
Change (%)	−75	−63	−57	−67	−71	−66	−81	−30

It is noticed that the simulated changes of temperature are consistent with observations for the last decades in China, e.g. the wide spread warming, the greater increase of temperature in winter and in northern China, simultaneous increase of T_{max} and T_{min}, and decrease of diurnal range (Wang et al. 2002).

III. CHANGES OF PRECIPITATION IN CHINA

Besides the change of temperature, increased CO_2 can also cause the change of precipitation result from the change of temperature, moisture, radiation etc.

1. *Changes of Monthly and Seasonal Mean Precipitation*

Figure 4 shows the monthly mean percentage change of precipitation simulated by CSIRO and RegCM for each month averaged over China. The simulated precipitation change by CSIRO (dashed line) indicates an increase in all months of the year, with the range from a maximum 38% in December in winter and a minimum 4% in September in autumn. Mean of the changes is 16%.

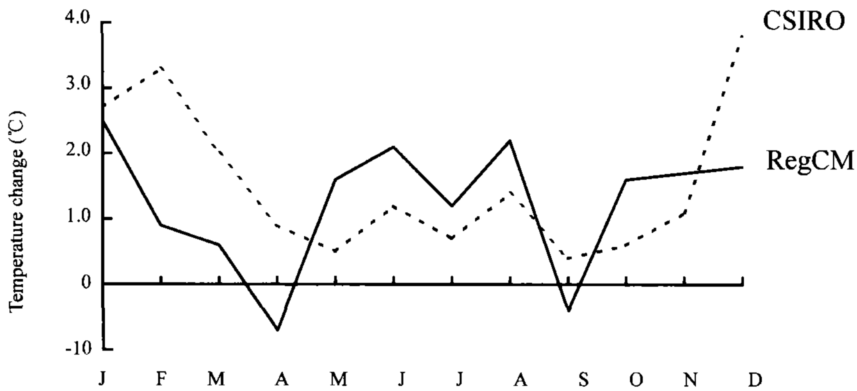

Fig. 4. Changes of monthly mean precipitation due to $2\times CO_2$. The dashed line shows the simulation by CSIRO; and the solid line the simulation by RegCM.

The simulated precipitation change by RegCM (solid line) shows also a general increase in most of the months. There are two periods with a greater increase. One is from October to January in winter half year, with a mean increase of 15%. The maximum is found also in the period, 25% in January. The other period lasts from May to August in summer half year. The increase is usually greater than 10%, with maxima in June and August (>20%). Smaller changes of ±10% are found in the other months. Decreased precipitation about −5% is found in April and September. Mean change of the 12 months is 13%.

Table 3 shows the seasonal changes. From discussions above and Table 3, it is clear that simulations by the two models showed some similarities. The annual mean monthly changes are close (16% and 13% respectively), the increase is greater in summer and smaller in autumn. But RegCM simulated a higher increase in summer, a lower increase in spring, and a decrease in April and September which are different from the CSIRO simulations.

Table 3. Seasonal Changes of Precipitation in China due to $2\times CO_2$ (unit: %)

	Winter	Spring	Summer	Autumn
CSIRO	33	12	11	6
RegCM	17	6	19	6

To further compare the difference of model simulations, 8 stations are selected as listed in line 1 of Table 4. Correlation coefficient and sign consistency of the changes in 12 months between the two simulations are listed in lines 2 and 3. Differences between CSIRO and RegCM results can be observed when concerning local changes.

Validation of present climate simulations by the two models showed a better performance of the RegCM. Thus the climate change scenario simulated by RegCM should

Table 4. Correlation Coefficient and Sign Consistency of Precipitation Change between the Two Model Simulations

	Harbin	Beijing	Shanghai	Guangzhou	Wuhan	Chongqing	Lanzhou	Urumqi	Ave.
corr. coef.	−0.32	0.16	0.53	−0.25	0.22	−0.31	−0.24	−0.35	−0.08
symb. cons. (%)	50	50	58	67	58	75	50	75	60

be considered more important. Meanwhile, uncertainties can be seen in simulating future climate change by using of numerical models.

2. *Changes of Annual Mean Precipitation*

Figure 5 shows the annual mean change of precipitation simulated by the two model.

The annual mean change of precipitation simulated by CSIRO shows a general increase over the region. The regional average increase is 11%. The increase is more pronounced in southern China and in Xinjiang, ranging from 10% to 15%. Maximum increase by 20%−30% is simulated in Huanan (South China) coastal areas. The only place with decreased precipitation is located in the bordering area of Shanxi, Hebei and Henan Provinces.

Similar to CSIRO, precipitation change simulated by RegCM shows also a basic increase over the region with the average of 12%. But in the RegCM simulations, the most prominent area with precipitation increase is located in West China, covering the area from west Huabei (North China) extending to Xinjiang. The increase in the area is usually in excess of 20%. The other areas with pronounced increase are the area from east of Guangdong to west of Fujian Province in Huanan and northeast portion of Guangxi Region. Precipitation change in middle and lower reaches of the Yangtze River is not so pronounced, with increase in most of the areas, and decrease in some places. Northern part of Northeast China is also the area with a greater precipitation increase, the increase amount can reach 20% in some places. A decrease in precipitation is observed in the area from southern Northeast to northern Huabei. The amount of decrease can be in excess of −10%.

Like temperature, some of the simulated precipitation change by RegCM, for example, the more precipitation in West China, less precipitation in portions of Northeast and Huabei, agree with the observation for the last decades (Ren et al. 2000; Wang et al. 2002).

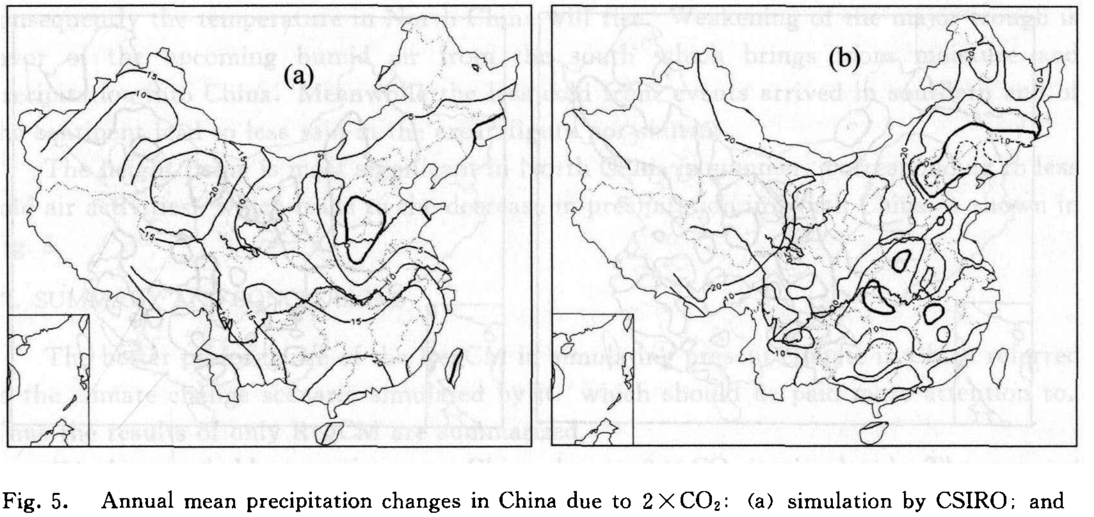

Fig. 5. Annual mean precipitation changes in China due to $2\times CO_2$: (a) simulation by CSIRO; and (b) simulation by RegCM (unit: %).

3. *Changes of Precipitation in Summer*

Located in East Asian monsoon area, summer precipitation takes an important place in China. The change of summer precipitation simulated by RegCM is shown in Fig. 6. A general precipitation increase can be seen in the region, with a greater increase in south of Yangtze River. However a pronounced precipitation decrease is found in east part of Northeast to Huabei in northern China. It refers to the weakening of precipitation in northern rain season. In the word of operational short-term climate prediction in China, the climate background of the rain season is that the occurrence of rain pattern III (more rain in southern China) will be more frequent, while the rain patterns I and II will happen less.

4. *Change of Heavy Rain Events in China*

Figure 7 shows the change in the simulated number of heavy rain events, which are defined as daily precipitation in excess of 35 mm. It can be seen that significant changes mostly occur in southern China, especially in the southeast area including the Fujian Province and the western portion of Jiangxi Province. An additional center of increase in heavy rain events occurs in south of Guizhou and Sichuan Provinces in Southwest China. Thus more heavy rain events and the consequently floods are expected in these areas under the greenhouse effects. Some increases can be also found in northern China, while a small area of decrease is indicated, where the average precipitation also decreases as discussed above. Overall, however, it is suggestive of a general increase in heavy precipitation events highly variable at the sub-regional scale.

IV. CHANGES OF TYPHOON AFFECTING CHINA

In the regional model a tropical storm is identified by a low sea level pressure (SLP) center of less than 1 0 0 5 hPa with a duration of at least three days . The movement of

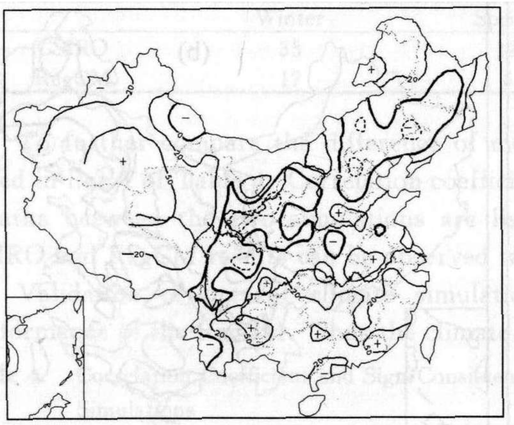

Fig. 6. Summer mean precipitation changes (%) in China simulated by RegCM due to 2× CO_2.

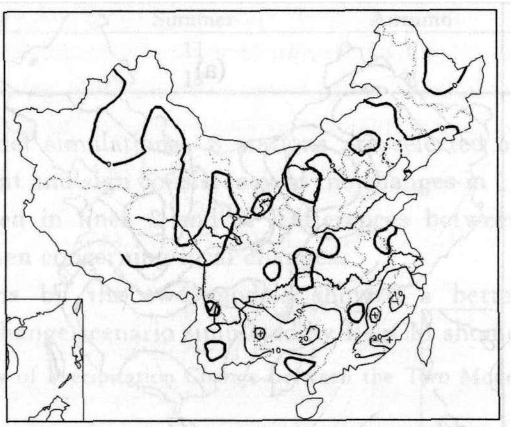

Fig. 7. Changes of heavy rain events in China (unit: d/5a).

typhoons was classified as Route I and Route II. Route I includes typhoons that movewestward across the western tropical Pacific and impinge upon central/East China; Route II typhoons move from South to north across the South China Sea towards the coastal regions of South China.

Table 4 shows the numbers of affecting and landing typhoons (July and August only) in the control and $2\times CO_2$ experiments, along with their partitioning into Route I and Route II typhoons.

In $2\times CO_2$ conditions we find an increase of 26% in the number of affecting typhoons and much more (doubled) landing typhoons. The characteristics of the typhoon route change significantly in $2\times CO_2$ conditions. However, in control run the largest fraction of typhoons (63%) follows Route I, in the $2\times CO_2$ simulation about 67% of typhoons follow Route II.

Table 4. Typhoon Numbers Per Year and Their Changes in July and August due to $2\times CO_2$

	Control	$2\times CO_2$	Change (%)
Numbers of affecting typhoons	3.8	4.8	+26
Numbers of landing typhoons	1.6	3.2	+100
Numbers (percentage) of affecting	2.4	1.6	−38
Typhoons moved in Route I	(63 %)	(33 %)	
Numbers (percentage) of affecting	1.4	3.2	+129
Typhoons moved in Route II	(37 %)	(67 %)	

V. CHANGES OF 500 HPA HEIGHT IN EAST ASIA

Figure 8 shows the changes of 500 hPa height field in winter and summer. It is observed from the figure that there is a general rise in the 500 hPa height, but the rise shows different pattern and value in the different seasons.

In winter, the area with higher rise is located in the region from east coast of the continent to Japan. The rising refers to the weakening of the East Asia major trough, and consequently the temperature in North China will rise. Weakening of the major trough is favor of the upcoming humid air from the south which brings more moisture and precipitation into China. Meanwhile the less cold front events arrived in southern end of the continent lead to less rain in the area (figure not shown).

The height rising is most significant in North China in summer, corresponding to less cold air activities, which leads to the decrease in precipitation in North China as shown in Fig. 8.

VI. SUMMARY AND CONCLUSIONS

The better performance of the RegCM in simulating present climate in China referred to the climate change scenario simulated by it, which should be paid more attention to. Thus the results of only RegCM are summarized.

(1) A remarkably warming over China due to $2\times CO_2$ is simulated. The regional average warming is 2.5℃. The warming is more pronounced in northern China than in the southern, and more pronounced in winter and spring than in summer and autumn. Daily

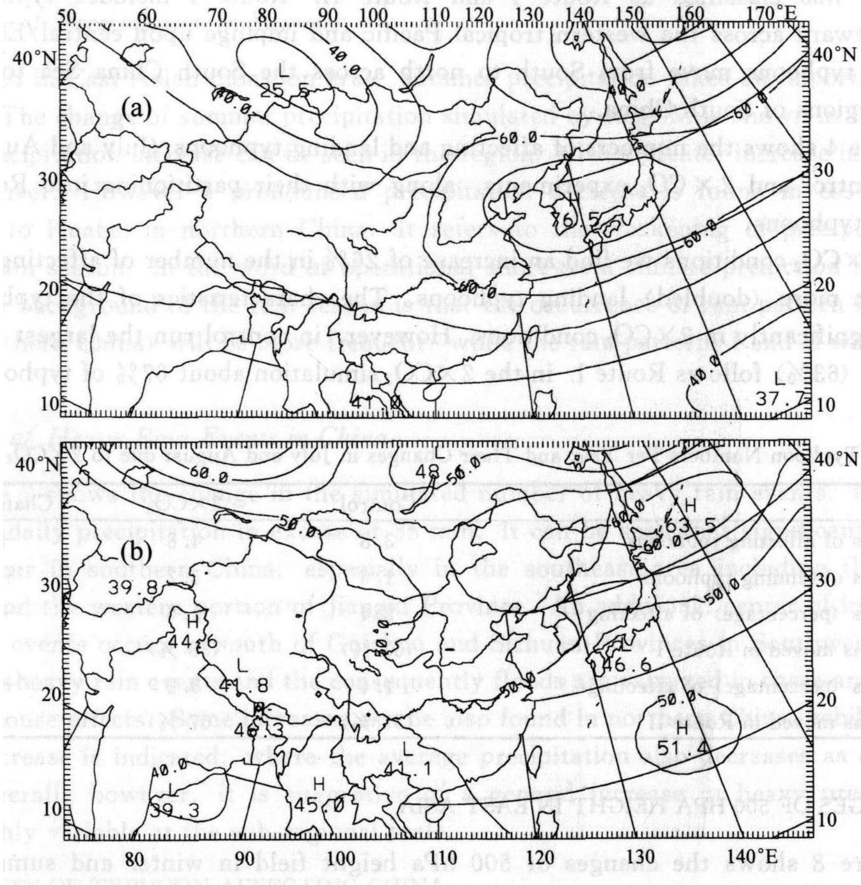

Fig. 8. Changes of 500 hPa height (in gpm) in East Asia for (a) winter and (b) summer.

maximum and minimum temperatures also rise significantly while the diurnal temperature range slightly decreases. Changes of the extreme temperature lead to more hot spells in summer and less cold spells in winter.

(2) Precipitation increases significantly over China, with the annual regional average increase by 12%. Greater increase is simulated in summer and winter. There will be more rain pattern III and less rain patterns I and II in the rain season in China. More heavy rain events are found in southern China, correspondingly the more floods are in the areas. Tropical storms affecting and landing over China tend to increase. Finally the 500 hPa height in East Asia might rise significantly due to $2\times CO_2$, which leads to the changes of temperature and precipitation in China.

(3) It is noticed that the simulated changes of temperature and precipitation show their similarities to the observed climate changes in China in the last decades.

(4) There are still a great number of uncertainties in simulating greenhouse effects on climate. More research is needed to better evaluate the effects of greenhouse on climate.

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