Climate Dynamics (2004) 23: 279–302
DOI 10.1007/s00382-004-0430-0

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Evaluating the influence of different vegetation biomes on the global climate

Received: 24 October 2003 / Accepted: 5 March 2004 / Published online: 29 July 2004

Abstract The participation of different vegetation types within the physical climate system is investigated using a coupled atmosphere-biosphere model, CCM3-IBIS. We analyze the effects that six different vegetation biomes (tropical, boreal, and temperate forests, savanna, grassland and steppe, and shrubland/tundra) have on the climate through their role in modulating the biophysical exchanges of energy, water, and momentum between the land-surface and the atmosphere. Using CCM3-IBIS we completely remove the vegetation cover of a particular biome and compare it to a control simulation where the biome is present, thereby isolating the climatic effects of each biome. Results from the tropical and boreal forest removal simulations are in agreement with previous studies while the other simulations provide new evidence as to their contribution in forcing the climate. Removal of the temperate forest vegetation exhibits behavior characteristic of both the tropical and boreal simulations with cooling during winter and spring due to an increase in the surface albedo and warming during the summer caused by a reduction in latent cooling. Removal of the savanna vegetation exhibits behavior much like the tropical forest simulation while removal of the grassland and steppe vegetation has the largest effect over the central United States with warming and drying of the atmosphere in summer. The largest climatic effect of shrubland and tundra vegetation removal occurs in DJF in Australia and central Siberia and is due to reduced latent cooling and enhanced cold air advection, respectively. Our results show that removal of the boreal forest yields the largest temperature signal globally when either including or excluding the areas of forest removal. Globally, precipitation is most affected by removal of the savanna vegetation when including the areas of vegetation removal, while removal of the tropical forest most influences the global precipitation excluding the areas of vegetation removal.

1 Introduction

A rapid increase in human population and development pressures has put a considerable strain on the Earth's ecosystems. A large portion of the Earth's surface has already been modified for urban and industrial development, agriculture, and pastureland. Nearly 35% of the land surface (approximately 55 million km^2) has been modified as a direct result of human interaction with the landscape (Ramankutty and Foley 1999). Of the remaining land surface, the tropical rainforests of South America, Africa, and Southeast Asia are among the ecosystems most at risk due to demographic pressure in these regions. Other ecosystems are not spared however; as the population and development pressures increase, the demand for natural resources, forest and agricultural products also increases, putting at risk natural ecosystems across the entire planet.

Along with these changes in the Earth's terrestrial ecosystems, there may also be a corresponding change in the climate. Vegetation and soils exchange water, energy, and momentum with the atmosphere. Given that the atmosphere can be acutely sensitive to changes in the surface fluxes of water, energy, and momentum, a given change in any one of these fluxes can have a significant impact on the thermodynamics and the general circulation of the atmosphere. These changes can in turn influence the same regions where the land surface has

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been altered or regions far removed from the original surface forcing.

Many modeling-based studies have been undertaken to determine the influence of particular vegetation types or biomes on land surface biophysical processes and the physical climate system. Early work on land use change and its role in forcing the atmosphere (in particular, focusing on drought mechanisms of the Sahel) was proposed by Charney (1975), and Charney et al. (1975, 1977). Since Charney (1975) introduced the problem of land use change and its influence on the climate, many other studies have been undertaken in the last 25 years; most notably in the tropical rainforest biome of South America, Africa, and Southeast Asia (Dickinson and Henderson-Sellers 1988; Sud et al. 1988; Lean and Warrilow 1989; Nobre et al. 1991; Dickinson and Kennedy 1992; Henderson-Sellers et al. 1993; Eltahir 1996; Sud et al. 1996; Zhang et al. 1996a,b; Lean and Rowntree 1997; Costa and Foley 2000; Delire et al. 2001). Moreover, Thomas and Rowntree (1992), Bonan et al. (1992), and Foley et al. (1994) explored the role of the boreal forest on the climate and found that feedbacks exist that act to change the climate as a result of changes in the surface albedo between boreal forest and bare snow. Other studies have explored the relationship between historical land use change in North America and trends in the climate record (Bonan 1997, 1999, 2001). A comprehensive review of land surface schemes designed for climate models and a summary of the important processes that need to be modeled is provided by Pitman (2003). Furthermore, a comprehensive review of atmosphere-biosphere process for different biomes can be found in Bonan (2002).

Although these studies have improved our understanding of the effects of particular vegetation types on land surface processes and the atmosphere, no comprehensive analysis has yet been undertaken to describe the effect of each biome on the climate system. However, two studies have considered the effects of vegetation extremes on the atmosphere (Fraedrich et al. 1999; Kleidon et al. 2000). In these studies, vegetation extremes were defined as either a global land cover of thick forest or bare desert. The difference between temperature, precipitation, and energy in the two extremes leads to an improved understanding of the role of the energy and water cycling in maintaining the climate system as well as identification of geographic regions that may be especially sensitive to biosphere-atmosphere interactions. However, a more recent study of global deforestation using a three-dimensional coupled atmosphere-sea-ice-ocean-vegetation model has shown that a much stronger response of the climate system occurs when interactive sea surface temperatures are used (Renssen et al. 2003).

Nevertheless, there has still been no systematic study that examines how each of the major vegetation biomes of the planet affects the climate. Here we attempt to address these questions in a comprehensive manner by examining the influence of six major biomes on the climate using a coupled atmosphere-biosphere model. Using this approach we can identify the vegetation types and geographic locations that are most important in influencing the climate.

To achieve this goal we use a coupled atmosphere-biosphere model consisting of an atmospheric general circulation model (AGCM) and a detailed land surface model. A specific vegetation biome is completely removed and replaced with desert (bare soil and no vegetation). The vegetation biomes included in this study are the tropical, temperate, and boreal forests, savanna, grassland and steppe, and shrubland and tundra. The response of the climate to the simulation with the vegetation removed is compared to a control simulation with potential vegetation. (Potential vegetation is defined as the vegetation that would exist in a location in the absence of anthropogenic land use change). The difference in the climate between the two simulations is representative of the maximum influence that particular vegetation type may have on the climate. While completely removing the vegetation of a particular type may be unrealistic for most regions of the world, it does represent a theoretical maximum signal of the vegetation's influence on the climate system. By approaching the problem in this way the biophysical and atmospheric mechanisms responsible for forcing the climate can be determined as well as the vegetation types and geographic regions that are most influential.

2 Description of the coupled atmosphere-biosphere model, CCM3-IBIS

We use the coupled atmosphere-biosphere model, CCM3-IBIS (Delire et al. 2002). This model has been well tested by Delire et al. (2002) and the simulated climate compares favorably to the observed climate for the 1961–1990 period using the CRU05 data set (New et al. 1999). The atmospheric component of the coupled model is the Community Climate Model (CCM3) version 3.2 (Kiehl et al. 1998a). CCM3 is a fully dynamic atmospheric model that supports a variety of spatial resolutions, 18 vertical levels, and a 20-min time step. This version of CCM3 more accurately portrays the dynamical processes (Hurrell et al. 1998) and energy budget (Kiehl et al. 1998b) than its predecessor, CCM2. Furthermore, new to CCM3 is a more representative precipitation model that includes both shallow and deep convective schemes as well as large-scale precipitation estimates (Hack et al. 1998). This revised precipitation model eliminates the overactive hydrology of the CCM2 model and more accurately portrays precipitation and convective processes.

CCM3 is coupled to the Integrated Biosphere Simulator (IBIS) version 2.1 (Foley et al. 1996; Kucharik et al. 2000). IBIS is a global model of terrestrial ecosystem processes that represents the physical, physiological, and ecological processes occurring in vegetation and soils in a coherent and semi-mechanistic way. IBIS simulates land surface processes (energy and water balance), vegetation phenology (budburst and senescence), and vegetation dynamics (competition between vegetation types). IBIS calculates these processes on a spatial and temporal scale consistent with that of the AGCM spatial and temporal resolutions. IBIS represents vegetation as two layers (taller "trees" and short "shrubs" and "grasses"). In IBIS a grid cell can contain one or more plant functional types (PFTs) that together comprise a vegetation type (Foley et al. 1996). For instance, the tropical evergreen forest vegetation type (that is part of the tropical forest biome) is dominated by the tropical evergreen tree PFT but also contains the tropical broadleaf deciduous tree PFT as well as some shrub and grass PFTs. Soil is represented with six layers in the model and simulates temperature, water, and ice content down to a depth of 4 m. Canopy photosynthesis is realistically modeled using the C_3 and C_4 physiology scheme of Farquhar et al. (1980). Canopy stomatal conductance (Collatz et al. 1991; 1992) and respiration (Amthor 1984) are also calculated to establish a link between the exchanges of energy and water from the vegetation and the atmosphere. Budburst and senescence are determined by climatic factors.

We run the model with a fixed vegetation distribution, so that vegetation structure and biogeography are not allowed to change in response to the climate. IBIS uses a prescribed "potential vegetation" distribution representing the vegetation that would exist in the absence of anthropogenic land use change (Ramankutty and Foley 1999). The soil texture is defined in IBIS according to the IGBP-DIS global gridded texture database (International Geosphere-Biosphere Programme – Data and Information System), (IGBP-DIS 1999).

3 Simulation design

In order to determine the role that different vegetation types have on the climate system, we employ a systematic modeling approach whereby vegetation removal simulations are performed for six groups of vegetation types. Although there are 15 vegetation classes defined in IBIS, computing constraints require the grouping of physiologically and geographically similar vegetation classes. For example, the tropical biome simulation uses an aggregation of the tropical evergreen forest and woodland class, the tropical deciduous forest and woodland class, and certain cells of the mixed forest and woodland class into one tropical forest biome. Table 1 lists the suite of simulations presented in this study, the IBIS vegetation types used in each simulation, the approximate land surface area for which the vegetation was removed, and the percentage of the total land area of the Earth for that biome. Figure 1 shows the distribution of the biomes as defined in this study.

A total of seven simulations were run: a control run using potential vegetation (all biomes intact, and in their "natural" locations) and six vegetation removal runs (where different biomes are removed, replaced by desert, one at a time). In this context vegetation removal means that a cell's vegetation is completely removed and replaced with desert (bare soil and no vegetation). Each of the simulations was run at a spectral resolution of T31 (∽3.75° × 3.75° latitude/longitude grid). All atmospheric and most land surface calculations were run at a temporal resolution of 20-min. In order to isolate the

Table 1 Description of simulations presented in this study. Percentages of area affected represent the portion of the total land area of the earth. 1014 vegetated cells (121 994 300 km^2) out of 4608 cells (145 911 370 km^2) are used in this study. This does not include deserts or the polar regions of Greenland and Antarctica

Simulation name	Description	IBIS vegetation removed	Number of cells changed	Area affected (km^2)
Control	Potential vegetation	No vegetation removed	0	0
Tropical Forest	Tropical Forest-Control	Tropical evergreen forest/woodland Tropical deciduous forest/woodland Mixed forest/woodland	136	22 728 580 (16%)
Boreal Forest	Boreal Forest-Control	Boreal evergreen forest/woodland Boreal deciduous forest/woodland Mixed forest/woodland	263	22 429 940 (15%)
Temperate Forest	Temperate Forest-Control	Temperate evergreen broadleaf forest/woodland Temperate evergreen conifer forest/woodland Temperate deciduous forest/woodland Mixed forest/woodland	173	19 011 680 (13%)
Savanna	Savanna-Control	Savanna	121	19 078 920 (13%)
Grassland and Steppe	Grassland and Steppe-Control	Grassland and steppe	112	14 120 550 (10%)
Shrubland/Tundra	Shrubland/Tundra-Control	Dense shrubland Open shrubland Tundra	209	24 624 630 (17%)

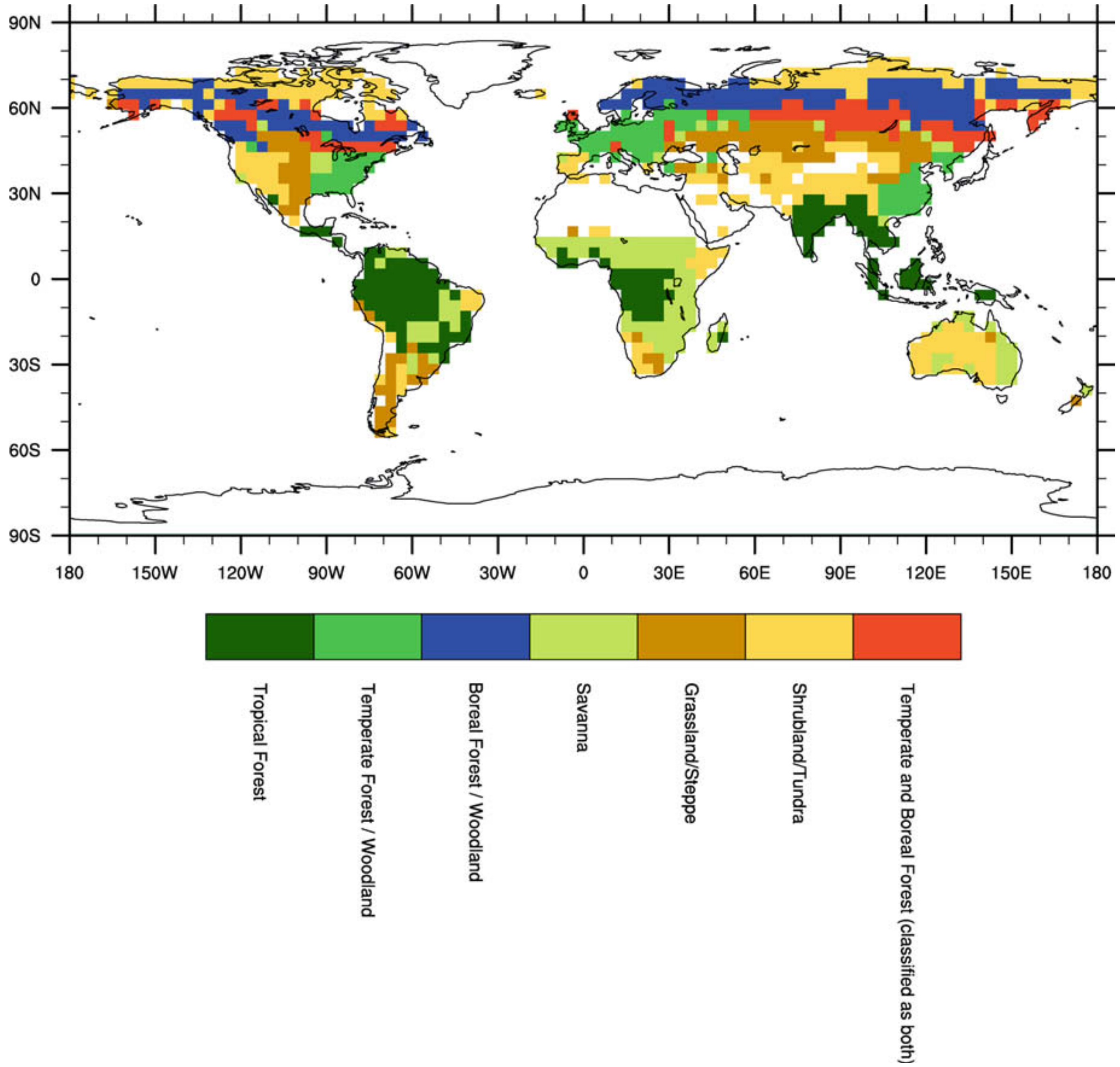


Fig. 1 Global distribution of the six potential vegetation biomes defined in this study at T31 spatial resolution. Each biome includes one or more vegetation types as defined in the IBIS land-surface model. The 'Temperate and Boreal Forest' class represents the cells that are included in *both* the temperate and the boreal deforestation simulations since they contain vegetation representative of both ecosystems

effect of the vegetation alone, we ran all simulations with climatologically prescribed sea-surface temperatures (SSTs) and a fixed atmospheric CO_2 concentration of 350 ppmv. While we acknowledge that prescribed SSTs are not as physically representative as interactive SSTs, especially in high-latitude regions, it is necessary to limit what can change so that we may isolate the climate forcing due to removal of a particular vegetation type. However, there are certainly important feedbacks operating between the vegetation, atmosphere, ocean, sea-ice, and surface albedo that must be represented for a more detailed modeling of the climate system as a whole (Bonan et al. 1992; Ganopolski et al. 2001; Brovkin et al. 2003).

Each of the seven simulations was run for 25 years. The last 20 years of each run are used for averaging and all results present in this paper are significant at the 95% confidence level using a Student's *t*-test. The statistical significance was computing independently for the monthly, seasonal, and annual results.

4 Effects of tropical forests on climate

An early study by Dickinson and Henderson-Sellers (1988) explored how tropical deforestation could affect the local and regional climate by using a land-surface model coupled to an AGCM. Dickinson and Henderson-Sellers (1988) quantified the biophysical changes in the aerodynamic roughness and the corresponding reduction in the turbulent exchange of water, energy, and momentum between the surface and the PBL as well as modification to the surface radiation budget and the water cycle. Dickinson and Henderson-Sellers (1988) concluded that deforestation of the Amazon could result in a temperature increase of 3–5 °C when forest land was converted to grassland. More recent Amazon deforestation studies have been conducted with a variety of results, however all the studies found a warming of the surface air temperature, a reduction in evapotranspiration, and most all found a reduction in precipitation (Lean and Warrilow 1989; Nobre et al. 1991b; Dickinson and Kennedy 1992; Henderson-Sellers et al. 1993; Lean and Rowntree 1993, 1997; Polcher and Laval 1994; Hahmann and Dickinson 1997; Costa and Foley 2000). A summary of recent AGCM studies in the Amazon basin is provided by Costa and Foley (2000).

Although many AGCM studies have found a decrease in precipitation from large-scale tropical deforestation, several higher-resolution and well parameterized modeling studies have shown the opposite effect for more sporadic deforestation. A recent mesoscale modeling study has found that sporadic deforestation of the tropical rainforests can lead to an increase in precipitation through changes to the synoptic circulation patterns that affect the transport of heat and moisture (Baidya Roy and Avissar 2002). Furthermore, a study by Dias et al. (2002) has explored the effect that tropical deforestation has on cloud formation due to a reduction in cloud condensation nuclei (CCN) from biogenic origins.

Figure 2 illustrates the basic processes at work in the tropical forest vegetation removal scenario. Complete removal of tropical forest vegetation leads to a reduction in evapotranspiration due to the replacement of trees with grasses or in our case desert. Soil evaporation does increase once the covering vegetation is gone, however, this rate is much less than what vegetation can

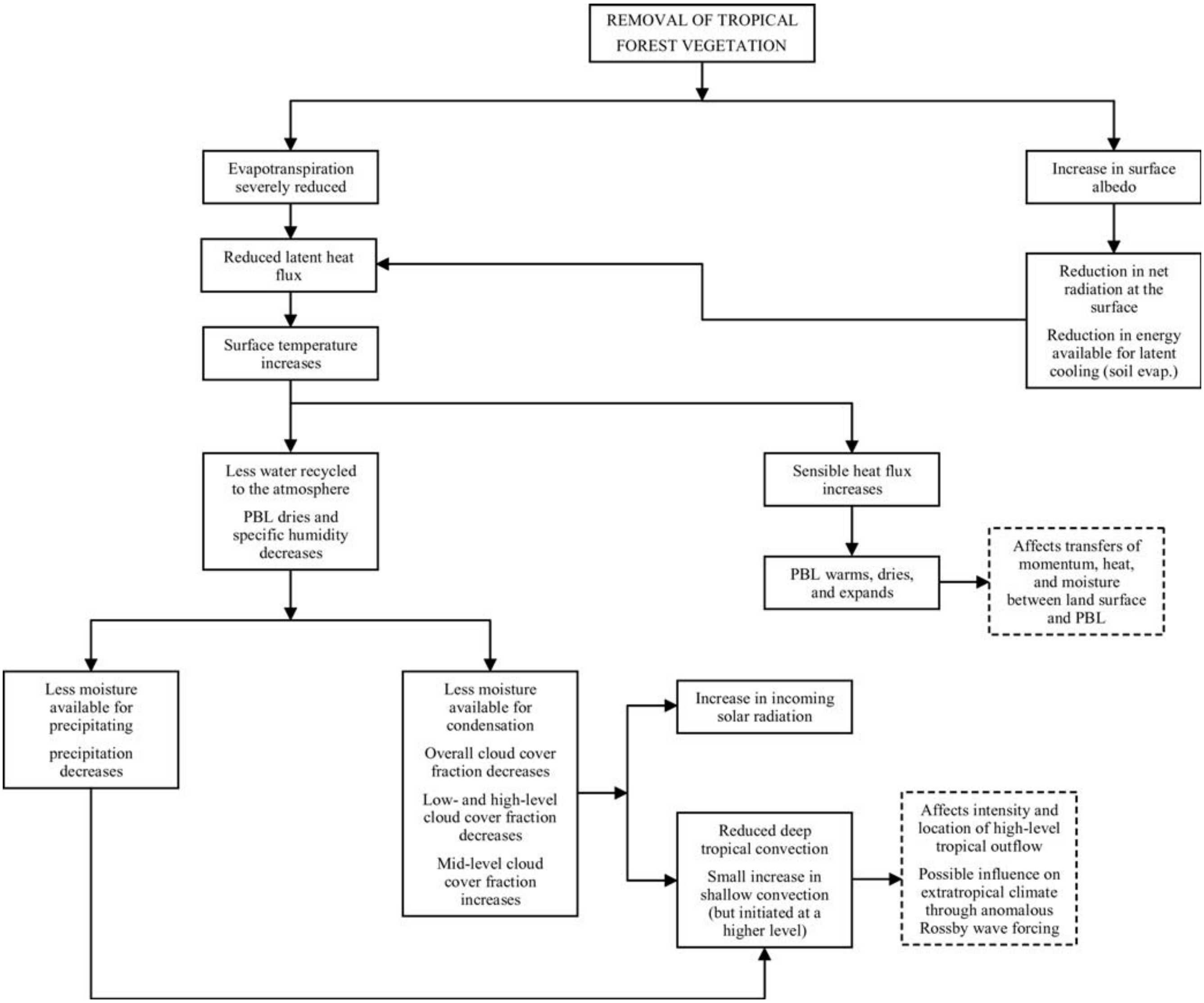


Fig. 2 Conceptual flowchart representing the impact of tropical forest vegetation removal on the climate

transpire for a given time period. An increase in the surface albedo with vegetation removal reduces the net radiation absorbed at the surface and acts to cool the surface; however, the effect of reduced evapotranspiration is much larger than the albedo effect and the surface temperature increases. Lower evapotranspiration rates lead to a drier planetary boundary layer as less water is transported to the atmosphere from the surface. Moisture convergence can act to partially offset the reduction, however the overall result is that the atmosphere dries, less precipitation falls, and water recycling is reduced.

For our tropical forest vegetation removal simulation we replaced the tropical evergreen forest and woodland cells, tropical deciduous forest and woodland cells, and all cells of the mixed forest and woodland class that fall within the northern and southern extent of the two tropical forest classes with desert (Fig. 1). The area of vegetation removal as represented in the model is just under 23 000 000 km^2 or about 16% of the Earth's land surface area (Table 1).

In our simulation the annual-average change in evapotranspiration is –1.1 mm day^{-1} for all regions where the vegetation has been removed, or about –30 W m^{-2} (a 30% reduction) in terms of the latent heat flux (Table 2). The largest decrease in the latent heat flux occurs in SON and is approximately 40 W m^{-2} (Fig. 3a). In the Amazon the decrease reaches 50 W m^{-2} (41%) (an evapotranspiration rate of 1.7 mm day^{-1}) at the start of the wet season as represented in the model.

Tropical forests are densely vegetated with a large concentration of biomass and a relatively low albedo (annual average of 0.13) as compared with vegetation in other biomes. As a result, removal of the tropical forest vegetation leads to an increase in the surface albedo as vegetation is replaced with bare soil. Over the entire tropics the annual-average surface albedo increases by 33% with the largest change taking place in Africa where the albedo increases by 0.08 (63%) in JJA. The increase in albedo has a considerable effect on the surface energy budget with the annual net radiation decreasing by almost 20 W m^{-2} (16%) in the tropics and by as much as 33 W m^{-2} (24%) in Africa in SON when vegetation is replaced with bare soil.

Even though removal of the tropical forest vegetation causes a reduction in the net radiation absorbed at the surface, the surface temperature increases as the loss of net radiation is more than compensated for by the increased energy at the surface due to reduced latent cooling. This also results in an increase in the annual-average sensible heat flux by almost 11 W m^{-2} over all tropical forest regions. Correspondingly, the surface temperature increases by 1.2 °C annually and 1.5 °C in the SON season within the regions where the vegetation has been removed (Table 2 and Fig. 3b). Regionally, the Amazon basin has the largest temperature increase of 1.5 °C annually and 2.0 °C in the SON season. An overall warming of the Amazon basin from removal of the tropical forest vegetation is consistent with other studies as summarized by Costa and Foley (2000). In all cases the surface temperature increases with removal of the tropical forest vegetation anywhere from 0.6 °C to 3.8 °C with many of the studies noting a temperature increase in the 1–2 °C range. Annually, Africa and Southeast Asia have a smaller warming with vegetation removal of 1.0 °C and 0.8 °C, respectively. Southeast Asia's modest warming relative to the other two deforested regions is mostly due to the moderating influence of the surrounding ocean.

Removal of the tropical forest vegetation leads to a reduction in precipitation annually by as much as 1.3 mm day^{-1} (24%) over the entire biome and by 1.7 mm day^{-1} (31%) in Africa (Table 2). The largest seasonal reduction occurs in the Amazon and Africa in SON and is 2.2 (30%) and 3.2 mm day^{-1} (47%), respectively (Fig. 3c). The larger decrease in precipitation in Africa is coherent with the larger albedo increase as dry soils are more reflective. This acts as a positive feedback mechanism whereby the reduction in net radiation at the surface due to the higher albedo inhibits the potential development of convective precipitation since there is less energy available. Furthermore, the surface temperature increase for the Africa region is less than the Amazon region or the average of all the tropical regions and is partially due to the larger reduction in net radiation. The reduction in precipitation compares well with previous studies by Xue et al. (1991) (–1.5 mm day^{-1}), Dickinson and Kennedy (1992) (–1.4 mm day^{-1}), Henderson-Sellers et al. (1993) (–1.6 mm day^{-1}), and Hahmann and Dickinson (1997) (–1.0 mm day^{-1}). However, it is important to note that most of these studies did not examine the complete removal of vegetation cover as undertaken here and therefore may not be entirely comparable. Instead, these studies simulated a deforestation in which the forest was converted to a residual vegetation cover with mostly grasses and shrubs. Other studies as summarized in Costa and Foley (2000) note smaller reductions in precipitation that may also be due to differences between the choice of the vegetation residual as already noted.

The reduction of precipitation is clear throughout the tropics, however there are regions both inside and outside the regions of vegetation removal where tropical precipitation increases. For example, the precipitation map for the JJA season (Fig. 3c) illustrates that there is a region of increased precipitation over eastern India and Bangladesh most likely associated with an increase in moisture convergence during the monsoon season. The precipitation map for the SON season (Fig. 3c) shows increased precipitation in the northern Amazon basin (Venezuela) that may be due to the advection of moisture from other regions or changes in the regional circulation or boundary layer thermodynamics that alter the conditions favorable for development of convective precipitation. As a result, the deforested regions not only see a reduction in precipitation, but also a redistribution of the regions of convection as well as a change in the intensity of deep versus shallow convection. These

Table 2 Selected results from the tropical forest vegetation removal simulation

Variable	Amazon Basin					Africa					Southeast Asia					All Tropical				
	DJF	MAM	JJA	SON	annual	DJF	MAM	JJA	SON	annual	DJF	MAM	JJA	SON	annual	DJF	MAM	JJA	SON	annual
Temperature (K)	1.6	0.9	1.4	2.0	1.5	1.1	1.3	0.4	1.1	1.0	0.5	0.9	0.8	1.1	0.8	1.2	1.0	1.0	1.5	1.2
Net radiation (W m^{-2})	–15.4	–15.3	–23.6	–26.1	–18.9	–23.3	–19.6	–32.9	–33.4	–26.1	–15.5	–31.4	–10.9	–15.0	–16.6	–17.2	–21.5	–22.0	–24.5	–19.8
Albedo (fraction)	0.03	0.03	0.06	0.05	0.04	0.03	0.04	0.08	0.06	0.05	0.05	0.06	0.02	0.03	0.04	0.04	0.04	0.05	0.05	0.04
Latent heat flux (W m^{-2})	–31.9	–25.3	–36.4	–49.8	–33.3	–31.1	–32.1	–36.9	–42.3	–34.3	–21.7	–32.3	–21.1	–23.2	–22.8	–28.8	–29.1	–32.4	–39.8	–30.4
Sensible heat flux (W m^{-2})	17.0	8.5	15.6	20.0	14.7	10.5	12.5	4.1	9.5	8.1	5.8	–3.3	9.8	9.1	6.1	12.4	6.3	11.2	14.4	10.8
Specific humidity (g kg^{-1})	–1.6	–1.1	–2.1	–2.8	–1.7	–1.4	–1.3	–1.9	–2.6	–1.5	–1.0	–1.6	–0.5	–1.1	–0.9	–1.3	–1.3	–1.6	–2.3	–1.4
Precipitation (mm day^{-1})	–1.4	–1.5	–0.9	–2.2	–1.4	–2.4	–1.9	–0.7	–3.2	–1.7	–1.4	–1.6	–0.5	–0.6	–0.9	–1.7	–1.6	–0.8	–2.0	–1.3
PBL height (m)	125.7	28.7	31.7	220.9	94.9	97.2	27.7	–124.7	174.3	34.7	–81.7	–50.5	–34.0	12.3	–35.8	51.6	3.2	–20.8	145.1	43.4
Total cloud cover (fraction)	–0.09	–0.05	–0.09	–0.13	–0.07	–0.08	–0.06	–0.07	–0.17	–0.08	0.02	–0.06	0.01	–0.02	–0.01	–0.05	–0.06	–0.06	–0.11	–0.06

Results are presented as differences (tropical forest vegetation removal – control) and averaged annually and seasonally for both individual regions and the entire biome. Averages include only values significant at the 95% significance level using a two-sided Student's *t*-test. Seasonal averages may not equal annual averages since locations significant on an annual average may not always be significant for an individual season. All variables shown represent surface-level values except the planetary boundary layer height ('PBL height') and total cloud cover

changes in convective activity can have a significant impact on the climate outside of the tropics as the modified tropical outflow teleconnects to the extratropics by the anomalous forcing of Rossby waves (Chase et al. 2000).

5 Effects of boreal forests on climate

Land cover change in the boreal forest has a significant influence on the climate system mostly through changes to the surface radiative energy budget. Changes in the surface albedo due to snow versus vegetation cover and the variability of cloud cover combine to strongly influence the radiative balance at the surface. As a result, modest land use changes in the boreal ecosystem can have a considerable impact on the Northern Hemisphere climate.

Early research on the interaction of the boreal forests and the atmosphere has focused on the role of the albedo in modifying the surface radiation budget. Thomas and Roundtree (1992) first examined the influence of changing the surface albedo on the climate by simulating a boreal forest-covered surface and a bare snow-covered surface. They found an increase in the surface albedo, reductions in net radiation, surface air temperature, and precipitation, and changes in the snow cover and persistence. Bonan et al. (1992, 1995) also explored the role of the boreal forest ecosystem in influencing the climate. They found that a redistribution of the boreal forest ecosystem due to land use change or global warming could instigate important climate feedbacks that might influence regions outside the current boundary of the ecosystem.

Figure 4 illustrates the important biophysical processes occurring after complete removal of the boreal forest vegetation. Unlike the tropical forest biome, removal of the boreal forest vegetation has a large effect on the surface radiative balance because of the strong snow/ice/albedo feedback. Replacing the forest vegetation with bare ground that will be snow covered increases the albedo considerably. The land surface responds by absorbing less net radiation as more incoming solar radiation is reflected from the surface. The air temperature at the surface will cool considerably as there is less energy absorbed at the surface. A reduced sensible heat flux occurs because of the colder land surface and the latent heat flux is also reduced during the growing season because of a reduction in evapotranspiration due to vegetation removal. While the overall response of total boreal vegetation removal is to cool the land surface, the climate response is amplified with the addition of interactive SSTs and sea-ice through a SST/sea-ice/albedo/thermohaline circulation feedback mechanism (Bonan et al. 1992; Ganopolski et al. 2001; Brovkin et al. 2003).

For this simulation the boreal forest spans two large regions of the high latitude northern hemisphere (see Fig. 1) and includes the boreal evergreen forest and

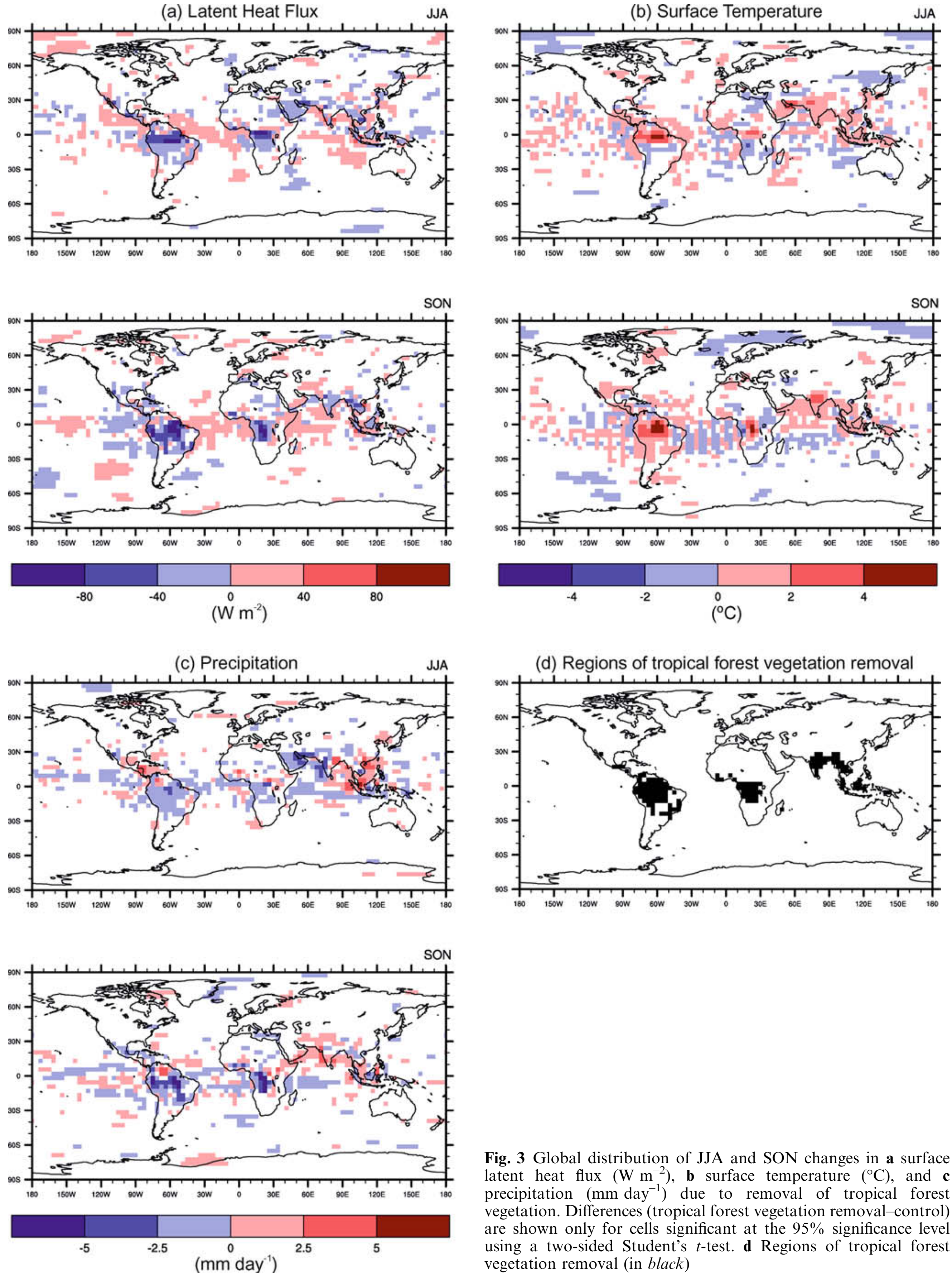


Fig. 3 Global distribution of JJA and SON changes in **a** surface latent heat flux (W m^{-2}), **b** surface temperature (°C), and **c** precipitation (mm day^{-1}) due to removal of tropical forest vegetation. Differences (tropical forest vegetation removal–control) are shown only for cells significant at the 95% significance level using a two-sided Student's *t*-test. **d** Regions of tropical forest vegetation removal (in *black*)

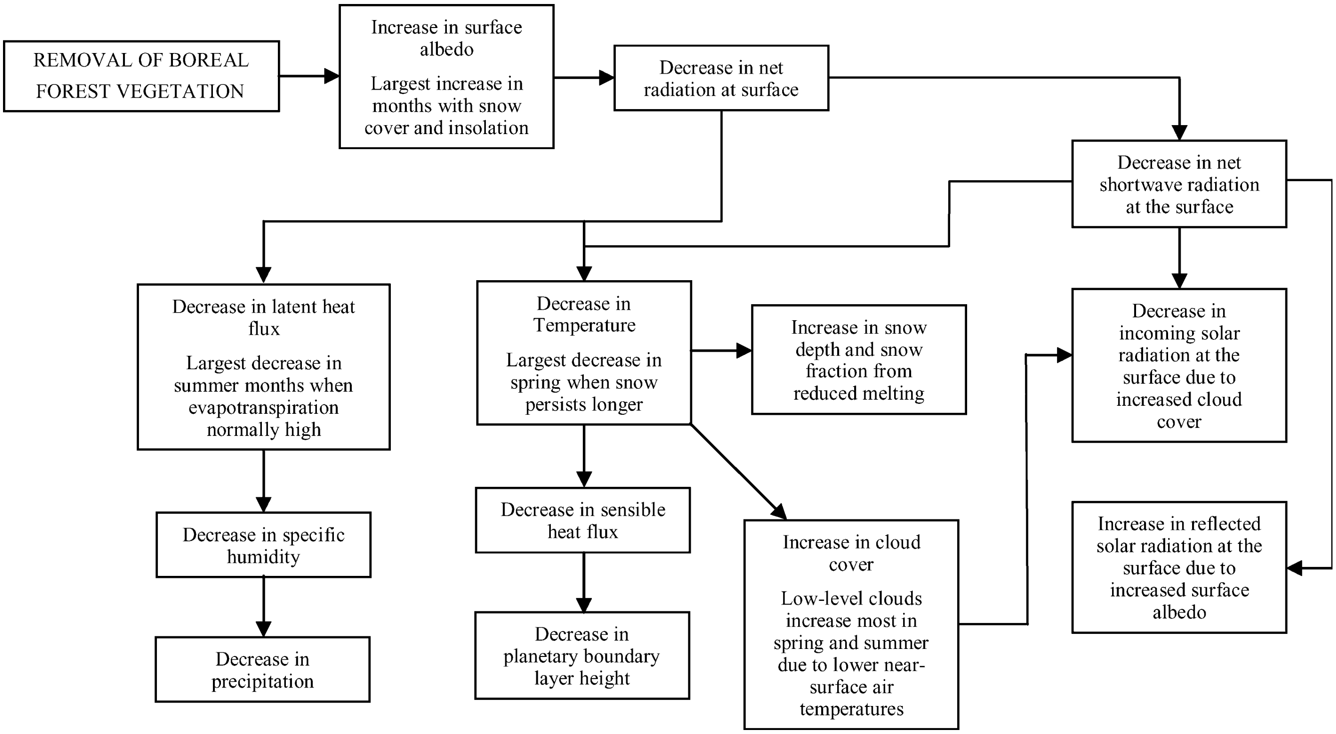


Fig. 4 Conceptual flowchart representing the impact of boreal forest vegetation removal on the climate

woodland class, the boreal deciduous forest and woodland class, and some cells of the mixed forest and woodland class. In the model the biome covers over 22 000 000 km^2 which is about 15% of the land surface of the Earth (Table 1).

In our simulation, removal of the boreal forest vegetation causes a large annual-average increase in the surface albedo of 0.26 (156%) over the entire biome (Table 3). The albedo change is largest in the winter and spring seasons (0.51 and 0.37) when removal of the vegetation exposes the more reflective snow underneath. However, it only becomes climatically important late in February when the incoming solar radiation becomes a factor.

The large increase in the surface albedo decreases the net radiation in the deforested regions annually by 14 W m^{-2} (a 27% reduction). The seasonality of the net radiation is more pronounced with a reduction of 30 W m^{-2} (44%) in MAM, a 21 W m^{-2} (19%) reduction in JJA, and little change in the SON and DJF seasons when there is little or no incoming solar radiation to be reflected. The large reduction in net radiation in MAM (and to a lesser extent JJA) acts to keep the surface much cooler than normal.

As a result of the large changes in the surface energy budget from vegetation removal, our results show that the temperature responds quite dramatically throughout the entire biome with the annual-average temperature

Table 3 Selected results from the boreal forest vegetation removal simulation. Results are presented as differences (boreal forest vegetation removal – control). Averaging and statistical significance as in Table 2. All variables shown represent surface-level values except PBL height, total cloud cover, and low-level clouds

Variable	North America					Eurasia					All Boreal				
	DJF	MAM	JJA	SON	annual	DJF	MAM	JJA	SON	annual	DJF	MAM	JJA	SON	annual
Temperature (K)	–1.4	–4.9	–2.5	–1.0	–2.2	–2.6	–6.9	–4.7	–0.7	–3.2	–2.1	–6.2	–3.8	–0.9	–2.8
Net radiation (W m^{-2})	–5.9	–27.6	–22.3	–1.0	–13.3	–2.5	–31.3	–20.8	–1.4	–13.6	–3.9	–29.9	–21.3	–1.2	–13.5
Albedo (fraction)	0.51	0.32	0.03	0.12	0.25	0.51	0.39	0.03	0.17	0.27	0.51	0.37	0.03	0.15	0.26
Latent heat flux (W m^{-2})	–4.6	–4.3	–18.1	–6.7	–8.3	–2.5	–7.8	–16.4	–4.5	–6.9	–3.4	–6.6	–17.0	–5.4	–7.4
Sensible heat flux(W m^{-2})	1.7	–23.3	–11.2	6.9	–6.8	3.0	–19.5	–15.4	5.3	–6.9	2.5	–21.0	–13.9	6.0	–6.9
Specific humidity (g kg^{-1})	0.0	–0.3	–0.9	–0.2	–0.3	0.0	–0.6	–1.3	0.1	–0.5	0.0	–0.5	–1.1	–0.1	–0.4
Precipitation (mm day^{-1})	–0.3	–0.3	–0.6	–0.3	–0.3	–0.1	–0.3	–0.7	–0.4	–0.3	–0.2	–0.3	–0.7	–0.3	–0.3
Snow fraction	–0.08	–0.01	0.00	–0.01	–0.02	–0.01	0.14	0.04	0.00	0.05	–0.05	0.10	0.02	0.00	0.03
PBL height (m)	–199.4	–291.5	–162.9	–141.0	–195.7	–155.3	–284.4	–186.9	–136.8	–190.4	–172.1	–287.1	–178.2	–138.4	–192.4
Total cloud cover (fraction)	0.01	0.12	0.08	0.04	0.05	0.00	0.12	0.09	0.03	0.06	0.00	0.12	0.09	0.04	0.05
Low-level clouds (fraction)	0.01	0.19	0.10	0.06	0.07	–0.01	0.21	0.15	0.05	0.10	0.00	0.20	0.14	0.05	0.09

dropping by 2.8 °C. When examining individual seasons MAM has the largest temperature decrease at 6.2 °C (Fig. 5a) followed by JJA when the temperature drops by 3.8 °C over all deforested regions. The large temperature decrease in MAM is coherent with an increase in the snow cover fraction (and corresponding albedo) due to a reduction in snow melt even though precipitation (primarily falling as snow) decreases (Fig. 5b). Interestingly the Eurasian region is 1.0 °C colder annually and 2.0 °C and 2.2 °C colder in MAM and JJA, respectively. The colder Eurasian temperatures may be due to a number of factors such as a weak enhancement of the Siberian High, changes in the general circulation as a result of variations in the snow cover (Cohen et al. 2001), changes in the cloud cover fraction and spatial distribution, and differences in the size of the deforested area and position on the continent, and proximity to the ocean.

The extreme drop in temperature between the vegetation removal and control simulations can be explained by a combination of two processes. First, there is the large surface albedo difference that reduces the amount of net radiation absorbed at the surface. This makes the surface colder and inhibits mixing of the PBL. Second, there is a large reduction in the PBL height of 192 m (33%) annually over the entire biome. The MAM season has a lowering of the PBL height of almost 287 m (44%) averaged over the deforested regions. As a result of the reduced PBL height the low-level cloud cover fraction over the deforested regions increases by 0.09 annually and by as much as 0.20 (51%) during the MAM season (Fig. 5c). Furthermore, increasing the low-level cloud cover reduces the incoming shortwave radiation and further acts to keep the surface colder than normal.

Vegetation removal has an impact on the hydrologic cycle most during the JJA season when the vegetation is normally photosynthetically active and when there is enough available solar radiation. Consistent with the removal of vegetation in other regions, removal of the boreal forest decreases the JJA latent heat flux and the corresponding near-surface specific humidity as the flux of moisture to the atmosphere is also reduced. Coherent with changes in the latent heat flux and specific humidity, precipitation differences are largest during the JJA

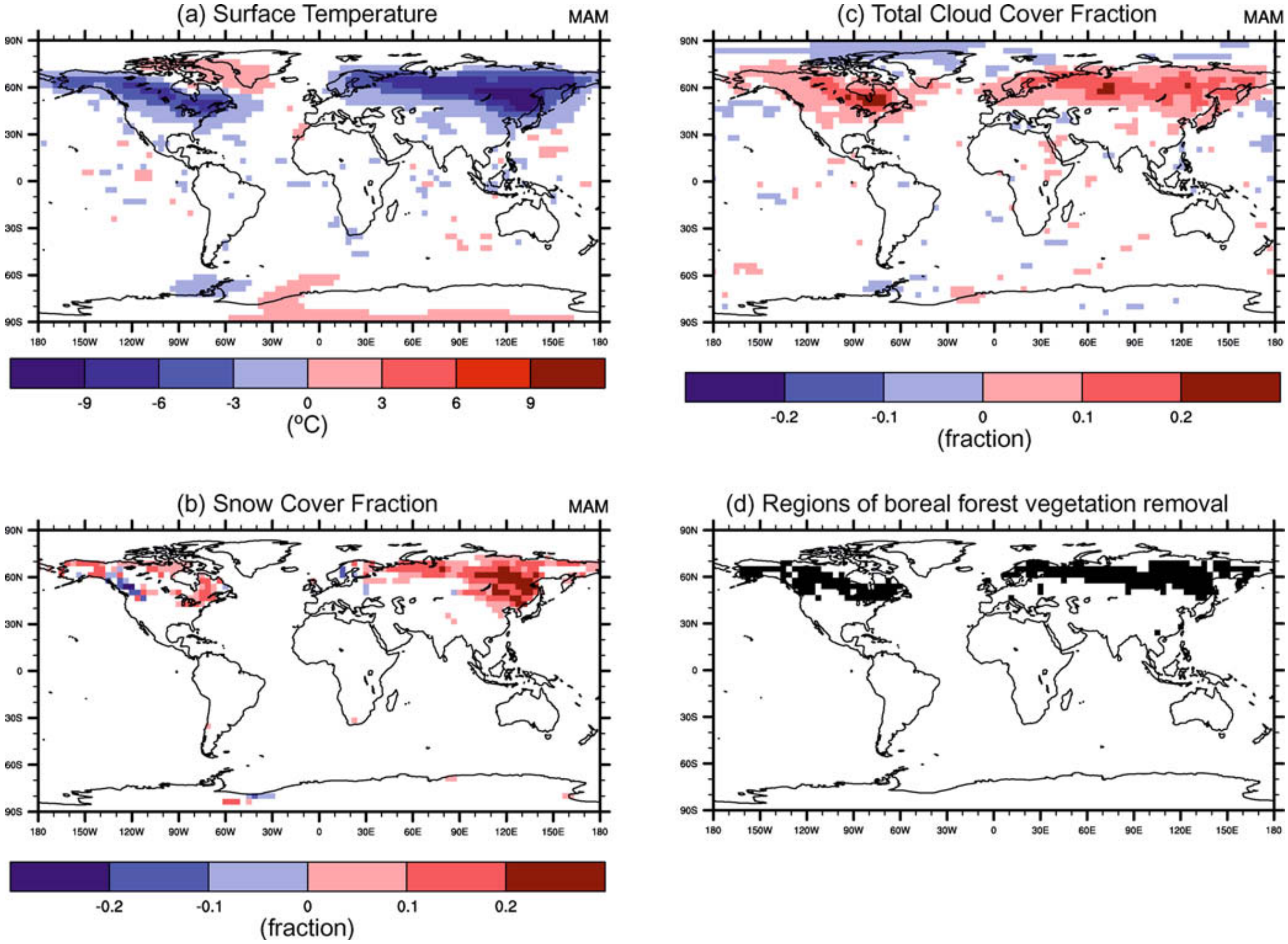


Fig. 5 Global distribution of MAM changes in **a** surface temperature (°C), **b** snow fraction, and **c** total cloud fraction due to removal of boreal forest vegetation. Significance of differences as described in Fig. 3. **d** Regions of boreal forest vegetation removal (in *black*)

season when the moisture flux from the transpiring vegetation would normally be largest. As a result, the air becomes less humid and the only additional moisture available for precipitating must be advected from outside the deforested regions. Averaged over the entire biome the annual-average precipitation decrease is 0.3 mm day^{-1} (15%) while over just the JJA season the reduction is 0.7 mm day^{-1} (25%).

6 Effects of temperate forests on climate

There have been several studies exploring the impact of land use change in temperate forest regions. Bonan (1997, 1999, 2001), for example, looked at the climatic effect of replacing much of the native temperate forests of the Eastern United States with crops. Bonan (1997, 1999, 2001) found that the change from natural to modern vegetation has significantly altered the climate through cooling the eastern United States in spring by 1.0 °C and the central United States in summer by 2.0 °C, warming the western United States in spring by 1.0 °C, altering the diurnal temperature range, and increasing the humidity of the near-surface atmosphere.

The temperate forest biome is unique in that it is located in a large latitude band between the tropical and boreal forest biomes. As a result of its geographic location, removal of the temperate forest vegetation interacts differently with the atmosphere depending on the season. In winter and spring removal of the temperate forests behaves more like the boreal forest removal simulation with lower surface temperatures, more snow cover due to less snowmelt, a higher surface albedo, less net radiation absorbed at the surface, and an increase in low-level cloud cover. In summer, the temperate forest removal simulation behaves more like the tropical forest removal simulation with higher temperatures due to a reduction in latent cooling, an increased surface albedo, and decreases in net radiation and cloud cover. Therefore, during the summer and fall seasons the important physical mechanisms outlined in Fig. 2 are applicable for the temperate forest case. During the winter and spring seasons the physical mechanisms described in Fig. 4 are more appropriate.

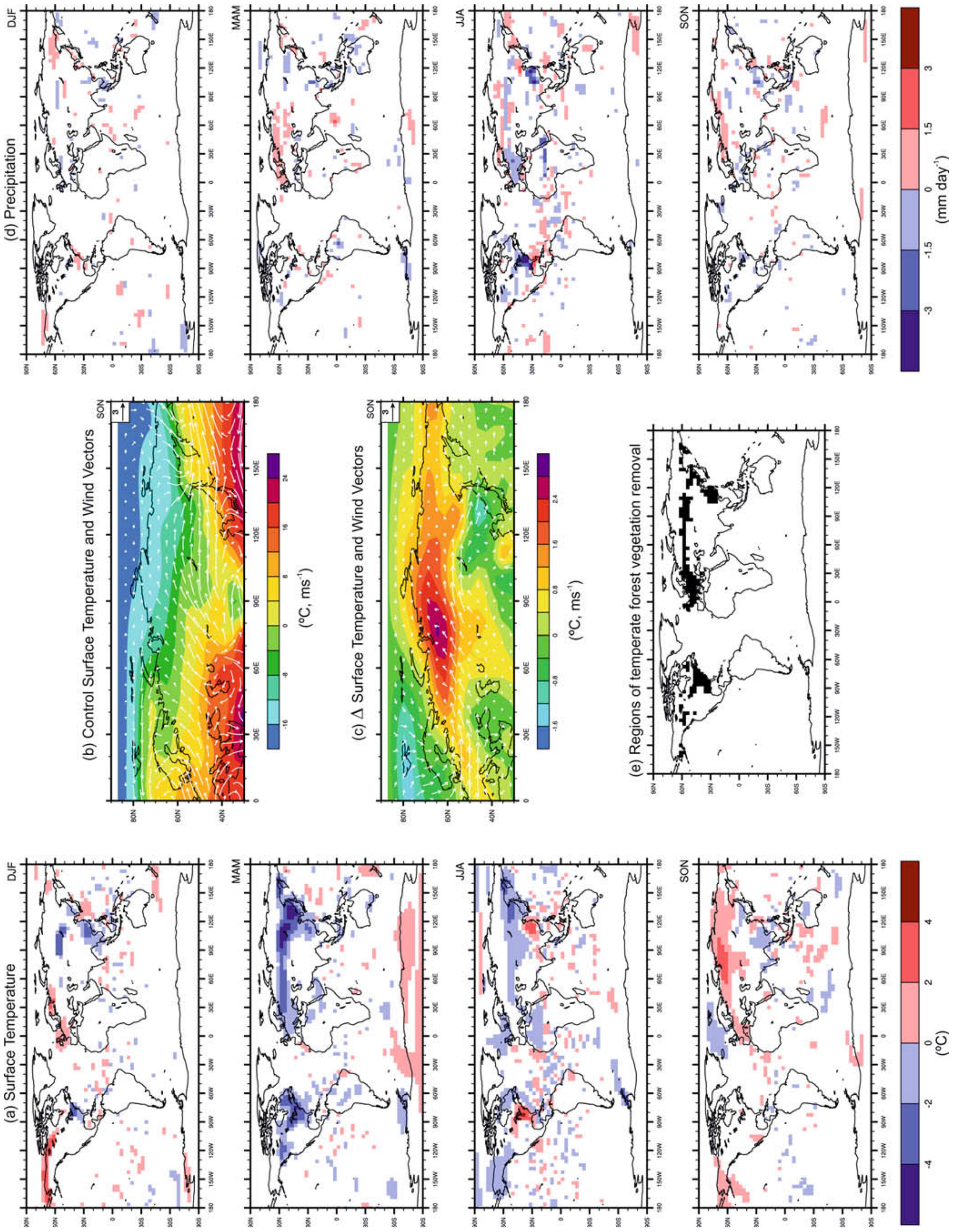
For our simulation, the temperate forest biome is assumed to include temperate evergreen broadleaf forests and woodlands, temperate evergreen conifer forests and woodlands, temperate deciduous forests and woodlands, and a mixed forest and woodland category (Fig. 1). This biome covers a little over 19 000 000 km^2 in the model which is about 13% of the total land cover area of the Earth (Table 1).

Our temperate forest vegetation removal results show a decrease in the surface temperature of the regions where the vegetation has been removed by 1.1 °C annually with the largest decrease in MAM of 2.4 °C (Table 4; Fig. 6a). In contrast, the temperature increases slightly in JJA and SON by 0.3 °C and 0.6 °C, respectively. The small JJA average change hides the strong warming in the Eastern United States and China (1.3 °C) and the modest cooling of 0.9 °C in the high-latitude mixed forest region of Asia (Fig. 6a).

There is a considerable warming in the SON season centered over north-central Siberia at 70°E. This region of warmer surface temperatures is located near the temperate forest region yet it is directly affected by the removal of the forests to the south and southwest. Figure 6b shows the control simulation surface temperature and wind vectors for the region in SON. Figure 6c illustrates the difference in surface temperature and wind vectors between the temperate vegetation removal and control simulations. In this case removal of the temperate forests reduces the roughness of the surface and increases the low-level winds. Increased low-level winds

Table 4 Selected results from the temperate forest vegetation removal simulation. Results are presented as differences (temperate forest vegetation removal – control). Averaging and statistical significance as in Table 2. All variables shown represent surface-level values except PBL height and total cloud cover

Variable	High-latitude temperate forests					Temperate forests					All temperate				
	DJF	MAM	JJA	SON	annual	DJF	MAM	JJA	SON	annual	DJF	MAM	JJA	SON	annual
Temperature (K)	–1.6	–3.0	–0.9	1.1	–1.3	–1.1	–1.9	1.3	0.2	–0.8	–1.3	–2.4	0.3	0.6	–1.1
Net radiation (W m^{-2})	–5.8	–23.5	–18.1	–1.6	–11.9	–3.3	–11.8	–31.0	–9.1	–13.2	–4.4	–17.2	–25.4	–6.0	–12.7
Albedo (fraction)	0.52	0.28	0.03	0.12	0.23	0.16	0.06	0.05	0.04	0.08	0.32	0.16	0.04	0.07	0.15
Latent heat flux (W m^{-2})	–3.7	–2.1	–20.5	–6.5	–7.4	–4.7	–3.0	–36.9	–13.1	–14.0	–4.2	–2.6	–31.0	–10.3	–11.3
Sensible heat flux (W m^{-2})	0.8	–22.5	–6.6	5.8	–6.2	4.0	–11.5	6.3	5.9	0.7	2.5	–17.0	0.2	5.8	–2.5
Specific humidity (g kg^{-1})	0.0	0.1	–0.9	0.1	–0.3	0.0	–0.3	–1.9	–0.8	–0.7	0.0	–0.1	–1.5	–0.3	–0.5
Precipitation (mm day^{-1})	–0.1	–0.4	–0.9	–0.4	–0.3	–0.2	–0.7	–1.5	–0.7	–0.6	–0.1	–0.5	–1.3	–0.5	–0.5
Snow fraction	–0.04	–0.04	0.00	–0.05	–0.02	–0.11	–0.02	0.01	–0.03	–0.03	–0.08	–0.03	0.00	–0.04	–0.03
PBL height (m)	–182.4	–277.1	–146.2	–152.9	–179.6	–145.7	–175.7	46.5	–98.1	–96.1	–161.5	–219.2	–39.2	–123.8	–132.8
Total cloud cover (fraction)	0.00	0.08	0.02	0.01	0.03	0.08	0.07	–0.10	–0.03	0.01	0.05	0.07	–0.06	–0.02	0.02


(a) Surface Temperature
DJF
MAM
JJA
SON
(°C)
-4
-2
0
2
4
(b) Control Surface Temperature and Wind Vectors
SON
(°C, ms-1)
-16
-8
0
8
16
24
(c) Δ Surface Temperature and Wind Vectors
SON
(°C, ms-1)
-1.6
-0.8
0
0.8
1.6
2.4
(d) Precipitation
DJF
MAM
JJA
SON
(mm day-1)
-3
-1.5
0
1.5
3
(e) Regions of temperate forest vegetation removal

◀

Fig. 6 Global distribution of seasonal changes in **a** surface temperature (°C) due to removal of temperate forest vegetation. Significance of differences as described in Fig. 3. **b** Control simulation surface temperature (°C) and winds (m s^{-1}) for SON. **c** Difference plot of SON surface temperature and winds. **d** Global distribution of seasonal changes in precipitation (mm day^{-1}). **e** Regions of temperate forest vegetation removal (in *black*)

enhance the advection of warm air into the region from the south and the west. The convergence of warm air in this region increases the temperature of the boreal and tundra regions by greater than 2 °C. This example illustrates how the removal of vegetation in one region can affect the climate of regions adjacent to or partially removed from the surface forcing.

With removal of the temperate forest vegetation, the annual-average surface albedo increases by 0.15 and is largest in winter (0.32) where the snow is no longer covered by the forest canopy. The high-latitude mixed forest region of the temperate forest class contributes the most to the large increase in the albedo (0.52 versus 0.16) as this region behaves like the boreal forest removal simulation. In summer the albedo is still high as the bare soil also has a slightly higher albedo (0.04) than the vegetation. As with the tropical forest removal simulation the higher surface albedo reduces the net radiation absorbed at the surface and reduces the energy available for use in convective precipitation during JJA (25.4 W m^{-2}). This positive feedback mechanism is most important in the low-latitude temperate forest regions of the eastern United States and China where precipitation is normally at a maximum during the JJA season (Fig. 6d).

How the land surface partitions the net radiation at the surface into latent and sensible heating is dependent on the season as well as the latitude. The latent heat flux changes by –11.3 W m^{-2} annually and the change is largest in JJA (–31.0 W m^{-2}) when vegetation is normally transpiring the most. Regionally in JJA the lower-latitude temperate forest regions have a larger decrease in the latent heat flux (36.9 W m^{-2}) versus the high-latitude mixed forest regions (20.5 W m^{-2}). There is little change in the sensible heat flux with a reduction of 2.8 W m^{-2} annually. Seasonally the sensible heat flux reduction with vegetation removal is largest in MAM (17.0 W m^{-2}) with the high-latitude mixed forest region contributing the most (22.5 W m^{-2}). The large reduction in sensible heat flux in MAM is due to the reduced net radiation absorbed at the surface and the colder surface temperatures. The latent heat flux is not a factor during this time as the land surface is still too cold for much evapotranspiration to occur.

As was seen with the tropical forest results, removal of the temperate forests reduces the latent heat flux and the corresponding flux of moisture into the atmosphere as seen by the reduction in the near-surface specific humidity (Table 4). The reduction is largest during the growing season (JJA) and contributes to a drying of the atmospheric column and a decrease in precipitation (Fig. 6d). The annual-average decrease in precipitation for the entire biome is 0.5 mm day^{-1} while the JJA season contributes the most to this decrease (1.3 mm day^{-1}). As with the specific humidity, the lower-level temperate forest removal regions have a larger precipitation decrease while the higher-latitude mixed forest precipitation rate is slightly less negative.

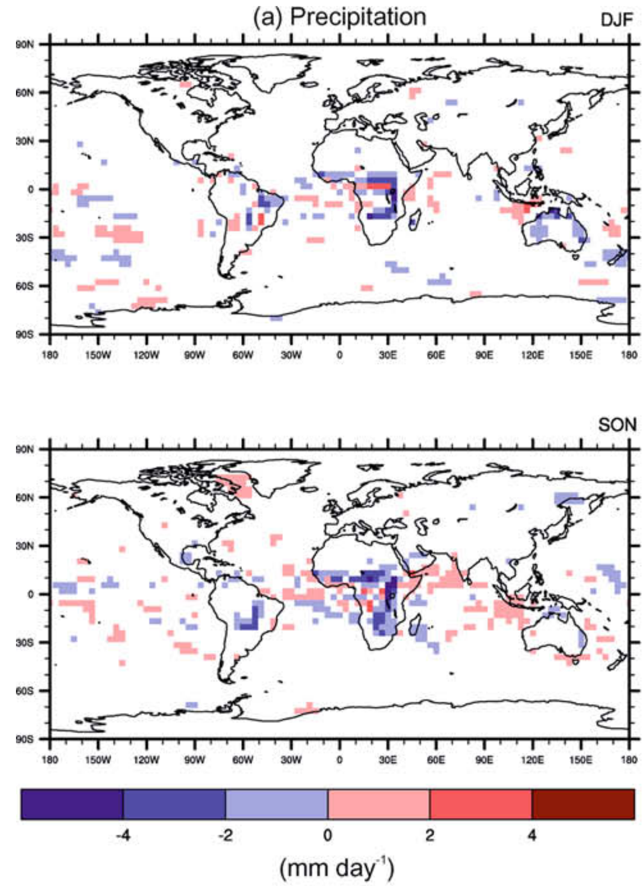
7 Effects of savanna vegetation on climate

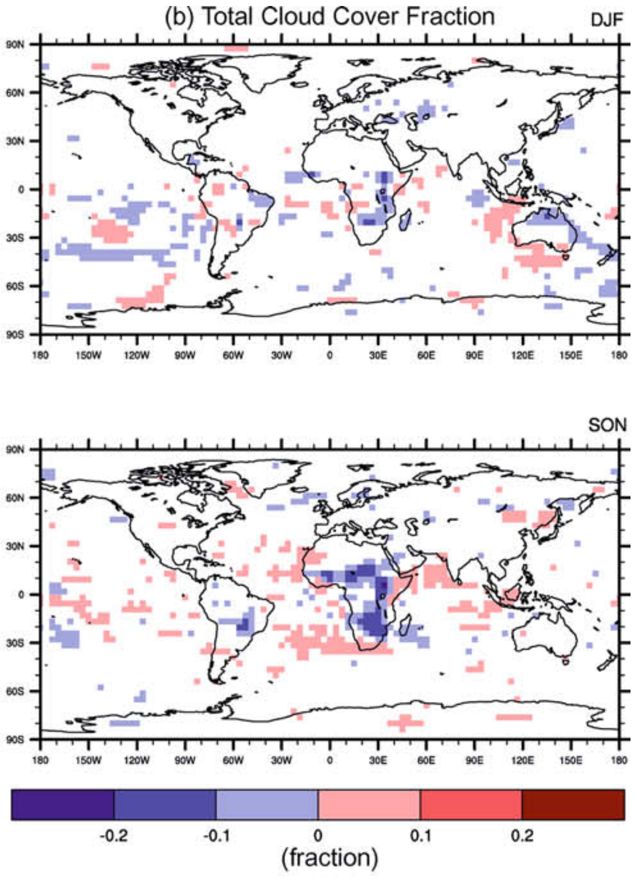
Similar to the tropical forest vegetation removal scenario (see Fig. 2), removal of the savanna vegetation leads to a large reduction in precipitation due to both the reduced moisture flux from the land-surface as well as weakened moisture convergence into the regions. The reduced moisture flux from the surface is related to the reduction in the latent heat flux. Correspondingly, the weakened precipitation, of which most is of the convective type, translates to fewer clouds and an increase in the incoming solar radiation. The albedo increases modestly and reduces the amount of net radiation absorbed at the surface. Finally, the surface warms with a reduction in latent heating due to removal of the vegetation.

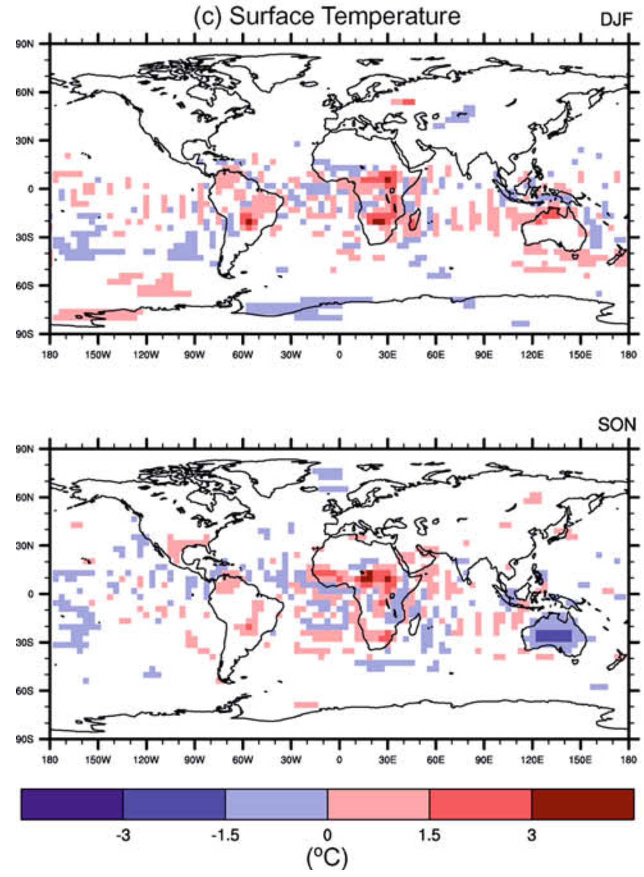
In our simulation the regions comprising the savanna biome are located north and south of the tropical rainforest centers in South America and Africa, eastern Africa, parts of the north, south, and eastern coasts of Australia, the northern Midwest in the United States, and scattered locations in the Northern Hemisphere (Fig. 1). In CCM3/IBIS the savanna biome represents a little over 19 000 000 km^2 or about 13% of the land surface area in the model (Table 1).

Our model results indicate that the most dramatic effect of removing the savanna vegetation is the large reduction in precipitation (Fig. 7a; Table 5). Averaged over all savanna regions, the annual precipitation reduction is 1.1 mm day^{-1} (32%). Seasonally the reduction is largest in SON (1.9 mm day^{-1}) and DJF (2.1 mm day^{-1}); greater than a 50% reduction. The savanna regions of South America and Africa contribute most to the reduction as this is the beginning of the wet season as determined by the model. There is a small region of Australia where the precipitation actually increases in JJA and also in Africa in DJF over the northern tropical forest boundary, however, the overall effect is to reduce the precipitation considerably. It is clear that the savanna vegetation plays an important role in the precipitation intensity and position and that climate-vegetation feedbacks may be very important in this ecosystem.

The decrease in precipitation is brought on both by changes in the moisture convergence due to modification of the regional circulation as well as by changes in the moisture flux from the land-surface into the atmosphere. In our simulation, removal of the savanna vegetation causes a large decrease in the latent heat







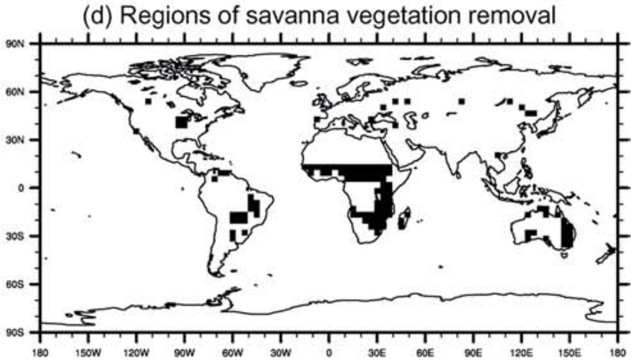


Fig. 7 Global distribution of DJF and SON changes in **a** precipitation (mm day^{-1}), **b** total cloud fraction, and **c** surface temperature (°C) due to removal of savanna vegetation. Significance of differences as described in Fig. 3. **d** Regions of savanna vegetation removal (in *black*)

Table 5 Selected results from the savanna vegetation removal simulation. Results are presented as differences (savanna vegetation removal – control). Averaging and statistical significance as in Table 2. All variables shown represent surface-level values except PBL height and total cloud cover

Variable	South America					Africa					Australia					All savanna				
	DJF	MAM	JJA	SON	annual	DJF	MAM	JJA	SON	annual	DJF	MAM	JJA	SON	annual	DJF	MAM	JJA	SON	annual
Temperature (K)	1.4	1.2	0.6	0.8	0.8	1.1	1.3	1.2	1.1	1.2	1.2	0.1	–0.6	–1.0	–0.4	1.2	1.1	0.9	0.7	0.9
Net radiation (W m^{-2})	–27.0	–21.9	–23.7	–32.1	–24.8	–34.0	–30.8	–22.4	–37.8	–29.3	–42.1	–24.1	–8.4	–36.1	–27.7	–31.2	–26.4	–22.0	–33.4	–26.8
Albedo (fraction)	0.03	0.04	0.05	0.05	0.04	0.07	0.06	0.05	0.07	0.06	0.07	0.06	0.02	0.08	0.06	0.08	0.06	0.05	0.06	0.06
Latent heat flux (W m^{-2})	–29.1	–25.3	–16.4	–23.7	–20.1	–33.7	–29.7	–27.2	–37.2	–28.4	–40.0	–34.2	–5.9	–18.1	–18.3	–31.0	–27.5	–24.1	–30.9	–23.9
Sensible heat flux (W m^{-2})	–0.6	5.4	–9.3	–17.7	–7.0	–1.9	–2.9	–0.5	–7.0	–2.8	–18.0	–7.2	–8.0	–33.4	–15.5	–3.2	–2.9	–4.6	–11.8	–5.6
Specific humidity (g kg^{-1})	–1.1	–1.2	–0.7	–1.1	–0.9	–1.8	–1.5	–1.5	–1.9	–1.5	–1.5	–1.2	0.5	–0.8	–0.6	–1.6	–1.4	–1.1	–1.7	–1.2
Precipitation (mm day^{-1})	–2.4	–1.0	–1.3	–1.7	–1.0	–2.2	–1.3	–1.3	–2.2	–1.2	–1.8	–1.2	0.1	–0.7	–0.7	–2.1	–1.3	–1.2	–1.9	–1.1
PBL height (m)	118.4	106.0	68.2	108.1	82.5	141.5	128.8	150.6	182.3	142.1	147.2	28.6	–58.4	–41.0	15.1	112.2	93.4	90.6	117.1	95.5
Total cloud cover (fraction)	–0.04	–0.07	–0.03	–0.07	–0.03	–0.07	–0.09	–0.09	–0.10	–0.07	–0.07	n/a	0.07	n/a	–0.01	–0.07	–0.09	–0.07	–0.09	–0.06

flux by 23.9 W m^{-2} (32%) annually over all the regions. Consistent with the tropical forest removal results, a reduction in the surface latent heat flux translates well to a reduction in the flux of moisture to the atmosphere. Annually the near-surface specific humidity is reduced by 1.2 g kg^{-1} and is largest in the SON and DJF wet seasons as defined in the model (Table 5). As a result of the reduction in precipitation and the moisture flux from the surface, the cloud cover fraction decreases over the areas where the savanna vegetation has been removed. The savanna region of Africa is most affected and is largest in the SON season (Fig. 7b).

The response of the surface albedo and net radiation to the removal of savanna vegetation is consistent with the tropical forest removal results and the albedo-precipitation positive feedback mechanism. Removal of the savanna vegetation increases the annual-average surface albedo by almost 40%. This causes a decrease in the net radiation absorbed at the surface and reduces the energy available for use in driving convective precipitation. The albedo and net radiation changes are largest in the tropical wet seasons (SON and DJF) and match the reduction in the latent heat flux, near-surface specific humidity, and precipitation.

Throughout the entire biome there is a modest increase in the annual temperature at the surface of 0.9 °C, however there is a seasonal variation between the savanna regions that hides some of the magnitude of the temperature response (Fig. 7c). When the individual regions are examined separately, the South American and African regions show temperature increases of 0.8 and 1.2 °C, respectively. Australia shows a net decrease in surface temperature annually of –0.4 °C and can be explained by the greater seasonal fluctuation in surface energy due to its higher latitude. Overall, the response of removing the savanna vegetation is similar to that of the tropical forests where the surface temperature increases during the peak growing season when latent cooling is normally most active.

8 Effects of grassland and steppe vegetation on climate

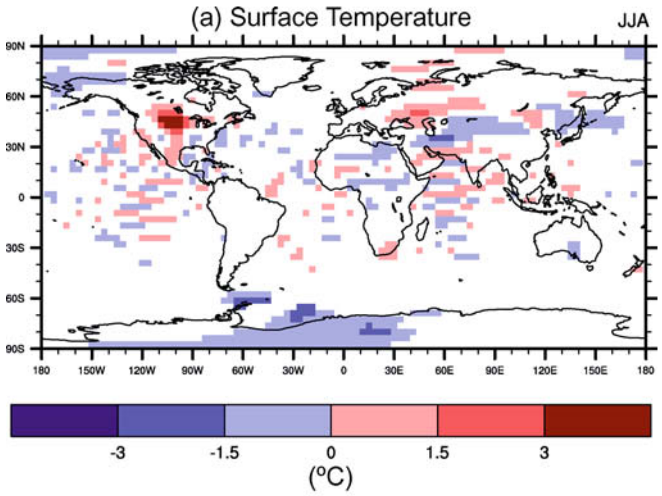
There have been no specific studies describing the influence of grassland/steppe vegetation on the climate. However, there have been several land use change studies that have examined the climate response from the conversion of grasslands to croplands in the central plains as part of a larger analysis of overall land use change in the United States (Copeland et al. 1996; Bonan 1997, 1999, 2001). Although these studies examined the climate response from the conversion between natural vegetation and croplands, the general response of completely removing the natural vegetation can be inferred.

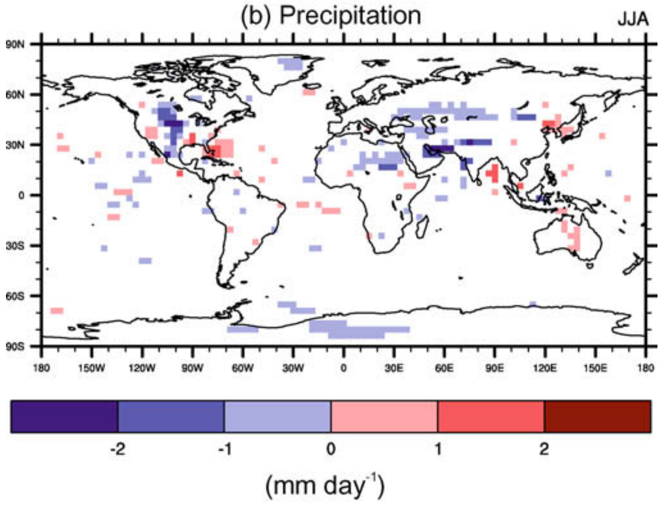
In CCM3-IBIS, grasslands and steppe vegetation are located in the dry and seasonally hot climates of the prairie of the United States Great Plains, south of 30°S in Argentina, the steppes of Central Asia, and part of the southern tip of Africa (Fig. 1). The area of this biome is the smallest of all the vegetation removal simulations in our study and is just over 14 000 000 km^2 or close to 10% of the Earth's land area (Table 1).

The dominant response to the removal of grassland/steppe vegetation is to increase the surface temperature (Fig. 8a). Annually our results indicate a surface temperature increase of 0.7 °C over all the regions (Table 6). A warming occurs in all seasons except DJF which is influenced by the lower winter temperature change just north of Lake Balkhash in the Asian Steppe. The temperature change is largest in North America where the MAM, JJA, and SON seasons show the greatest increases of 1.4 °C, 2.2 °C, and 1.1 °C, respectively. Interestingly, there is little response in the surface temperature in the Asian Steppe region except for a small area in JJA when the northwestern region warms and the southern and central region cools. This is in part due to the subtle difference between how the grassland and steppe vegetation is modeled in IBIS as well as the geographic location of the biomes.

Removal of the grassland/steppe vegetation causes a annual decrease in precipitation by 0.4 mm day^{-1} (22%) over the entire biome (Fig. 8b). The MAM and JJA seasons have a slightly larger decrease in precipitation of 0.8 mm day^{-1} (36%). Consistent with the change in temperature, the precipitation and specific humidity decreases are largest in the central plains region in JJA (1.4 mm day^{-1}, a 53% decrease for precipitation and 2.1 g kg^{-1}, a 23% decrease for specific humidity). The large temperature and precipitation changes that occur in JJA in the North American grasslands are indicators of how important the latent cooling mechanism is for the ecosystem. It is evident from the net radiation and specific humidity results that the moisture and energy fluxes at the surface are important in driving localized convection during the summer months in the great plains (Pielke 2001). Other times of the year synoptic-scale frontal systems generate precipitation with the advection of moisture from outside the region and the land surface has less of an affect on precipitation rates. Furthermore, the reduction in total cloud cover fraction is largest in the North American region in summer (0.09 or 25%). The reduction in total cloud cover fraction is due mostly to reductions in low- and high-level clouds indicative of summertime convective activity.

In our simulation the annual albedo only increases by 0.03 with the small change due to the sparseness of the grassland/steppe vegetation. Seasonally there is a larger albedo increase in DJF for all regions of 0.08 with the Asian Steppe region contributing the most (0.11) due to the higher albedo of the underlying snow cover. The albedo increase reduces the net radiation by more than 15 W m^{-2}. The largest decreases in net radiation occur during the seasons when there is the most incoming solar radiation. In North America the reduction in net radiation is 47.4 W m^{-2} (30%) in JJA. Annually the reduction in the latent heat flux is small when averaged over all the regions (10.7 W m^{-2}), however it is quite large in North America during the peak growing season in JJA (44.8 W m^{-2} or a 52% reduction). The large reduction in the latent heat flux in the Central Plains of





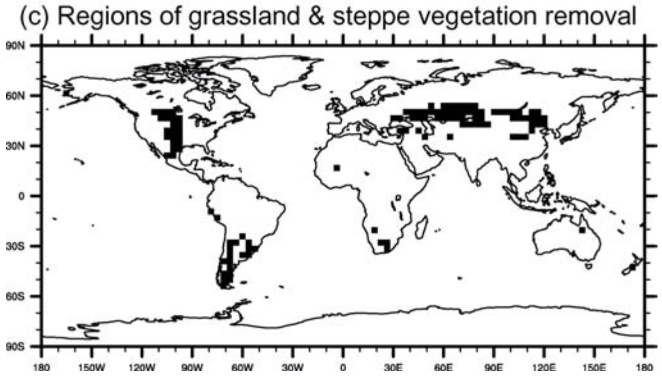


Fig. 8 Global distribution of JJA changes in **a** surface temperature (°C) and **b** precipitation (mm day^{-1}) due to removal of grassland and steppe vegetation. Significance of differences as described in Fig. 3. **c** Regions of grassland and steppe vegetation removal (in *black*)

Table 6 Selected results from the grassland and steppe vegetation removal simulation. Results are presented as differences (grassland and steppe vegetation removal – control). Averaging and statistical significance as in Table 2. All variables shown represent surface-level values except PBL height, total cloud cover, and high-level clouds

Variable	North America					Asian Steppe					Southern Hemisphere					All grassland and steppe				
	DJF	MAM	JJA	SON	annual	DJF	MAM	JJA	SON	annual	DJF	MAM	JJA	SON	annual	DJF	MAM	JJA	SON	annual
Temperature (K)	0.8	1.4	2.2	1.1	1.1	–1.3	n/a	0.4	0.8	0.0	0.1	0.5	0.4	0.4	0.4	–0.5	1.0	1.0	0.8	0.7
Net radiation (W m^{-2})	–2.3	–18.0	–47.4	–12.1	–19.5	–3.6	–10.4	–32.0	–5.3	–12.4	–36.5	–12.7	–6.6	–24.9	–18.3	–12.1	–12.6	–28.4	–12.1	–15.5
Albedo (fraction)	0.04	0.03	0.05	0.02	0.04	0.11	0.03	0.04	0.00	0.05	0.04	0.00	–0.02	0.02	0.01	0.08	0.02	0.03	0.01	0.03
Latent heat flux (W m^{-2})	–3.3	–19.7	–44.8	–10.2	–18.0	–2.1	–10.1	–18.5	–3.9	–7.6	–17.2	–13.1	–9.8	–13.3	–10.8	–6.5	–13.5	–23.0	–8.6	–10.7
Sensible heat flux (W m^{-2})	–4.0	–2.8	–8.4	–2.3	–2.5	1.1	–7.4	–17.6	–3.3	–7.1	–21.2	–3.9	–0.2	–16.6	–9.3	–7.2	–5.5	–11.2	–7.7	–7.0
Specific humidity (g kg^{-1})	–0.5	–0.9	–2.1	–0.6	–0.9	–0.1	–0.4	–0.9	–0.4	–0.3	–0.5	–0.6	–0.2	–0.6	–0.3	–0.4	–0.7	–1.1	–0.6	–0.5
Precipitation (mm day^{-1})	–0.2	–0.9	–1.4	–0.4	–0.6	–0.2	–0.5	–0.5	n/a	–0.2	–0.6	–0.6	–0.3	–0.6	–0.4	–0.5	–0.8	–0.8	–0.5	–0.4
PBL height (m)	–25.0	91.7	215.2	46.0	83.8	–29.2	–4.0	56.6	–32.7	6.5	–5.0	6.9	–47.2	–14.0	–14.0	–21.4	27.9	84.3	–3.5	25.1
Total cloud cover (fraction)	n/a	–0.04	–0.09	–0.03	–0.04	0.03	0.03	–0.05	0.01	–0.02	–0.03	–0.04	0.04	–0.02	–0.03	0.01	–0.02	–0.07	–0.01	–0.03
High-level clouds (fraction)	–0.02	–0.03	–0.09	n/a	–0.04	–0.04	–0.04	–0.04	0.03	–0.02	–0.04	–0.01	n/a	–0.03	–0.02	–0.04	–0.03	–0.07	–0.02	–0.03

North America during the summer is coherent with the temperature, specific humidity, and precipitation changes in the region.

9 Effects of shrubland and tundra vegetation on climate

The combined shrubland and tundra biome is spatially the largest aggregation of vegetation included in this study yet it has the least influence on the climate system due to the vegetation's physiology and geography. The shrubland/tundra vegetation classes represent close to 25 000 000 km^2 or 17% of the Earth's land area (Table 1; Fig. 1). IBIS does simulate the freezing of soil, but only crudely represents permafrost processes. Therefore, feedbacks of tundra removal on permafrost are not completely represented although in reality they may act to amplify the climate signal. For this simulation the regional averages for most variables are more meaningful than the total biome averages since the various regions are located in different hemispheres and latitudes.

Our simulation results show an overall annual increase in the surface temperature for all regions of 0.3 °C (Table 7). There is a slightly larger warming in DJF of 0.9 °C, however the main contributor is from the shrubland of northwest Australia where the temperature increases by 1.2 °C (Fig. 9a). Australia shows a moderate cooling during the austral winter with temperatures dropping by less than 1.0 °C. Although the temperature change is mostly situated over the regions where the vegetation has been removed, a large temperature anomaly exists in central Siberia (northwest of Lake Baikal) where there is a region with a large cooling of greater than 2.0 °C in DJF. The most plausible explanation for this temperature anomaly is from the increase in the surface pressure in a large region just north of the cooling center that enhances the wintertime high pressure pattern over Siberia. This acts to weaken the advection of warm air from the southwest, thus keeping surface temperatures colder than normal throughout the winter.

The precipitation response is limited to the Southern Hemisphere regions of the eastern tip of Brazil, Ethiopia and Somalia, and most of Australia (Fig. 9b). For the Southern Hemisphere region there is an annual-average decrease in the precipitation by 0.4 mm day^{-1} with the DJF season having the largest decrease over the three regions by 1.4 mm day^{-1} (a 46% reduction). There are also slight precipitation decreases in Australia in SON, in the western United States in JJA, and in Pakistan and north of India in JJA, however the primary response is located in the Southern Hemisphere during the MAM season. Reasons for the reduction in precipitation in the Southern Hemisphere are similar to the tropical forest and savanna ecosystems. Mainly, the removal of vegetation limits the concentration of water vapor in the region due to the reduced flux from the surface during transpiration.

Table 7 Selected results from the shrubland/tundra vegetation removal simulation. Results are presented as differences (shrubland/tundra vegetation removal – control). Averaging and statistical significance as in Table 2. All variables shown represent surface-level values except PBL height and total cloud cover

Variable	Asia and Southwest US					S. America and Australia					Canada/Siberia					All shrubland/tundra				
	DJF	MAM	JJA	SON	annual	DJF	MAM	JJA	SON	annual	DJF	MAM	JJA	SON	annual	DJF	MAM	JJA	SON	annual
Temperature (K)	−0.1	0.6	0.3	0.5	0.3	1.2	0.2	−0.4	−0.7	0.3	−2.1	−1.0	−0.3	1.1	n/a	0.9	0.5	0.1	0.0	0.3
Net radiation (W m^{-2})	−6.1	−13.3	−18.6	−9.4	−11.2	−29.2	−13.6	−6.5	−22.7	−17.9	−1.0	−0.8	−1.2	−1.0	−1.1	−14.4	−12.8	−13.6	−13.1	−12.8
Albedo (fraction)	−0.02	0.01	0.02	0.00	0.00	0.04	0.01	−0.01	0.03	0.02	0.01	−0.01	−0.06	−0.04	−0.02	0.01	0.01	−0.01	0.01	0.01
Latent heat flux (W m^{-2})	-3.4	−10.7	−12.4	−9.7	−7.0	−27.7	−11.1	−6.0	-9.6	-9.9	−0.4	2.7	−1.2	−1.7	−1.0	−14.3	−10.5	−10.9	−8.1	−7.5
Sensible heat flux (W m^{-2})	−4.2	−10.0	−12.0	−6.9	−6.9	−16.4	−8.0	−5.1	−16.7	−9.9	1.9	−1.2	−3.1	3.0	−0.3	−7.4	−8.9	−8.3	−10.7	−7.5
Specific humidity (g kg^{-1})	−0.1	−0.4	−0.7	−0.5	−0.3	−1.7	−0.5	−0.1	−0.5	−0.5	0.1	n/a	−0.3	0.1	−0.1	−1.3	−0.4	−0.6	−0.4	−0.4
Precipitation (mm day^{-1})	−0.2	−0.6	−0.8	−0.5	−0.3	−1.4	−0.5	0.0	−0.5	−0.4	0.1	n/a	−0.2	−0.7	0.0	−1.0	−0.5	−0.7	−0.5	−0.3
PBL height (m)	83.9	83.2	62.4	65.9	56.2	176.1	61.6	36.9	29.5	75.6	15.1	−12.9	−13.5	6.5	−5.0	136.0	69.0	48.3	50.6	56.4
Total cloud cover (fraction)	0.01	−0.04	−0.05	−0.04	−0.02	−0.09	−0.03	0.01	−0.03	−0.03	−0.01	0.03	0.04	−0.05	0.02	−0.07	−0.03	−0.03	−0.04	−0.02

10 Cross-biome comparisons

In order to compare the relative influence that the different biomes have on the climate system, Table 8 lists the change in temperature and precipitation between

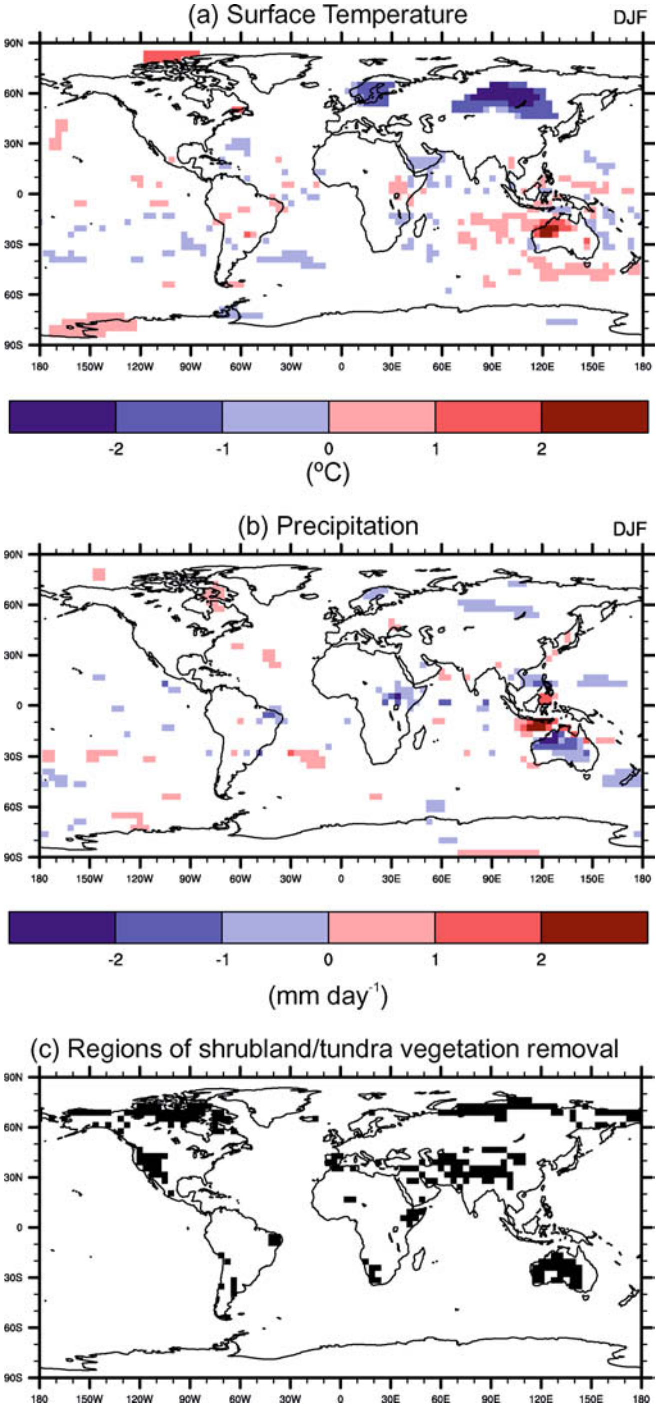


Fig. 9 Global distribution of DJF changes in **a** surface temperature (°C), and **b** precipitation (mm day^{-1}) due to removal of shrubland and tundra vegetation. Significance of differences as described in Fig. 3. **c** Regions of shrubland and tundra vegetation removal (in *black*)

Table 8 Summary of each biome's influence on the annual average temperature (°C) and precipitation (mm day^{-1}). Results are presented as differences (vegetation removal - control) averaged using all cells comprising the biome where the vegetation has been removed (column 2), the global average using all cells in the model (column 3), the global average over only land cells (column 4), the normalized (change divided by the total biome area) global average (column 5), and the global average of all land cells *except* those comprising the biome (column 6). Statistical significance as in Table 2

Biome	$\Delta T_{\text{devegetated region}}$	ΔT_{global}	$\Delta T_{\text{global land}}$	$\Delta T_{\text{global normalized}}$ $(10^{-9} \times °\text{C km}^{-2})$	$\Delta T_{\text{global land except devegetated region}}$
Tropical forest	1.18	0.24	0.71	10.5	0.20
Boreal forest	–2.75	–0.77	–1.58	–34.4	–0.85
Temperate forest	–1.07	–0.22	–0.46	–11.5	–0.27
Savanna	0.87	0.12	0.37	6.36	0.06
Grassland and steppe	0.75	0.05	0.20	3.80	0.04
Shrubland/tundra	0.32	–0.01	0.04	–0.286	–0.15

Biome	$\Delta P_{\text{devegetated region}}$	ΔP_{global}	$\Delta P_{\text{global land}}$	$\Delta P_{\text{global normalized}}$ $(10^{-9} \times \text{mm day}^{-1}\ \text{km}^{-2})$	$\Delta P_{\text{global land except devegetated region}}$
Tropical forest	–1.34	–0.11	–0.55	–4.75	0.18
Boreal forest	–0.27	0.00	–0.11	0.0134	0.04
Temperate forest	–0.49	–0.06	–0.18	–2.90	0.00
Savanna	–1.10	–0.19	–0.61	–9.98	–0.03
Grassland and steppe	–0.41	–0.12	–0.31	–8.65	–0.22
Shrubland/tundra	–0.35	–0.08	–0.31	–3.27	–0.23

each of the vegetation removal simulations and the control simulation. Changes are represented as annual averages over just the biome region (column 2), as a global average (column 3), as a global average of just land cells (column 4), as a normalized (change divided by the total biome area) global average (column 5), and as a global land average excluding the region of vegetation removal (column 6).

Within the individual biome areas, it is clear that the larger biomes with denser vegetation cover are the most influential. From Table 8 (column 2) removal of the boreal forest vegetation yields the largest temperature response of –2.8 °C annually averaged over the entire biome. The tropical forest biome also has a large temperature increase of 1.2 °C annually with vegetation removal. Removal of the tropical forest vegetation influences the climate mostly through large reductions in water recycling by changing the annual average precipitation by –1.3 mm day^{-1}. The boreal forest biome has a rather small decrease in precipitation annually of only 0.3 mm day^{-1}. Therefore, removal of the tropical forest vegetation influences the climate through changes in the precipitation, and to a lesser degree temperature, while removal of the boreal forest vegetation influences the climate strongly through a reduction in temperature, but weakly with respect to precipitation.

Globally, removal of the boreal forest vegetation also most influences the temperature while removal of savanna vegetation, grassland/steppe vegetation, and tropical forest vegetation most influences the precipitation (Table 8 columns 3 and 4).

In order to remove the effect of the biome's area on the global averages, we normalized the temperature and precipitation changes (Table 8 column 5). By ranking the normalized temperature changes, removal of the boreal forest vegetation remains the most influential on the global climate. The tropical and temperate forest vegetation removal simulations switch places with the temperate forest simulation affecting the global temperature slightly more than the tropical forest simulation.

With respect to precipitation there is little difference between the global average and the normalized average ranking. The savanna vegetation simulation has the strongest affect on the normalized global precipitation followed by grassland/steppe, tropical forest, shrubland/tundra, temperate forest, and boreal forest. It is interesting to note that the first five ranked biomes have a more significant influence on the global precipitation than the boreal forest simulation.

Another way to represent the removal of individual biomes on the climate system is by examining the effects from two main physical processes occurring at the land surface: changes in albedo, and changes in water cycling (through evapotranspiration) (Table 9). The ranking is based on a qualitative assessment of the results from each of the vegetation biome simulations. Changes in albedo strongly affect the climate in the boreal forest biome while changes in evapotranspiration strongly affect the climate in the tropical forest and savanna biomes. For all the other biomes the climatic changes resulting from a change in albedo are moderate while they vary from moderate to weak with respect to changes in evapotranspiration. A change in albedo strongly affects the temperature of the boreal biome due to the snow cover that becomes visible once the vegetation is removed. Changes in evapotranspiration strongly affect the temperature and precipitation of the tropical forest and savanna biomes as latent cooling is severely reduced with removal of the vegetation.

All of the biomes have a certain degree of influence on the climate within their particular region, however, certain biomes can significantly modify regions adjacent to or far removed from the surface forcing. For example, our results indicate that the temperate forest vegetation removal and the shrubland/tundra vegetation removal

Table 9 Summary of each biome's influence on the climate due to albedo and evapotranspiration effects. Ranking is from 'strong' to 'moderate' to 'weak' and is qualitatively based on the results from the individual biomes as described in the paper. A brief description highlights the important mechanisms and climatic effects

Biome	Effects of changing albdeo	Effects of changing evapotranspiration	Description
Tropical forest	Moderate	Strong	Moderate surface albedo increase causes a decrease in surface net radiation. Severe reduction in evapotranspiration (ET) along with reduction in surface energy limits latent cooling and surface warms considerably. Near-surface specific humidity and precipitation reduced. Cloud cover decreases.
Boreal forest	Strong	Weak	Large surface albedo increase causes a large decrease in net radiation and the surface cools. Reduction in ET limits near-surface moisture and precipitation only during summer growing season. Surface cooling leads to a reduction in planetary boundary layer height and a large increase in cloud cover.
Temperate forest	Moderate	Moderate	Increase in albedo decreases net radiation during all seasons. Winter and spring increase causes a cooling while summer and fall increase causes a warming when combined with a moderate reduction in ET. Decrease in ET reduces near-surface moisture and precipitation (mostly in summer).
Savanna	Moderate	Strong	Moderate surface albedo increase causes a decrease in surface net radiation. Large reduction in ET limits latent cooling and surface warms. Near-surface humidity and precipitation severely reduced. Cloud cover decreases.
Grassland and steppe	Moderate	Moderate	Moderate surface albedo increase causes a reduction in net radiation. In winter and spring this cools the surface while in summer it warms the surface when combined with a moderate reduction in ET. Grassland region of Central US most affected by ET reduction (warming). Steppe region of Asia most affected by albedo increase (cooling).
Shrubland/tundra	Moderate	Moderate/weak	Moderate surface albedo increase causes a reduction in net radiation over all regions. Albedo increase in tundra regions causes a cooling. Albedo increase in shrubland region of Australia combined with a reduction in ET causes a warming during austral summer and a cooling in austral winter. Very weak reduction in ET in tundra regions.

simulations both influence the temperature of locations adjacent to, but outside of their respective regions. Work by Eltahir (1996) and others have identified regional connections in the tropics due to changes in the low-level circulation and moisture convergence.

The result of vegetation removal on the temperature and precipitation *outside* the region of vegetation forcing is listed in Table 8 (column 6). The change in temperature averaged annually over the globe (only land cells) excluding the biome's area shows that removal of the boreal forest vegetation has the largest effect (–0.85 °C) on the global temperature outside the region of vegetation forcing, followed by the temperate (–0.27 °C) and tropical forest (0.20 °C) simulations. The shrubland and tundra annual global temperature signal is also large (–0.15 °C) and is primarily due to the large cooling in central Siberia in DJF as discussed in Sect. 9 and shown in Fig. 9a.

To better illustrate the magnitude of the vegetation removal signal on the global climate we compare the effect of the El Nino Southern Oscillation (ENSO) climate anomaly to the magnitude of global temperature change. By taking a composite of the warm phase of ENSO for the years from 1950 to 1995 using the CRU05 climate dataset (New et al. 1999) we found that the global annual temperature over land warms by approximately 0.08 °C. When compared to the global temperature change over land outside of the regions of vegetation removal in Table 8 (column 6) the tropical, boreal, and temperate forest vegetation removal simulations along with the shrubland/tundra vegetation removal simulation all show a temperature change whose magnitude is greater than the climatic effect from ENSO (although the local and regional effects of ENSO can be quite large). This further illustrates the potential effects of large-scale vegetation removal on the climate.

With respect to precipitation (Table 8, column 6), the shrubland/tundra, grassland/steppe, and tropical forest vegetation removal simulations show the largest effect outside of their regions over land only. The shrubland/tundra and grassland/steppe simulations show a precipitation decrease outside of their regions, perhaps indicative of a reduction in moisture advection, while the tropical forest simulation has an increase outside of the regions of vegetation removal and is consistent with other studies on large-scale tropical deforestation (Henderson-Sellers et al. 1993; Baidya Roy and Avissar 2002). There is little change for the temperate and boreal forests and the savanna vegetation simulations and may indicate that they play a minor role in forcing the larger-scale hydrologic cycle.

Based on the results from all the simulations and the global average temperature and precipitation changes listed in Table 8, Table 10 qualitatively shows the influence that a particular biome has on regions adjacent to (regional connections) and far removed from the biome's region (global teleconnections). Removal of the tropical forest vegetation can have a considerable impact on the global climate and especially the northern hemisphere (Chase et al. 1996, 2000; Zhao et al. 2001). Boreal and temperate forest vegetation removal can also have an effect on the northern hemisphere circulation that may translate to changes in the climate in other locations confined to the northern hemisphere (Pielke and Vidale 1995). Regional connections are more prevalent with the tropical, temperate, and boreal forest biomes, however, even the shrubland/tundra biome can influence the climate in other regions as previously shown. Future work is needed to address the role of different teleconnection mechanisms on the removal of the vegetation of the tropical, temperate, and boreal forest biomes.

11 Summary and conclusions

Land cover change can have a significant influence on the climate system through exchanges of water, energy, and momentum. Large portions of the Earth's surface have already been modified for human use and as a result, noticeable changes in the climate have already occurred in some places. While it is now understood that land use change can have an effect on the climate, it is less well known what biomes and regions are most influential to the climate system. Moreover, the exact physical processes operating on the climate system after land use and land cover change have not been systematically illustrated until now.

This study has attempted to comprehensively analyze the influence of most of the Earth's biomes on the climate system. We have quantified the changes that have occurred with removal of the vegetation and shown the importance of a particular biome's contribution to the Earth system. We have identified the biomes and regions that affect the climate most strongly through changes in different atmospheric variables and we have described

Table 10 Qualitative summary of each biome's influence on regions removed from the surface forcing (global teleconnections) and regions adjacent to the surface forcing (regional connections). Ranking is from 'strong' to 'moderate' to 'weak'. A brief description highlights the important mechanisms and climatic effects

Biome	Regional and/or global teleconnection	Description
Tropical forest	Strong	Removal of tropical forest vegetation leads to a change in the intensity and location of the high-level tropical outflow from deep tropical convection. This may influence the extratropics through anomalous Rossby wave forcing. Regional-scale connections include changes in the temperature, moisture flux, and precipitation due to changes in the regional circulation and the planetary boundary layer (PBL).
Boreal forest	Strong	Removal of boreal forest vegetation can affect the entire northern hemisphere climate through modification of the general circulation due to changes in the surface pressure, the PBL, and atmospheric thermodynamics. Regional-scale changes are primarily due to changes in the land surface properties that affect the transport of heat, energy, and moisture in the regional circulation.
Temperate forest	Moderate	Removal of temperate forest vegetation can cause northern hemisphere-scale circulation changes, however the magnitude of the effect is uncertain and may not be comparable to the boreal forest vegetation removal case. Temperate forest vegetation removal has a larger effect on the regional climate due to changes in the advection of heat and moisture between the deforested regions and adjoining regions.
Savanna	Weak	The removal of savanna vegetation has no significant influence outside of the areas of surface forcing. There are no identifiable global teleconnections, although there are weak regional-scale connections that influence the temperature and precipitation patterns in areas immediately adjacent to the areas where the savanna vegetation has been removed. Changes in convective precipitation do not appear to influence the extratropics as it does for the tropical forest vegetation removal simulation.
Grassland and steppe	Weak	The removal of grassland steppe vegetation does not appear to influence the global climate through any teleconnection mechanism. Regional-scale connections also do not appear to influence the climate very much.
Shrubland/tundra	Weak/moderate	The removal of shrubland vegetation has no discernable influence on the global climate and a very weak influence on the regional climate. The tundra vegetation has no apparent influence on the global climate but has a significant influence on the regional climate through reducing the advection of heat into a region due to changes in the surface pressure.

the underlying physical processes that are important in each case. Furthermore, in some cases we have examined the influence of different vegetation types on regions outside of the areas of surface forcing.

Specifically, this study has quantified the climatic effects of complete vegetation removal for the following biomes: tropical forest, boreal forest, temperate forest, savanna, grassland and steppe, and shrubland and tundra. There have been numerous studies on the influence of large-scale tropical and boreal deforestation on the climate, and our results support these findings. In the case of tropical forest vegetation removal, our results show a warming and drying of the areas where the vegetation had been removed due to severely reduced latent cooling. With respect to the boreal forest biome our results indicate that removal of the boreal forest vegetation leads to cooler surface temperatures due to a higher surface albedo with snow persisting later into the spring season.

Although studies on the climatic effects of tropical and boreal deforestation are numerous, this is not the case for the remaining vegetation biomes analyzed in this study. Results from the temperate forest vegetation removal simulation show climate behavior characteristic of both the higher-latitude boreal forest simulation and the lower-latitude tropical forest simulation. That is, removal of temperate forest vegetation leads to a warming and drying during the summer and fall months due to a reduction in latent cooling with removal of the normally transpiring vegetation and a cooling in the winter and spring as the surface albedo of snow is higher than the vegetation. Furthermore, an important regional teleconnection in northern Siberia was identified in the temperate forest vegetation removal case where warm air advection from the southwest was found to increase surface temperatures upwards of 2 °C during the SON season (Fig. 6c).

The simulation of savanna vegetation removal has shown that it behaves similarly to the tropical forest biome with a large reduction in precipitation and warmer surface temperatures. A significant difference between removal of the two biomes is in how they affect regions outside of their areas. The tropical forest simulation can influence the temperature, and more importantly, the precipitation outside of the areas of surface forcing while the savanna simulation shows that the temperature and precipitation changes are mostly limited to the areas of surface forcing.

The results from the grassland and steppe vegetation removal simulation were shown to primarily influence the summertime climate over the central United States with a modest reduction in latent cooling. As with the tropical forest, temperate forest, and savanna simulations, this causes an increase in the surface temperature and a reduction in precipitation due to the weakened flux of moisture from the land surface.

Removal of the shrubland and tundra vegetation was shown to have a small influence on the global climate, but a larger signal in particular regions. For instance, it was found that the removal of shrubland vegetation has a large effect on the Australian climate with a modest warming during the austral summer (DJF) and a reduction in precipitation from the weakened surface latent heat flux. Removal of the tundra vegetation in Asia was shown to cause a large temperature anomaly to develop northwest of Lake Baikal in central Siberia during the DJF season. This regional teleconnection (outside the area where the tundra was removed) is most likely due to an increase in the surface pressure just north of the cooling anomaly that weakens the advection of warm air from the southwest.

Using a cross-comparison of each of the vegetation biome removal simulations, we have shown the relative influence that each vegetation biome has on the climate at the regional and global scales. Regionally, our results indicate that removal of the boreal forest biome has the largest influence on the temperature field when averaged within the region of vegetation removal, globally (over all cells and only land cells), normalized by the area of the biome, and when excluding the region where the vegetation has been removed. With respect to precipitation, our results show that the removal of the tropical forest biome has the largest influence on the precipitation field when averaged over the areas of surface forcing. However, when normalized by the area of the biome, the savanna and grassland and steppe vegetation biomes showed the largest precipitation response. By examining the global average excluding the areas where the vegetation was removed, the grassland and steppe, shrubland/tundra, and tropical forest simulations showed the largest influence on global precipitation. Finally, by comparing the global temperature response outside of the areas of surface forcing with the signal from a composite of ENSO events we showed that the removal of many of the vegetation biomes had a temperature response that exceeded that of ENSO. This is indicative of the strong influence that the biosphere has on the atmosphere.

Finally, given that the two basic processes modulating the removal of vegetation are the surface albedo and evapotranspiration, we made an informed ranking (based on the results) of each of the vegetation biomes as to how important the processes were with removal of the vegetation. We also qualitatively evaluated the influence that the different vegetation biomes had on influencing the regional and global climate through atmospheric teleconnection mechanisms. It was found that the tropical and boreal forest biomes have the most potential for influencing the climate remotely, however, the temperate forest and shrubland/tundra biomes were also found to exhibit specific regional teleconnection patterns primarily due to changes in the advection of air with removal of the vegetation.

Although it is unrealistic to assume that such large areas of biomes may have vegetation removed, it is realistic to assume that land use change will occur sporadically throughout biomes and that different vegetation may replace what is removed (e.g., tropical forest converted to pastureland). These changes can still significantly influence the climate with repercussions on the native vegetation. Land use change occurring in some biomes may alter the climate enough such that the vegetation that remains is subject to climatic conditions outside its optimal growing environment (Wang and Eltahir 2000a, b, c). This illustrates a positive feedback whereby the vegetation helps maintain the climate necessary for the vegetation to exist in its environment. Anthropogenic land use change can alter the climate, thus setting the process in motion that causes further destruction of the remaining vegetation. For instance, it is conceivable that a large enough temperature decrease in the boreal forest ecosystem could shift the environment from a boreal biome to a sub-polar biome where only tundra could exist (Levis et al. 1999).

While we believe that this study has identified the dominant mechanisms responsible for influencing the climate in different biomes, there are major limitations of this work and many potential avenues for future research. First, we acknowledge that wide-scale vegetation removal is unrealistic for most of the biomes (the tropical forests may be an exception). Future work will need to address more realistic or observed land use change occurring within several biomes and key regions. Second, it is important that the ocean dynamics be realistically represented using a coupled atmosphere-ocean-biosphere model as there are many important feedbacks between the three systems that act to amplify the climate response to vegetation removal (Delire et al. 2001). Finally, there are many questions regarding the role of different biomes in influencing the climate through teleconnections and regional connections. Future work must examine how the removal of vegetation affects the local and regional circulation as well as how certain biomes influence the climate through global teleconnections.

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