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MODELING THE POTENTIAL OF THE NORTHERN CHINA FOREST SHELTERBELT IN IMPROVING HYDROCLIMATE CONDITIONS[1]

Yongqiang Liu, John Stanturf, and Houquan Lu[2]

ABSTRACT: The forest shelterbelt (afforestation) project in northern China is the most significant ecosystem project initiated in China during the past three decades. It aims to improve and conserve the ecological environment in the project areas. The tree belt stands along the southern edge of the sandy lands, nearly paralleling to the Great Wall. This study used a regional climate model to simulate the potential of improving regional hydroclimate conditions resulting from the afforestation project. Two simulations with preafforestation and postafforestation land cover were performed over East Asia from January 1987 to February 1988. The model resolution is 60 km. The differences between the two simulations suggest that the northern China forest shelterbelt project is likely to improve overall hydroclimate conditions by increasing precipitation, relative humidity, and soil moisture, and by reducing prevailing winds and air temperature. The effects are more significant in spring and summer than fall and winter. Changes in many hydrologic properties (e.g., evapotranspiration, soil moisture, and water yield), however, differ between the dry Northeast China and the moist Northeast China. The hydroclimate effects are also found in the surrounding areas, featured by noticeably moister conditions in the area south of the afforestation project. The results imply that the shelterbelt project would reduce water yield in afforested Northwest and North China during spring, but increase water yield in the afforested Northeast China as well as in the southern surrounding area, offset some greenhouse effects, and reduce the severity of dust storms. Possible improvements of this study by using actual afforestation data, modeling with higher resolution, longer integration and more detailed processes, and analyzing the physical mechanisms are discussed.

(KEY TERMS: afforestation; hydrology; climate; northern China forest shelterbelt; regional climate modeling.)

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INTRODUCTION

Afforestation to reverse deforestation and land degradation has a long history, usually following failed attempts to cultivate fragile soils for agriculture (Stanturf *et al.*, 2000; Madsen *et al.*, 2005) or surface mining (Lamb *et al.*, 2005). Afforestation currently is conducted not only to meet diverse environmental objectives that include reversing land degradation but also to enhance wildlife habitat and protect water quality (Stanturf *et al.*, 2000; Gardiner and Oliver,

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[2]Respectively, Research Meteorologist and Research Ecologist, Center for Forest Disturbance Science, USDA Forest Service, Athens, Georgia 30602; and Research Scientist, Division of Agrometeorology and Ecology, National Meteorological Center, China Meteorological Administration, Beijing, China (E-Mail/Liu: yliu@fs.fed.us).

2005). Afforestation may also be advanced as a tool of social policy, for example to retire land from active agriculture (Weber, 2005) or to sequester carbon (Ciccarese *et al.*, 2005). Related efforts to convert vegetation from native forest, shrubland, or grassland to commercial tree plantations also occur (Cossalter and Pye-Smith, 2003).

Increasingly, these land-cover changes have come under scrutiny for their effects on water resources (Jackson *et al.*, 2005). Especially in drier climates, the greater use of water by trees as compared with shallower-rooted agricultural crops or grasses has been controversial (Farley *et al.*, 2005), although not always negative (Robinson *et al.*, 2006). At times the issue is the conversion to particular trees, such as fast-growing species of eucalyptus, pine, acacias, or poplar (Cossalter and Pye-Smith, 2003). Much of the research on afforestation effects on water resources has been at the local or watershed scale (Farley *et al.*, 2005). McVicar *et al.* (2007) reviewed the studies on the hydrological impacts of the afforestation in the Loess Plateau of Northwest China. The positive impacts included a reduction in erosion and the risk of average flooding. A counter to the positive impacts is the often observed reduction in annual streamflow (Sun *et al.*, 2006), largely due to increasing rates of evapotranspiration.

Recognizing the reciprocal effect of vegetation change on climate has broadened the focus of climate change research (Pielke and Avissar, 1990; Henderson-Sellers and McGuffie, 1995; Foley *et al.*, 2003, 2005; Li *et al.*, 2007). Explorations at the biome level of the upper limits of conversion (Köhler and Fischer, 2004; Snyder *et al.*, 2004; Brovkin *et al.*, 2006) have shown that climate forcing from anthropogenic change in land cover can be substantial. In a long-term field experiment of the role of tree shelter in the western Northeast China and northeastern North China, temperature and humidity increase by 2°C and decrease by 16%, respectively, without building a shelter (Chao and Xin, 1999). Regional alteration of landscape also affects global climate through teleconnections (Chase *et al.*, 2000; Feddema *et al.*, 2005).

Afforestation and reforestation in eastern Asia are increasing the forested area (Fang *et al.*, 2001; Foley *et al.*, 2003). In China, a forest shelterbelt project started in 1978 across northern China where annual precipitation is generally less than 400 mm (Fang *et al.*, 2001; Zhang *et al.*, 2007). The project aims to prevent southward expansion of the desert, improve hydroclimate conditions, and conserve the natural environment in the project areas. The forest shelterbelt is about 7,000 km long zonally and 400-1,700 km wide. It stands along the southern edge of the sandy lands, nearly paralleling to the Great Wall, thereby gaining the name the Green Great Wall (GGW) (SFA, 2006). The target is to cover 60% of the project areas by 2000, 85% by 2020, and 100% by 2050. When the GGW project is completed, forest coverage will increase from 5% to 15% of northern China. Until now, 25.07 million hectares of trees have been planted and are growing (SFA, 2006).

The purpose of our study was to estimate the potential impact of the northern China forest shelterbelt project on hydroclimate conditions. Hydroclimate conditions are indicated by soil water balance components (precipitation, evapotranspiration, and runoff) and soil and air water contents. Attention will be paid to the comparison of afforestation-induced disturbances between evapotranspiration and precipitation, geographic and seasonal variability, and changes outside the afforestation areas. Our approach is to compare two simulations using a regional climate model (RCM): one simulation uses current land cover and another replaces the current cover with trees in the project areas. The methods are first described in the next section. Results and discussion are presented in the following two sections. Conclusions are given in the final section.

METHODS

Study Area

Northern China encompasses the three geographic regions of Northwest, North, and Northeast China (Figure 1). Northern China covers about one-third of the total land area of the country, which is 9.6 million km^2. These regions, especially Northwest China, are characterized by dry climate and severe water supply shortages. Annual precipitation is below 200 mm in most of Northwest China, increasing to between 200 and 400 mm in northern North China and western Northeast China, but much less than the more than 1,000 mm in Southeast China (Lu and Gao, 1983). Water supply per cultivated land in these three regions is about only 50, 15, and 25% of the amount of 38×10^3 m^3/ha in Southeast China (Jin, 1999).

The dry conditions have worsened since the middle of the 20th Century, as temperature increased in eastern Northwest and northern North China and precipitation declined in northern North and Northeast China (Chen *et al.*, 2004). Conditions are expected to continue this drying trend in this century due to global warming. Many general circulation models (GCMs) project a warmer and drier climate in northern China in response to the increased atmospheric CO_2 concentration. According to projections

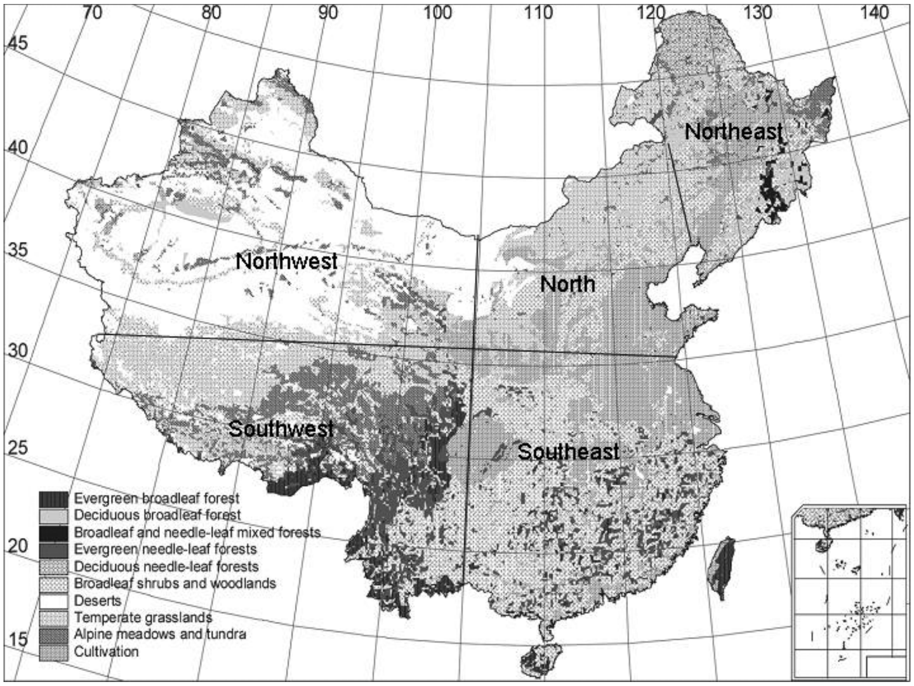

FIGURE 1. Land Use Type in China. China is roughly divided into Northwest, North, Northeast, Southeast, and Southwest regions. Northern China consists of the first three regions (the land use type image originally from S. Piao *et al.*, 2004.

by the Geophysical Fluid Dynamics Laboratory (GFDL) GCM (Delworth *et al.*, 2006), for example, the temperature in most of northern China would increase by up to 5°C and daily precipitation would decrease by up to 1 mm by 2080, as compared with conditions in the period of 1961-1990.

The worsening hydroclimate conditions have already led to adverse environmental effects such as desertification and more frequent severe dust storms (Laurent *et al.*, 2006). Desertification expanded at an annual rate of 1,560 km^2 during the 1950s and 1960s; 2,100 km^2 during the 1970s and 1980s; and 2,948 km^2 during the 1990s. Northern China now has 2.64 million km^2 of desertified areas, and more than a quarter of China's total land area has been classified as desertified (Zhang *et al.*, 2007). Land degradation adversely affects the lives of more than 400 million people, or 30% of the Chinese population. Meanwhile, the number of strong dust storms has increased, from 5 per year in the 1950s to 23 per year in the 1990s.

Land cover conversions, specifically deforestation, have been implicated as a cause of land degradation in Northern China (Zha and Gao, 1997). Today, forest cover percentage in Northern China is 5%, which is much smaller than the national average of about 14%. Forest coverage has changed dramatically with significant reductions in Northeast and North China. Forest land cover was reduced by 25, 20, and 7% in Northeast, North, and Northwest China, respectively, during the first half of the 20th Century (Houghton and Hackler, 2003), corresponding to annual deforestation rates of 0.5, 0.15, and 0.15%. During the last 30 years, the annual rate increased to 3% in Northeast and 1% in North China. Currently, forest land is found only in the eastern and northern Northeast China, with the rest of the region mainly covered by agricultural uses and grassland. Northwest China is mostly covered by desert, dry land, and mountains, and North China is mostly covered by grasslands, small desert, and agricultural land (Figure 1).

Model

We used a RCM to simulate and predict atmospheric and soil conditions, variability, and changes in our specific study. A RCM is constructed usually based on a limited-area meteorological model (LAM) by adding detailed descriptions of some physical processes important to climate, including radiation, land surface, planetary-boundary-layer, and precipitation. The lateral boundary conditions are provided by either a GCM or actual measurements. The regional climate modeling technique was first developed in the late 1980s in the United States (U.S.) National Center for Atmospheric Research (NCAR) based on the standard NCAR/Penn State Mesoscale Model Version 4 (MM4) (Anthes *et al.*, 1987; Dickinson *et al.*, 1989; Giorgi and Bates, 1989). Many RCMs have been

developed using other LAMs, including the National Centers for Environmental Prediction (NCEP) Regional Spectral Model (RSM) (Juang and Kanamitsu, 1994), the climate version of the Colorado State University regional atmospheric modeling System (RAMS) (Liston and Pielke, 2000), the Hadley Centre regional climate modeling system (Jones *et al.*, 1995), the Canadian Regional Climate Model (CRCM) (Caya and Laprise, 1999), and the climate version of the weather research and forecast (WRF) model (Liang *et al.*, 2006), which was developed based on MM5.

RCMs can be a tool for partially solving the problems associated with low resolution of three-dimensional GCMs. With a resolution of only a few hundred kilometers, GCMs have limited capability to simulate climate at regional scale, and GCMs largely miss the mesoscale systems responsible for convective precipitation events. The effects of local and regional forcings such as terrain, land cover, and aerosols emitted from natural and anthropogenic sources are often not well represented in GCMs. RCMs, on the other hand, have spatial resolution at tens of kilometers or higher and are often equipped with more detailed schemes for local and regional properties, thereby providing a better tool for understanding climate at regional scale. Unlike GCMs, which can be run as long as thousands of years, RCMs usually are run from months to years because of extreme computer time consumption due to high resolution and more detailed description of physical processes. Also unlike GCMs, which are mostly spectral models, RCMs are mostly grid-point models.

The RCM for this study is the NCAR RCM (Giorgi *et al.*, 1993a,b) with modified explicit rainfall calculation (Giorgi and Shields, 1999). RCM characterizes regional features of climate by incorporating biosphere-atmosphere transfer scheme (BATS) land-surface physics (Dickinson *et al.*, 1993a) and the NCAR radiative transfer model (Kiehl *et al.*, 1996), into the standard NCAR/Penn State Mesoscale Model (Anthes *et al.*, 1987). The Kuo-type subgrid convective scheme (Anthes, 1977) was utilized. RCM is able to reproduce some important high-resolution spatial characteristics of climate for major geographic regions over the world, including East Asia (e.g., Liu *et al.*, 1994, 1996; Lee and Suh, 2000).

Simulations

The simulation domain is centered at 34°N and 116°E and contains 90 by 79 grid points with a horizontal resolution of 60 km (Figure 2). There are 14 vertical layers with the top model atmosphere at 80 hPa. The initial and horizontal lateral boundary conditions of wind, temperature, water vapor, and surface pressure were interpolated from the analysis of the European Center for Medium-Range Weather Forecast (ECMWF), whose resolution is 1.875° of latitude and longitude (roughly 200 by 175 km at mid-latitudes). Soil water content was initialized as described in Giorgi and Bates (1989) (i.e., the initial soil moisture content depends on the specified type of vegetation). Time dependent sea-surface temperature was interpolated from a set of observed, monthly means with a resolution of 1° (Shea *et al.*, 1992). All these data were obtained from archives of the NCAR Scientific Computing Division. Land type is specified based on the global 1-km resolution International Geosphere Biosphere Program (IGBP) land cover dataset (Zeng *et al.*, 2000).

We used an integration period from January 1987 to February 1988 with the first two months as the spin-up period. A time step of 3 min was used. Two simulations were performed: The one using present land cover specified by the IGBP land cover data (our control) and the other replacing agriculture, grass, or sandy lands in the GGW areas with needle pine trees (our experiment). The control simulation is part of an 11-year simulation presented in Liu (2003). Comparison with precipitation observations indicated that this long-interval simulation was able to reproduce spatial patterns, but overestimated magnitudes in many continental areas. In our experiment simulation, conditions were the same as the control simulation except the replacement of grass, sand, agriculture, and other

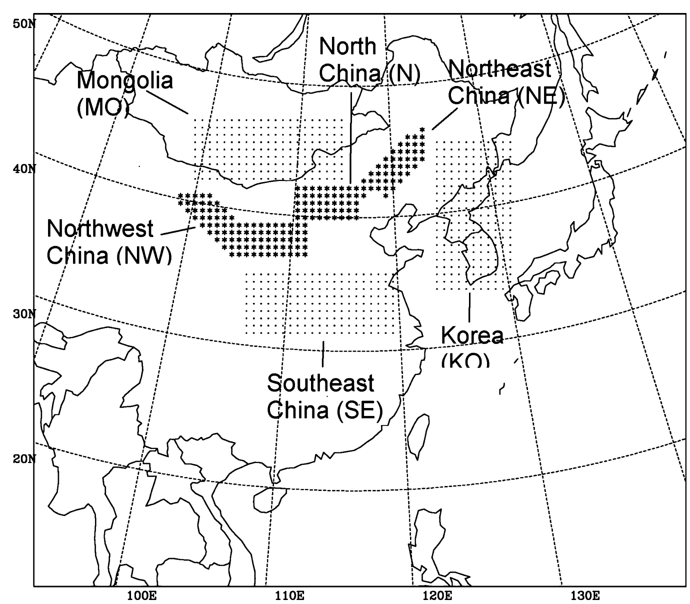

FIGURE 2. Simulation Domain. The dark-shaded regions are the afforested areas in Northwest (NW), North (N), and Northeast (NE) China. The light-shaded regions are the surrounding areas of Southeast (SE) China, Mongolia (MO), and Korea (KO). Regional averages of the simulation results are made over each of the areas.

land cover types in the GGW areas with evergreen needleleaf tree. Roughness is 0.02-0.06 for these land cover types, whereas 1.0 for the needleleaf tree in the BATS, and the root depth is 1 and 1.5 meter, respectively. The GGW areas are divided into Northwest (NW), North (N) and Northeast (NE) China for regional analyses. In addition, analyses were also performed for the three surrounding areas of Southeast China (SE), Mongolia (MO), and Korea (KO) located in the south, north, and east, respectively, of the GGW areas. The simulation results were used to represent the hydroclimate conditions expected when the GGW afforestation project is completed. The differences between the experiment and control simulations represent the potential impacts of afforestation.

Note that the GGW lasts for about 70 years and the planted trees may take tens of years to grow up. A much longer integration is needed to fully simulate the afforestation processes with different plantings and growth stages. For this study, we assumed that all trees have been planted and are at their mature stage. So the simulated impacts are potential.

RESULTS

Circulations

Atmospheric circulations control spatial distribution and seasonal variability of precipitation. Figure 3 shows the simulated surface wind vectors averaged over each of the four seasons. There are two planetary-scale circulation systems in spring. One is the mid-latitude westerly jet with the trough line along

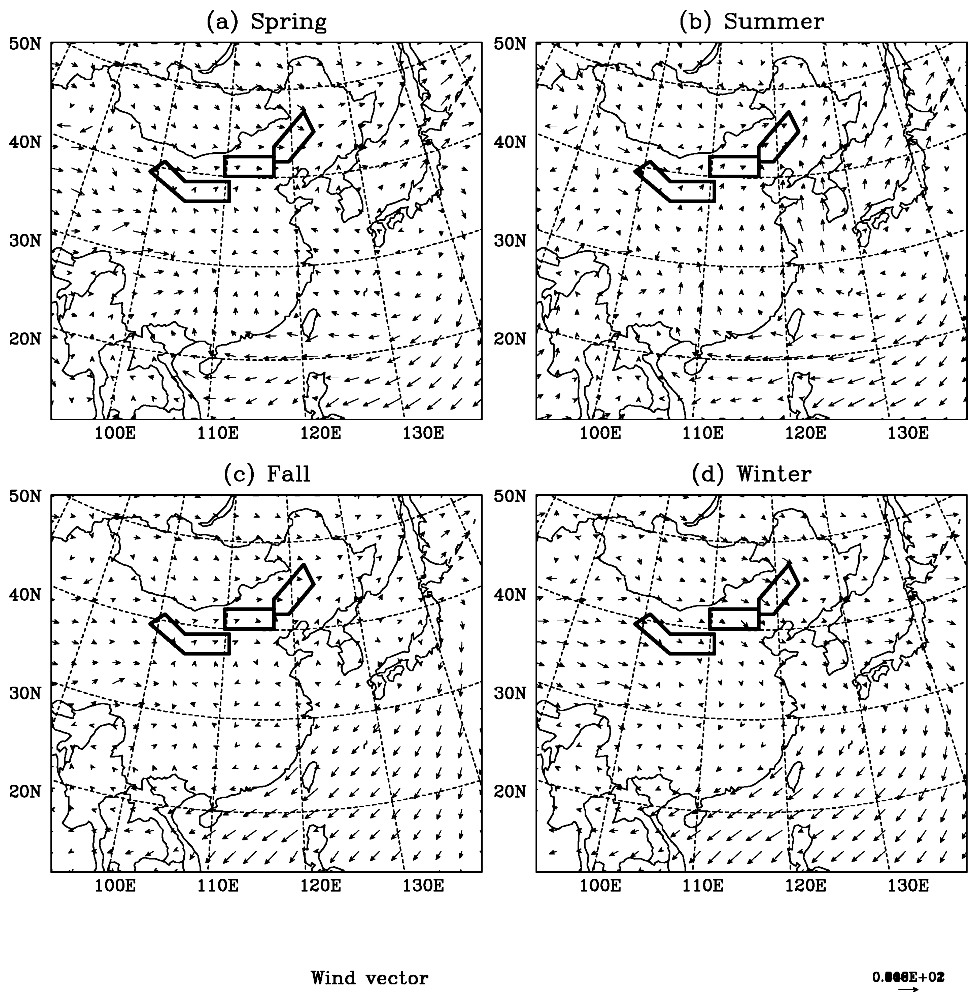

FIGURE 3. The Surface Wind Direction From the Control Simulation Averaged Over Spring (a), Summer (b), Fall (c), and Winter (d). The three boxes from left to right are the afforested areas in Northwest, North, and Northeast China.

the coast. The GGW areas are under the control of this system. The other circulation is the northwestern Pacific subtropical anti-cyclonic high with the ridge line between 25°N and 30°N. Water vapor is transported to eastern China by the airflows in the southwestern sector of the system. Meanwhile, the northward warm airflows from the high and the southward cool airflows from the trough meet in-between the two planetary-scale systems to form monsoon fronts, which are major synoptic systems that produce precipitation. The systems move northward and the effects of the subtropical high reach the GGW areas during summer. The systems retreat southward during fall. An anti-cyclonic system becomes a dominant system over the continental during winter, which carries the dry, northerly airflows.

Disturbance in the surface winds is measured by the difference between the experiment and control simulations (Figure 4). During all seasons the disturbed wind direction is nearly easterly in the afforested areas, opposite to the simulated prevailing wind direction. This indicates that the prevailing wind speed is reduced due to afforestation. The magnitude in wind speed disturbance is more than 3 m/s. In the south of the afforested areas, the disturbed airflows move towards west from the subtropical Pacific Ocean and turn northwards over the land area. They carry more atmospheric water vapor to the afforested areas.

Precipitation

The spatial distribution and seasonal variability of precipitation are shown in Figure 5. During spring, a rain belt of 4 mm per day or more spreads nearly zonally between 20°N and 32°N, with a major rainfall center of more than 10 mm per day between 110°N and 120°E (the eastern Southwest and western Southeast China). The rain belt and the center

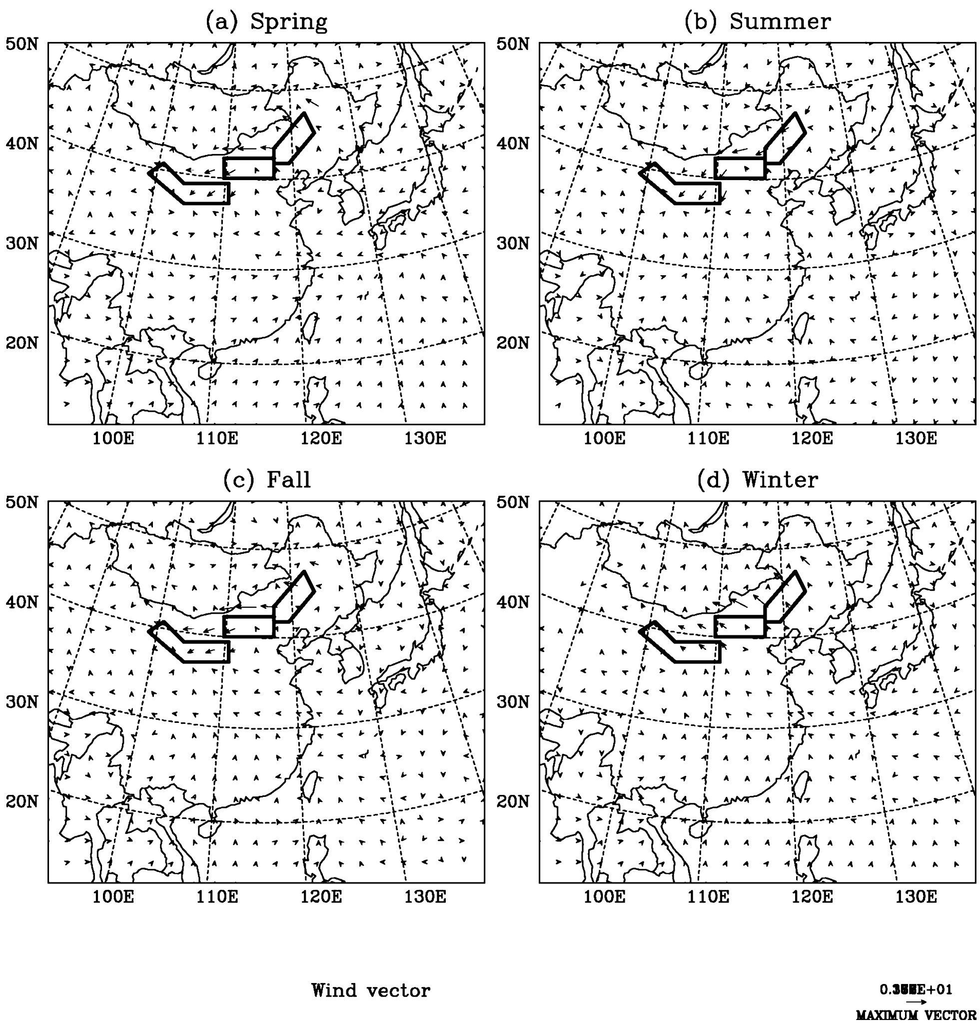

FIGURE 4. Same as Figure 3 Except for Disturbance Due to Forestation.

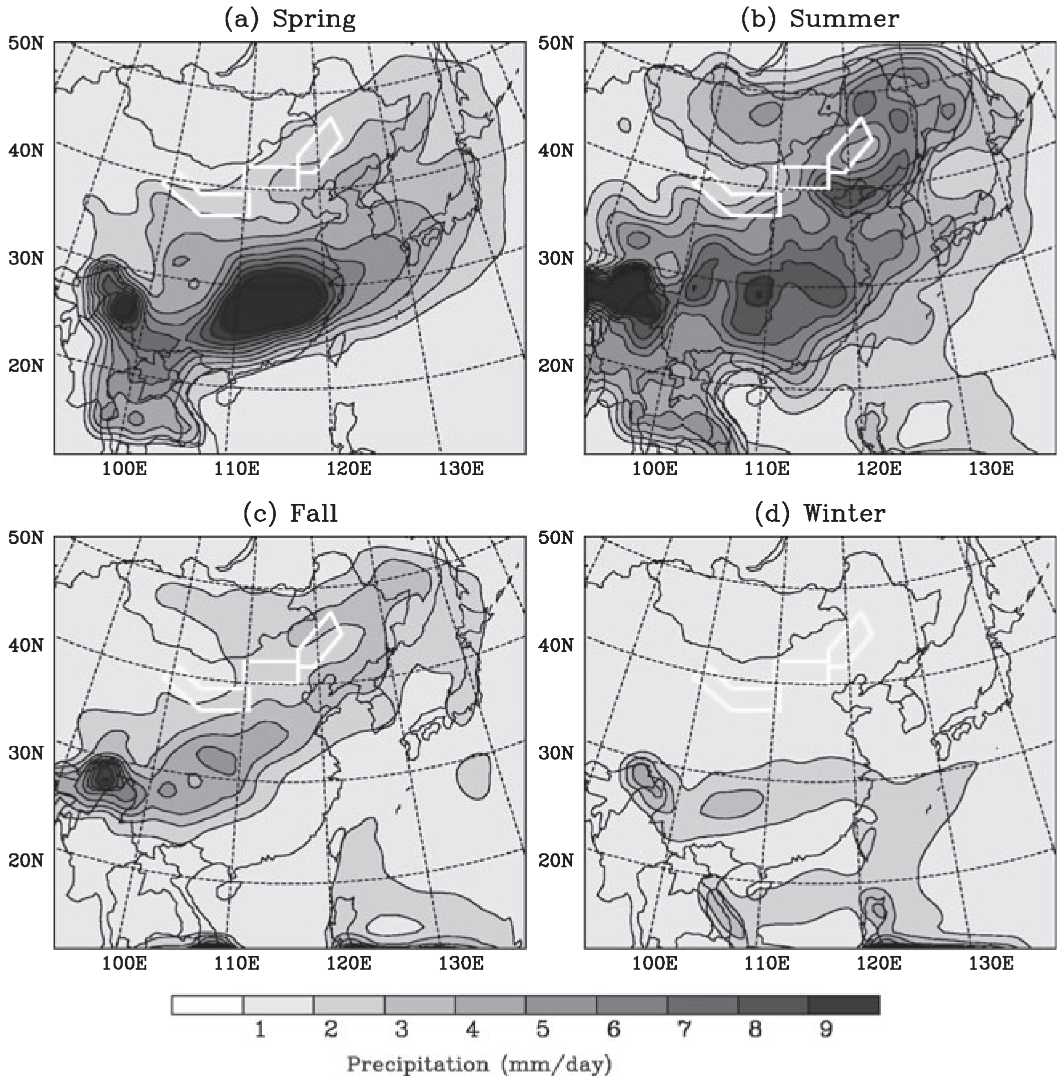

FIGURE 5. Same as Figure 3 Except for Precipitation (mm/day).

remain during summer, although the intensity of the center becomes weaker. Meanwhile, the rain belt extends towards Northeast China with a large precipitation of 5 mm per day in southern North China and Northeast China. During fall, the rain belt remains but the amount of precipitation is much smaller. Winter precipitation is even smaller and is located in southern Southeast China.

The relative disturbance in precipitation, measured as the difference in precipitation between the experiment and control simulations divided by precipitation in the control simulation multiplied by 100, is shown in Figure 6. During spring, the disturbance is overall positive in the afforestation areas, indicating that precipitation is increased due to afforestation. The magnitude is up to 20%. Positive disturbance is also found in south of the afforestation areas over southern North China. The positive disturbance is surrounded by a negative disturbance, mainly east of the afforestation areas along the China border, indicating decreased precipitation due to afforestation. The disturbance turns positive again with the most significant increase over the oceanic region south to Korea.

The spatial pattern of the disturbance is similar in summer, with two differences. First, a positive disturbance over the ocean region south to Korea in spring moves northward and merges with the positive disturbance over the afforestation areas. Accordingly, the surrounding negative disturbance includes Southeast China, Japan, and Mongolia. The negative disturbance is mixed with patches of positive disturbance. Second, the magnitude is larger, up to 30% for both the positive and negative disturbance. In comparison with summer, the spatial pattern in fall is closer to that in spring. During winter, a

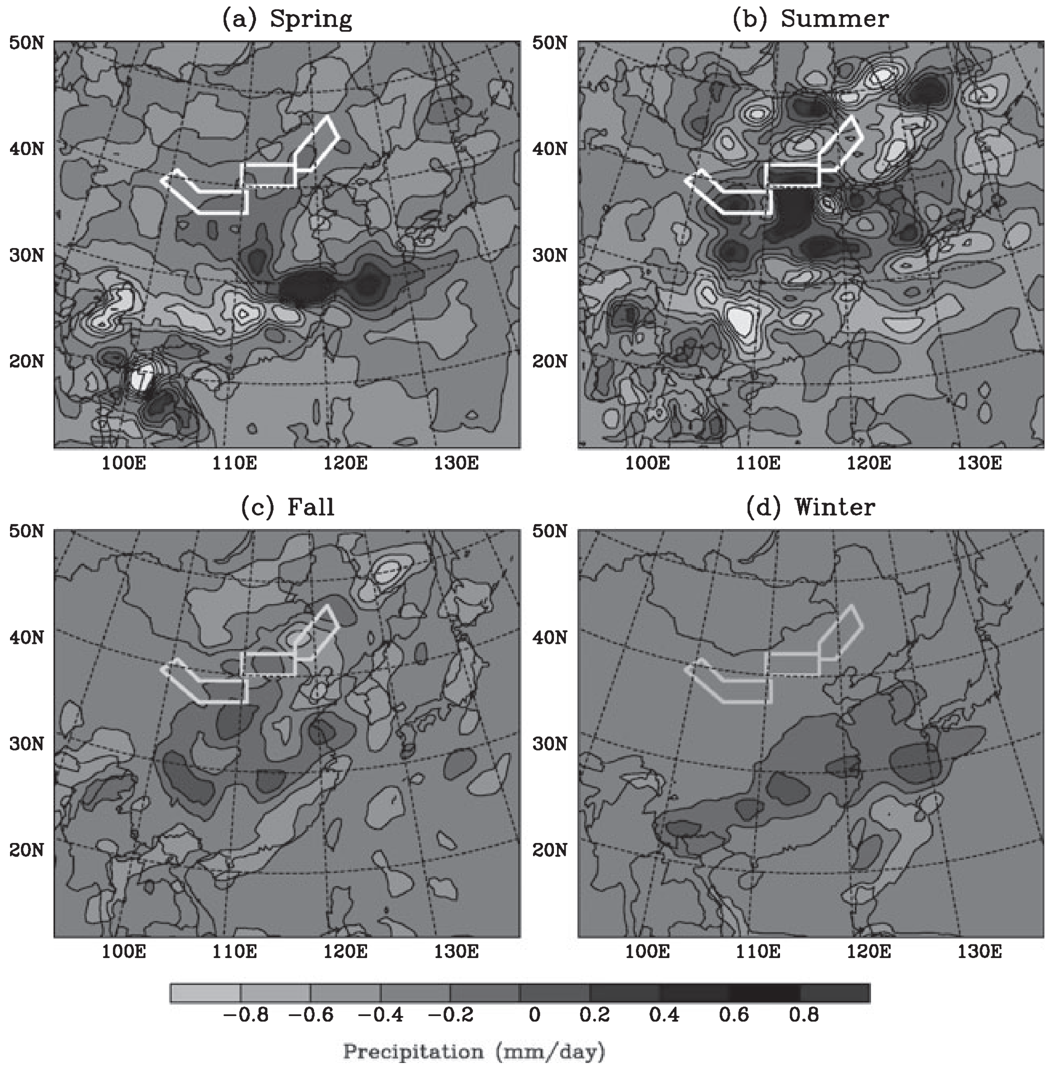

FIGURE 6. Same as Figure 5 Except for Disturbance Due to Forestation.

positive disturbance is dominant and occurs mostly southeast of the afforestation areas.

To estimate precipitation more quantitatively, averages were made over the three afforestation areas (NW, N, and NE) and three surrounding areas (SE, MO, and KO) (Figure 2). The simulated precipitation increases from spring to summer, then decreases in fall, and decreases further in winter (Figure 7, expressed in the same units as in Figure 6). In each season, precipitation is generally the largest in Area SE, smallest in NW and MO, and in-between in N, NE, and KO. Precipitation disturbance is positive in all afforestation areas with the largest relative change in NW in all seasons except winter, and the smallest relative change in NE. Precipitation disturbance is also consistently positive in SE. The disturbance in KO is positive with a large value in winter but very small in other seasons. The disturbance is small in all seasons in MO.

In summary, precipitation is increased in NW and N as well as in SE during all seasons, NE in spring, and KO in winter due to afforestation. The magnitude is up to about 15%.

Evapotranspiration and Runoff

Evapotranspiration is one component of the soil water balance, expressed in Figure 8 as regional averages. Its seasonal and geographic variability is basically the same as that of precipitation with slightly smaller magnitude for the most part. Disturbance is also similar, that is, evapotranspiration generally increases as precipitation does. However, two differences can be found. First, evapotranspiration disturbance in NE is much smaller during spring and even negative during summer. Second, evapotranspiration disturbance is significant mainly in the

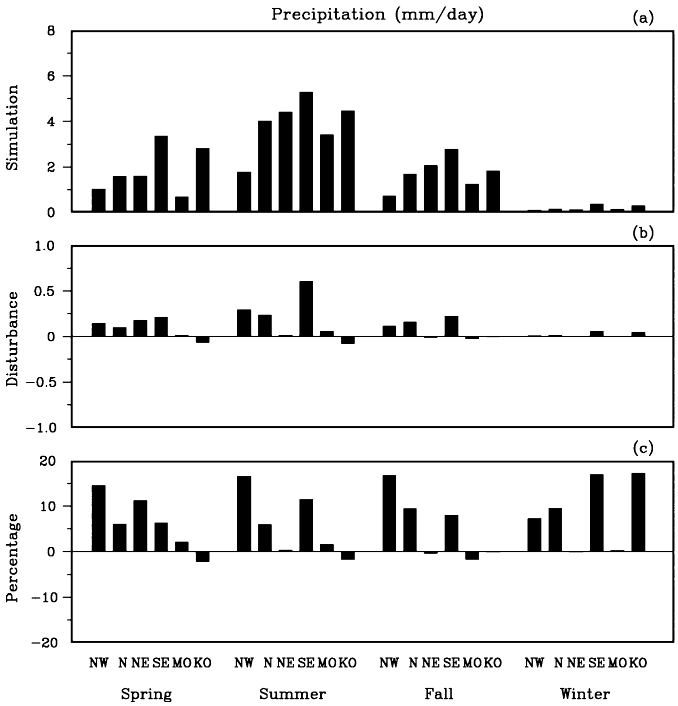

FIGURE 7. Regional Averages of Precipitation (mm/day). (a-c) are control simulation, disturbance, and ratio of the difference to simulation (%). Four seasons are shown, each for the afforested areas in Northwest (NW), North (N), and Northeast (NE) China, and the surrounding areas in Southeast China (SE), Mongolia (MO), and Korea (KO).

afforested areas, with the exception of a large positive disturbance in Area SE during winter.

In comparison with the precipitation disturbance, in spring, evapotranspiration disturbance is larger in Areas NW and N, but smaller in Areas NE, SE, and MO. It becomes about the same magnitude in Areas NW and N, but turns negative in Area NE in summer. The disturbance is slightly positive in fall and small in winter in the three afforested areas.

Runoff (Figure 9) is another component of the soil water balance. The simulated runoff is mostly below 0.5 mm per day, much smaller than precipitation. This leads to large values of relative disturbance with the magnitude of up to 50%. Runoff disturbance differs from precipitation and evapotranspiration in the afforested areas in that it is negative in all seasons except fall in Area N. Disturbance outside the afforestation areas can be either positive or negative, but mostly positive for disturbance with large magnitude. These results indicate that runoff is mostly decreased in and outside the afforested areas.

Air Humidity

Relative humidity is proportional to water vapor content, but inversely proportional to temperature. Regional averages of air relative humidity are shown

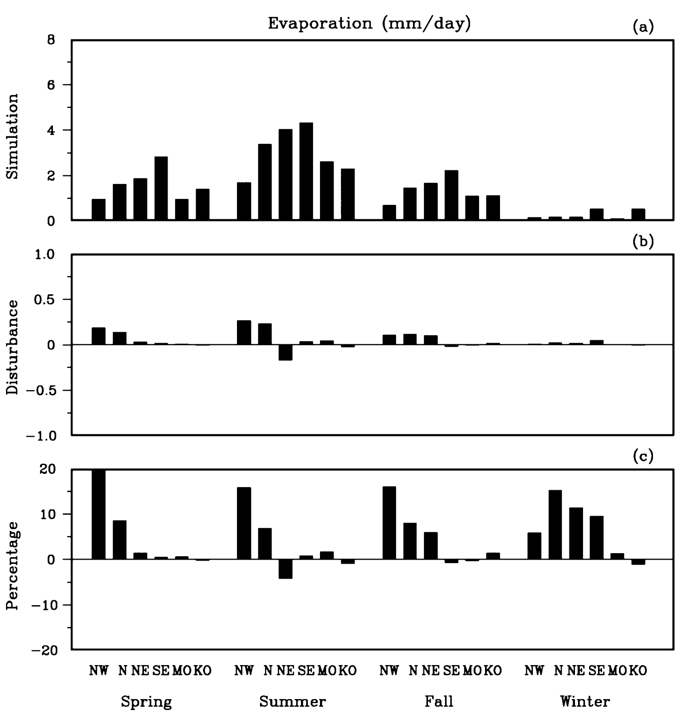

FIGURE 8. Same as Figure 7 Except for Evapotranspiration.

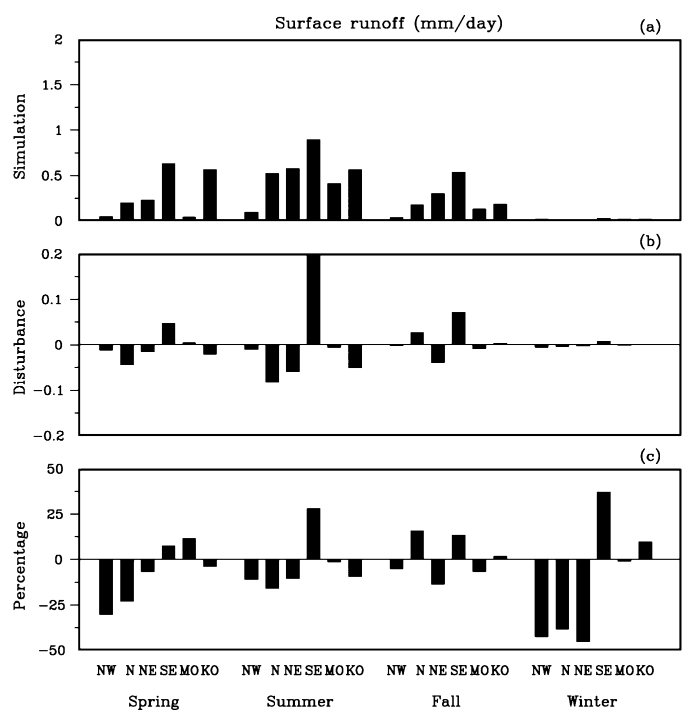

FIGURE 9. Same as Figure 7 Except for Runoff.

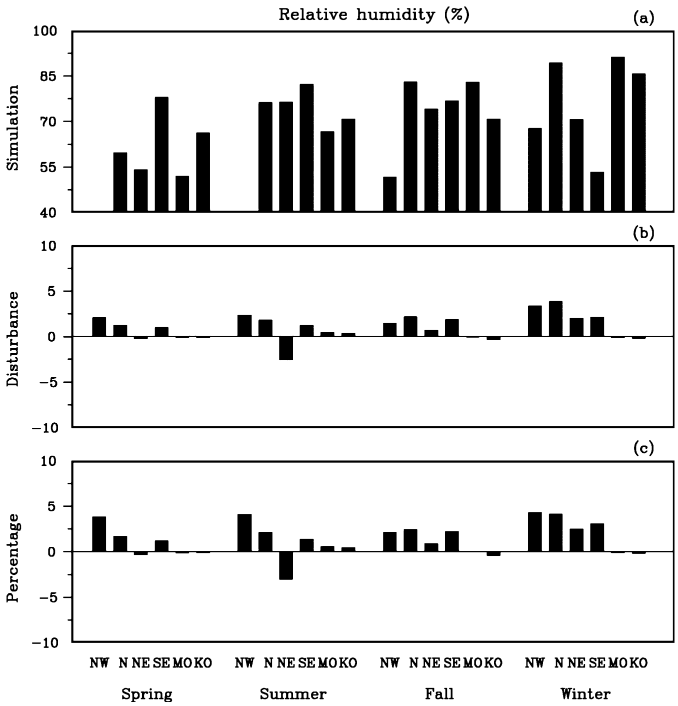

FIGURE 10. Same as Figure 7 Except for Air Relative Humidity (%).

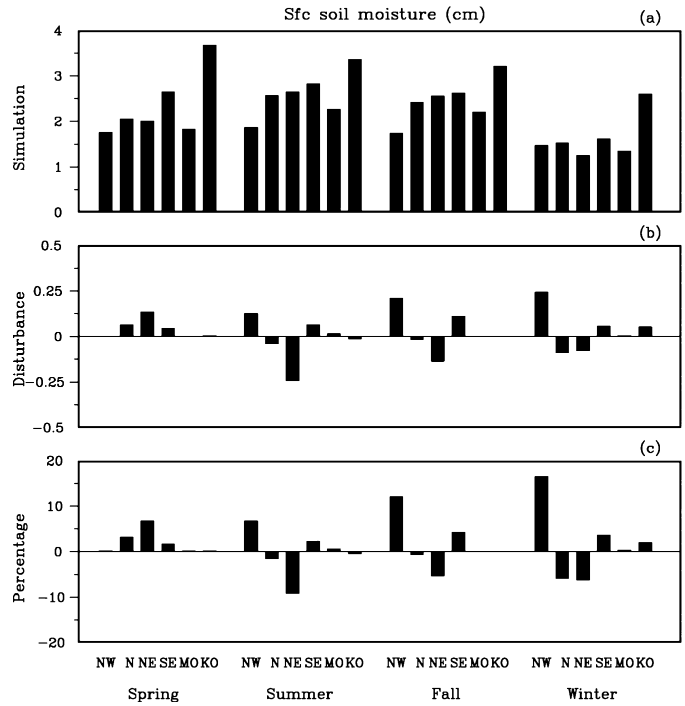

FIGURE 11. Same as Figure 7 Except for Moisture of Surface Soil Layer (cm).

in Figure 10. The atmosphere has more water vapor, but temperature is higher during summer as compared with winter, resulting in little seasonal variability. Disturbance in air relative humidity is increased in various areas during all seasons except summer in Area NE.

Soil Moisture

The soil component in BATS used for this simulation has three hydrologic layers: a surface layer of 0.1 m, root layer of 1~2 m depending on vegetation type, and a bottom layer. The regional averages of soil moisture of the surface layer are displayed in Figure 11. Simulated soil moisture of the surface layer generally is similar to precipitation. Seasonal variability in soil moisture however is less. Soil moisture in winter is large, mainly because of lower evapotranspiration. In addition, the largest soil moisture is found in Area KO, although Area SE had the highest precipitation.

Disturbance in soil moisture of the surface layer varies with region. It is positive during all seasons for NW and SE, and positive in spring but negative during the three other seasons for N and NE. The depth of the root layer increases after afforestation. As a result, soil moisture increased in the afforested areas.

Air Temperature

Even though air temperature is not a hydroclimate element, it is an important factor for evapotranspiration. Its disturbance is often related to drought events. Regional averages of air temperature are shown in Figure 12. The simulated air temperature follows a seasonal cycle, as is seen with precipitation; that is, air temperature increases from spring to sum-

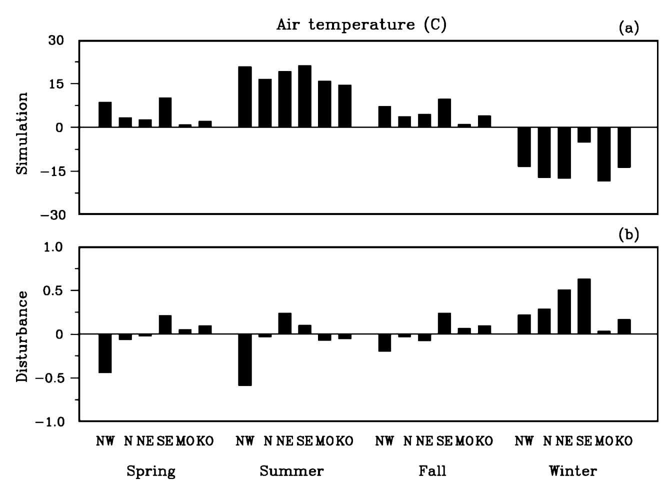

FIGURE 12. Same as Figure 7 Except for Surface Air Temperature (°C). No disturbance percentage is shown.

mer, then decreases in fall and decreases further in winter when it is below 0°C in all areas. Disturbance in air temperature is positive in winter for all areas, but varies among areas in other seasons. It is reduced by nearly 0.5°C in NW, and slightly reduced in the other afforested areas with the exception of a large positive disturbance that occurs during summer in NE.

Physical Processes

The land surface and atmosphere interact through the exchange of energy, water, and momentum. The possible physical processes responsible for the disturbances in the hydroclimate conditions due to afforestation are as follows (Figure 13).

When sandy or grass lands are replaced with pine trees, surface albedo is reduced. Thus, more solar radiative energy is absorbed by the ground and part of the increased energy is used to evaporate more soil water into the atmosphere. Meanwhile, the land cover change leads to larger transpiration that moves soil water in the root layer into the atmosphere through leaf stomata. The combined effect is to increase evapotranspiration. Other increased energy is used to increase soil temperature. This leads to increased sensible heat flux and, as a result, increases surface air temperature. On the other hand, the increased evapotranspiration leads to cooling due to consumption of latent heat. The balance between the changes in sensible and latent heat fluxes determines the sign of air temperature disturbance, which varies among the afforested areas.

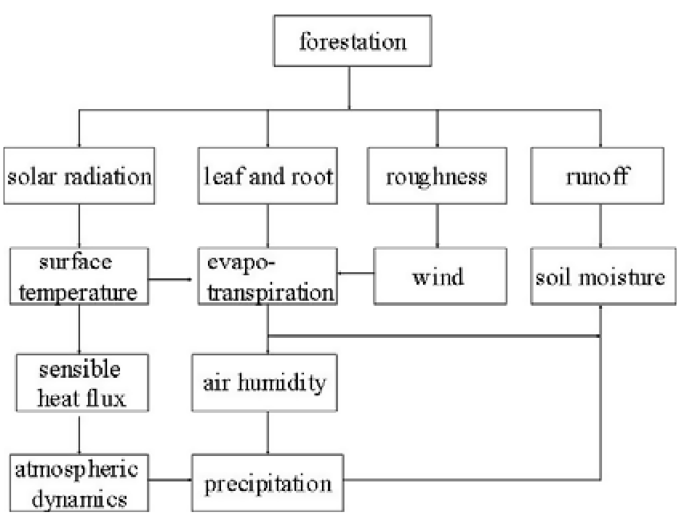

FIGURE 13. A Diagram of Physical Processes Through Which Land Cover Change Affects the Hydroclimate Conditions.

The increase in evapotranspiration increases water vapor content in the atmosphere. In the areas where air temperature is reduced, air relative humidity increases. In the areas where air temperature is increased, the sign of the disturbance in relative humidity could be positive if the disturbance in water vapor content is more important than that in air temperature, or negative if otherwise. Precipitation is a very complex process. It is determined by air water vapor availability, vertical velocity, and instability of the atmosphere. The increased evapotranspiration and relative humidity contribute to available water vapor but disturbances in the two other factors are yet to be understood.

Surface roughness length is increased with pine trees, which reduces prevailing wind speeds. The processes responsible for the disturbance in circulations outside the afforested areas are unknown. The disturbance in circulations is closely related to the precipitation disturbance in these areas.

Runoff is proportional to the balance between precipitation and evapotranspiration, and the ratio of soil moisture and its saturation value. Forested land has a larger saturation value than sand or grassland. Therefore, the afforestation contributed to the decrease in runoff. Two factors contributed to the increase in soil moisture, that is, increased precipitation and greater water holding capacity of soil under pine trees than other vegetation types. More water stored in the soil contributed to reduced runoff. The increased evapotranspiration, however, reduced the actual amount of moisture stored in soil.

DISCUSSION

The importance of land cover change to regional climate has been emphasized in many studies (Pielke and Avissar, 1990; Copeland *et al.*, 1996; Bonan, 1997; Chase *et al.*, 2000; Feddema *et al.*, 2005). Changes in land cover can affect regional climate through the global carbon cycle and release of anthropogenic CO_2 and by changing biophysical processes (Foley *et al.*, 2005). The primary biophysical mechanisms are changes in albedo, surface roughness, and the balance between sensible and latent heat loss. Early studies focused on tropical deforestation, primarily in Amazonia (Lean and Warrilow, 1989; Nobre *et al.*, 1991; Dickinson and Kennedy, 1992). Shukla *et al.* (1990) found that if the tropical forests in the Amazon were replaced with degraded grassland, surface temperature significantly increased and evapotranspiration and precipitation decreased. Dickinson *et al.* (1993b) conducted a more detailed study of soil

processes and found that deforestation of the Amazon basin would cause a decrease in evapotranspiration by 0.7 mm per day and total runoff by 0.7 mm per day. Temperature increased by 1-4°C and precipitation decreased by 25% or 1.4 mm per day in their simulation.

The effects of land cover change, however, could be much different from results of the Amazon deforestation studies, depending on geographic region, type of land cover change, and modeling technique. Several studies have attempted to isolate the effects of vegetation and identify the primary processes responsible by completely removing the natural (current) vegetation. Snyder *et al.* (2004) assessed the influence of different vegetation biomes on global climate using a coupled atmosphere-biosphere model. Removal of tropical and boreal forests had strong influences on regional and global climate but the influence of temperate forest removal on global climate was less strong than for tropical and boreal forests. Nevertheless, they found that temperate deforestation would have a larger effect on regional climate. Grassland and steppe vegetation removal had little effect globally or regionally, probably because this vegetation is already sparse. The processes responsible also varied by biome: tropical deforestation caused a warming effect primarily due to water balance alteration; temperate and boreal deforestation caused a cooling effect on climate through changes in radiation balance (Snyder *et al.*, 2004).

A different approach was taken by Brovkin *et al.* (2006); they simulated historical deforestation over the last 300 years using six models with explicit climate variability and consistent scenarios of land use change and their more detailed results are in general agreement with the GCM studies. Future land cover changes will be different from historical changes, however, because most deforestation is likely to occur in the southern hemisphere (Brovkin *et al.*, 2006). Additionally, significant afforestation is occurring in the northern hemisphere (Foley *et al.*, 2005; Weber, 2005).

Afforestation is an opposite process of deforestation (Stanturf, 2005), although its effects are not simply opposite because of nonlinear properties of the interactions among atmospheric, soil, and vegetation processes. In addition, it is unlikely that the scale of afforestation will approach the scale of deforestation (van Dijk and Keenan, 2007) and the resulting spatial heterogeneity of vegetation could have a different impact on precipitation, for example (Pielke *et al.*, 2007). Afforestation affects surface temperature and moisture flux into the atmosphere (Bruijnzeel, 2004) and depending upon the size of the afforested area, could affect regional circulation and weather patterns. Although the impact on rainfall generation is still unclear (van Dijk and Keenan, 2007), impacts on streamflow have been demonstrated (Farley *et al.*, 2005) with the largest absolute change in high-rainfall regions and the greatest proportional effect in low-rainfall regions (Bosch and Hewlett, 1982; Farley *et al.*, 2005).

Our study found overall increases in precipitation, evapotranspiration, root-layer soil moisture, and relative air humidity, and decreases in wind speed and air temperature in the afforested areas. These results generally agree with the findings from deforestation studies. Unlike the moist Amazon, however, northern China has diverse climate types, from dry climate in Northwest China to semi-humid in Northeast China. Thus, the effects of afforestation show a significant geographic dependence, as indicated by the difference in disturbance in evapotranspiration and soil moisture between Northeast China and the two other afforestation areas.

Furthermore, land cover changes such as tropical deforestation or tropical and temperate afforestation mostly occur in patches or blocks. The change they cause to large-scale airflow patterns is relatively small because airflows can go around the patches or blocks. In contrast, airflows can be more effectively blocked by the belt-like structure of the northern China afforestation. This may explain the significant disturbance in wind field and the associated disturbance in precipitation outside the afforestation areas, especially their south side. Although the hydroclimate conditions are improved in the afforested areas, they may become worse in some of the surrounding areas. These remote hydroclimate effects of afforestation may be important for afforestation policy, planning, and management. To minimize adverse effects, coordination is needed by forest, water, and air managements from all regions under the effects of afforestation.

The climate effects of land cover change in northern China have been extensively simulated in recent decade. Two major common results can be found among these studies and the present one, that is, afforestation generally increases rainfall and decreases temperature in northern China, and land cover change can modify atmospheric circulation of a larger region and therefore affect climate of other areas of China. There is a specific modeling study on the GGW (Wang and Zhou, 2003). The Global Land Cover Characteristics Database (GLCCD) generated by the U.S. Geological Survey (USGS) and University of Nebraska-Lincoln (UNL) were used to identify the achievements of constructing GGW forest shelterbelt and to update the lower boundary conditions of MM5, which was run for 21 days during a spring season. The simulation shows significant reduction in wind speed in the GGW areas and a small increase in

precipitation in Northwest China. The short integration period, however, was not long enough to catch full response of the land-vegetation-atmosphere coupled system to the land cover change because the dominant time scales in the system are monthly and seasonal (Delworth and Manabe, 1993; Liu and Avissar, 1999).

There is significant uncertainty in the magnitude and spatial pattern of the disturbances. The potential factors causing uncertainty include location and scope, period, type of land cover change, model used, and simulation and experimental setup. The location and scope can be categorized into national (e.g., Fu and Yuan, 2001; Gao *et al.*, 2003; Ding *et al.*, 2005; Li *et al.*, 2007), regional (e.g., Xue, 1996), and project groups (e.g., Wang and Zhou, 2003 and this study). The periods of land cover change processes range from current (e.g., Xue, 1996), to postindustrial (e.g., Li *et al.*, 2007), to civilization era (e.g., Zheng *et al.*, 2004). Most studies examined land cover change due to deforestation and desertification, while few studies investigated afforestation. The early studies (e.g., Xue, 1996) used GCMs, but RCMs have increased in popularity as a modeling tool. Understanding the uncertainty is an important but difficult issue because of the differences in the factors. Adding to the difficulty is that all studies used ideal, extreme, or virtual land cover change because few measurements of actual climate change were available.

Perhaps the biggest uncertainty is the effect on precipitation. In spite of the results of overall increase (decrease) with afforestation (deforestation) in most studies, other results have been obtained in some studies. For example, a recent study of afforestation in Southeast U.S. showed little effect on precipitation (Jackson *et al.*, 2005). Precipitation is determined by water vapor content, stratification instability, and atmospheric disturbance system. The effects of land cover change on these processes could be different. Afforestation is likely to favor the formation of precipitation through increasing water vapor content due to greater evapotranspiration, but could have the opposite effect by decreasing the surface temperature and therefore reduce the degree of atmospheric instability. In general, in the dry areas where water vapor is a major limiting factor for the formation of precipitation, afforestation is more likely to increase precipitation. In contrast, in the moist areas where the atmosphere has sufficient water vapor supply, the reduced instability becomes a major factor and afforestation may lead to little or even negative effects on precipitation. These opposite effects seem to account for the effects in northern China and Southeast U.S., respectively. The effects on general circulation systems and the associated water vapor transport are even more complex. Afforestation can also generate mesoscale circulations such as a land breeze, which can further affect shallow convections (Avissar and Liu, 1996; Liu, 2005). Precipitation is one of the physical processes that are not described well in RCMs, partially because the convective processes occur at scales smaller than the grid spacing and therefore have to be estimated using some approximating techniques such as parameterization.

The role of afforestation in water yield (the amount of water flowing out of a watershed or catchment) has been noted increasingly as an effect of afforestation (Farley *et al.*, 2005; van Dijk and Keenan, 2007). Water yield ultimately determines how much water will be available for urban use, irrigation, other industries, or for maintaining river flows. Sun *et al.* (2006) investigated the effects of afforestation on water yield in China. Their results suggested great potential for afforestation to reduce water yield in the semi-arid Loess Plateau region (the afforested area of Northwest China in this study). More soil water is lost through transpiration on afforested lands than grassland. It was pointed out that afforestation is relatively small for most large basins with mixed land uses in China, thus the regional effects of afforestation on water resource management may not be of major concern. The increase in evapotranspiration and reduction in runoff in Northwest China obtained from our simulations provide new evidence for their results. Our simulations also indicate some other features. First of all, precipitation is increased in this area, which would partially offset the effect on water yield of the increased evapotranspiration. Furthermore, the reduction in water yield is likely to happen only in spring. Additionally, the effect of afforestation on water yield in Northeast China is opposite to that in Northwest China. Finally, the GGW project leads to land use change at a scale much larger than catchments and may even be comparable to some major watersheds.

These results may have other important implications, for example, global warming. Offsetting the possibly negative effect of reducing water yield and changing precipitation patterns, the GGW project would offset some greenhouse effects. As noted above, the GFDL GCM projects an increase in temperature by up to 5°C and a decrease in precipitation by up to 1 mm per day by the 2080s in most of northern China due to greenhouse effects. Many other GCMs have projected a similar warmer and drier climate for this region. The results from our study suggest that precipitation could be increased by up to 0.5 mm per day in part of northern China due to the GGW project. Projection of future climate trend would differ if the possible hydroclimate effects of afforestation in northern China were considered.

The GGW also would reduce the severity of dust storms occurring mostly in spring (Laurent *et al.*, 2006). Strong winds and dry soil are two important conditions for sands to be lifted into the atmosphere. The results of our study show that wind speed would be reduced and soil moisture increased in spring due to afforestation, thereby contributing to reduced dust storm activity.

CONCLUSIONS

The potential impacts of the northern China forest shelterbelt on hydroclimate conditions have been investigated by conducting simulations with the National Center for Atmospheric Research RCM. The results indicate that afforestation leads to overall increases in precipitation, soil moisture and air relative humidity, and decreases in wind speed and air temperature in the afforested areas. It is therefore concluded that the afforestation effort with the GGW project would have great potential in improving the overall hydroclimate conditions in the project areas. In addition, the results also have shown significant change outside the afforested areas, suggesting an important role of afforestation in changing hydroclimate conditions in a remote region. The GGW would reduce water yield in afforested Northwest and North China during spring, but increase water yield in the afforested Northeast China as well as in the southern surrounding area, offset some greenhouse effects, and reduce the severity of dust storms.

There are a number of limitations with the RCM modeling technique (Giorgi and Means, 1999; Liu, 2007). First of all, RCMs are driven by GCMs or measurements and any errors in lateral conditions will be passed to RCMs. Experiments have indicated large sensitivity of RCM simulations to lateral conditions. Most of the western boundary of the domain for this study is over the Tibetan Plateau, which creates difficulties in generating reliable boundary conditions. Even though complex local land-surface conditions was one of the reasons for using RCMs, information deficiencies limit the ability of RCMs to reproduce important features in the atmosphere and other earth components. Soil moisture and snow are among the data elements for which very little information is available in some areas. In addition, domain size and internal variability created by disturbances in initial and boundary conditions also affect RCM performance (Seth and Giorgi, 1998; Giorgi and Bi, 2000).

There are limitations in simulation setup for this study and there are other ways our understanding could be improved. Because we lacked specific data on land use change, we assumed the entire afforestation area would be planted with conifers, with uniform spacing, mortality, and growth rates. Our results indicate the potential effects of fully planted, mature forest. More realistic simulations could be conducted by using information on actual planting areas, tree species used and establishment success, as well as growth rates. Efforts are needed to obtain this information from ground survey and report and remote sensing measurements, and from ecosystem modeling. We would expect to see some different effects from the improved realism of these simulations, especially for Northwest China, where the dry climate does not provide the conditions needed for full growth of most tree species. Shrub and grass are likely the more appropriate species to be planted, which we expect would result in smaller change in the regional hydroclimate conditions than would conifers.

A more complete and deeper understanding of the role of the GGW project in improving hydroclimate conditions would also result from improving simulations by including longer integration and higher spatial resolution. The simulation for this study was conducted only a little longer than one year, which captured much of variability at diurnal and seasonal scales, but missed variability at interannual and longer scales. There were no significant floods or droughts in northern China during the simulation period. Thus, the results of this study more likely present a case of a normal year. It is expected that the effects of the GGW would be more significant for a dry year because of the relatively larger role of the local land-atmosphere processes (Liu and Avissar, 1999). On the other hand, the afforestation with the GGW is spatially inhomogeneous. Increased modeling resolution will better represent this spatial variability. The hydroclimate conditions vary at multiple temporal scales, including the regular diurnal and seasonal cycles, and irregular variability of floods and droughts, interannual fluctuations responding to, for example, El Niño and decadal oscillation, and a long-term trend responding to, for example, greenhouse effects.

Sensitivity experiments are needed to further interpret the results and understand the involved mechanisms. There are complex processes, interactions, and feedback in the RCM used to simulate the changes in the hydroclimate conditions in response to the GGW. Both internal (increased water vapor transport from the ground to the atmosphere due to the increased evapotranspiration) and external (increased water vapor transport from the moist ocean area to the GGW areas) processes could have contributed to the increase in precipitation due to the GGW. Model experiments with fixed evapotranspiration rate would improve understanding of the relative importance of the two processes.

Evaluation of the modeling results with measurements is a necessary part of this study, but a difficult prospect because only potential rather than actual impacts were obtained. Thus, the first effort towards an evaluation study is to conduct simulations using actual afforestation information. In addition, meteorological, hydrological, and ecological measurements need to be collected. There are two types of measurements needed, data from long-term regular monitoring systems (such as soil moisture measurements) and from short-term experimental sites between afforested and unforested lands.

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