Agricultural Land Use Effects on Climate over China as Simulated by a Regional Climate Model*

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ABSTRACT

The Abdus Salam International Centre for Theoretical Physics (ICTP) Regional Climate Model version 3 (RegCM3) is used to investigate the climate effects of land use change related to agriculture over China. The model is driven by the European Center for Medium-range Weather Forecast 40-yr Re-Analysis (ERA40) data. Two sets of experiments for 15 yr (1987–2001) are conducted, one with the potential vegetation cover and the other the agricultural land use (AG). The results show that the AG effects on temperature are weak over northern China while in southern China a significant cooling is found in both winter (December-January-February) and summer (June-July-August). The mean cooling in the sub-regions of South China (SC) in winter and the sub-regions of Southeast (SE) China in summer are found to be the greatest, up to 0.5° and 0.8°C, respectively. In general, the change of AG leads to a decrease of annual mean temperature by 0.5–1°C in southern China. Slight change of precipitation in western China and a decrease of precipitation in eastern China are simulated in winter, with the maximum reduction reaching –7.5% over SE. A general decrease of precipitation over northern China and an increase over southern China are simulated in summer, in particular over SE where the increase of precipitation can be up to 7.3%. The AG effects on temperature and precipitation show strong interannual variability. Comparison of the climate effects between AG and the present-day land use (LU) is also performed. In southern China, the ratio of temperature (precipitation) changes caused by AG and LU is greater than (closer to) the ratio of the number of grid cells with changed vegetation cover due to AG and LU variations.

Key words: agricultural land use, regional climate model, regional climate change

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1. Introduction

It is well known that land use/land cover changes can significantly affect local and regional climate through the alteration of surface properties, e.g., albedo and roughness length, and result in changes in surface-atmosphere flux of water and energy. Land use forcing is considered as a very important aspect in the anthropogenic impacts on climate (Christensen et al., 2007).

The pioneer research conducted by Charney (1975) showed that the desertification in Sahel leads to the increase of surface albedo, thus alters the surface energy balance and consequently climate. Many studies have been conducted since then in order to better understand the land use effects on climate with the focus on tropical regions. The studies are based either on numerical simulations by climate models or analysis of the observation data. It is concluded that the major land use changes of deforestation and desertification over tropics can reduce the ability of the vegetation in transpiring water vapor to the atmosphere, and lead to an increase of temperature and decrease of precipitation (e.g., Gedney and Valdes, 2000). Furthermore, the local changes can affect the Hadley circulation and thus propagate the perturbations into midlatitude

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regions (e.g., Voldoire and Royer, 2004; Avissar and Werth, 2005).

The early studies conducted over mid and high-latitude regions are more or less limited to the effects of changes in individual properties (albedo, soil moisture, roughness length, etc.). Later on, climate models are introduced to study the combined effects. For example, by using a global climate model, Bonan et al. (1992) investigated the effects of replacing boreal forest with tundra and bare soil. A cooling effect is found in their study. Recent studies have also reported that historical land cover changes by human activities in midlatitudes, characterized by deforestation and agriculture, caused a regional cooling of 1–2°C (Bonan, 1997; Bonfils and Lobell, 2007; Kueppers et al., 2007).

Agriculture and cultivation are one of the most important activities in the human history in changing the original land cover to present-day land use. Statistics show that the present-day agricultural land occupies a total of 12% of the earth's land surface, with 17% of it being irrigated agricultural land. Agricultural land use plays an important role in the formation and evolution of local and regional climate (Bonfils and Lobell, 2007).

Increasing research efforts have been devoted in estimating the contribution of land use to climate over China and much was learnt from the works of Zhang et al. (2005a), Zhang J. Y. et al. (2005), Gao et al. (2007), etc. However, few studies are specifically focused on the agricultural land use (AG) forcing.

Previous studies showed that high resolution regional climate models perform better in simulating the monsoon climate over China and East Asia compared to the coarser resolution global models (Zhang et al., 2005b; Zhou and Yu, 2006; Gao et al., 2006, 2008). Gao et al. (2007) investigated the effects of the present-day land use (LU), possessing 71% of the land coverage over China, on climate by using a regional climate model. They found that LU has significant impacts on temperature and precipitation over the region. In their study, the AG occupies 18% of the land coverage over China.

China is a country with a long history of agricultural activities and a high population density. Although noticeable efforts have been made by the central and local governments in converting many agriculture fields back to forest or grassland for the restoration of ecological systems, existence of large portions of AG in China is still expected in the future. Thus, further studies to assess the AG effects on local and regional climate over China are needed.

In this study, we use the same model as Gao et al. (2007) to investigate the impacts of AG on climate. Comparisons of the climate effects of AG and LU (Gao et al., 2007) are also presented in this paper.

2. Model, data, and experimental design

The model employed in this study is the Regional Climate Model version 3 (RegCM3) developed at the Abdus Salam International Centre for Theoretical Physics (ICTP) (Pal et al., 2007). The model is centered at 36°N, 105°E, and extends 160 grid points in the west-east direction and 109 grid points in the north-south direction. The domain encompasses the whole China and surrounding areas at a horizontal grid spacing of 50 km (see Fig. 1). The model is run at its standard configuration of 18 vertical sigma layers and with a model top at 100 hPa. The CCM3 radiation scheme is used in the atmospheric radiative transfer process. Land surface process is represented by the BATS1e, while planetary boundary layer computation employs the Holtslag scheme. The mass flux scheme of Grell is selected to describe convective precipitation. Sea surface temperature of OISST data are from NOAA. The initial and time-evolving lateral boundary conditions (updated every 6 h) are derived from the ERA40 data.

Two sets of experiments are conducted in the study. For each experiment, the model is run from 1 October 1986 to 1 January 2002 for a total of 15 years plus 3 months. The first 3 months are used as the spin-up time for the model and are not included in the analysis.

Potential vegetation data (Holdridge, 1967; Zhang, 1993) over China as described in Gao et al. (2007) and GLCC (Global Land Cover Characterization) data from USGS (United States Geological Survey) are used in the first experiment (Exp. 1). All conditions are kept the same in Exp. 2 compared with Exp. 1, except that AG from the observed land use data (Hou, 1982) is introduced in the land surface. Differences in the output between Exp. 1 and Exp. 2 are considered as the climate effects of AG.

The model output is interpolated to $0.5° \times 0.5°$ latitude-longitude grid points as Gao et al. (2007) did in order to facilitate the data analysis. A two-tailed t-test with the confidence level at 95% is carried out to assess the statistical significance of the changes.

Distributions of vegetation cover over China in Exps. 1 and 2 are presented in Figs. 2a and 2b, respectively. The AG is found to mainly spread in eastern China, including the crop/mixed farming land in North and Northeast China, the Yellow River and Huaihe River valley, the irrigated crop land in Sichuan basin, the middle and lower reaches of the Yangtze River, and some costal areas of Southeast China (Fig. 2b). The AG is converted from forest or grass in the areas. Some scattered crop/mixed farming lands are also found in the desert and semi-desert areas in Northwest China. The change of AG leads to the change of surface parameters, e.g., decrease (increase) of surface roughness, increase (decrease) of albedo in eastern (western) China, etc. (figures omitted).

Within continental China (CN) we identify eight sub-regions as shown in Fig. 1, based on the consideration of climate regimes, for a more specific analysis. They are NE (Northeast), NC (North China), NW1 (Northwest 1), NW2 (Northwest 2), TB (Tibetan Plateau), SE (Southeast), SC (South China), and SW (Southwest). Among them, SE, SC, and SW are named as south-sub-regions, and the others are named north-sub-regions.

The number of total grid cells (Tnos) and number of the grid cells with AG (AGnos) and LU (LUnos) coverage over CN and eight sub-regions are summarized in Table 1. Greater AG possession is noted in NC and SE, with values of the AGnos/Tnos (proportion) being 190/415 (46%) and 215/458 (45%), respectively. For CN in general, the value is 752/4219 (18%).

3. Effects on surface air temperature

3.1 Effects on multi-year average surface air temperature

The effects of AG on multi-year average surface air temperature over China are shown in Fig. 3. Slight change of temperature in the range of –0.25 to 0.25°C is found in winter in the north of the Yangtze River

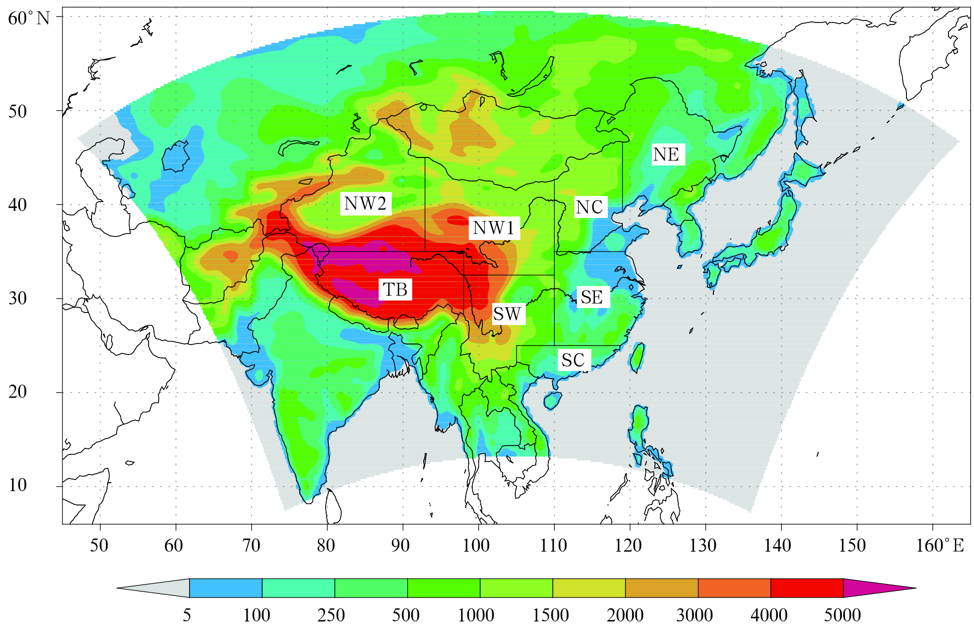

Fig. 1. Model domain, topography (m), and the sub-regions.

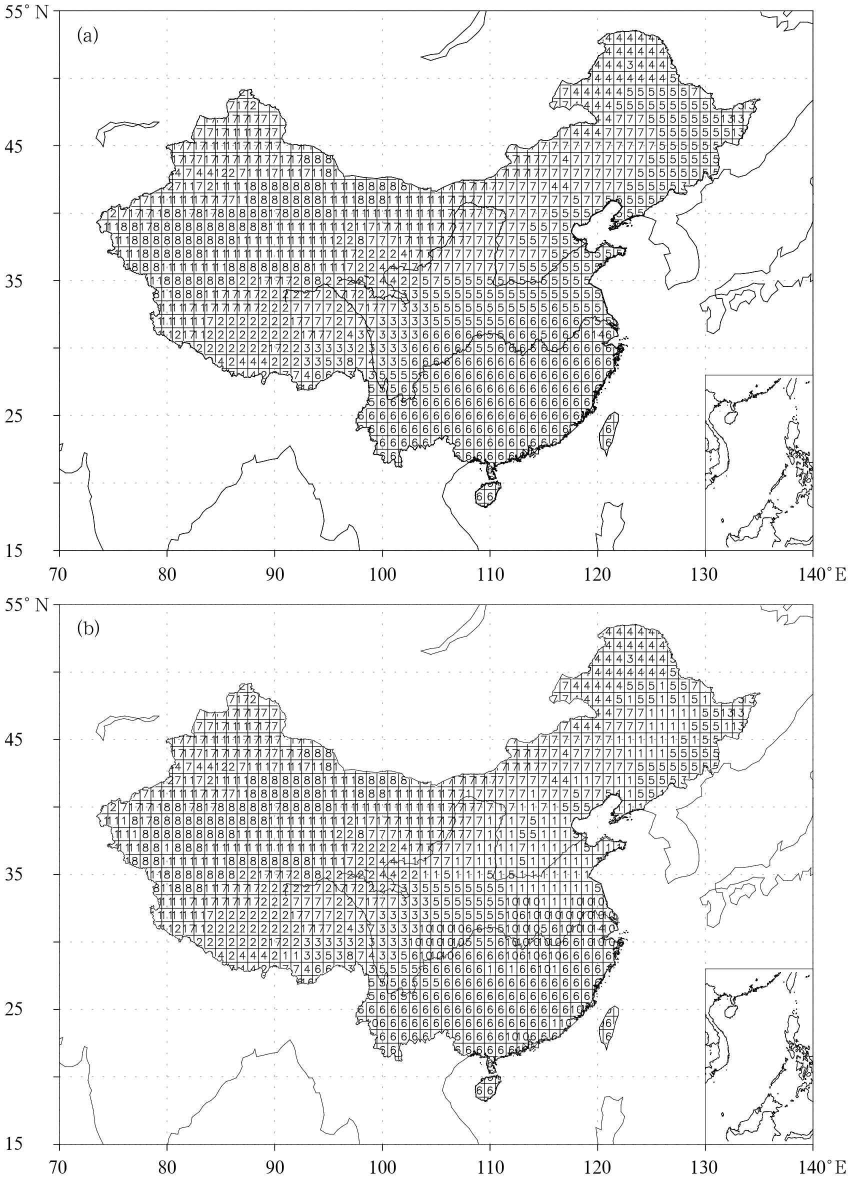

Fig. 2. Vegetation coverage over China prescribed in (a) Exp. 1 and (b) Exp. 2. 1: crop/mixed farming, 2: short grass, 3: evergreen needle leaf tree, 4: deciduous needle leaf tree, 5: deciduous broadleaf tree, 6: evergreen broadleaf tree, 7: tall grass, 8: desert, 10: irrigated crop, 11: semi-desert, 16: evergreen shrub, and 17: deciduous shrub.

Table 1. Total grid cell numbers, changed grid cell numbers, temperature and precipitation changes in AG and LU for CN and the sub-regions (the values of AG/LU are specified in parenthesis)

Total numbers	Changed numbers	Ts-DJF (°C)	Ts-JJA (°C)	Ts-Annual (°C)	Pr-DJF (%)	Pr-JJA (%)	Pr-Annual (%)
CN–4219	752/2992 (0.25)	–0.1/–0.4(0.2)	–0.1/–0.0(5.7)	–0.1/–0.2 (0.6)	–1.0/–4.7(0.2)	0.4/0.1(2.9)	–0.3/–1.4(0.2)
NE–655	162/465(0.35)	0.0/–0.2(–0.0)	0.0/0.1(0.0)	0.0/–0.0(–0.1)	1.2/1.2(1.0)	–0.2/–2.1(0.1)	0.4/–0.6(–0.6)
NC–415	190/332(0.57)	0.1/–0.3(–0.2)	–0.0/0.1(–0.3)	0.0/–0.0(–0.7)	–2.7/2.3(–1.2)	–2.6/–8.2(0.3)	–2.3/–5.1(0.5)
NW1–671	67/460(0.15)	0.0/–0.3(–0.0)	0.0/0.1(0.1)	–0.0/–0.1(0.3)	0.5/1.3(0.4)	–4.2/–7.7(0.5)	–2.3/–5.8(0.4)
NW2–798	9/391(0.02)	0.0/–0.2(–0.1)	–0.0/–0.0(1.9)	–0.0/–0.1(0.3)	0.4/–0.3(–1.3)	–0.2/–10.4(0.0)	0.3/–5.7(–0.1)
TB–548	6/326(0.02)	0.0/–0.0 (–0.8)	–0.0/–0.1(0.4)	–0.0/–0.1(0.3)	1.6/–0.2(–7.6)	–0.5/–3.4(0.1)	0.4/–1.5(–0.3)
SE–458	215/456(0.47)	–0.3/–0.7(0.4)	–0.8/–0.8(1.0)	–0.5/–0.7(0.7)	–7.5/–14.1(0.5)	7.3/17.1(0.4)	–0.5/3.4(–0.1)
SC–228	44/202(0.22)	–0.5/–1.2(0.4)	0.1/0.9(0.1)	–0.3/–0.4(0.9)	–2.5/–11.2(0.2)	1.1/5.8(0.2)	–1.0/0.6(–1.7)
SW–446	59/360(0.16)	–0.1/–0.5(0.2)	–0.3/–0.1(3.9)	–0.2/–0.3(0.7)	1.5/–8.3(–0.2)	0.8/4.3(0.2)	1.1/–0.4 (-2.9)

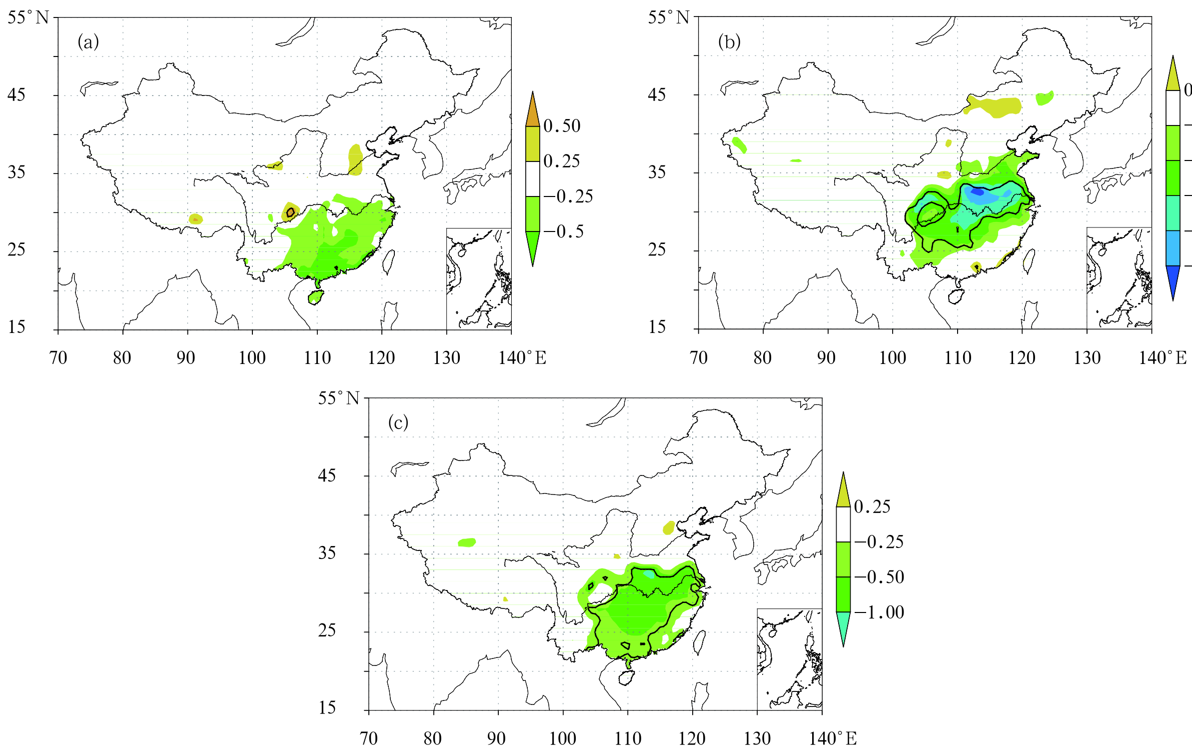

Fig. 3. Effects of AG on mean temperature (°C) over China in (a) winter, (b) summer, and (c) annual mean. Dark solid lines indicate changes significant at the 95% confidence level.

(Fig. 3a). A general decrease greater than 0.25°C is simulated over the south of the Yangtze River with the maxima in excess of 0.5°C in the south of Guangdong and Guangxi.

The sub-regional mean temperature changes in winter in the eight sub-regions as well as in CN for both AG and LU are shown in Table 1. The values of temperature change for AG and LU is –0.1°C and 0.4°C over CN. Little change in AG and a general decrease of 0.3°C in LU are found over the north-sub-regions. For south-sub-regions, general decrease of temperature can be observed in both AG and LU with the latter more pronounced. The greatest cooling is found in SC. The ratio of temperature change between AG and LU in SC is 0.4 (–0.5°C/–1.2°C).

Similar to winter, the effects of AG on summer temperature in northern China are relatively weak as shown in Fig. 3b. Conversely, substantial cooling is found in southern China. The cooling is statistically significant over large areas centered at the Yangtze River valley, with values mostly greater than 1°C. The largest cooling exceeding 1.5°C is found over the areas dominated by irrigated agriculture (Fig. 2b).

As can be expected, minor changes in the north and larger decrease in the south can be found for the sub-regional mean temperature in Table 1. It is noted that the values (ratios) of the cooling for AG and LU in the SW and SE sub-regions located in the mid-latitudes are 3.9 (–0.3°C/–0.1°C) and 1.0 (–0.8°C/–0.8°C), respectively. The cooling caused by AG in SW exceeds that by LU while in SE the cooling is comparable to each other. Located in the more tropical latitude, the temperature change in SC is opposite to the cooling elsewhere. A slight warming of 0.1°C is found for AG, relative to a greater warming of 0.9°C for LU.

A general decrease of over 0.5°C of annual mean temperature is simulated in southern China. The decrease is statistically significant in most areas (Fig. 3c). In northern China, the overall change of annual mean temperature is small.

Changes of annual mean temperature in CN for

AG and LU are small, –0.1°C and –0.2°C, respectively, as shown in Table 1. In north-sub-regions, AG derived changes in temperature are within the range of –0.1–0.1°C. Substantial cooling can be found over south-sub-regions. In addition, the ratios of temperature change between AG and LU are greater than that of the numbers of changed grid cells there. The greatest decrease is found over SE, with the value of –0.5°C for AG and –0.7°C for LU.

3.2 Effects on interannual variability of surface air temperature

As discussed in Section 2, the two sub-regions with the most intensive agriculture cultivation are SE and NC. Temperature changes over SE and NC derived from AG and LU for each year during the simulation are calculated and presented in Fig. 4.

Over SE, the simulated temperature in winter shows a decrease for both AG and LU cases during all the years (Fig. 4a). A greater decrease in the range of –1.1 to –0.2°C can be found for LU comparied to that for AG ranging from –0.5 to 0.0°C.

Cooling is also found in most of the years in summer over SE, but to a greater extent compared to winter (Fig. 4c). The ranges are –2.2 to 0.9°C for AG and –2.2 to 0.2°C for LU, respectively. It is noted that the magnitude of cooling in AG are in general close to that in LU. However, in some years, the cooling in AG is more pronounced. For example, in 2000, the cooling for AG and LU are –2.2 and –1.5°C, respectively.

A general decrease of annual mean temperature is found for AG and LU for all the years over SE (Fig. 4e), with the range between –1.0 and 0.0°C in AG, which is somewhat smaller than that in LU (–1.2 to –0.2°C).

The dominant AG land use is irrigated crop over SE (see Fig. 2b). Temperature changes in summer there exhibit a negative correlation with the

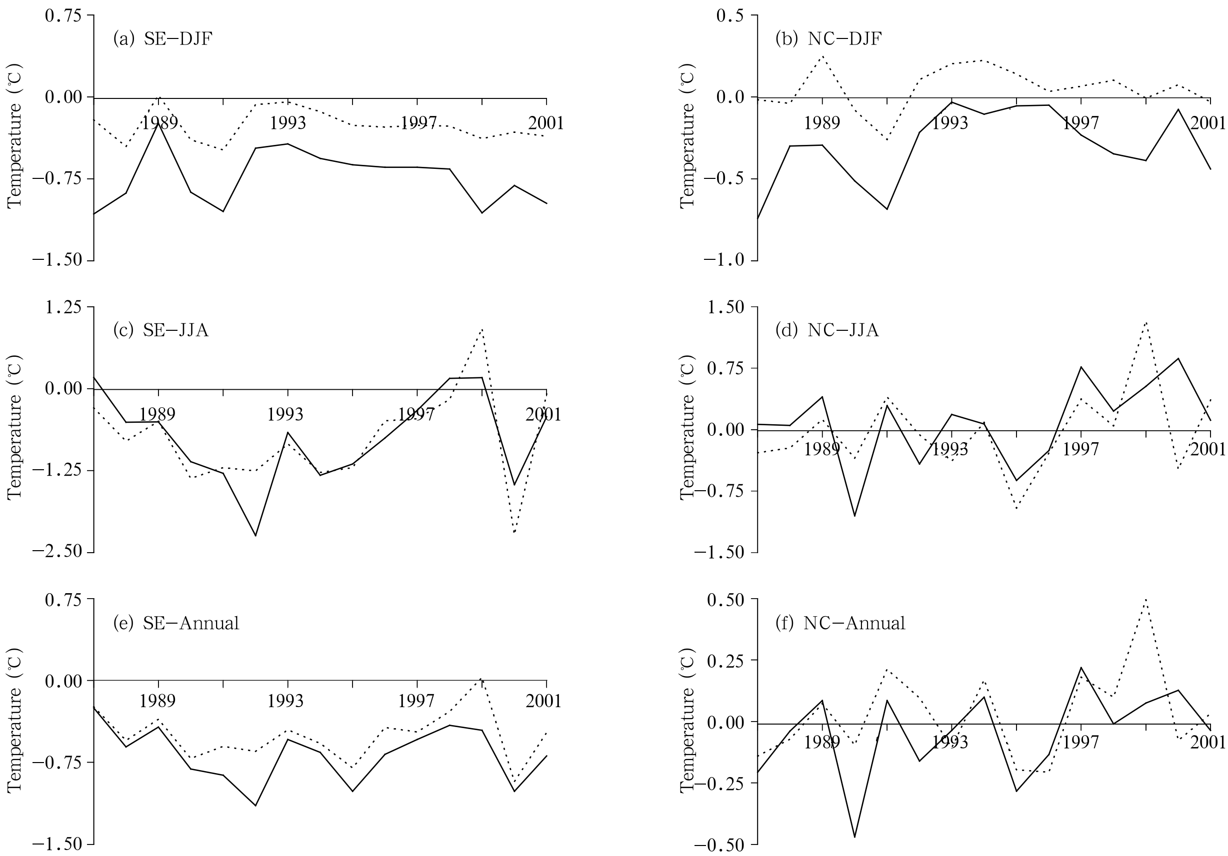

Fig. 4. Effects of AG (dashed lines) and LU (solid lines) on temperature (°C) in each year in (a, b) winter, (c, d) summer, and (e, f) annual mean over the SE sub-region (left panels) and the NC sub-region (right panels).

preceding winter precipitation changes (see Figs 4c, 6a, 6c, and 6e). For example, the pronounced cooling in summers of 1992, 1994, and 2000 are following the great reduction of precipitation in the previous winters of 1991, 1993, and 1999. Meanwhile, the winters of 1996–1998 with less change of precipitation are followed by the less cooling or a little warming summers of 1997–1999.

The RegCM3 simulation conducted by Kueppers et al. (2007) in studying the irrigation cooling effect over the U.S. also showed that the summers following relatively wetter winters tend to have less pronounced cooling from irrigation, and vice versa.

A minor warming can be found for most winters for AG over NC, while LU leads to a general cooling (Fig. 4b).

In summer, a mixture of cooling and warming over NC are simulated for AG and LU. The temperature changes are in a range of –1.2 to 1.2°C (Fig. 4d). In some of the years, AG and LU cause the same sign changes, e.g., both decrease in 1995 and increase in 1997. Meanwhile, in other years changes of opposite signs are found (e.g., 1993 and 2000). In general, the effects of AG and LU on temperature over NC show differences compared to that over SE characterized by the overall cooling. Greater interannual variability instead of general cooling or warming and different impacts between AG and LU are observed. It suggests that AG and LU possibly affect more on the interannual variability than on the mean climate over NC, although further study and analysis are needed to better understand this. The change of annual mean temperature shows similarities with that in summer, but with a smaller magnitude (Fig. 4f).

4. Effects on precipitation

4.1 Effects on multi-year mean precipitation

Changes of multi-year mean precipitation induced by AG over China are presented in Fig. 5.

The precipitation change in winter exhibits a clear decrease in eastern China, with a reduction of 10%–20% in the middle and lower reaches of the Yangtze River (Fig. 5a).

The winter precipitation change over CN and the eight sub-regions for AG and LU (Table 1) is

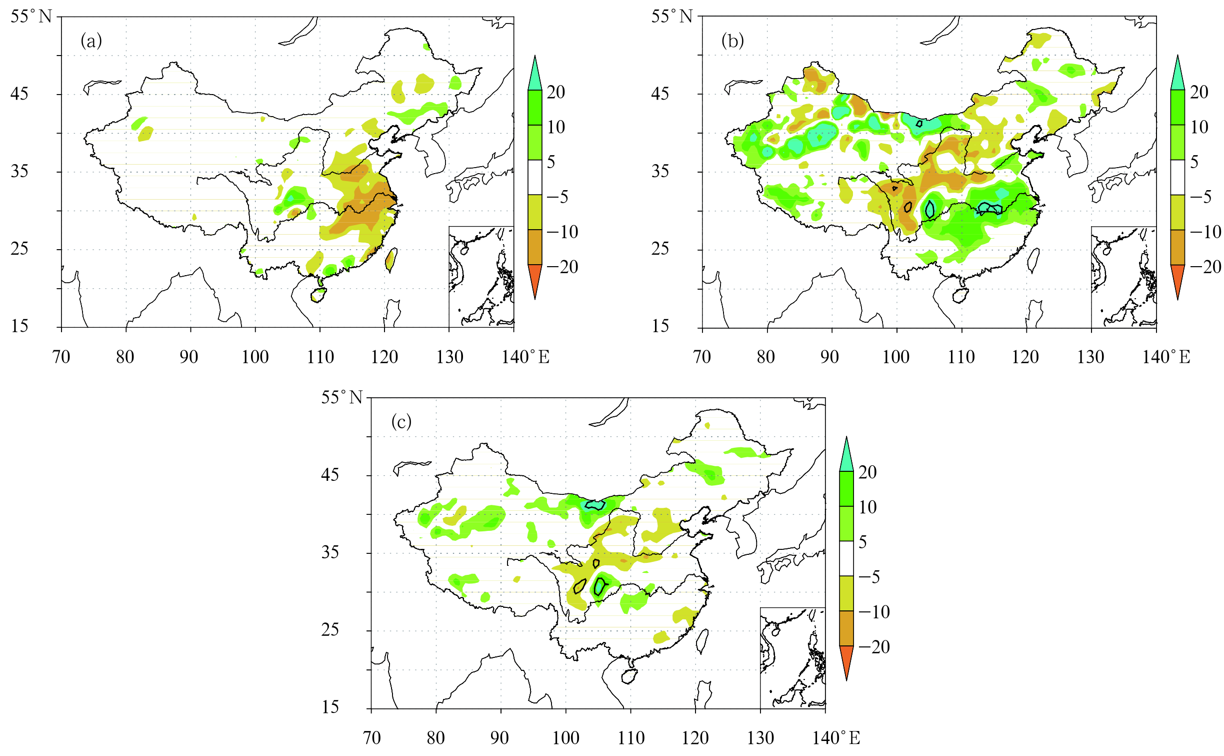

Fig. 5. As in Fig. 3, but for precipitation changes (%).

characterized by a slight decrease over CN, a minor change of less than ±3% over north-sub-regions, and a general reduction over south-sub-regions, except for AG over SW. The largest decrease is found to be located in SE where the precipitation change (ratio) between AG and LU is –7.5%/–14.1% (0.5), which is close to that of AGnos and LUnos of 215/456 (0.47).

Summer is the main rainy season in China. A spatial distribution of the precipitation change shows a general decrease in northern China and an increase in southern China (Fig. 5b). The decrease is greater than 10% in the Hetao area. A statistically significant increase with the values in excess of 20% can be found in portions of the middle and lower reaches of the Yangtze River and Sichuan basin. As shown in Figs. 5b, 2a and 2b, areas with larger changes are in conjunction with the intensive agriculture cultivation. The largest increase is found over two areas dominated by irrigated crop land, i.e., the middle and lower reaches of the Yangtze River and the Sichuan basin. The corresponding AG in Hetao and North China where decreased precipitation is simulated is crop/mixed farming.

The overall regional mean change of CN is small as indicated in Table 1. Relatively larger decreases of precipitation are found over NW1 and NC in the north-sub-regions. The values of change and ratios for LU and AG are –4.2%/–7.7% (0.5) and –2.6%/–8.2% (0.3), respectively. Increased precipitation can be found over south-sub-regions, in particular over SE, with the values (ratio) of 7.3%/17.1% (0.4) in AG and LU. The ratios of precipitation change between AG and LU over south-sub-regions are close to that of the AGnos and LUnos.

The annual mean precipitation shows few changes due to the opposite impacts in winter and summer, although portions of increase and decrease can be found in Fig. 5c.

When averaged over CN (Table 1), the annual mean precipitation decreases by –0.3% and –1.4% in AG and LU, respectively, with the ratio being 0.2. The corresponding AGnos/LUnos (ratio) is 752/2992

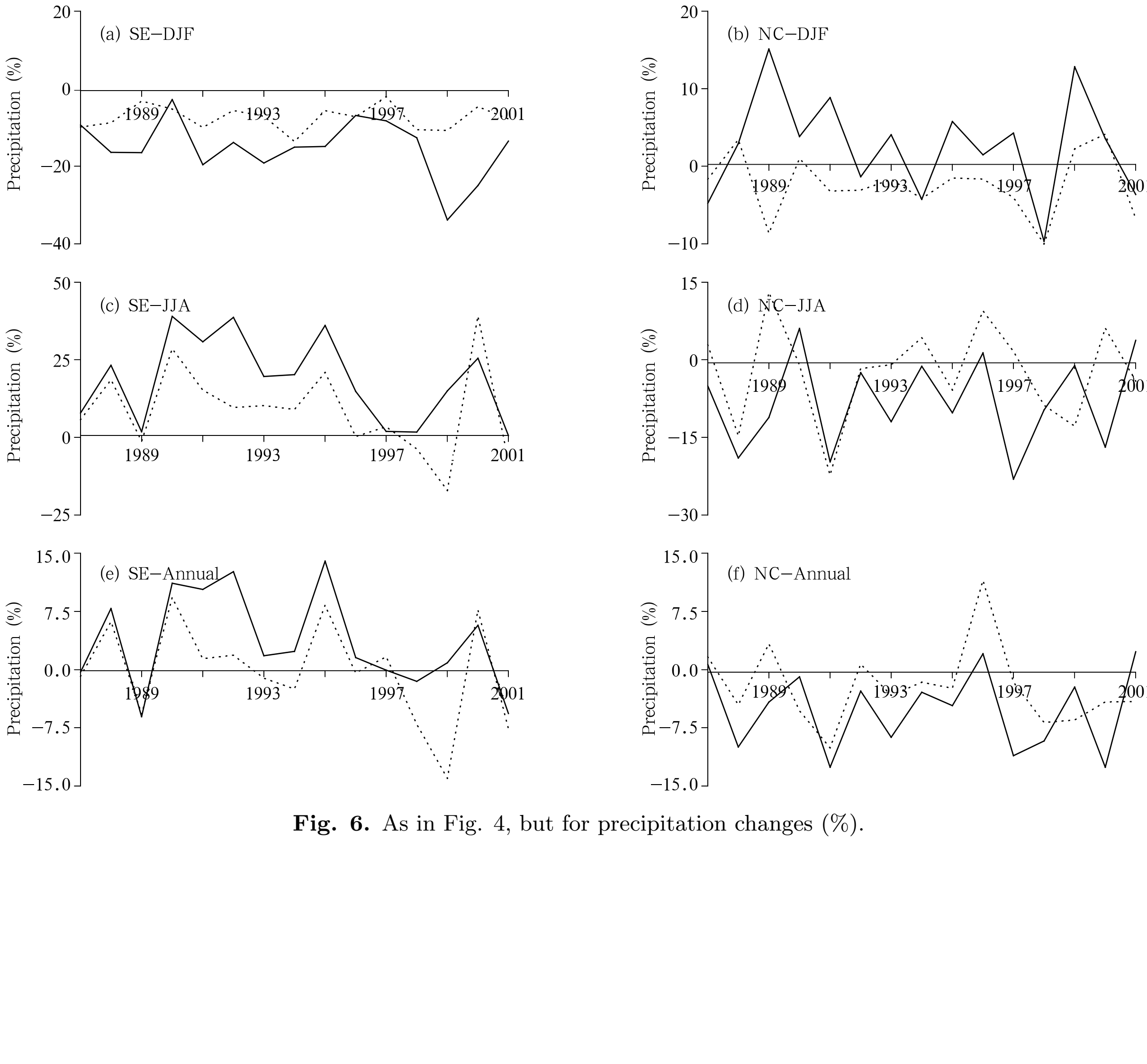

Fig. 6. As in Fig. 4, but for precipitation changes (%).

(0.25). As in summer, the maximum change is found in NC and NW1 where the ratios between AGnos and LUnos are 0.57 and 0.15, respectively. Mean precipitation changes there are –2.3%/–5.1% (0.5) and –2.3%/–5.8% (0.4). The values of annual mean precipitation change for south-sub-regions are small in general because the increase in summer is compensated by the decrease in winter.

4.2 Effects on interannual variation of precipitation

Figure 6 shows the mean precipitation changes over SE and NC for both AG and LU during the simulation period.

The winter precipitation is decreased over SE for 1987–2001 for both LU and AG, while the decrease for AG is smaller than that for LU (Fig. 6a). Conversely, increased precipitation is simulated in almost all the summers except in 1999 for AG that exhibits a large decrease of precipitation. A possible reason for the exception is that the monsoon rain penetrated too far northward in the year. The less than normal precipitation leads to a weaker feedback thus a less effect of AG. The annual mean precipitation changes show similar behavior to that in summer, but with smaller values (Fig. 6e).

Over NC, the winter precipitation change differs between AG and LU. In the total of 15 yr, there are 11 yr with decreased precipitation for AG, while 10 yr with increased precipitation for LU (Fig. 6b). For summer and annual precipitation, reduction can be found in most years (Figs. 6d and 6f).

5. Summary and conclusions

In this paper, the effects of AG on climate over China are investigated by using a regional climate model–RegCM3, and are compared with the effects of LU. Main conclusions are obtained as follows.

(1) Temperature in southern China is greatly affected by AG. The AG leads to the decrease of temperature in both winter and summer over south-sub-regions. The cooling is more significant in summer than in winter. In winter, the ratio of cooling between AG and LU is close to that of the AGnos to LUnos, while for summer and annual mean temperature the ratio of cooling is greater than that of the AGnos to LUnos. This indicates that reforestation in southern China with the present agricultural land may not be so effective in reducing the current LU derived cooling.

(2) AG causes a general reduction of precipitation in eastern China in winter, in particular over SE. In summer it causes decrease of precipitation over north-sub-regions and increase over south-sub-regions with the most pronounced increase found over SE. The AG has less effect on precipitation compared to LU over most of the sub-regions both in winter and summer. The ratio of precipitation change between AG and LU is comparable to that of the AGnos and LUnos, indicating that the future ecological restoration measures may partially weaken the effects of southern flood and northern drought derived from present LU (Gao et al., 2007).

(3) Different impacts of vegetation under different climate conditions exist, as indicated by the strong interseasonal and interannual variability in temperature and precipitation for both AG and LU. In other word, the impact may be seasonal and regional dependent. In some cases AG and LU affect more on the mean climate, while in other cases they affect more on interannual variability.

(4) Similar to LU, the dynamical effect due to the reduction of surface roughness and the dynamical effect compounded with thermodynamic effects related to the change of surface energy flux may contribute more to the climate effects of AG in winter and summer, respectively (Gao et al., 2007). Analysis of the AG effects on circulation and heat fluxes shows similarities to that of LU but to a weaker extend, thus not shown here for brevity (Figs. 5 and 6 in Gao et al., 2007). Further experiments and analysis are needed to identify the individual and joint effects of the surface roughness, albedo, stomatal resistance, etc., on climate, and to better understand the physical mechanism of land use change on climate.

(5) It is noted that for irrigated crops, some of the parameter settings, such as roughness length, minimum stomatal resistance, soil water holding capacity, etc., may be too sensitive in RegCM3. Moreover, the root zone soil moisture over irrigated crop areas is assumed to be saturated during the whole simulation.

These may cause an overestimation of the irrigated crop's effects on climate. Further simulations with improved RegCM3 and other climate models will help to reduce the relevant uncertainties.

(6) The anthropogenic influences on climate include forcings of greenhouse gases, land use change, etc. Simulations that incorporate all these factors (e.g., Costa and Foley, 2000; Zhao and Pitman, 2005) are needed to better address the issues related to the regional climate and climate change over China.

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