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Simulation of Effects of Land Use Change on Climate in China by a Regional Climate Model

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ABSTRACT

Climate effects of land use change in China as simulated by a regional climate model (RegCM2) are investigated. The model is nested in one-way mode within a global coupled atmosphere-ocean model (CSIRO R21L9 AOGCM). Two multi-year simulations, one with current land use and the other with potential vegetation cover, are conducted. Statistically significant changes of precipitation, surface air temperature, and daily maximum and daily minimum temperature are analyzed based on the difference between the two simulations. The simulated effects of land use change over China include a decrease of mean annual precipitation over Northwest China, a region with a prevalence of arid and semi-arid areas; an increase of mean annual surface air temperature over some areas; and a decrease of temperature along coastal areas. Summer mean daily maximum temperature increases in many locations, while winter mean daily minimum temperature decreases in East China and increases in Northwest China. The upper soil moisture decreases significantly across China. The results indicate that the same land use change may cause different climate effects in different regions depending on the surrounding environment and climate characteristics.

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

1. Introduction

Vegetation cover on the surface of the Earth has changed considerably due to human activities, in particular over China with its long history of agricultural activities and its high population.

Land use change, i.e., the change of vegetation cover at the interface between the surface and the atmosphere, influences climate through changes in surface albedo, land roughness, and soil hydrological and thermal features. These result in changes of surface solar and longwave radiation fluxes, and fluxes of momentum, sensible heat, and latent heat. The study of the effects of land use change on climate is very important within the global change debate. Research work on this topic is usually based on numerical model experiments, and several such experiments have been carried out with a focus on the East Asia region. For example, with the use of a GCM, Fan et al. (1998) simulated the effects of afforestation in Northwest China on the climate of East and South Asia. Wang (1999) studied the role of vegetation and soil conditions in the Holocene megathermal climate over China.

Due to their coarse resolution, GCMs often perform poorly in simulating regional climate and its changes, especially in regions where the local fine-scale forcing of topography and land use is important. Regional climate models (RCMs) can be used to enhance the GCM regional climate information (e.g., Giorgi and Mearns, 1991, 1999). In particular, with the use of higher horizontal resolution and comprehensive physical processes, RCMs can improve the representation of regional climatic features over China by better describing the evolution of monsoon features (e.g., Gao et al., 2001).

A number of studies have used RCMs to investigate

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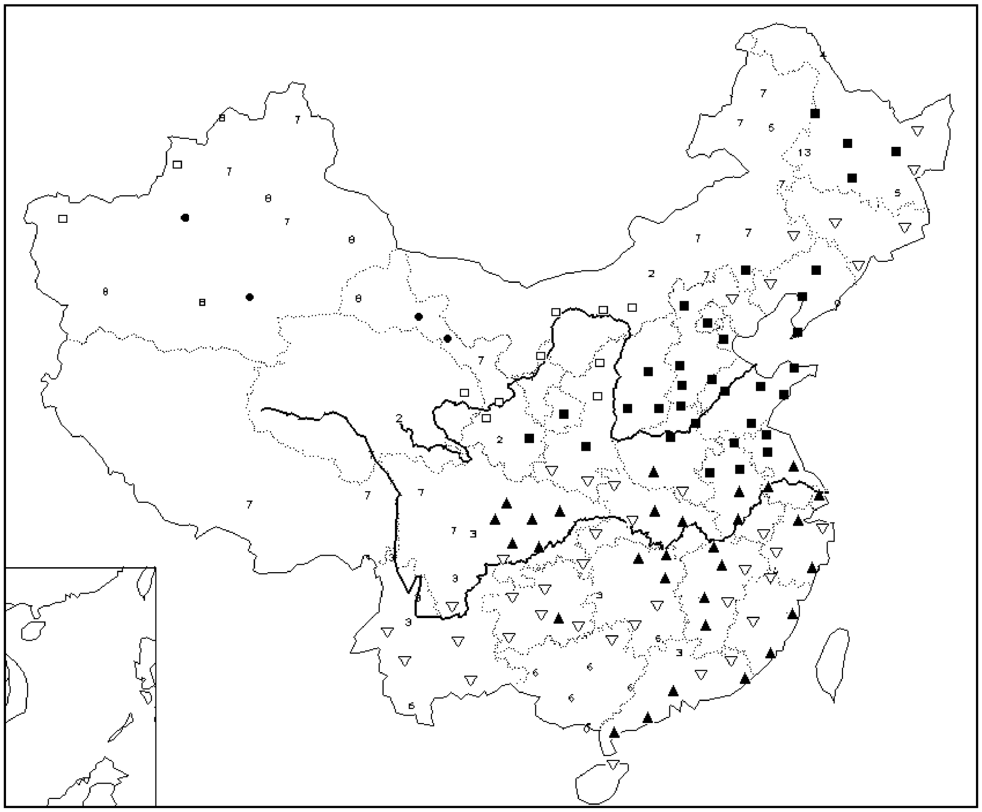

Fig. 1. Land use change in China. ■: areas from forest to crop/mixed farming, ▲: areas from forest to irrigated crop farming, □: areas from forest to crop/mixed, ▽: areas from forest to shrub, ●: areas of desertification. The numbers are the areas with no change, corresponding to vegetation cover of 2: short grass, 3: evergreen needle leaf tree, 5: deciduous broadleaf tree, 6: evergreen broadleaf tree, 7: tall grass, 8: desert.

the effects of regional changes in land vegetation cover on the climate of East Asia. Fu et al. (1996) studied the climatic effects of the desertification of the North China climate-shift zone currently covered by grassland. Xue et al. (1998) examined the effects of changing grassland in Mongolia to desert, and crop in East China to bare soil. Lu and Chen (1999) investigated the influence of land cover change in Northwest China on the summer climate of China. Finally, Wang et al. (2001) completed RCM simulations of the effects of present-day land use change on climate. While much was learned from these works, further research is still needed since the duration of the simulations completed in these previous studies was relatively short (usually several months) and the model domains only covered portions of China. In addition, the experiment designs in the studies mentioned above were idealized, mostly consisting of simple vegetation changes from one type to another over extended areas.

In this study, we completed two multi-year simulations using an RCM driven by output from a GCM experiment. The two RCM simulations make use of present-day land use conditions and potential vegetation cover, respectively. The model domain encompasses the entire China region. In all of these features, our work represents a significant advancement compared to previous studies. The objective of this paper is to investigate the possible effects and feedbacks induced by anthropogenic land use change on the climate of China. We do so by analyzing the differences in various simulated climatic variables between the two experiments with different land surface conditions.

A brief description of the model and experiment design is first presented in section 2. Results of the simulations are then analyzed in section 3, while summary considerations are presented in section 4.

2. Model description and experiment design

The RCM used in the present work is the RegCM2 developed by Giorgi et al. (1993a, b) with some of the developments discussed in Giorgi and Shields (1999). The model domain encompasses a large area including

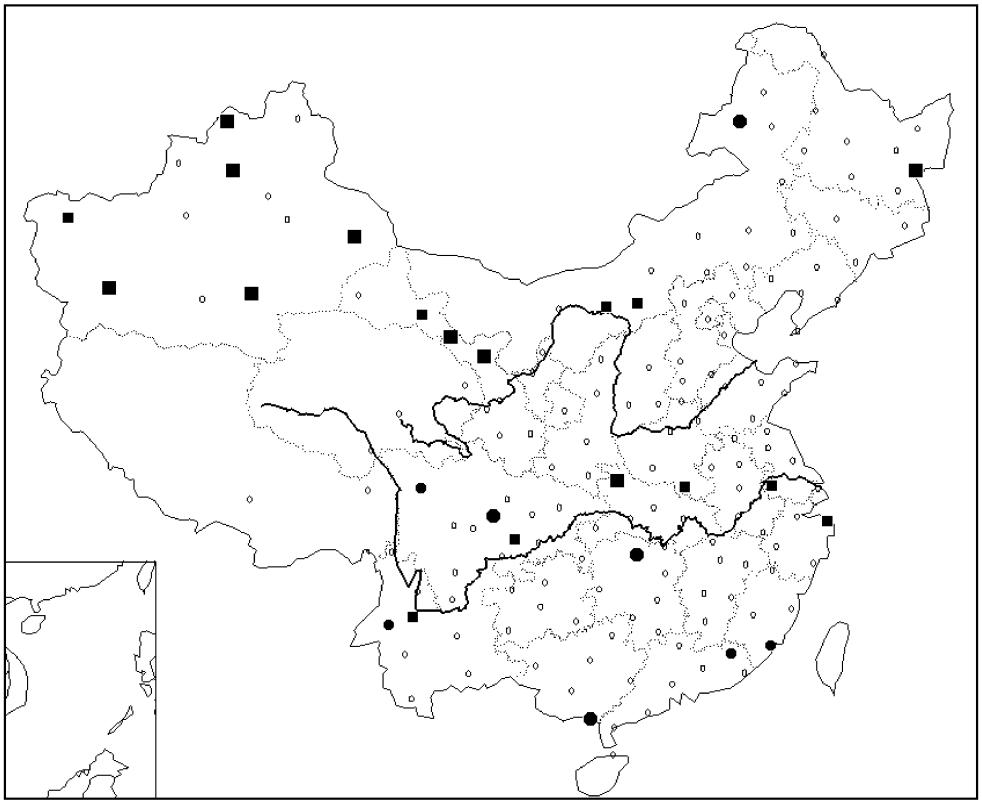

Fig. 2. Effects of land use change on annual mean precipitation in China. ■: change <–20%, ▪: change –20%–0, •: change 0–20%, ●: change >20%, o: no significant change, same as below.

East Asia, most of India, and the Tibetan Plateau at a horizontal gridpoint spacing of 60 km. Sixteen vertical sigma layers are used, with the model top at 10 hPa. Surface processes are represented via the Biosphere-Atmosphere Transfer Scheme (Dickinson et al., 1993). Resolvable-scale precipitation is represented via the simplified explicit scheme described by Giorgi and Marinucci (1996) and Giorgi and Shields (1999), which includes a prognostic equation for cloud water content, while the mass flux scheme of Grell (1993) is used to describe convective precipitation. Gao et al. (2001, 2002) used this model configuration to study changes in monsoon climate and extreme events over the region due to increased concentration of greenhouse gases.

Meteorological initial and time-evolving lateral boundary conditions are needed to integrate the RCM. They can be obtained either from analyses of observations or from GCM simulations. In our study, we utilize the driving boundary conditions from present-day climate simulations performed with the CSIRO AOGCM (Gordon and O' Farrel, 1997) with 12-hourly updates. This is because we plan to perform similar experiments in projected future climate conditions in order to study the effects of land use changes in conjunction with increased GHG concentrations. In addition, we can refer to the studies of Gao et al. (2001, 2002), who used the same nested RCM-AOGCM experiment design, for more detailed information about the quality of the model simulations. Gao et al. (2001, 2002) showed that the RegCM2 performs reasonably well in simulating present-day regional climate over China (Gao et al., 2001). For example, the spatial correlation coefficients between simulated and observed mean annual surface air temperature and precipitation are high, 0.94 and 0.80 respectively. The simulated climatology of extreme events is also quite realistic compared to observations.

Both the experiments with actual land use cover and potential vegetation cover are of 5 year length with boundary conditions from the present-day CSIRO simulation. In the first experiment (Exp.1), the NCAR $30' \times 30'$ vegetation cover is used, which is representative of potential vegetation cover. In the second experiment (Exp.2), all conditions are the same as in Exp.1 except that actual vegetation cover over China is used. The differences between Exp.2 and Exp.1

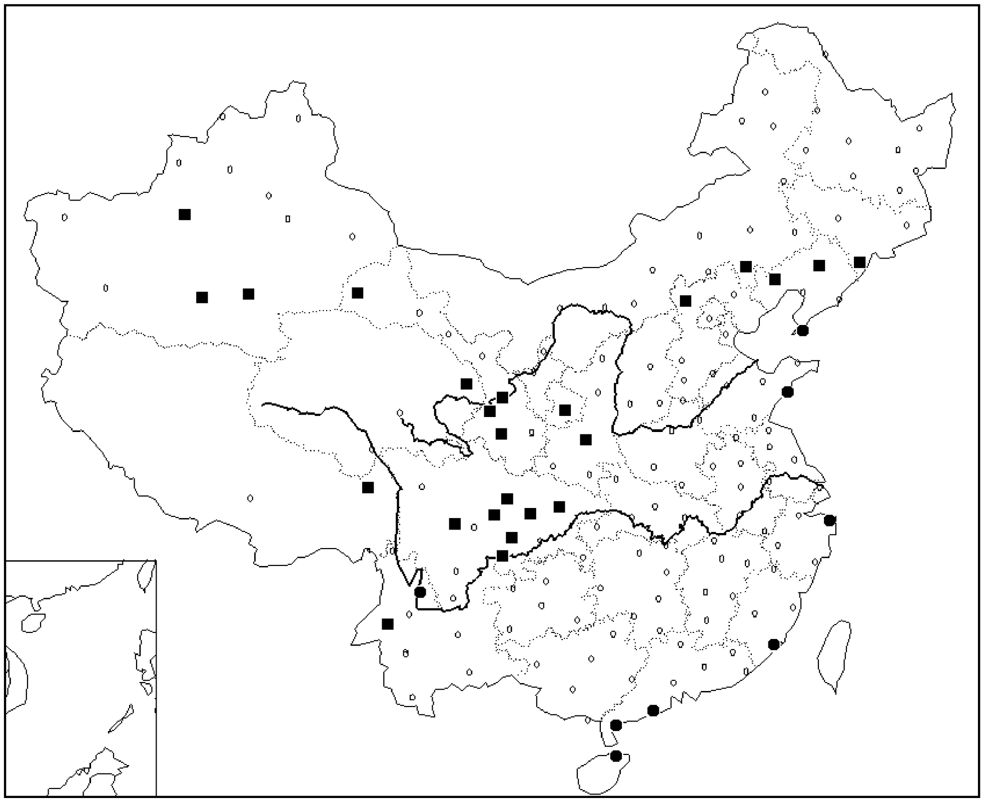

Fig. 3. Effects of landuse change on annual mean air surface temperature in China. ■: areas of increase, ●: areas of decrease, both range from –1°C to 1°C.

are considered as the climatic effects of land use change in China. As mentioned, a description of Exp.2, i.e., the simulation of present-day climate with actual vegetation cover, is given by Gao et al. (2001).

Figure 1 shows the land use change over different areas of China. The figure shows substantial changes in vegetation cover over China compared to the potential one. This is mostly a result of agricultural activities and deforestation. More specifically, there are changes from forest to cropland over regions of Northeast China, the Huabei plain, the Sichuan Basin, the mid and lower Yangtze River valley, and some coastal areas. Changes from grassland to cropland are found in the mid and upper valleys of the Yellow River, and from forest to shrub in parts of Northeast China and some mountainous areas of South China. Finally, we find extensive desertification in Northwest China.

For the convenience of data analysis, the model output was interpolated to 160 stations throughout China, as is done in Gao et al. (2001, 2002). The analysis mainly focuses on the mean annual change of climate variables.

3. Analysis of the effects of land use change on principal climate elements in China

3.1 *Effects on precipitation*

The effect of land use change on precipitation is first analyzed. The percent difference of mean annual precipitation between Exp.2 and Exp.1 was calculated and inspected by a 90% significance t-test. Stations that passed the test are dotted with a different mark in Fig. 2 according to their symbol and value.

Figure 2 shows that areas with a significant change in precipitation caused by land use change are mainly located in Northwest China. The change is mostly negative, and can be large, in excess of –20%. From Fig. 1, we see that the primary vegetation changes over the area are from grassland to cropland and desertification. Therefore, our results indicate that in arid and semi-arid regions with vulnerable ecosystems, such as is found in Northwest China, inappropriate land use may cause a reduction of precipitation and thus worsen the environmental conditions for the local ecosystem. It is also noticed that a land use change from forest to

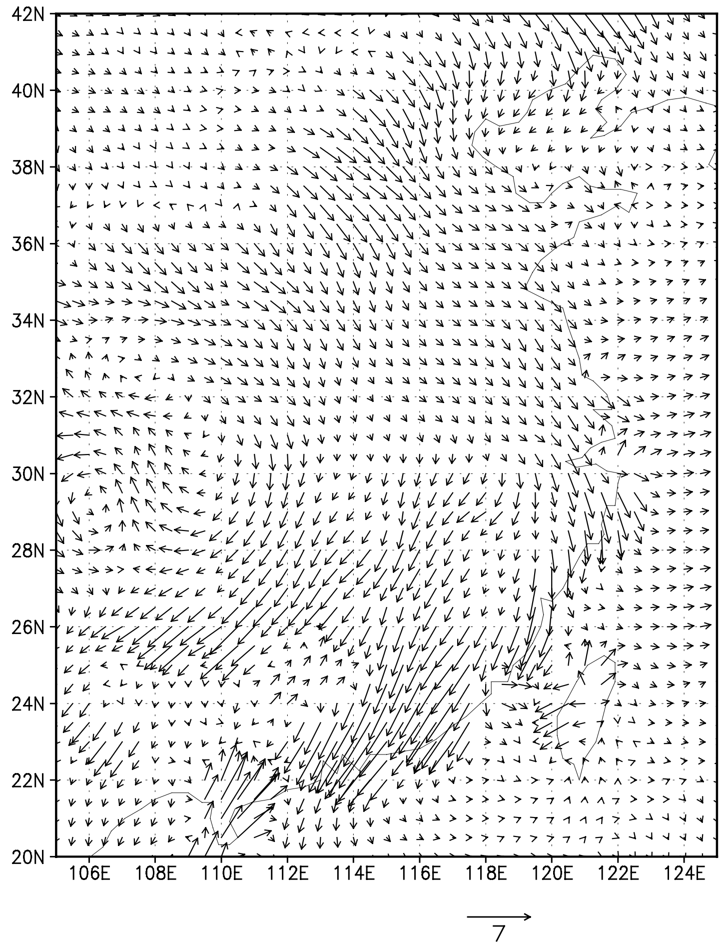

Fig. 4. Effects of landuse change on winter mean surface wind in East China. (units: m s^{-1}).

cropland causes a precipitation decrease also in some of the areas along the mid and lower valleys of the Yangtze River.

As indicated by the simulations of Gao et al. (2001), increasing GHG concentrations may cause an increase of precipitation in Northwest China, which appears consistent with observations for the last decades. This is because of more intense monsoon precipitation, and it is therefore tied to changes in large-scale circulations. The simulated land use change effect is more local in nature and it is in the opposite direction. Therefore, our results indicate that the regional forcing due to land use change would tend to counterbalance the effects of the large-scale forcing due to GHG concentration increase.

Figure 2 also shows that in general, precipitation over East China does not show systematically significant changes in response to land use changes, i.e., the model simulations suggest that the land use changes which occurred in history and in past decades, mainly due to agricultural practices, have not affected precipitation over the region in a significant way.

3.2 *Effects on surface air temperature*

The mean annual surface air temperature change caused by land use changes varies from –1°C to 1°C. Stations which exceeded the 90% confidence test are dotted in Fig. 3. It is shown that the current land use caused temperature to significantly rise in the southern portions of Northeast China, the Sichuan Basin, and portions of Northwest China. This is due to an increase of sensible heat flux over these regions associated with the reduction of vegetation cover and drying of the soil (see later). Areas where the temperature increase is statistically significant are mainly located north of the Yangtze River. No significant changes were found to the south. This is because the temperature there rises in summer but decreases in winter (not shown) with these effects compensating each other when estimating the annual mean.

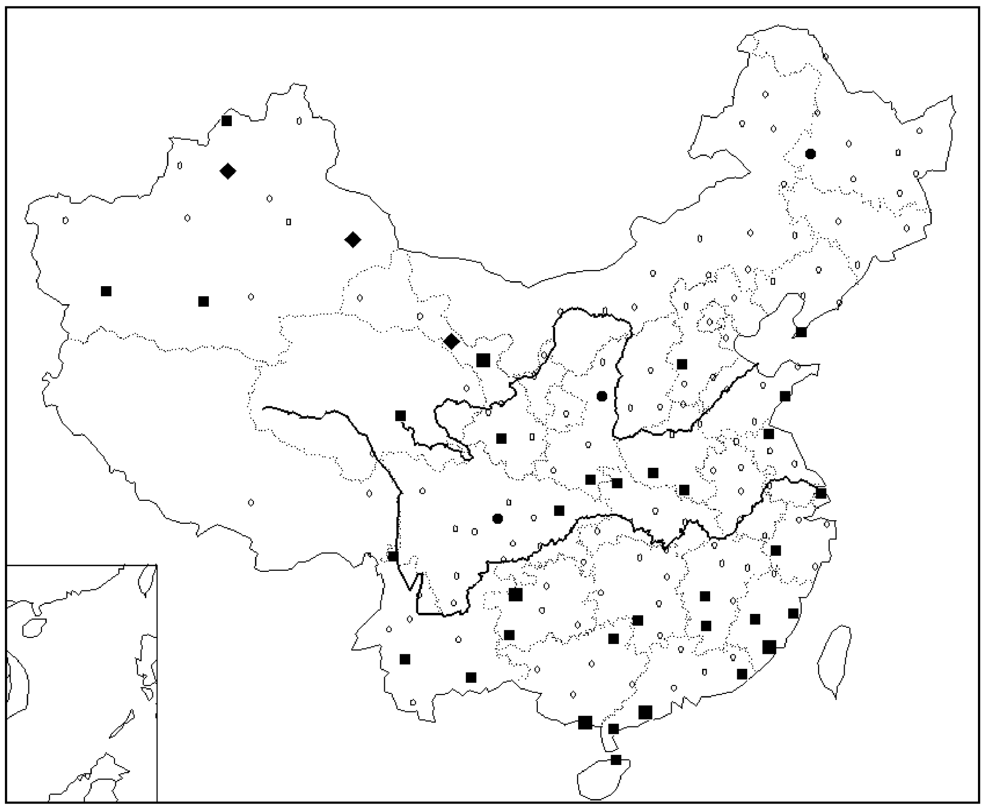

Fig. 5. Effects of landuse change on summer mean $T_{\max}$ in China. ●: change –2–0°C, ■ change 0–2°C, ■: change 2–4°C, ■: change>4°C.

For the regions with significant temperature increase, the relevant land use change mainly consists of deforestation, i.e. from forest to shrub and from forest to cropland. Similar land use changes can however be found in many other locations where the temperature has no significant change. This implies that the temperature response to the same land use change can vary widely in different regions.

It is interesting to note that differently from the inland locations, temperature along coastal areas decreases. This is due to changes in wind circulations caused by the vegetation cover change. As mentioned, during summer over East China, deforestation causes an increase in temperature. This intensifies the upward motions and the sea breeze circulations which, in the lower levels, are directed from ocean to land (not shown). The situation in winter is opposite, with the deforestation causing temperature to decrease over land and thus reinforcing the land breeze from land to ocean (see Fig. 4).

It is well known that climate in coastal areas is strongly influenced by the sea. In general, in summer the cooler ocean affects land by decreasing the temperature there. In winter, the warmer ocean causes an increase of temperature over neighbouring coastal areas. As a result, the climate along coastal areas is usually milder than inland, i.e., it has a cooler temperature in summer and a warmer one in winter.

The intensification of the summer sea breeze circulations caused by the land use change therefore further lowers the temperature over coastal areas in summer. Conversely, in winter the stronger off-shore winds carry colder air from inland to the coasts thereby causing a temperature decrease there. This winter effect tends to dominate and to lead to the negative annual mean temperature change over coastal areas observed in Fig. 3.

The change in circulation described above may also be a reason for the increase of precipitation in some areas along the coast (Fig. 2). Precipitation in China takes place usually in the summer season. The intensification of the summer sea breeze can thus bring more moisture from the ocean to the coastal areas and enhance local precipitation.

Note that deforestation can also decrease the land roughness and this may also play a role in affecting the circulation. This effect, however, needs to be investigated with further work.

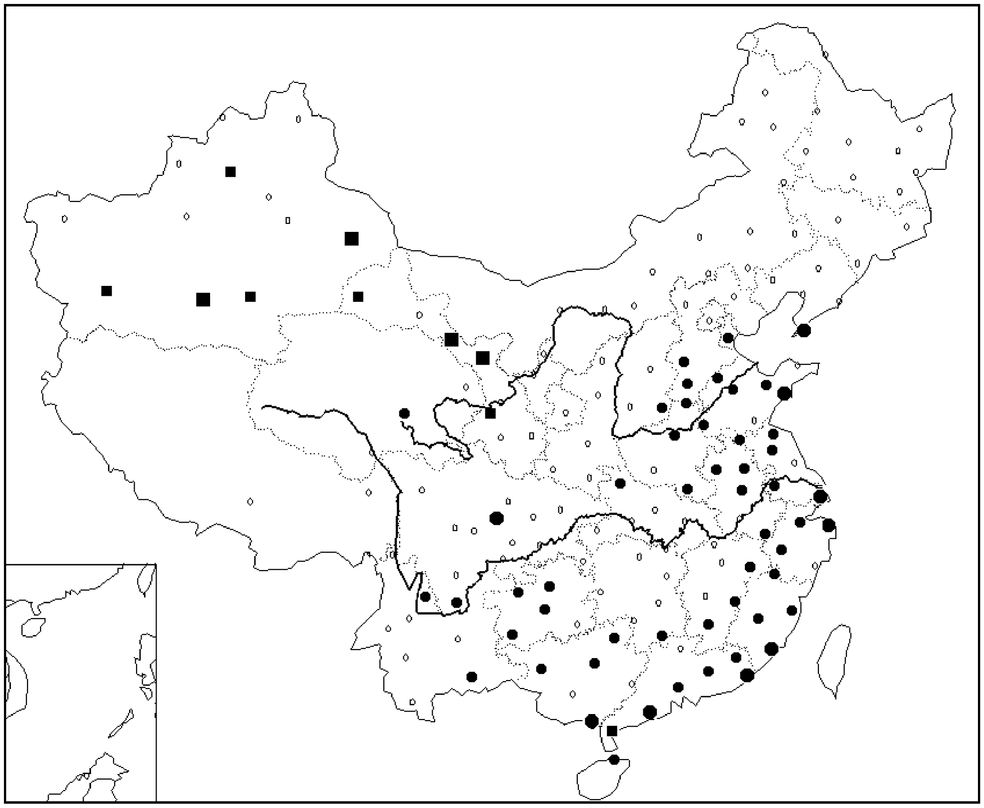

Fig. 6 Effects of landuse change on winter mean Tmin in China. ●: change <–2°C, •: change 0–2°C, ▪: change 0–2°C, ■: change >2°C.

The effect of land use change on temperature is mostly in the same direction as the effect of greenhouse gases (GHG), at least in some interior regions of China. Therefore, it is possible that land use change might have contributed to enhance the observed warming trend over these regions.

3.3 *Effects on summer mean daily maximum temperature (Tmax) and winter mean daily minimum temperature (Tmin)*

Of much interest for potential impacts of climate change is the occurrence of extreme temperature events, therefore we present here an analysis of summer mean $T_{\max}$ and winter mean $T_{\min}$. The change in summer mean $T_{\max}$ induced by land use modifications is shown in Fig. 5. Only stations exceeding the 90% confidence test are marked. It is shown that, except in Northeast China, the current land use change causes an increase of summer $T_{\max}$ over most areas. The increase is mostly in the range of 0–2°C, except in some desert and semi-desert areas such as the Hexi Corridor and part of Xinjiang in Northwest China, where the increase in $T_{\max}$ is much higher. The increase of $T_{\max}$ may be caused by the reduction of plant transpiration after deforestation and desertification. This increase in summer $T_{\max}$ caused by land use change is also in the same direction as that caused by the increase of GHG concentration (Gao et al., 2002), so that also in this case the land use forcing tends to reinforce the GHG forcing. If vegetation cover continues to decrease in the future its effect might further contribute to the warming induced by the GHG.

To summarize the results above, the climatic effects of current land use change in the desert and semi-desert areas of Northwest China are a decrease of precipitation, an increase of surface air temperature, and a substantial increase of summer maximum temperature. This indicates that the region is highly vulnerable to land use change that has and that the land use change that has occurred so far has increased the stress on local ecosystems.

The change of winter $T_{\min}$ is reported in Fig. 6. The change in $T_{\min}$ is not significant over Northeast and central China. A decrease in $T_{\min}$ is found over South and East China with values mostly around –1°C, and exceeding –2°C in some locations. Conversely, $T_{\min}$ increases in many locations of Northwest China, mostly characterized by little vegetation cover.

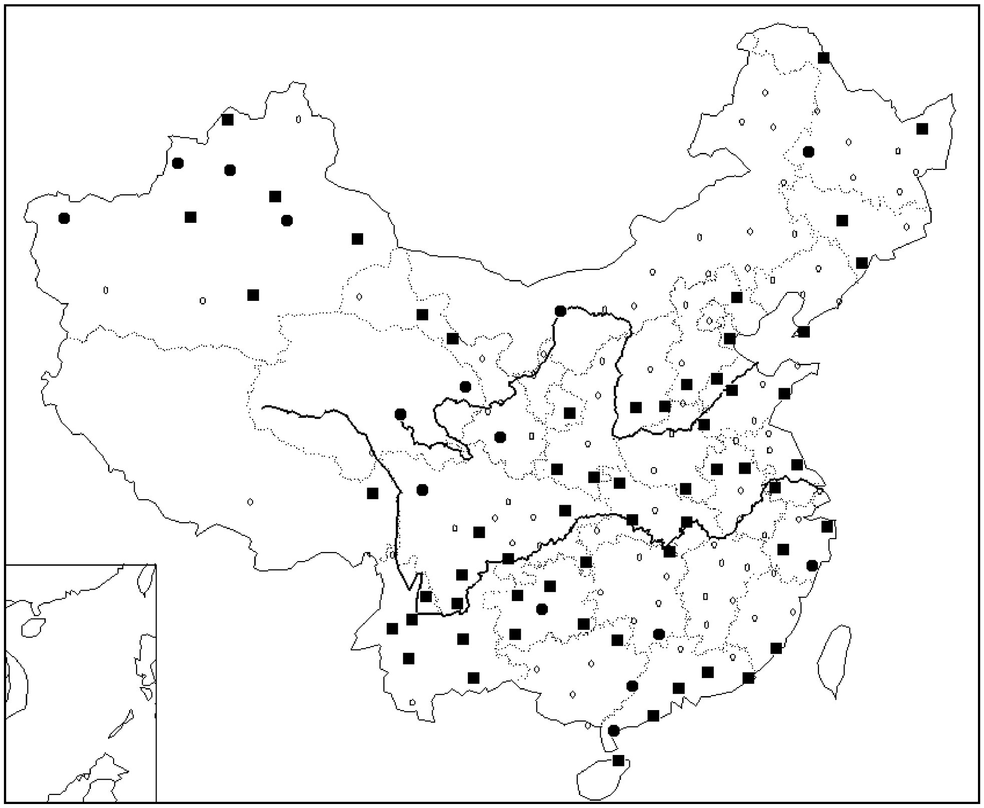

Fig. 7 Effects of landuse change on annual mean upper soil moisture in China. ●: areas of increase, ■: areas of decrease range from –20% to 20%.

The reason for the increase in $T_{\min}$ over Northwest China is that the desertification there may cause the vegetation to change into bare soil, thereby eliminating the "cold island effect" The "cold island effect" in Northwest China is attributed to the fact that, due to the thermal and dynamical difference of the underlying surface, temperature in the oasis is usually lower than in the surrounding desert areas of the Gobi (Hu et al., 1988). Observations from the HEIFE experiment also verified that the temperature in the desert is usually higher than in the oasis both during the day and at night (Hu et al., 1994). However, the influence of land use change on $T_{\min}$ remains to be explained in greater detail by further observations and simulations.

Figures 5 and 6 indicate that $T_{\max}$ and $T_{\min}$ do not change much over Northeast China compared to other regions. The possible reason for this result is that the land use change there was less pronounced than in other regions. In addition we note that the land use change in general has a greater effect on temperature than precipitation, since it directly affects the surface energy budget.

Finally, note that the effect of land use change on the winter $T_{\min}$ is in the opposite direction as that of the GHG over China (Gao et al., 2002) except in the Northwest China regions.

3.4 *Effects on soil moisture*

The simulated mean annual upper soil moisture change is given in Fig. 7. The change is mainly characterized by a widespread decrease over the country except in some areas, where the change is not significant (e.g., in Northeast) or shows a modest increase. The decrease is usually within 20%. Two reasons contribute to this result, a decrease in precipitation and an increase in evaporative drying caused by the higher surface temperatures. The root zone soil moisture, not shown for brevity, showed changes similar to those found for the upper soil.

4. Conclusions and discussions

The effects of land use change on climate are investigated by one-way nesting of the regional climate model RegCM2 within the CSIRO R21L9 global model. Two 5 year long experiments, one with present-day land use and one with potential vegetation cover, are carried out, and land use change effects are investigated based on the differences between these experiments. An analysis of the statistical significance of these differences is carried out. Our main conclusions are the following.

(1) Our results show that compared to the potential vegetation cover, the current land use in China has influenced many local climate elements. It caused a decrease of precipitation in Northwest China; it led to a temperature increase in the southern portions of Northeast China, the Sichuan Basin, and parts of Northwest China; it led to a temperature decrease over the coastal areas of China. Summer daily maximum temperature increased in many locations as a result of land use change while winter minimum temperature increased in Northwest China but decreased in East and South China. Soil moisture decreased in most areas. All these changes were statistically significant at the 90% confidence level based on a two-tailed t-test.

(2) It is important to note that the same land use change may induce different climatic effects over different areas. The effect of land use is thus dependent on the local environment and climatic conditions.

(3) The effects of the land use change analyzed in this paper were mostly in the same direction as those from increasing GHG forcing, except for precipitation over Northwest China and winter minimum temperature.

(4) Our study has some significant limitations. Due to limited computer resources, only 5 year long simulations were carried out for each experiment. Although these are the longest experiments carried out to date to study land use effects over China, longer runs are needed to fully evaluate the climatology of the land use effects in diverse climate conditions. Because we are planning to carry out similar sets of experiments for projected future climate conditions under increased GHG forcing, we used GCM fields to drive our regional climate model. Biases in the GCM fields can thus affect the regional model simulations, although these biases may at least partially cancel out themselves when we analyze differences across experiments. For these reasons, our results should mostly be seen as suggestive of qualitative trends rather than quantitative descriptions of the land use effects. More research is needed to understand the effects of land use change in terms of underlying processes related to the surface energy and water budgets and possible changes in atmospheric circulations.

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土地利用变化对我国区域气候影响的数值试验

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摘　　要

使用RegCM2区域气候模式单向嵌套澳大利亚CSIRO R21L9全球海–气耦合模式，通过将中国区域植被覆盖由理想状况改变为实际状况的数值试验对比分析，探讨了当代中国土地利用变化对中国区域气候的影响，并对结果进行了统计显著性检验。研究表明，土地利用的变化，会导致我国西北等地区年平均降水减少，导致年平均气温在内陆部分地区升高和在沿海个别地区降低，引起许多地方夏季日平均最高气温升高，而冬季日平均最低气温则在我国东部部分地区降低的同时在西北地区升高，土壤湿度的变化表现为大范围的降低。研究同时表明，相同的土地变化在不同的地理环境下引起的气候要素变化有一定的不一致性。

关键词：土地利用，区域气候模式，区域气候变化