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Potential impacts of human-induced land cover change on East Asia monsoon

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Abstract

As one major performance of anthropogenic activities, human-induced land use and land cover changes in East Asia have been one of the largest regions in the world. In the past 3000 years, more than 60% of the region has been affected by conversion of various categories of natural vegetation into farmland, conversion of grassland into semidesert and widespread land degradation. Such human-induced land cover changes result in significant changes of surface dynamic parameters, such as albedo, surface roughness, leaf area index and fractional vegetation coverage, etc.

The results of a pair of numerical experiments in this paper have shown that by altering the complex exchanges of water and energy from surface to atmosphere, the changes in land cover have brought about significant changes to the East Asian monsoon. These include weakening of the summer monsoon and enhancement of winter monsoon over the region and a commensurate increase in anomalous northerly flow. These changes result in the reduction of all components of surface water balance such as precipitation, runoff, and soil water content. The consequent diminution of northward and inland moisture transfer may be a significant factor in explaining the decreasing of atmospheric and soil humidity and thus the trend in aridification observed in many parts of the region, particularly over Northern China during last 3000 years.

The variation of East Asia monsoon presented here is the result of land cover changes only. It is very likely that the anthropogenic modification of monsoon system would have been occurred in the long history of civilization.

Keywords: East Asia; Monsoon; Land cover change

1. Introduction

Temperate East Asia comprises a major portion of the Earth's largest continent, and it is boarded by the planet's highest mountains and largest ocean. Mainly due to strong land–ocean thermal contrast and the dynamic and thermal effects of the Tibetan Plateau, East Asia has a well-developed monsoon climate system. The life of more than 1.5 billion human populations in East Asia depends on monsoon rainfall and also suffers from the drought and flood disasters related to the high variability of monsoon climate. Moreover, East Asia is the homeland of some of the world's oldest, most advanced and most rapidly evolving human civilizations. The human activities have powerfully influenced the changes in every aspect of the environment, including the monsoon climate.

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Both the observational and theoretical studies have proved that the destruction of natural vegetation cover, such as destructive lumbering of forests and overcultivation and overgrazing of grassland has been one of the major causes for the deterioration of regional climate and environment (e.g. Charney et al., 1975; Lean and Warrilow, 1989; Nobre et al., 1991; Xue, 1996; Wei and Fu, 1999; Pielke et al., 1991; Pielke, 2001). The climate–land cover interaction over the Asia monsoon region is particularly strong mainly in two aspects. In terms of natural process, the high variable monsoon climate, such as precipitation and temperature, forces the changes of terrestrial ecosystems in their function and structure on various time scales through changing their physiological processes (e.g. Fu and Wen, 1999). The long-term monsoon climate changes can even alter the biogeographic distributions of the ecosystems (An et al., 1990). These changes in the meantime bring about the feedback effects on the monsoon climate.

On the other hand, more than half of the world population lives in the Asia monsoon region. The long history of civilization has caused significant changes of land cover over Asia. It is likely that the anthropogenic modification of the monsoon system would occur through changing the surface fluxes of energy, water and greenhouse gases under the different land use patterns.

Can the monsoon system be modified by human-induced land cover change? In this paper the numerical experiments with a high-resolution regional climate model have been performed to examine the most likely response of the Asian monsoon system to human-induced land cover change.

2. History of land cover/use changes over East Asia

Owing to increasing population, industrialization and urbanization, the natural ecosystems over Asia

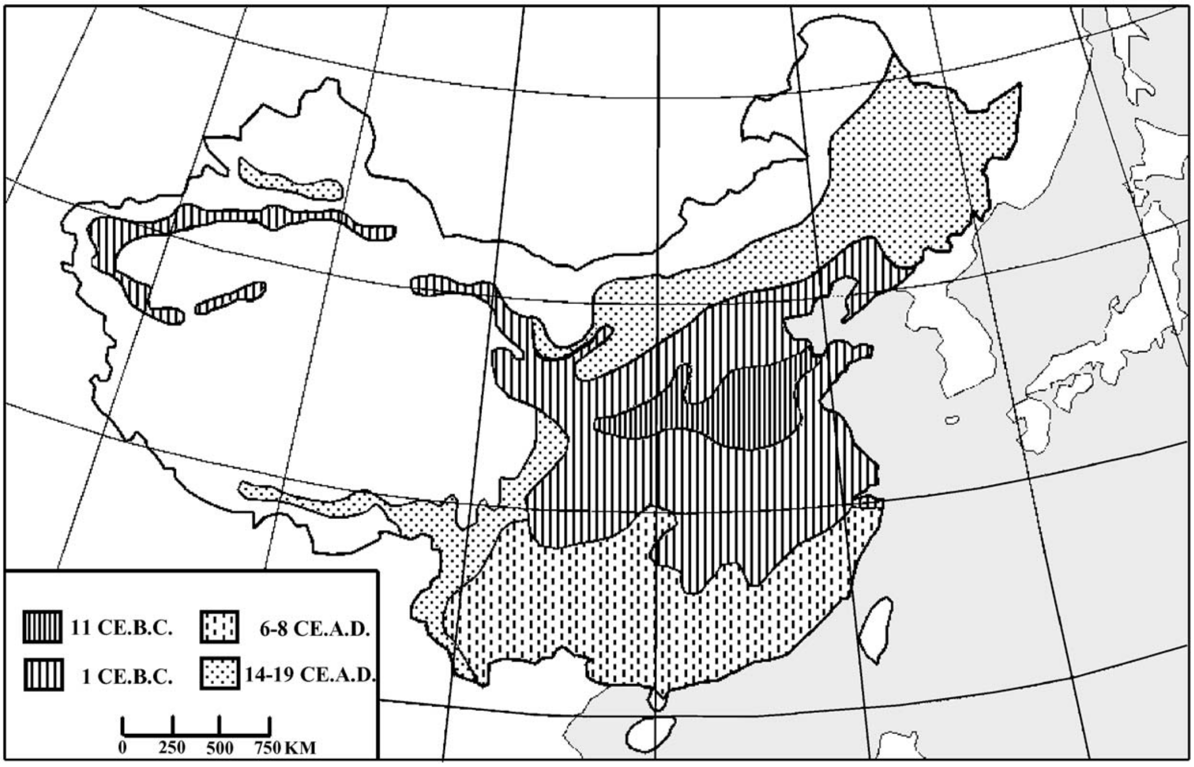

Fig. 1. Expansion of agriculture land over China since 11 century B.C. (Deng et al., 1983).

such as forest, grassland and wetlands have been encroached upon by farmland and other man-made ecosystems on a large scale. Fig. 1, as an example, presents the history of expansion of farmlands over China since 11 century B.C. (Deng et al., 1983). It is seen clearly that in the early days, all the country was covered by various kind of natural ecosystems except for a very narrow band of farmland over the lower reaches of Yellow River basin. The agricultural area was expanded gradually both southward and northward and to the upper reaches of major rivers basin. Around the later 19th century, the land use pattern was setup as it is today in general, although the land cover is continuously changing till recently. Now man-made ecosystems cover nearly 80% of the total terrestrial area. Such human-induced land cover changes have been as great in Asia as in any other in the world, if not greater. To what extent the monsoon system would have been modified by such changes? This is the question we would like to address in the paper.

3. Design the numerical experiments with the Regional Integrated Environmental Model System

The natural vegetation has been so altered in East Asia over millennia that its reconstruction other than by modeling is rather difficult. However, it is feasible to specify the equilibrium climax vegetation that may be expected at present based on the prevailing climate with a biome–climate matching approach which is widely used in the international ecological science community (Ojima et al., 2000). This kind of vegetation cover information is named as the potential vegetation (Vp) since all the man-made ecosystems were subtracted in the procession (Fig. 2a).

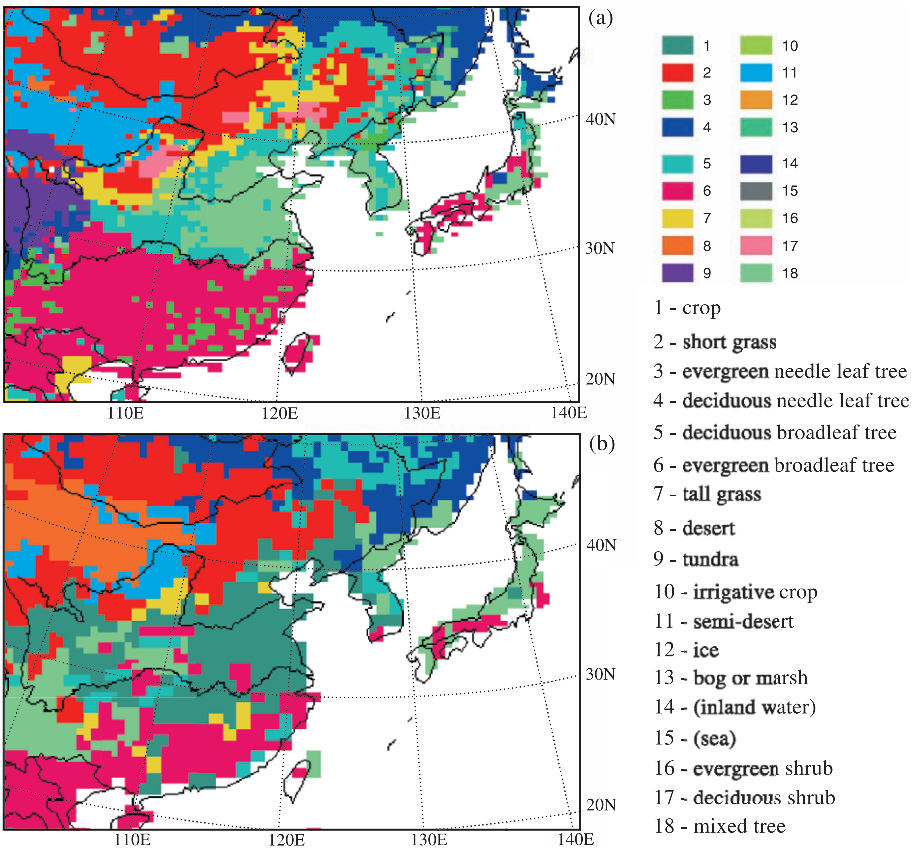

Fig. 2. Vegetation covers over East Asia (a) potential vegetation and (b) current vegetation.

The remote sensing information is now widely used to provide the maps of vegetation cover in rather high temporal resolution. The current vegetation used in this paper is based on the global land cover classification data as part of the Global Data Sets for land–atmosphere models, ISLSP initiative 1, developed in the International Satellite Climatology Project (ISLSCP) (Messon et al., 1995) (Fig. 2b). Although one has to realize that the actual current vegetation cover should have somewhat differences with this data set for 1987–1988, these differences are relatively smaller than the differences with the potential vegetation as described in previous paragraph. Therefore, we assume that this vegetation cover data (Vc) can be looked upon as the actual current vegetation cover approximately. The human-induced land cover change in this paper is defined as the difference between the potential and current vegetation as presented by Fig. 3. More than 80% of the region has been affected by conversion of various categories of natural vegetation into farmland, grassland into semidesert and widespread land degradation. The most pronounced changes occur in Northwest China where the grassland has been changed into semidesert or desert and in East China where the forest has been replaced by cropland. There are also significant changes over Japan.

A pair of numerical experiments is performed under the above two land cover conditions by using the Regional Integrated Environmental Model System (RIEMS) version 1 (Fu et al., 2000). This model consists of mainly three components of climate system: mesoscale atmospheric dynamic model, radiation scheme and land surface scheme and two components of major regional anthropogenic forcing factors: land cover changes and changes of greenhouse gases and

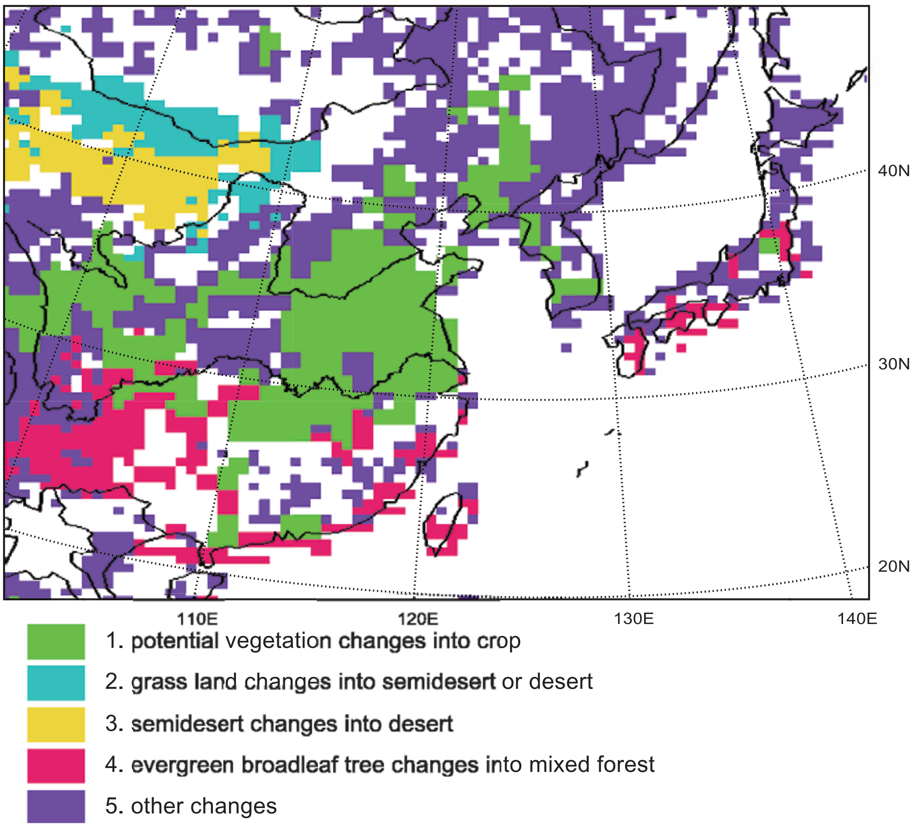

Fig. 3. Changes of vegetation cover from potential to current, green: forests to agriculture land; blue: grassland to semi-desert or desert; yellow: semi-desert to desert; red: evergreen broad leaf forest to shrub etc.; purple: other changes.

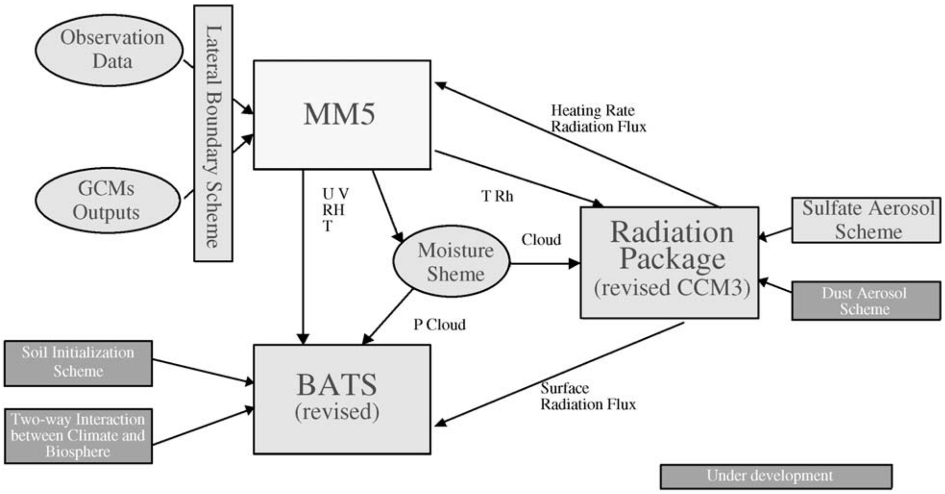

Fig. 4. Schematic diagram of the regional integrated environmental model system (RIEMS).

aerosols emission (Fig. 4). The validation study on the model performance has shown reasonably well results in its capacity to simulate the regional climate in Asia monsoon region (Fu et al., 1998).

The numerical simulation was made over East Asia at the horizontal resolution of 60 km and in the period of June to August for summer and December to February for winter. The integration was driven by the large-scale atmospheric circulation of a normal year from NCEP reanalysis data, as the initial and lateral boundaries. In order to maintain the linkages between the large-scale environment and the simulated region, a relaxation scheme with 10 buffer zones is applied for nesting at the lateral boundary (Wei et al., 1998).

The differential fields of integration by the two vegetation cover data sets (current minus potential vegetation) are used to represent the impacts of changing natural vegetation since the two simulations are identical to each other for all the conditions, including the large-scale driving fields used as the initial and lateral boundary conditions, and the parameters of all physical processes except for the vegetation cover.

4. Changes of surface dynamic parameters under two different types of vegetation coverage

Changes of four main surface parameters: albedo, surface roughness, leaf area index and total vegetation fractional coverage from potential to current vegetation distribution are shown in Fig. 5. The reduction of surface roughness (black areas of Fig. 5a) appears mainly over three areas. One in central China where the natural vegetation, mainly forests have been turned into farmland. Second is in Northwest China and some part of Mongolia where the grassland has been turned into semidesert or desert. The third is the region over southwest China where the evergreen broad leaf forest has been turned into mixed forest or shrub. There are also small areas with increasing roughness, such as in the Far East of Russia. The changes of leaf area index (Fig. 5b) show same pattern as that of surface roughness. The three areas mentioned above show the decrease of leaf area index due to the changes of vegetation cover types. The pattern of surface albedo change appears in an opposite direction with those of the surface roughness and leaf area index. The increase of surface albedo occurs over the regions where the natural vegetation covers were significantly destroyed as shown in area with grey (Fig. 5c). The total fractional vegetation coverage is higher in farmland area than in natural forests (grey area in Fig. 5d), but it is lower in the area of semidesert and desert in comparison with grassland and the area of mixed forests in comparison with evergreen broadleaf forests (black area in Fig. 5d). Changes of these surface parameters would surely modify the exchanges of energy and water between the land

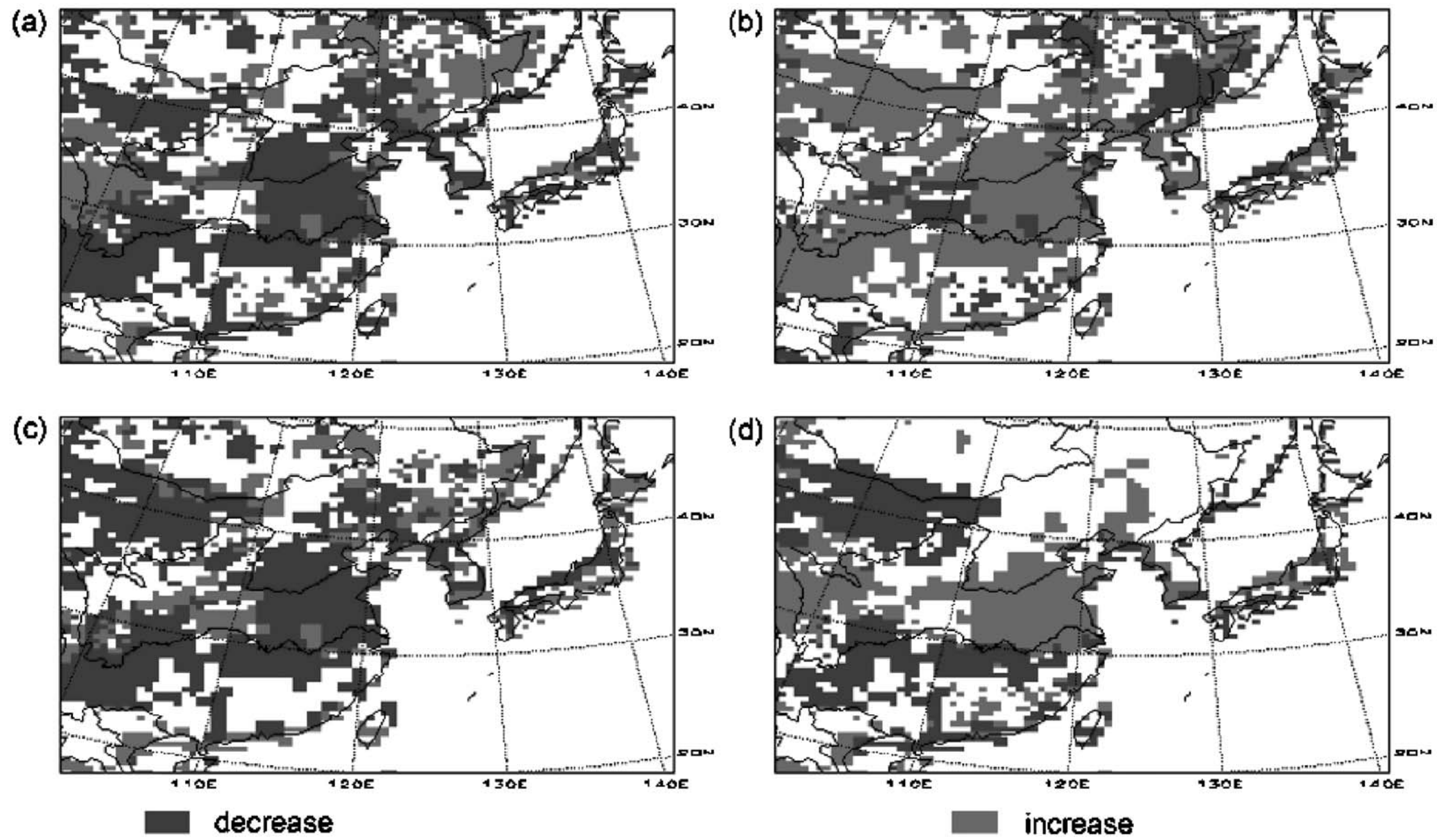

Fig. 5. Changes of four physical parameters of land surface from potential to current vegetation cover: (a) surface roughness; (b) surface albedo; (c) leaf area index and (d) fractional vegetation coverage.

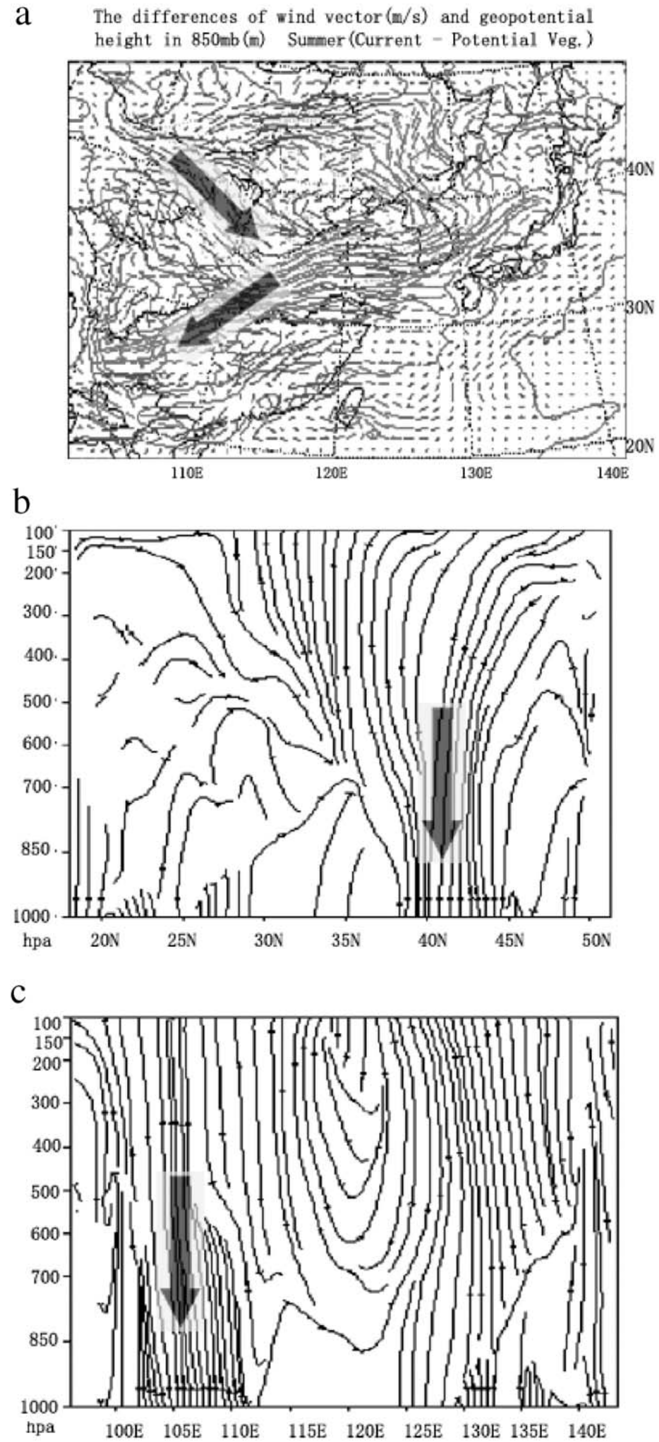

Fig. 6. Changes of summer monsoon circulation over East Asia under two vegetation covers (current minus potential): (a) vector wind and geopotential height at 850 hpa (m); (b) mean meridional circulation along 100–120E and (c) mean zonal circulation along 25–40N.

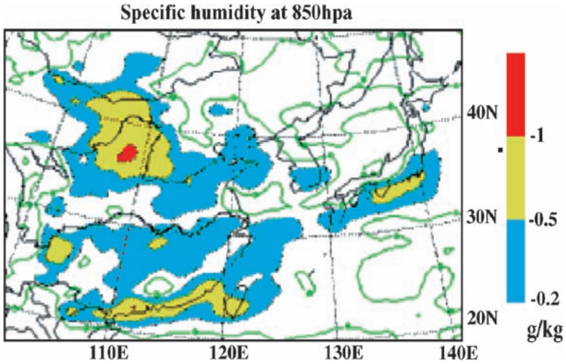

Fig. 7. As Fig. 6, but for specific humidity at 850 hpa (g/kg).

surface and the atmosphere and result in the changes of atmospheric circulation as shown in next section evidently.

5. Changes of summer monsoon by human-induced land cover changes

Since this paper aims to examine the potential modification of East Asian monsoon system, here the analyses focus on the changes of monsoon circulation and related surface climate. Fig. 6a presents the mean changes of vector wind and geopotential height in lower atmosphere (850 hpa) in summer over East Asia. The weakening of monsoon depression is shown by the positive anomalies in the region to the south of 30N and the weakening of summer monsoon are shown by the northerly anomalous flow. There is a negative departure of the height over the north part of the domain representing the development of low-pressure system over there, which brings about the anomalous northwest flow.

The changes of mean meridional circulation and zonal circulation are shown in Fig. 6b, c with major characteristics of enhancement of descending motion flows over 35–40N and 100–115E, respectively, which would prevent from the development of summer monsoon circulation.

Both these two northerly anomalous flows and the enhancement of descending motion over East Asia would prevent from the moisture transport northward and the development of convective activities, resulting in more dry condition of atmosphere over most of the domain, as indicated by the differential field of the

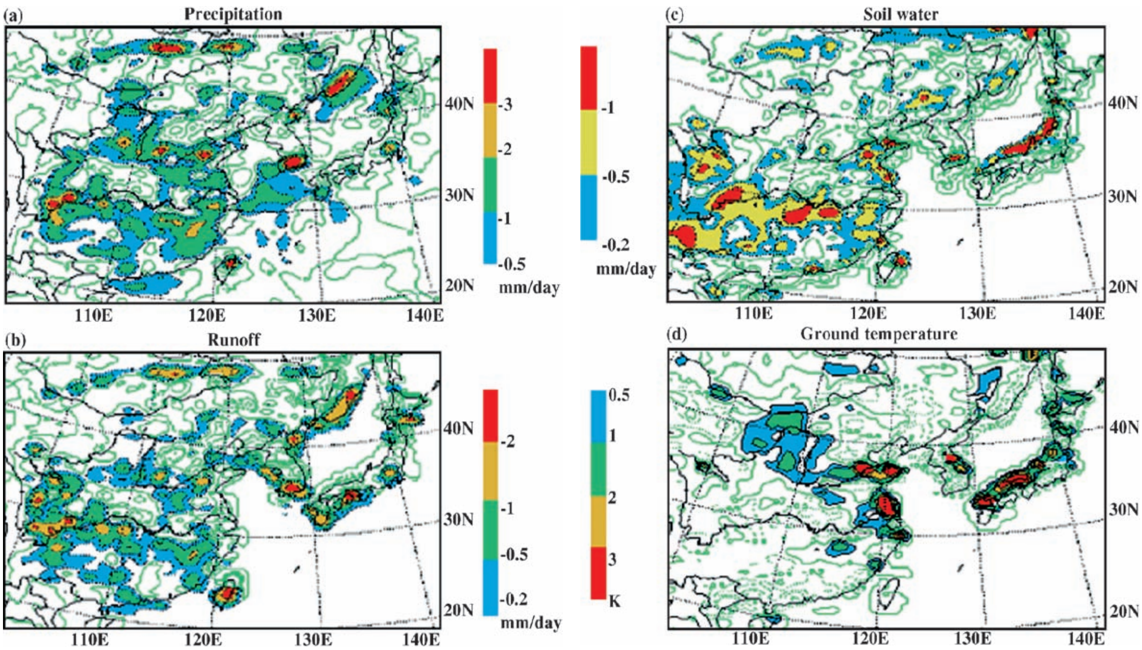

Fig. 8. As Fig. 6, but for surface climate: (a) precipitation (mm/day); (b) runoff (mm/day); (c) soil moisture (mm/day) and (d) ground temperature (K).

specific humidity at 850 hpa (Fig. 7). The center of dry area is just located over the middle reaches of Yellow River, the so-called Houtao area, the most decertified region in the past few hundred years. This area also extends southeastward to northern China plain where there was also an aridity trend in the past half century. While over most part of southern China and Japan Island, the decrease of atmosphere humidity was also observed.

Fig. 8 presents the changes of surface climate related to summer monsoon changes. The changes of summer total precipitation (Fig. 8a) show similar pattern as that of humidity field. The main dry area is located at the middle and lower reaches of Yellow River basin. The area to the south of Yangtze River also shows decrease of rainfall although not as high as that over northern China. Similar pattern can also be seen in the field of surface runoff (Fig. 8b). However, it is interesting to note that the major decrease of soil water content occurs in upper reaches of Yellow River basin and to the south of Yangtze River. Overall, it seems that all components of surface water cycle, such as precipitation, runoff and soil moisture are reduced over most part of the region. It indicates the weakening of water cycle under the condition of deterioration of natural vegetation. However, there are no significant changes in surface temperature except for a relative warming area in northern China plain (Fig. 8d), mainly related to the significant reduction of surface evaporation.

On contrary, the winter monsoon over East Asia become stronger under the deterioration of natural vegetation cover, as shown by the strong anomalous northerly flow in the differential fields of vector wind and geopotential height at 850 hpa of Fig. 9. This circulation pattern would bring dry and cold air mass from inland area down to all regions of East Asia and results in the changes of surface climate, such as the reduction of atmospheric humidity and precipitation mostly in southern part of the region and cold temperature over almost whole region.

6. Conclusions

According to above analysis, human-induced land cover changes have modified the monsoon circulation

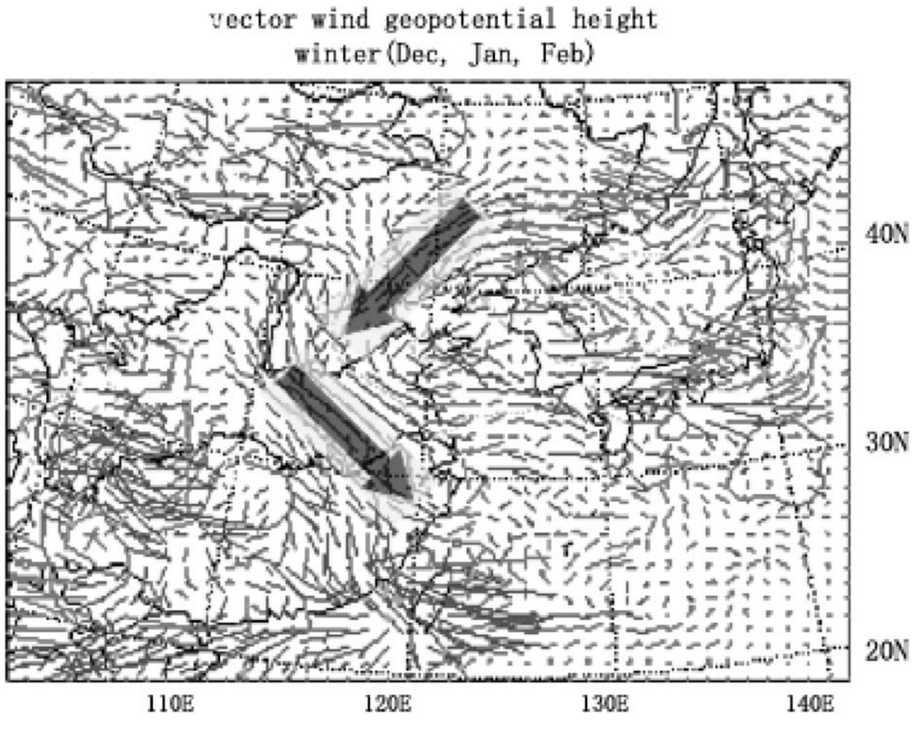

Fig. 9. Changes of winter monsoon circulation as shown in vector wind and geopotential fields.

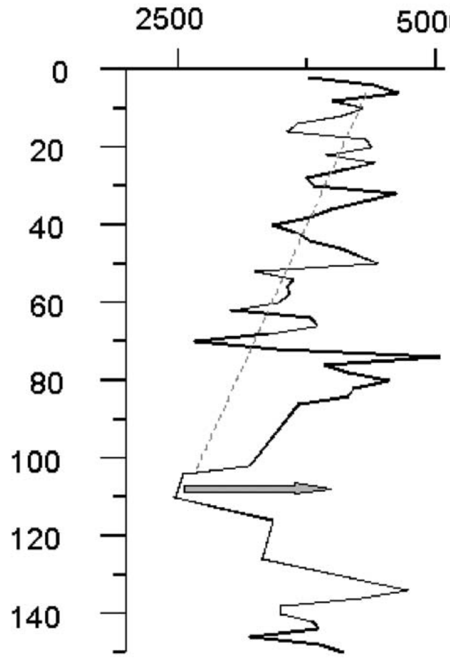

Fig. 10. Changes of salinity of Daihai Lake in the Inner-Mongolia since 5000 BP (Shen, 2001).

by the weakening of summer monsoon and the enhancement of winter monsoon over East Asia, which result in related changes of surface climate over the region. The conclusions from numerical experiments require the observational evidence to support.

Current paleoclimate researches indicate that prior to 3400 B.P., the climate in northern China was characterized by a strong summer monsoon and wet condition, while there was a weaker summer monsoon and dry climate during late Holocene after 3400 B.P. Such a change of East Asia monsoon and climate occurred just after the significant changes of land use pattern over east China began at 11 century B.C. It is very likely that the modification of East Asian summer monsoon, which superimposed on the natural variability of the system, had occurred in last 3400 years, showing the weakening of summer monsoon and aridification trend over the region.

As an example, Fig. 10 presents the changes of salinity of Lake Daihai, a closed lake in the Inner-Mongolia. It is seen clearly that there was an increasing trend of salinity beginning around some 3500 years ago, indicating the drying climate over there (Shen, 2001). A 25 000 year lake level data set for the Daihai Lake shows a significant reduction of its level beginning at about 4000 years ago (Wang, 1990) which provides additional support for above analysis.

Fig. 11 is the time evolution of aridity index over East China since 1880, showing a significant trend of

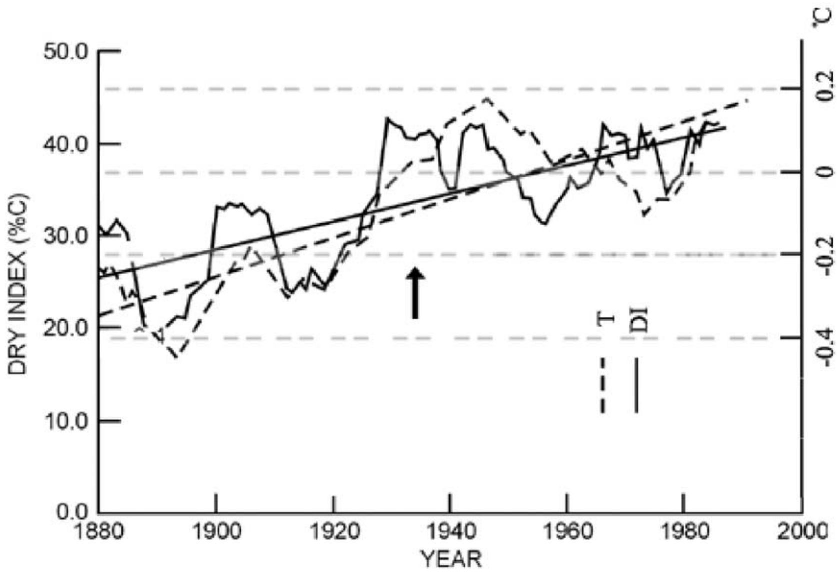

Fig. 11. Variations of aridity index of East China since 1880 (Fu, 1994).

aridification during last 120 years, with the period of 36 years oscillation (Brucker period) superimposed on it (Fu, 1994). Since the moisture condition over East China is mainly related to the intensity of summer monsoon, it is the reflection of the weakening of summer monsoon in that period.

It seems that the deterioration of nature vegetation due to development of human society is perhaps one of the anthropogenic factors superimposed on the natural variability of monsoon system.

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