Hydrological Impacts of forest restoration in the southern United States

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ABSTRACT

Landscape in the southern United States changed dramatically during the 1930s and the following decades when massive agriculture and abandoned logging lands were conversed to forest lands through natural restoration and plantation. The impacts of this forest restoration on hydrology were investigated using the National Center for Atmospheric Research regional climate model (RegCM) in this study. Simulations for Januarys and Julys of eight years were conducted with vegetation types before and after the forest conversion. The assemble results indicate overall precipitation decreases in summer and increases in winter, mainly caused by the reduction in the corresponding prevailing winds due to increased surface roughness after forest restoration. There is inter-annual variability with precipitation change, with summer precipitation overall decreased in 5 years, decreased but with small magnitude in 2 years, and increased in one year. Evapotranspiration, runoff and root-layer soil moisture increase in both seasons, which is closely related to the changes in vegetation and soil properties. Solar radiation increases due to smaller albedo, most of which is converted into sensible heat. Remarkable impacts are found in the surrounding areas of the conversion region, including large increases in summer precipitation, evapotranspiration and runoff in the central Midwest. This is resulted from the change in the large-scale atmospheric circulation. The implications of the results for the projected vegetation changes due to the climate change and the planned tree planting project in the Southeast and other regions are discussed.

KEY TERMS: forest restoration; hydrology; climate; regional modeling; southern U.S.

INTRODUCTION

The southern United States consists of 13 states from Taxes to the Atlantic coast and from Florida to Virginia. This region comprises one of the most productive forested areas in the U.S. with approximately 200 million acres or 40% of the Nation's forests in an area of just over half a billion acres or only 24% of the U.S. land area (SRFRR 1996). Furthermore, southern forests are dynamic ecosystems characterized by rapid growth within a favorable climate. The forest ecosystems bring great environmental benefits such as water conservation and climate regulation to this region.

Land cover in this region has changed dramatically in the past century (Sampson, 2004). The region's forest acreage declined in the 19th century and early 20th century and reached a low some time around 1920 as a result of agricultural land clearing and timber harvesting (USDAFS, 1988). This trend turned around in the 1930s when massive agriculture and abandoned logging lands were conversed to forest lands. Meanwhile, reforestation efforts were made through planting trees on public and private lands, as a part of the nationwide forestry and land conservation programs which planted billions of trees.

Land cover change at a regional scale such as the forest restoration in the southern U.S. can affect regional hydrologic conditions through changing the surface energy and water fluxes, soil hydraulic property, and surface roughness (Lean and Warrilow, 1989; Nobre et al., 1991; Dickinson and Kennedy, 1992; Henderson-Sellers et al., 1993). When land cover is replaced with a different type of vegetation, surface albedo is changed and thus the solar radiation absorbed on the ground will be different. This will change evapotranspiration. Soil properties such as porosity will changes, which means different holding capacity of soil and therefore different runoff. Change in roughness will modify turbulent water vapor and heat exchanges between the surface and the atmosphere.

Many studies have provided simulation and measurement evidence for the importance of land cover change to regional hydrology (Shukla et al., 1990, Pielke and Avissar, 1990; Dickinson et al., 1993; Xue, 1996; Bonan, 1997; Liu et al., 2008). Shukla et al. (1990) found that if the tropical forests in Amazon were replaced with degraded grassland, evapotranspiration and precipitation decreased. Dickinson et al. (1993) conducted a more detailed study of soil processes and found that deforestation of the Amazon basin would cause a decrease in both evapotranspiration and runoff by about 20 mm mon^{-1}. Most of other studies also concluded that deforestation would decrease precipitation and evapotranspiration, while afforestation would have opposite impacts.

McVicar et al. (2007) pointed out the positive hydrological impacts of the afforestation in the Loess Plateau of Northwest China, including a reduction in erosion and the risk of average flooding. A counter to the positive impacts is the often observed reduction in stream flow (Jackson et al., 2005; Sun et al. 2006), largely due to increasing rates of evapotranspiration. Jackson et al. (2005) investigated the impacts of different plantation scenarios in the eastern U.S. The global analysis of catchment observations indicated that afforestation dramatically decreased stream flow within a few years of planting. Projection with the Forest and Agricultural Sector Optimization Model–Greenhouse Gases (FASOMGHG) indicated that farmlands at some spot locations along the Gulf and southern Atlantic coast would be changed to evergreen needleleaf forest and large areas of farmlands in the Midwest are changed to deciduous broadleaf or evergreen needleleaf forest. And projection with the Regional Atmospheric Modeling System (RAMS) obtained mixed changes with dominated evapotranspiration increase and precipitation decrease in response to the plantations.

The purpose of this study is to investigate the impacts of the conversion of agricultural to forest lands in the southern U.S. on regional hydrology. The land cover change due to the forest restoration is specified based on forest monitoring data (Allen et al., 1996). This historical data has different features from the projected future plantations with FASOMGHG (Jackson et al., 2005). First, the forest coverage change during the conversion period occurred not only through plantation but also natural restoration and other restoration approach (Stanturf et al., 2000). The restoration was a more important mechanism. Second, the land cover change was limited in the southern region, but happened in more extensive areas. A regional climate model is used to conduct simulations using present land cover and agricultural lands, respectively. The impacts of the forest restoration on local and remote hydrological conditions are measured by the differences in hydrological processes (precipitation, evapotranspiration, and runoff) and soil and air moisture conditions between the two types of land cover.

The results from this study are expected to be useful for understanding the possible roles of the land cover change in the past hydrological and climatic variability. In addition, they should have important implications for future hydrological and climatic variability. Many global general circulation models (GCMs) have projected significant climate change by the end of this century due to the greenhouse effect, including warming and drying trends in many subtropical and mid-latitude regions (IPCC, 2007). The land cover condition is expected to change accordingly. A modeling study projected that a large portion of the temperate deciduous forests in the Southeast would be replaced with temperate deciduous savanna (Neilson et al., 1998, 2005). Furthermore, it has been planned to plant about 18 million acres of new trees to replace pasture and farming lands by 2020 in the Southeast, as well as in Great Lake states and the corn Belt states (Watson, 2009). The afforestation project would be even larger than one carried out by the Civilian Conservation Corps during the Great Depression, which planted 3 billion trees from 1933 to 1942. The primary purpose of this project is to sequestrate atmospheric carbon and improve water quality. The results from this study would provide useful information for assessing the hydrological and climatic consequences of the forest changes due to climate change and the new afforestation project.

METHODS

Model

A regional climate model (RCM) was used to simulate atmospheric and soil conditions and changes in this 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 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 regional climate models have been developed since using other limited-area meteorological models, including the National Centers for Environmental Prediction (NCEP) Regional Spectral Model (RSM) (Juang and Kanamitsu, 1994), the Hadley Centre regional climate modeling system (Jones et al., 1995), the Canadian Regional Climate Model (CRCM) (Caya and Laprise, 1999), the climate version of the Colorado State University regional atmospheric modeling System (RAMS) (Liston and Pielke, 2000), 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 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 variability, 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. Different from GCMS, which are mostly spectral models, RCMs are mostly grid-point models.

The National Center for Atmospheric Research regional climate model (RegCM) (Giorgi et al., 1993a, b) with modified explicit rainfall calculation (Giorgi and Shields, 1999) was used to conduct regional climate modeling. RegCM characterizes regional features of climate by incorporating Biosphere-Atmosphere Transfer Scheme (BATS) land-surface physics (Dickinson et al., 1993) and the NCAR radiative transfer model (Kiehl et al., 1996), into the standard NCAR / Penn State Mesoscale Model (Anthes et al., 1987). RegCM is able to reproduce some important high-resolution spatial characteristics of climate for major geographic regions over the world.

BATS has three soil layers of surface, root, and underground. The surface layer is up to 0.1 m deep, where soil moisture varies mainly as a result of precipitation, evaporation, and runoff. The root layer is about 1 to 2 m deep, depending land cover type. Soil moisture of this layer is determined by soil-vegetation water exchanges through root absorption and water exchanges with other soil layers. Water level in the underground layer is assumed to be constant.

Simulation

The simulation domain covers the continental U.S. (Figure 1). The topography is characterized by mountains in the west and flat lands in the east. The dominant land cover types in the South include deciduous forest, coniferous forest, and mixed forest and wet land. Agricultural lands are found in the Mississippi River Basin, eastern Taxes, as well as some spot locations along the Atlantic coast. The dominant land cover types in other regions include coniferous forest and grass in the Northwest, coniferous forest, grass, and desert in the Southeast, agriculture in the Midwest, and deciduous forest in the Northeast. The domain is centered at 40^{o}N and 99^{o}W and contains 97 by 61 grid points with a horizontal resolution of 60 km. There are 14 vertical layers with the top model atmosphere at 80 hPa. The Grell sub-grid convective scheme (Grell et al. 1994) was utilized.

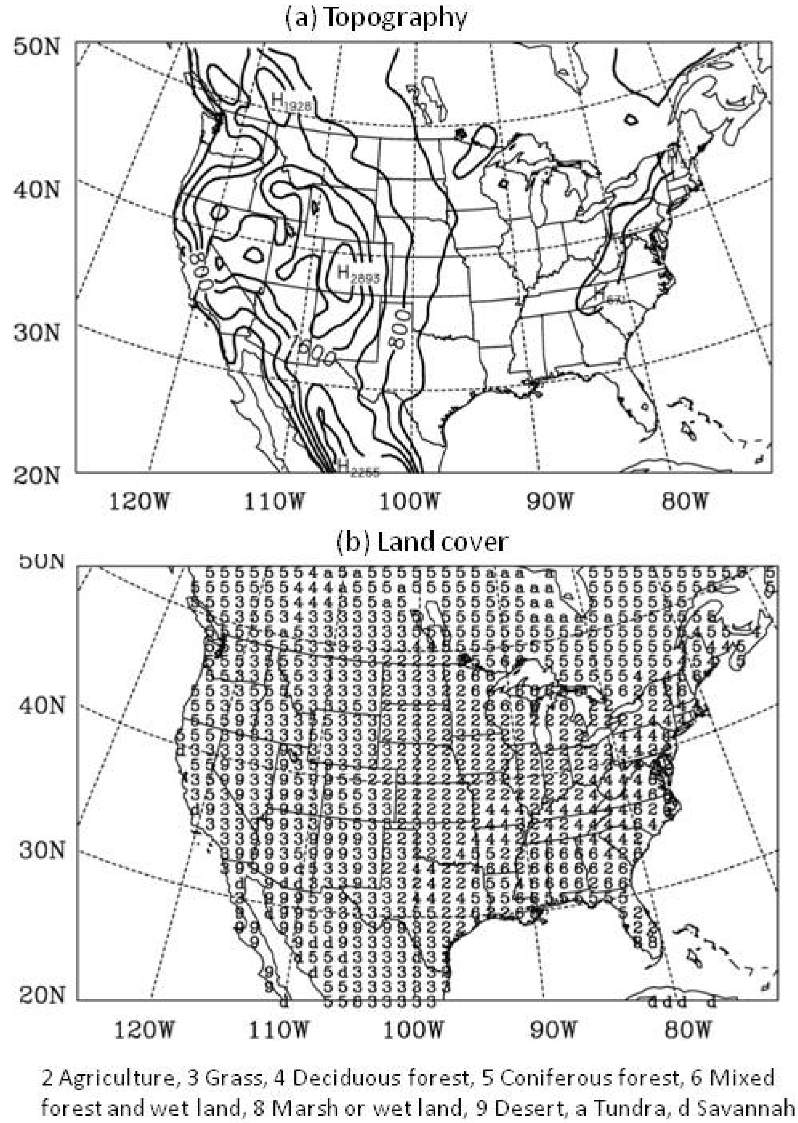

Figure 1 Simulation domain. (a) Topography with contour interval of 400 m. (b) Land cover with legend shown below the figure.

Two simulations, denoted as FOREST and AGRI, were conducted to simulate hydrological conditions with forest and agriculture dominant land cover, respectively. The model specifications in the two simulations are the same except land cover in the forest restoration region, where land cover types were specified based on the monitoring data (Allen et al., 1996). The conversion or forest restoration occurred through natural restoration and plantation. Natural pine forests dominant along the southern Piedmont, selected counties on the southern coastal plain, and upland areas west of the Mississippi River. Pine plantations dominated in northern Florida and other counties throughout the coastal plain. According to the data, a forest restoration region was assumed for the simulations (Figure 2). The vegetation types shown in Figure 1 were assigned to FOREST, but they were replaced with agricultural lands in the restoration region in AGRI. FOREST and the difference between FOREST and ADRI were used to describe present conditions and the changes due to the forest restoration, respectively.

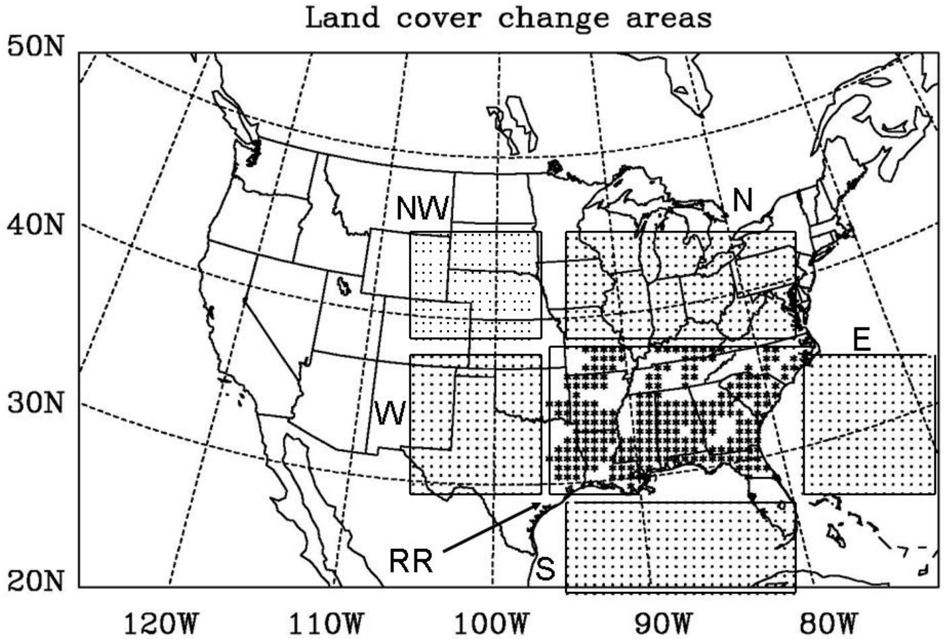

Figure 2 Forest restoration region (RR) indicated by asterisks in the central area and surrounding areas indicated by dots in north (N), northwest (NW), west (W, south (S), and east (E).

Eight simulations were conducted, each for one of the different sets of initial and boundary conditions during 1988 through1995. The ensemble of the 8 simulations was analyzed for all hydrological components, while precipitation was also analyzed for individual years. Each simulation included January and July runs, which represent winter and summer conditions, respectively.

The initial and horizontal lateral boundary conditions for the RegCM simulations 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^o 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 (SST) was interpolated from a set of observed, monthly mean with a resolution of 1^o (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 data set (Zeng et al., 2000).

The July simulations with present land cover have been used to understand climate and wildfire interactions, including the impacts of the 1988 Yellowstone National Park wildfire on the northern U.S. drought, wildfire potential evaluation, and future wildfire potential projection (Liu, 2005; Liu et al., 2009, 2010). It was indicated that the simulated features of spatial patterns in precipitation and temperature basically agree with the observation.

Note that the simulations do not reproduce the actual climatic and hydrological conditions during the forest conversion because current climate was used to drive the regional climate model. This approach was taken to separate the impacts of land cover change. Also note that there are a number of limitations with RCM modeling technique (Liu, 2007). First of all, RCMs are driven by GCMs and/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).

RESULTS AND DISCUSSION

Precipitation

Figure 3 shows assembled present precipitation obtained from FOREST and the change due to the forest restoration obtained from the difference between FOREST and AGRI. Present presentation occurs in two regions. One is the eastern U.S. with rainfall of about 160 mm off the southern Atlantic coast. The restoration region, located west to the precipitation center, has rainfall of about 120 mm. The other is the northwestern Pacific coast with the same intensity. Precipitation in summer is also large in the eastern U.S. The precipitation center is moved to the inland area from its winter location in the ocean area. Rainfall is about twice the winter amount. Rainfall decreases from about 300 mm in the northeast portion of the restoration region, which is within the major rainfall region, to about 160 mm in the southwest portion. Precipitation is relatively small in the western U.S. with rainfall less than 40 mm along the Pacific coast.

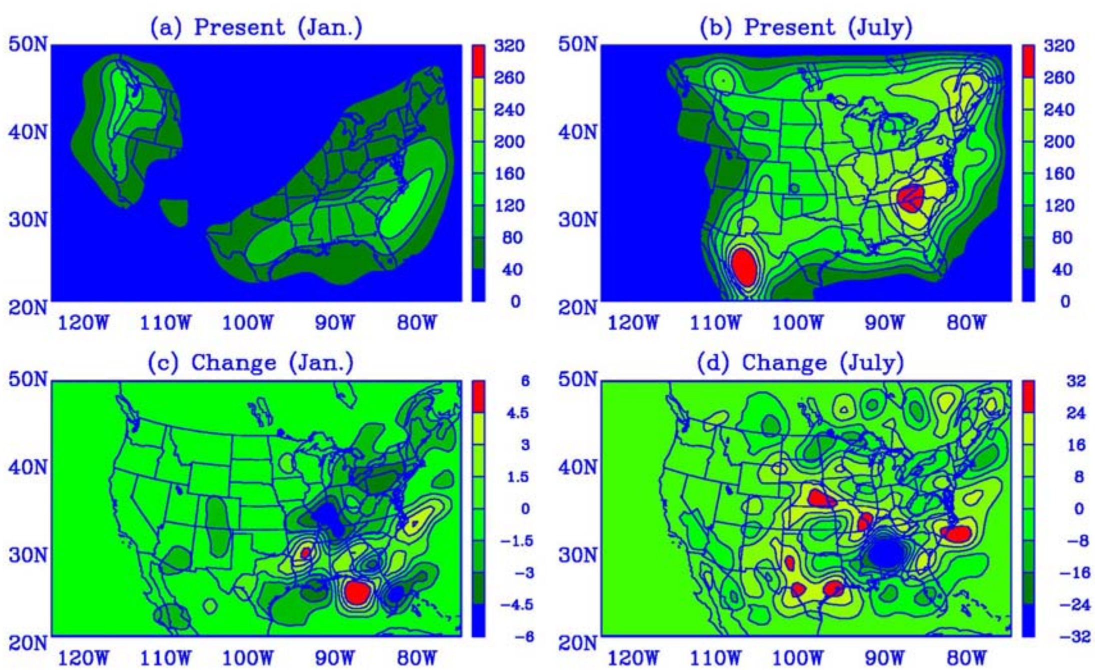

Figure 3 Precipitation (mm / mon) averaged over eight years for present precipitation in January (a) and July (b), and change due to forest restoration in January (c) and July (d).

Change in winter precipitation due to the forest restoration is positive in most of the restoration region with a magnitude of 5 mm. The restoration also affects precipitation in the surrounding areas. Precipitation increases in east and south, but decreases in north. Negative precipitation change is even seen in the remote regions such as the Northeast. Opposite to winter, summer precipitation is overwhelmingly negative in the restoration region with a magnitude of 30 mm. The change is mostly positive in the surrounding areas except in south and west.

To analyze precipitation and other properties more quantitatively, averages were made over the restoration region (RR) and 5 surrounding areas including 3 land ones in north (N), northwest (NW) and west (W), and 2 ocean or mostly ocean ones in south (S) and east (E) (see Figure 2 for their locations). Winter rainfall is 107 mm in RR, and between 20 mm and this amount in the surrounding areas (Table 1). The smallest rainfall is found in NW. The change due to the restoration is positive in all areas except N. The values are 0.3 mm in RR and −1.0 mm in N. Summer rainfall is 213 mm in RR, and between 76 mm and this amount in the surrounding areas. The smallest rainfall is found in E. The change is negative in two areas (−1.9 mm in RR and −2.6 mm in S) and positive in the other areas, including 4.7 mm in W and 9.8 mm in NW.

Table 1 Water fluxes (mm / mon) for the restoration region (RR), north (N), northwest (NW), west (W), south (S) and east (E) areas (see Figure 2 their locations).

Area	Precipitation		Evapotranspiration		Runoff	
	January	July	January	July	January	July
RR	107 (0.3)	213 (-1.9)	45 (0.3)	185 (1,5)	28 (5.6)	49 (7.7)
N	68 (-1.0)	209 (1.7)	18 (0.3)	174 (3.1)	15 (1.5)	41 (4.7)
NW	20 (0.1)	143 (9.8)	15 (1.0)	165 (12.7)	3 (0.6)	26 (5.8)
W	59 (0.2)	149 (4.7)	35 (1.5)	164 (9.8)	13 (2.2)	27 (3.5)
S	58 (0.8)	84 (-2.6)	148 (-3.5)	132 (-0.3)		
E	102 (0.7)	76 (2.7)	211 (-0.5)	113 (0.2)		

Figure 4 show inter-annual precipitation variability. The spatial patterns of precipitation change can be divided into 3 groups. The first group includes 5 years (1988, 90, 92, 94, and 95), when precipitation is remarkably reduced in most of the restoration region and other regions. In 1988, precipitation decreases extensively in the Southeast and from southern Plains to the Northeast. Meanwhile, precipitation increases in some spots of southern Taxes, mid-Atlantic coast, and the Great Lakes area. In 1990, there are two bands of reduced precipitation along the Gulf coast and the northern U.S. In between is a band of increase precipitation. Large precipitation reduction in 1992 is found in the northern restoration region and its surrounding areas. The spatial distribution in 1994 is similar to that in 1988. And precipitation reduction is dominant in 1995. The second group includes 1989 and 93 when precipitation is reduced in most of the restoration region but with small magnitude. The last group has only one case of 1991 when opposite change, that is, increase in precipitation, occurs in the restoration region.

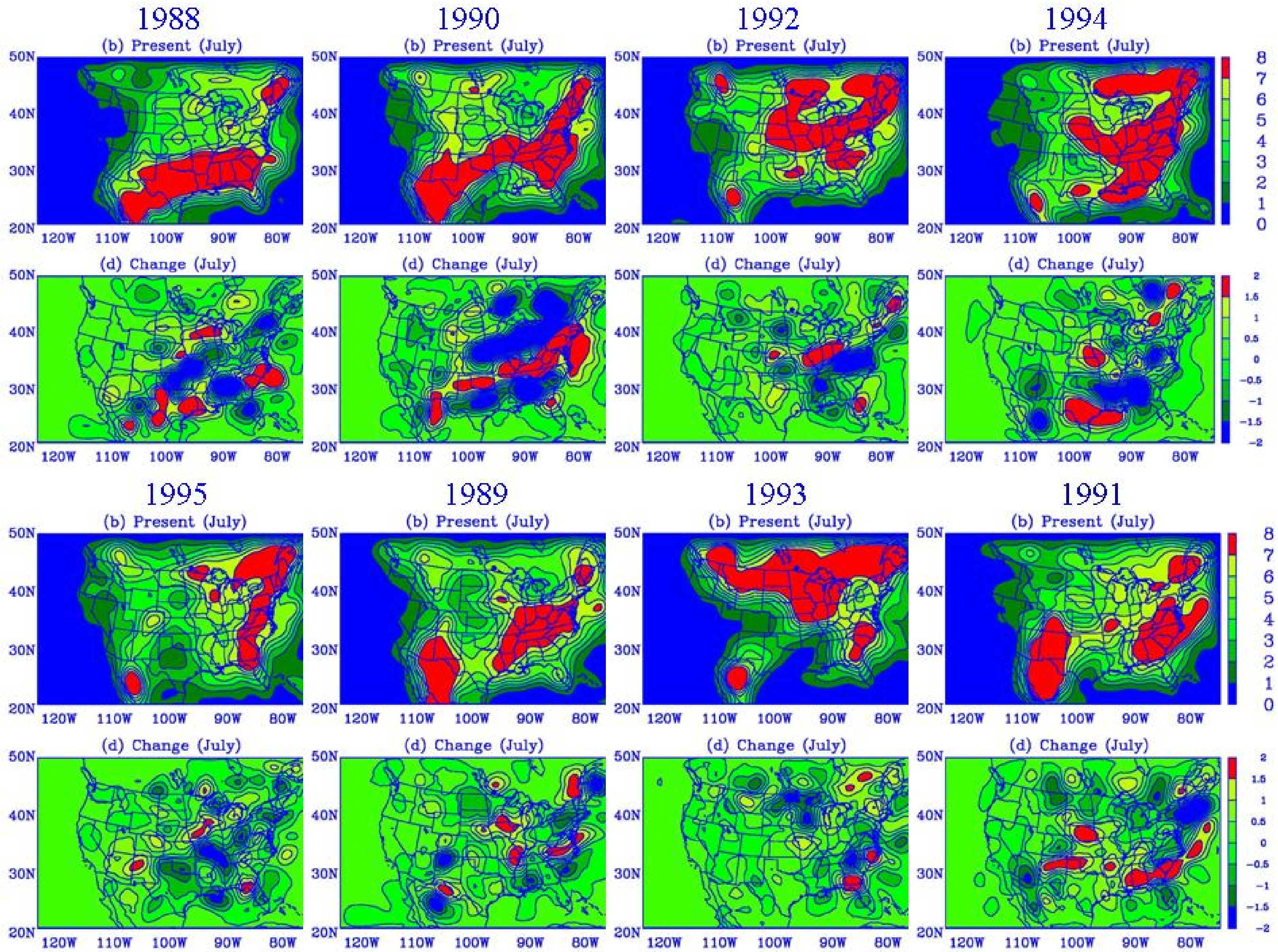

Figure 4 July precipitation (mm / mon) of individual years. The top and bottom panels for each year are present precipitation and change due to forest restoration.

It appears that any group is not related to a particular precipitation pattern. Major precipitation for the first group is found in the southern U.S. (1988 and 90), the northern U.S. (1992), the central as well as northern and southern U.S. (1994), and the Atlantic coast (1995). Major precipitation for the second group is found in the Southeast (1989) and the northern U.S. (1993). The spatial patterns of precipitation change have patchy structure with mixed increase and decrease signs. Precipitation is generated by weather systems such as fronts. Forest restoration can affect not only their intensity but also locations. If location of a weather system is forced to shift northward, precipitation would likely decrease at this location, but increase in north. Also, if water vapor in an area is reduced due to a change in the weather system, more water vapor is expected to be transported to its surrounding areas.

Evapotranspiration

The spatial patterns of evapotranspiration (Figure 5) are much different between the two seasons. Evapotranspiration consists of both evaporation and transpiration in land areas but only evaporation in ocean areas. Winter evapotranspiration is very small in the land areas, even negative in the middle latitudes where condensation of air water vapor on the ground often happens. It is large in the ocean areas. In summer, however, the eastern U.S. has the largest evapotranspiration of about 200 mm. Evapotranspiration decreases towards west and is below 60 mm in some Southwest areas. Different from the average, the spatial patterns in evapotranspiration change due to the restoration are similar between the two seasons. In addition, the major change does not occur in the restoration region where only slight increase is found; instead, large increase of 12 mm is found in NW and W.

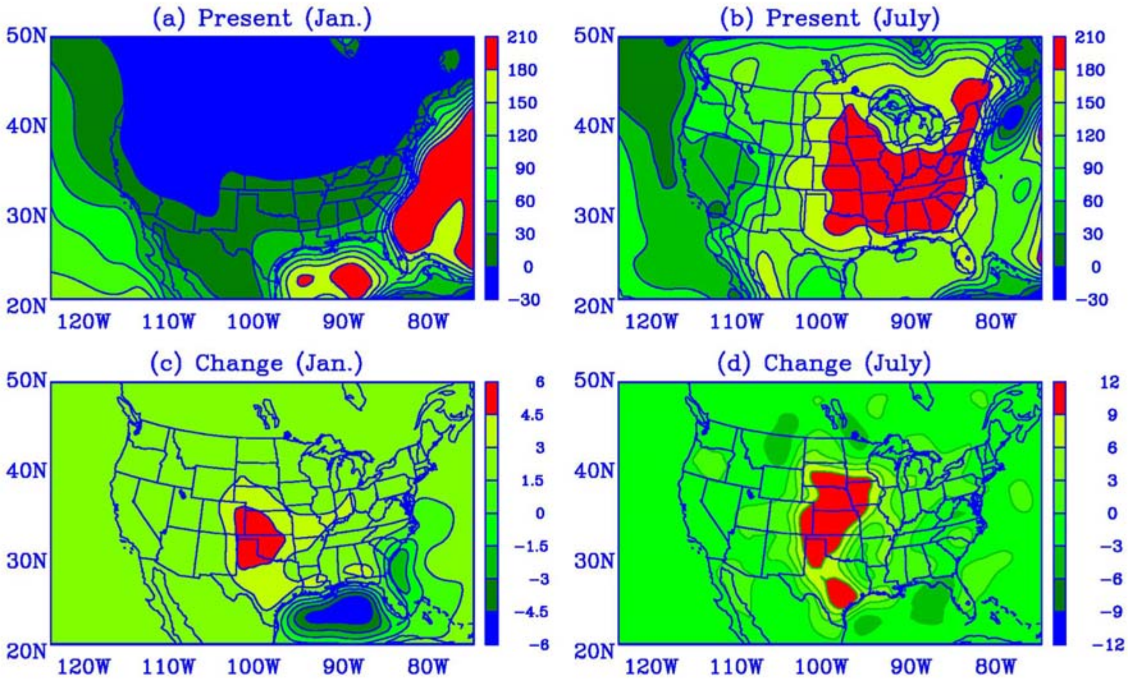

Figure 5 Same as Figure 3 except for evapotranspiration.

The regional values shows that winter evapotranspiration is 45 mm in RR and between 15 and 35 mm in the surrounding land areas, and as high as about 150 and 210 mm in the two surrounding ocean areas (Table 1). The change due to the restoration is positive in all land areas and negative in ocean ones. Summer evapotranspiration is 185 mm in RR, and between 113 mm and this amount in the surrounding areas. It is smaller in the ocean than land areas. The change is 1.5 mm in RR, 9.8 and 11.7 mm in NW and W, and little in the ocean areas.

Runoff

Present runoff has similar spatial patterns as precipitation, but with smaller magnitude (Figure 6). The change due to the forest restoration is mostly positive in both winter and summer in the restoration region and the land surrounding areas. The regional values show that winter runoff is 28 mm in RR, about half this amount in N and W, and 2.6 mm in NW (Table 1). The change due to the restoration has the largest magnitude of 5.6 mm in RR. Summer runoff is 49 mm in RR, and between 26 and 41 mm in the surrounding land areas. The change is 7.7 mm in RR, between 3.5 and 5.8 mm in the surrounding land areas.

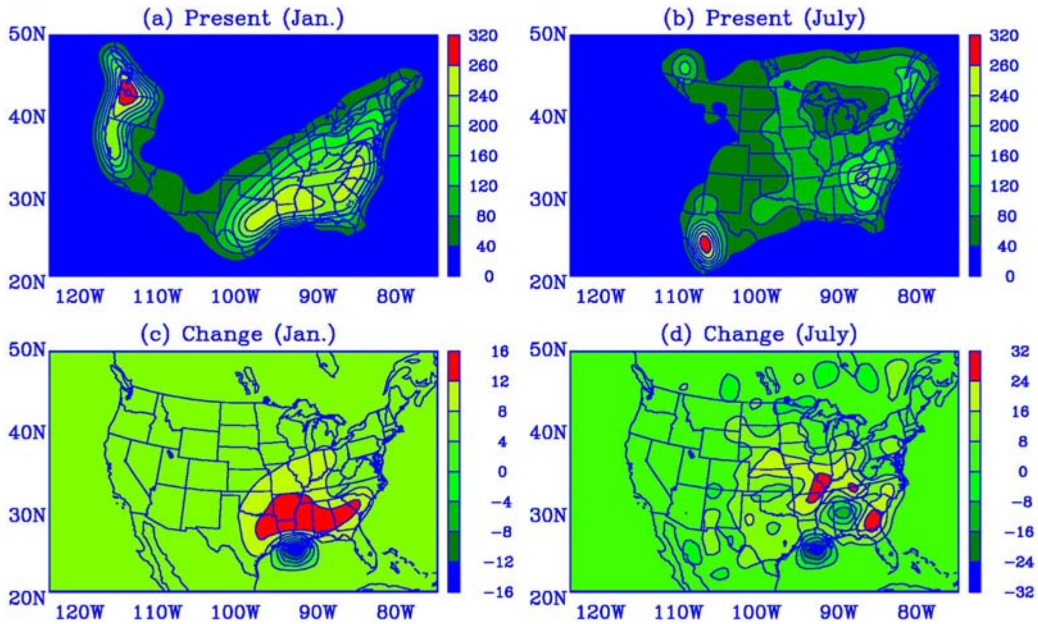

Figure 6 Same as Figure 3 except for runoff.

Soil Moisture

Soil moisture of the surface layer is larger in the eastern U.S. and smaller in the western U.S. (Figure 7). The largest value is about 40 mm in the northeastern U.S. during winter, and about 30 mm in the same region and in the Atlantic coast during summer. The smallest value is found in the Great Plains and central Rocky Mountains during winter and inter-mountains during summer. The forest restoration leads to soil moisture increase in winter and decrease in summer in the restoration region, and increase in NW and W in both seasons.

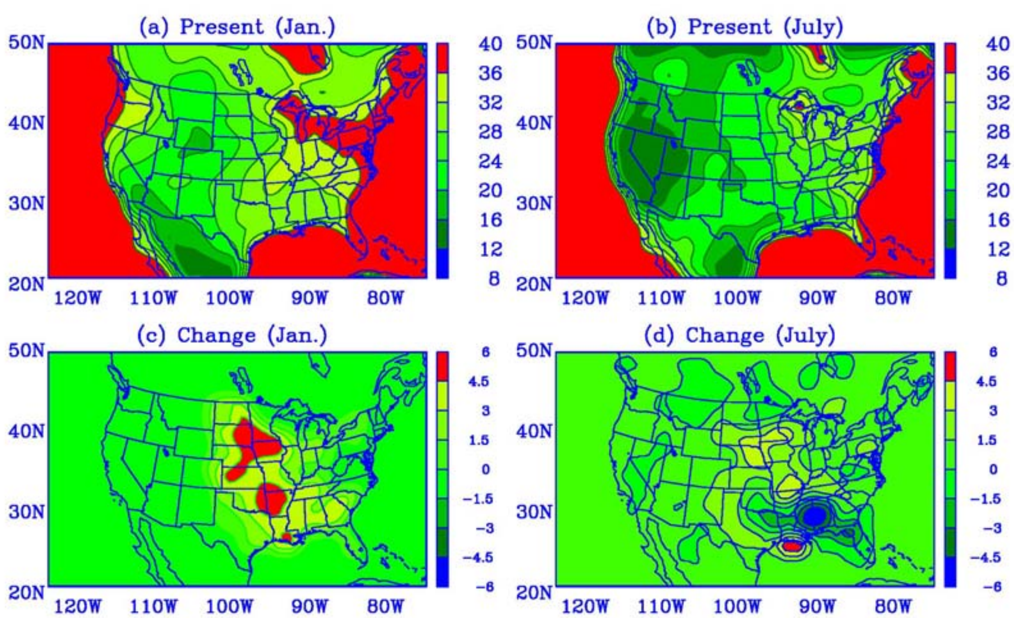

Figure 7 Same as Figure 3 except for surface-layer soil moisture (mm).

The regional values show that, winter soil moisture of surface layer is 32 mm in RR and between 26 and 35 mm in the surrounding land areas (Table 2). The change due to the restoration is 2.4 mm in RR and between 1.5 and 2.6 mm in the surrounding land areas. Summer soil moisture is 26 mm in RR and between 23 and 29 mm in the surrounding land areas. The change is slightly negative in RR and positive in the surrounding land areas.

Table 2 Same as Table 1 except for soil moisture (mm) and air humidity (g/kg).

Area	Surface soil moisture		Root soil moisture		Air specific humidity	
	January	July	January	July	January	July
RR	32 (2.4)	26 (-0.2)	548 (225)	525 (226)	5.0 (-0.02)	16.2 (-0.5)
N	35 (1.5)	29 (0.4)	428 (24)	413 (22)	2.5 (0.02)	14.0 (0.1)
NW	26 (2.6)	23 (0.8)	286 (32)	267 (31)	2.4 (0.04)	13.1 (0.5)
W	29 (1.5)	23 (0.5)	322 (28)	296 (27)	(3.9 (0.06)	14.7 (0.3)
S					13.4(0.01)	21.5(0.02)
E					14.0 (0.0)	20.8 0.01)

Soil moisture of root layer (not shown) is the largest in the Atlantic coast and smallest in the Pacific coast, with the magnitude of 600 and 200 mm, respectively. The change due to restoration is significant mainly in the restoration region. The spatial patterns are similar between winter and summer. The regional winter average is 548 mm in RR and between 286 and 428 mm in the surrounding land areas (Table 2). The change due to the restoration is 225 mm in RR and between 22 and 31 mm in other surrounding land areas. Also, there is only a small difference in the magnitude between the two seasons.

The small difference in root-layer soil moisture between the two seasons is mainly related to the way to specify initial soil moisture in the simulations and the nature of slow process in soil moisture variations. The initial soil moisture was specified based on soil type and land cover type, which are independent on time. This means that there was no difference in initial soil moisture condition between winter and summer. Temporal variations of soil moisture are slower than those in the atmosphere. The variations of the air temperature and precipitation are significant at short scales such as daily and weekly. Soil moisture of the surface layer is determined by the direct interactions with the atmosphere through water exchanges (precipitation and evapotranspiration). Thus, it basically responds to the atmospheric variations. Soil moisture of root layer, however, varies remarkably at monthly or longer scales mainly due to the its capacity of long memory. Thus, soil moisture does not respond fully to the atmospheric variations and changes over a short period (one month for this study).

Air humidity

Air humidity is determined mainly by latitude and the ground type. Winter air specific humidity increases from below 2 g/kg in middle latitudes to 8 g/kg in the low-latitude land areas and further to over 10 g/kg in the ocean areas (Figure 8). There are two differences in summer. First, a gradient with high moisture in the eastern U.S. and low moisture in the western U.S. is found. Second, air humidity magnitude in summer is about twice that in winter. The spatial patterns in the change due to the restoration are similar between winter and summer. Air specific humidity decreases in the restoration region and increases in the northwestern and western surrounding areas. The magnitude is larger in summer than winter in the restoration region.

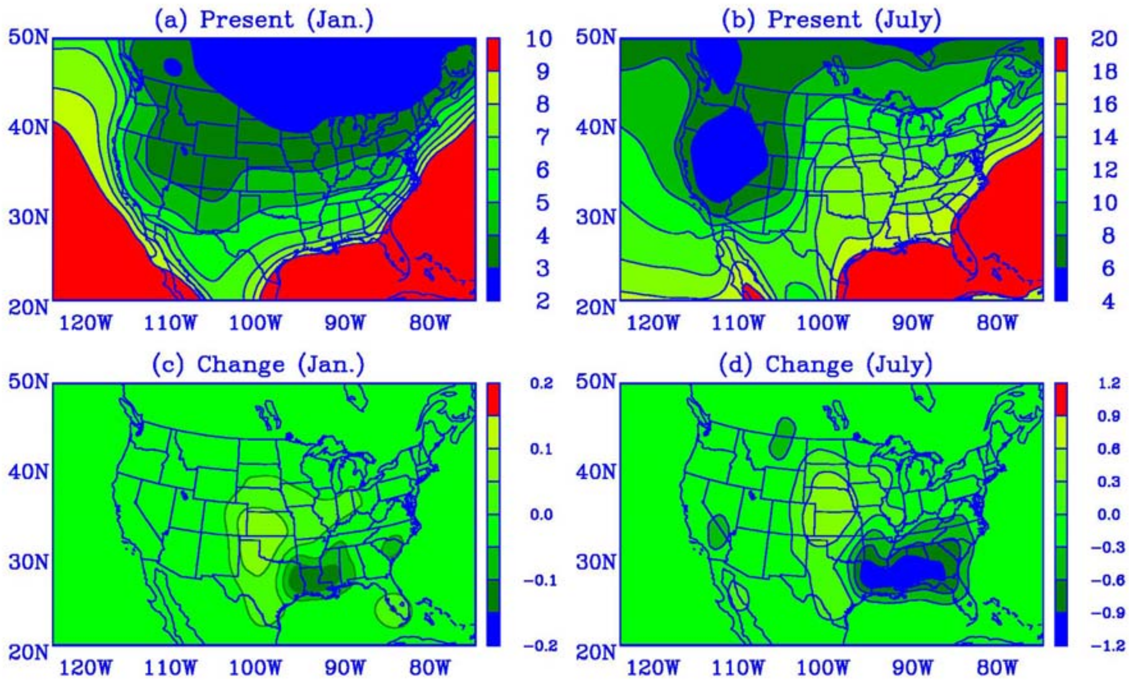

Figure 8 Same as Figure 3 except for air specific humidity (g/kg).

The regional values show that winter air specific humidity is 5 g/kg in RR and between 2.4 and 3.9 g/kg in the surrounding land areas and about 13 g/kg in the surrounding ocean areas (Table 2). The change due to the restoration is -0.02 g/kg RR and between 0.02 and 0.06 g/kg in the surrounding land areas and very little in the surrounding ocean areas. Summer humidity is 16.2 g/kg in RR and between 13.1 and 14.5 g/kg in the surrounding land areas and about 21 g/kg in the ocean areas. The change is -0.5 g/kg in RR and 0.5 g/kg in NW.

Physical Processes

When agricultural lands are replaced with forests, surface albedo in RR is reduced. Thus, more solar radiative energy is absorbed by the ground. It is shown in Table 3 that solar radiation is 137 and 298 Wm^{-2} in winter and summer, respectively, and increases by 1.8 and 5.9 Wm^{-2} due to the restoration. In winter, nearly half the increased winter solar radiation, 0.8 Wm^{-2}, is converted into sensible heat, while a smaller amount, 0.3 Wm^{-2}, is converted into latent heat. The rest of the increased solar radiation is used to increase soil temperature. In summer, nearly three fourths of the increased solar radiation are used to increase sensible heat flux.

Table 3 Same as Table 1 except for energy fluxes (Wm^{-2}).

Area	Solar radiation		Sensible heat flux		Latent heat flux	
	January	July	January	July	January	July
RR	137 (1.8)	298 (5.9)	11 (0.8)	48 (4.3)	43 (0.3)	178 (1.4)
N	95 (0.3)	298 (0.1)	-1.0 (0.3)	31 (-1.8)	17 (0.3)	168 (3.0)
NW	94 (0.4)	294 (0.0)	-13 (0.0)	48 (-7.6)	14 (0.9)	159 (11.3)
W	131 (0.5)	292 (0.1)	3.5 (-0.7)	57 (-7.0)	34 (1.5)	158 (9.5)
S	179 (0.5)	323 (1.2)	38 (-2.7)	17 (-0.1)	143 (-3.3)	127 (-0.3)
E	161 (0.0)	332(-0.1)	57 (-0.2)	7 (-0.3)	203 (-0.5)	109 (11.3)

The situation is different in the surrounding areas, especially in NW and W during summer. There is little change in solar radiation due to the restoration. But sensible heat flux is reduced by 7.6 and 7.0 Wm^{-2}, while latent heat flux is increased by 11.3 and 9.5 Wm^{-2}, respectively, in the two areas. These changes mean air cooling near the ground. The change in summer air temperature is a negative fraction in NW, but -0.43°C in W (Table 4).

Table 4 Same as Table 1 except for air temperature (°C) and winds (ms^{-1}).

	Air temperature		Westerly wind speed		Southerly wind speed	
	January	July	January	July	January	July
RR	4.7 (0.02)	26 (-0.01)	0.3 (-0.02)	0.4 (-0.32)	-0.02 (0.11)	0.83 (-0.55)
N	-5.5 (0.12)	22 (-0.2)	1.6 (0.0)	0.7 (-0.03)	0.6 (0.01)	0.6 (-0.08)
NW	-5.1 (0.11)	26 (-0.01)	2.6 (0.0)	0.0 (-0.04)	-1.0 (0.01)	0.8 (-0.6)
W	2.5 (0.02)	26 (-0.43)	0.9 (-0.01)	0.3 -0.03)	-0.4 (-0.03)	1.6 (-0.01)
S	18.0 0.13)	27 (0.0)	-2.2 (0.09)	-1.5 (0.1)	-1.3 (0.11)	1.1 (-0.04)
E	28.5 0.01)	26 (0.03)	0.8 (-0.02)	0.7 (0.02)	0.2 (-0.02)	2.6 (0.23)

The evapotranspiration change is related to precipitation change. The reasons for precipitation change, however, are very complex. There are three contributors for precipitation formation, that is, atmospheric circulation dynamical systems, water vapor transport, and vertical thermal stability. Figure 9 shows the simulated air streamlines and the change due to the forest restoration. The winter circulation is characterized by an anti-cyclonic circulation in the U.S., representing a high pressure system with cool and dry airflows. The center is located in the Southwest with two high pressure ridge lines, along which air pressure is higher than that in its two sides. One line extends northward along the Rocky Mountains. This explains why precipitation is very small in the central U.S. (Figure 3). The other line extends eastward along the Gulf coast. Between the two lines is the westerly trough in the eastern U.S., which is a rain generator for this region. The circulation systems in the ocean areas can be seen partially in the simulation domain. A trough exists in the northern Pacific as part of the planetary westerly system. It brings large rainfall in the northwest Pacific coast. Each of the two oceans has a high pressure system in the subtropical area. In summer, the Atlantic high pressure system advances northwestward into the land area, while the Pacific one moves up northward. Between them is extensive low pressure system in the U.S. with two trough lines near the U.S.-Canada and U.S.-Mexico border areas, respectively. The lines generate large rainfall. Note that the atmospheric systems at planetary scales usually expand from the ground to the free atmosphere. But the core of each system tilts eastward with increased height. Because condensation of atmospheric water vapor happens mostly in the free atmosphere, actual rainfall region is located more east than the location of a trough line near the ground.

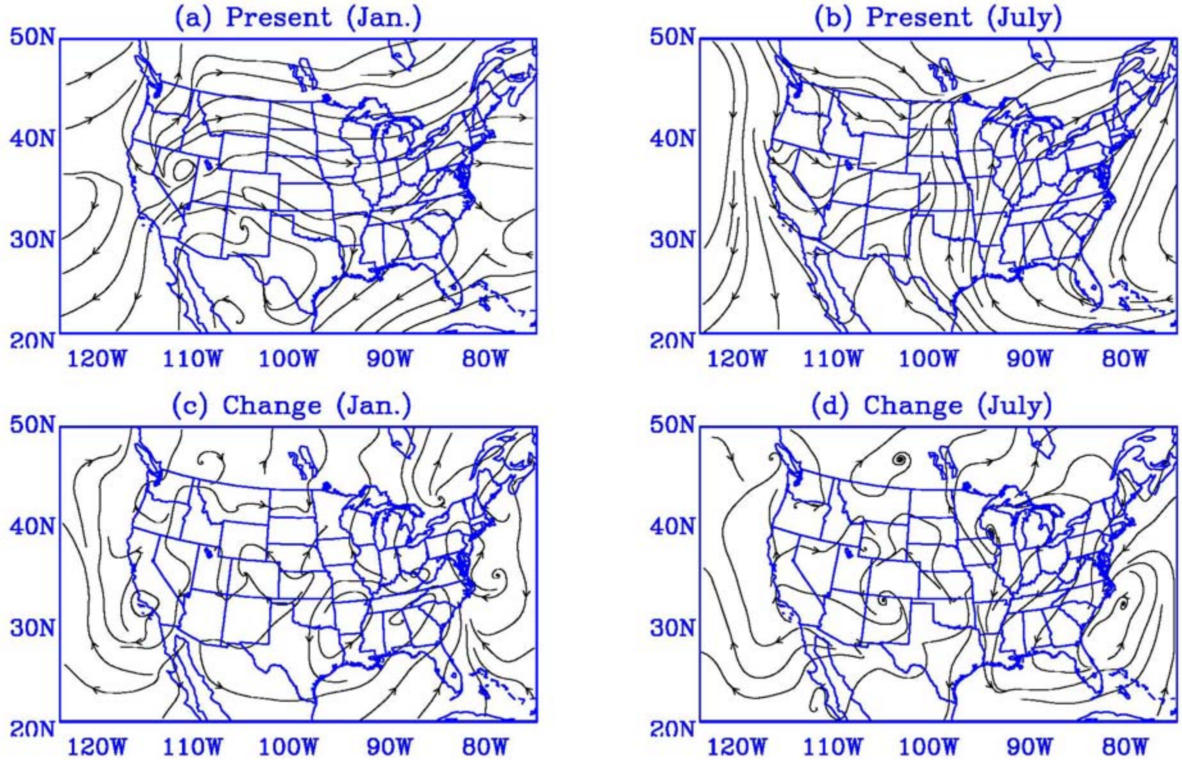

Figure 9 Same as Figure 3 except for airflow streamline on the ground.

The restoration region is under the control of northerly cool and dry airflows in winter and warm and moist ones in summer. Because of the increased roughness with forest restoration, the prevailing wind speed is reduced, as indicated by the opposite direction in the change of streamlines to that of original streamlines in both winter and summer. The regional westerly wind speed average in RR is 0.3 m s^{-1} in winter and 0.4 m s^{-1} in summer (positive value means airflows from west to east) and is reduced by 0.02 and 0.32 m s^{-1}, respectively, due to the restoration. The corresponding values for southerly wind are -0.02 m s^{-1} in winter and 0.83 m s^{-1} in summer for average (positive value means airflows from south to north) and 0.11 m s^{-1} and -0.55 m s^{-1} for changes. Note that the magnitude of changed wind speed is smaller than that of average wind speed in most cases, meaning that the direction of the original airflows remains the same after the restoration, but only their speed is reduced. The exception is the southerly wind in January when slight northerly wind turns to southerly wind after the restoration.

The decrease in northerly wind speed or change in direction from northerly to southerly wind in winter means more water vapor transported into the restoration region, which explains the increase in precipitation there. Meanwhile, there are two well developed circulation systems in the changed airflows in the surrounding areas. One is a cyclonic circulation located in Louisiana, Arkansas, and northeastern Taxes, and the other is an anti-cyclonic circulation located in the northern surrounding area. They explain the mostly positive and negative rainfall changes in these two areas, respectively.

In summer, the direction in the changed airflows due to the restoration is northerly (i.e., decrease in actual southerly wind speed), meaning less water vapor transported into the restoration region. This explains the decrease in precipitation there. There is a well developed cyclonic circulation in the Atlantic area in the changed airflows, which is responsible for the positive rainfall change there. On the other hand, the northerly winds in the changed airflows spread over the western surrounding area and there is an anti-cyclonic circulation in the Great Lakes area. They are responsible for the rainfall decrease in the two areas. Between the two areas is rainfall increase in the central Midwest.

Discussion

Ge et al. (2009) conducted a measurement study to compares energy and water balance between a forested site and a nearby cleanout site in North Carolina. Despite many differences in experiment setup from simulation setup in this study, the measurement is useful for evaluating our modeling results. The measurement indicated that the forest site had larger solar radiation due to smaller albedo, significantly higher latent heat flux, and small difference in air temperature. These are in agreement with the results found in this study. The measurement also indicated that the forest site had little difference in sensible heat flux and smaller runoff, which are different from the results from this study. BATS uses a formula to estimate runoff in which runoff is proportional to precipitation linearly and to the ratio of soil actual water to its capacity with a power of four. Despite the slight decrease in precipitation, runoff is increased due to the restoration because of the large increase in root-layer soil moisture. The difference in runoff between the measurement and simulation studies suggests the need for improvement of runoff calculation in BATS. The reason for the difference in sensible heat flux has yet to be examined.

The result of summer precipitation decrease from this study is opposite to the simulated precipitation change due to the afforestation in northern China. A forest shelterbelt project started in 1978 across dry northern China (SFA, 2006). The project aims to prevent southward expansion of the desert, improve hydroclimate conditions, and conserve the natural environment in the project region. The forest shelterbelt is about 7,000 km long zonally and 400 to 1700 km wide. It stands along the southern edge of the sandy lands, nearly paralleling to the Great Wall. It was targeted to complete by 2050. A similar modeling study indicated overall precipitation increase due to the afforestation (Liu et al., 2008). The difference in precipitation change between the two regions is related to the difference in their atmospheric circulation systems. Different from the forest restoration region in the sub-tropical southeastern U.S. where the prevailing summer winds are southerly, the afforestation region in the northern China is located in the middle latitudes with the westerly prevailing winds. The cool and dry winds are reduced due to the afforestation. In south of the afforested region, meanwhile, the warm and moist southerly airflows from the subtropical Pacific Ocean move closer to the afforested region, carrying more atmospheric water vapor and as a result, generating more precipitation.

Water yield (the amount of water flowing out of a watershed or catchment) 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 southern U.S. is a relatively moist region. This study indicates that the forestation in this region would increases the capacity of holding water by soil, meaning that more precipitation falling into the soil would flow out this region as runoff instead of increasing the soil water storage. As a result, water yield is increased.

Neilson et al. (1998, 2005) projected future vegetation change from the temperate deciduous forests to temperate deciduous savanna in a large portion of the Southeast due to the greenhouse effect. This is opposite to the vegetation change during the forest conversion investigated in this study. Thus, opposite impacts on hydrology and climate are expected for the projected vegetation change. On the other hand, the planned planting trees to replace pasture and farming lands in the Southeast, Great Lake states, and the corn Belt states (Watson, 2009) will affect hydrological and climate conditions in these regions. The results from this study suggest that the afforestation project would not only change hydrological conditions in the planting areas, but also their surroundings. It is important to assess both local and remote impacts and make a comprehensive plan to achieve best hydrological benefits in the entire U.S.

CONCLUSIONS

The impacts of the forest restoration in the southern U.S. on hydrology have been investigated by conducting simulations with the National Center for Atmospheric Research regional climate model. The simulated precipitation change is mainly caused by the reduction in the prevailing winds due to increased surface roughness with forest restoration. The reduction in southerly winds in summer means weaker moist transport and therefore smaller precipitation. In contrast, the reduction in the northerly winds in winter means weaker dry and cold airflows and therefore more precipitation. The difference in summer prevailing winds between the southern U.S. and northern China is also the main cause for opposite precipitation changes induced by afforestation in the two regions. There is inter-annual variability with precipitation change. Among the 8 years, summer precipitation is overall decreased in 5 years, decreased but with small magnitude in 2 years, and increased in one year.

The impacts on other hydrological properties in the restoration region are mostly related to the changes in vegetation and soil properties. Forest restoration brings larger vegetation coverage and larger transpiration, leading to larger total evapotranspiration. Soil moisture is increased, which is responsible for the increase in runoff.

The impacts on precipitation can go beyond the restoration region through the change in the atmospheric circulation. This change is responsible for a large increase in precipitation in the central Midwest as well as the western and northern surrounding areas. This further leads to large changes in other hydrological and climatic conditions, including increases in evapotranspiration (latent heat flux), runoff, soil moisture, and air specific humidity, and decreases in sensible heat flux.

More evaluation of the modeling results with measurement is needed. This, however, is a difficult issue because of the lack in soil hydrologic measurements across the afforestation region. In addition, the simulation period in this study is much shorter than the actual forest restoration process and historical meteorological conditions during the forest restoration period were not used in the simulation. The first efforts towards improving our understanding of the hydrological impacts of the restoration obtained from this study is to conduct long-term simulations using actual initial and boundary meteorological conditions and evaluate the results with more measurements.

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REFERENCES

Allen, A.W., Y.K. Bernal, and R.J. Moulton. 1996. Pine plantations and wildlife in the southeastern United States: an assessment of impacts and opportunities. U. S. Dept. of the Interior, National Biological Service, Information and Technology Report 3. 32 p. www.nwrc.usgs.gov/wdb/pub/others/1996_03.pdf.

Anthes, R.A., E.-Y. Hsie, and Y.-H. Kuo, 1987. Description of the Penn State/NCAR Mesoscale Model Version 4 (MM4), Technical Note, NCAR/TN-282+STR, National Center for Atmospheric Research, Boulder, Colorado, 66 pp.

Bonan, G.B., 1997. Effects of land use on the climate of the United States. Climatic Change, 37, 449-486.

Caya, D., and R. Laprise, 1999, A Semi-Implicit Semi-Lagrangian Regional Climate Model: The Canadian RCM, Mon. Wea. Rev. , 127, 341-362.

Dickinson, R. E., R. M. Errico, F. Giorgi, and G. T., Bates, 1989, A regional climate model for the western U.S., Clim. Change, 15, 383-422.

Dickinson, R. E. and P. Kennedy, 1992. Impacts on regional climate of Amazon deforestation. Geophy. Res. Letters, 19, 1947-1950.

Dickinson, R. E., Durbudge, T. B., Kennedy, P. J., McGuffie, K., and Pitman, A. J., 1993. Tropical Deforestation: Modeling local- to regional-scale climate change. J. Geophy. Res., 98, D4, 7289-7315.

Dickinson, R. E., A. Henderson-Sellers, and P.J. Kennedy, 1995. Biosphere-Atmosphere Transfer Scheme (BATS) Version 1E as Coupled to the NCAR Community Climate Model, NCAR Tech. Note/TN-387, Boulder, CO., 72pp.

Giorgi, F., and G.T. Bates, 1989.The climatological skill of a regional model over complex terrain. Mon. Wea. Rev., 117, 2325-2347.

Giorgi, F., M.R. Marinucci, G. De Canio, and G.T. Bates, 1993a. Development of a second generation regional climate model (RegCM2), I, Boundary layer and radiative transfer processes. Mon. Wea. Rev., 121, 2794-2813.

Giorgi, F., M.R. Marinucci, G. De Canio, and G.T. Bates, 1993b.Development of a second generation regional climate model (RegCM2), II, Convective processes and assimilation of lateral boundary conditions, Mon. Wea. Rev., 121, 2814-2832.

Giorgi, F. and C. Shields, 1999. Tests of precipitation parameterizations available in latest version of NCAR regional climate model (RegCM) over continental United States. J. Geophys. Res., 104, 6353-6375.

Giorgi, F., and X. Bi, 2000. A study of internal variability of a regional climate model. J. Geophys. Res., 105, 29503-29521.

Grell, G. A., J. Dudhia, and D. R. Stauffer, 1994, A description of the fifth generation Penn State/NCAR Mesoscale Model (MM5), NCAR/TN-398+STR, 122 pp., Natl. Cent. For Atmos. Res., Boulder, Colo.

Henderson-Sellers, A., McGuffie, K., 1995. Global climate models and 'dynamic' vegetation changes. Global Change Biology, 1, 63-75.

IPCC (Intergovernmental Panel on Climate Change), 2007. Climate Change 2007.

Jackson, R. B. E. G. Jobbagy, R. Avissar, S. B. Roy,D. J. Barrett, C. W. Cook, K. A. Farley, D. C. le Maitre, B. A. McCarl, B. C. Murray, 2005. Trading water for carbon with biological carbon sequestration. Science, 310, 1944-1947.

Jones, R. G., J. M. Murphy, and M. Noguer, 1995, Simulation of climate change over Europe using a nested regional-climate model. I: Assessment of control climate, including sensitivity to location of lateral boundaries. Q. J. R. Meteorol. Soc., 121, 1413-1449.

Juang, H. -M. H., and M. Kanamitsu, 1994, The NMC nested regional spectral model. Mon. Wea. Rev., 122, 3-26.

Kiehl, J.T., J.J. Hack, G.B. Bonan, B.A. Boville, B.P. Briegleb, D.L. Williamson, and P.J. Rash, 1996. *Description of the NCAR Community Climate Model (CCM3),* NCAR/TN-420+STR, National Center for Atmospheric Research, Boulder, CO.

Lean, J., Warrilow, D.A., 1989. Simulation of the regional climatic impact of Amazon deforestation. Nature, 342, 411-413.

Liang X.-Z., J. Pan, J. Zhu, K. E. Kunkel, J. X. L. Wang, A. Dai, 2006: Regional climate model downscaling of the U.S. summer climate and future change, J. Geophys. Res., 111, D10108, doi:10.1029/2005JD006685.

Liston, G. E., and R. A. Pielke Sr., 2000, A climate version of the regional atmospheric modeling system. Theor. Appl. Climatol., 66, 29-47.

Liu, Y. –Q., 2005. Enhancement of the 1988 Northern U.S. drought due to wildfires, Geophysical Research Letters 32 (No. 10), L1080610.1029/2005GL022411.

Liu, Y. –Q., 2007. Advances in regional climate modeling, Proceedings of Int'l Symposium on Advances in Atmospheric Science and Information Technology, Nanjing, China, 94-100.

Liu, Y.-Q., J. Stanturf, H. Lu, 2008, Modeling the potential of the Northern China forest shelterbelt in improving hydroclimate conditions, Journal of the American Water Resources Association, 44(5): 1176-1192

Liu Y.–Q., J. Stanturf, S. Goodrick, 2009, Trends in global wildfire potential in a changing climate, Forest Ecology and Management, doi:10.1016/j.foreco.2009.

Liu, Y.-Q., J. Stanturf, S. Goodrick, 2010, Wildfire potential evaluation during a drought event with a regional climate model, Ecological Informatics (submitted).

McVicar, T. R., L.T. Li, T. G. V. Niel, L. Zhang, R. Li, Q.K. Yang, X.P. Zhang, X.M. Mu, Z.M. Wen, W.Z. Liu, Y.A. Zhao, Z.H. Liu, P. Gao, 2007. Developing a decision support tool for China's re-vegetation program: Simulating regional impacts of afforestation on average annual streamflow in the Loess Plateau. Forest Ecology and Management, 251, 65-81.

Neilson, R.P.; Pitelka, L.F.; Solomon, A.; Nathan, R.; Midgley, G.F.; Fragoso, J.; Lischke, H.; Thompson, K. 2005. Forecasting regional to global plant migration in response to climate change: challenges and directions. BioScience. 55: 749-759.

Neilson, R.P.; Prentice, I.C.; Smith, B.; Kittel, T.G.F.; Viner, D. 1998. Simulated changes in vegetation distribution under global warming. In: Watson, R.T.; Zinyowera, M.C.; Moss, R.H.; Dokken, D.J., eds. The regional impacts of climate change: an assessment of vulnerability. Cambridge, United Kingdom: Cambridge University Press: 439-456.

Nobre, C.A., Sellers, P.J., Shukla, J., 1991. Amazonian deforestation and regional climate change. J. Climate, 4, 957-988.

Pielke, R.A., Avissar, R., 1990. Influence of landscape structure on local and regional climate. Landscape Ecology, 4, 133-155.

Sampson, R.N., 2004, Southern Forests: Yesterday, Today, and Tomorrow, In: Southern Forest Science: Past, Present, and Future (Eds. H. Michael Rauscher and Kurt Johnsen), Department of Agriculture Forest Service, General Technical Report SRS-75, pp408.

Seth, A., and F. Giorgi, 1998. The effects of domain choice on summer precipitation simulation and sensitivity in a regional climate model. J. Clim., 11, 2698-2712.

SFA (China State Forest Administration), 2006. China's forest shelter project dubbed "green Great Wall", www.chinaview.cn 2006-07-09.

Shea, D.J., K.E. Trenberth, and R.W. Reynolds, 1992. Global monthly sea surface temperature climatology, J. Clim., 5, 987-1001.

Shukla, J., C. A. Nobre and P. J. Sellers, 1990. Amazonia deforestation and climate change. Science, 247, 1322-1325.

SRFRR, 1996, Southern Region Forest Research Report, 7th American Forest Congress, Feb. 1996.

Stanturf, J. A., E.S. Gardiner, P.B. Hamel, M.S. Devall, T.D. Leininger, and M.E. Warren, 2000. Restoring bottomland hardwood ecosystems in the Lower Mississippi Alluvial Valley. Journal of Forestry. 98, 10-16.

Sun, G, G.Y. Zhou, Z.Q. Zhang, X.H.Wei, S.G. McNulty, and J.M. Vose, 2006. Potential water yield reduction due to forestation across China. J. Hydrology, 328, 548-558.

Sun, G, A. Noormets, M.J. Gavazzi1, S.G. McNulty, J. Chen, J-C. Domec, J.S. King, D.M. Amatya, and R.W. Skaggs. Energy and water Balance of two contrasting Loblolly pine plantations on the lower coastal plain of North Carolina, USA. Forest Ecology and Management. doi:10.1016/j.foreco.2009.09.016

USDAFS (U.S. Department of Agriculture, Forest Service). 1994. Pest and pesticide management on southern forests. Manage. Bull. R8–MB 60. Atlanta: U.S. Department of Agriculture, Forest Service, Southern Region.

Watson, T., 2009, Climate plan calls for forest expansion, USA TODAY. www.usatoday.com/news/nation/environment/2009-08-19-forest_N.htm

Xue, Y.K., 1996, The impacts of desertification in the Mongolian and the Inner Mongolian grassland on the regional climate. J. Clim., 9, 2173-2189.

Zeng, X., R.E. Dickinson, A. Walker, M. Shaikh, R.S. DeFries, and J. Qi. 2000. Derivation and evaluation of global 1-km fractional vegetation cover data for land modeling, J. Appl. Meteor., 39, 826-839.