

OPEN ACCESS

The effects of climate, permafrost and fire on vegetation change in Siberia in a changing climate

To cite this article: N M Tchebakova *et al* 2009 *Environ. Res. Lett.* **4** 045013

View the [article online](#) for updates and enhancements.

You may also like

- [Siberia Integrated Regional Study: multidisciplinary investigations of the dynamic relationship between the Siberian environment and global climate change](#)
E P Gordov and E A Vaganov
- [Pine nut collection facilities in oil and gas development areas](#)
G B Dugarova
- [XVIII International Scientific Symposium in Honour of Academician M. A. Usov: Problems of Geology and Subsurface Development](#)

The effects of climate, permafrost and fire on vegetation change in Siberia in a changing climate

N M Tchebakova^{1,3}, E Parfenova¹ and A J Soja²

¹ V N Sukachev Institute of Forest, Siberian Branch of the Russian Academy of Sciences, Academgorodok, Krasnoyarsk, 660036, Russia

² National Institute of Aerospace (NIA), NASA Langley Research Center, Climate Sciences, 21 Langley Boulevard, Mail Stop 420, Hampton, VA 23681-2199, USA

E-mail: ncheby@forest.akadem.ru and Amber.J.Soja@nasa.gov

Received 23 March 2009

Accepted for publication 3 September 2009

Published 15 October 2009

Online at stacks.iop.org/ERL/4/045013

Abstract

Observations and general circulation model projections suggest significant temperature increases in Siberia this century that are expected to have profound effects on Siberian vegetation. Potential vegetation change across Siberia was modeled, coupling our Siberian BioClimatic Model with several Hadley Centre climate change scenarios for 2020, 2050 and 2080, with explicit consideration of permafrost and fire activity. In the warmer and drier climate projected by these scenarios, Siberian forests are predicted to decrease and shift northwards and forest–steppe and steppe ecosystems are predicted to dominate over half of Siberia due to the dryer climate by 2080. Despite the large predicted increases in warming, permafrost is not predicted to thaw deep enough to sustain dark (*Pinus sibirica*, *Abies sibirica*, and *Picea obovata*) taiga. Over eastern Siberia, larch (*Larix dahurica*) taiga is predicted to continue to be the dominant zonobiome because of its ability to withstand continuous permafrost. The model also predicts new temperate broadleaf forest and forest–steppe habitats by 2080. Potential fire danger evaluated with the annual number of high fire danger days (Nesterov index is 4000–10 000) is predicted to increase by 2080, especially in southern Siberia and central Yakutia. In a warming climate, fuel load accumulated due to replacement of forest by steppe together with frequent fire weather promotes high risks of large fires in southern Siberia and central Yakutia, where wild fires would create habitats for grasslands because the drier climate would no longer be suitable for forests.

Keywords: climate change, forest fire, permafrost, vegetation, Siberia

1. Introduction

Regional studies in Siberia have documented a change in climate toward the end of the 20th century: in West Siberia the annual temperature has increased 1 °C; in the southern Urals, winter temperatures have risen 0.6–1.1 °C over the last 20–30 years; in central Siberia and central Yakutia, winter temperatures have risen 2–4 °C and 3–10 °C, respectively;

and in southern Siberia, annual temperature anomalies varied between 0.4 and 1.5 °C (Tchebakova and Parfenova 2006). According to general circulation model projections, significant temperature increases in Siberia in the 21st century are expected to have profound effects on Siberian vegetation directly (Tchebakova *et al* 2003, Soja *et al* 2007) and indirectly through increased permafrost thawing and forest fires, both of which have a feedback affect on climate itself.

Climate controls weather, fire and vegetation distribution, and vegetation distribution and fire feedback to the climate

³ Author to whom any correspondence should be addressed.

system (Soja *et al* 2009, Flannigan *et al* 1998, 2001). Weber and Flannigan (1997) concluded that an altered fire regime may be more important than the direct effects of climate change in forcing or facilitating species distribution changes through migration, substitution, and extinction.

The objective of this work is to use the Siberian BioClimatic Model (SiBCliM) to highlight interactions between climate, vegetation and fire in the changing climate of Siberia in the 21st century. We simulate vegetation cover, hot spots of vegetation change, and high fire danger across Siberia using two Intergovernmental Panel on Climate Change (IPCC) climate change scenarios that reflect opposite ends of the spectrum, the Hadley Centre HadCM3 A1FI and B1 (IPCC 2000). The A1FI scenario corresponds to the largest temperature increase and represents a world with rapid economic and population growth (nine billion by 2050, then declining), a quick spread of new and efficient technologies, a globally convergent way of life with extensive social and cultural interactions, and an emphasis on fossil fuel. In contrast, the B1 scenario corresponds to the smallest temperature increase and represents a world with rapid economic and population growth (nine billion by 2050, then declining), a reduction in material intensity, the introduction of clean resource efficient technologies and an emphasis on global solutions to economic, social and environmental stability.

2. Methods

Climate has been known since at least the 18th century as the main factor controlling the large-scale distribution of vegetation across landscapes (see the reviews Milkov (1977) and Woodward (1987)). Recent models of climate–vegetation interactions tend to follow one of two basic approaches, static (time independent) and dynamic (time dependent) (Peng 2000). The simplest static approach assumes equilibrium conditions in both climate and vegetation and is based on climate–vegetation classifications. We modified a Siberian bioclimatic model, SiBCliM (Tchebakova *et al* 2003), a static envelope-type large-scale bioclimatic model based on the vegetation classification of Shumilova (1962) from a Siberian vegetation model (Tchebakova *et al* 1994) used to simulate Siberian zonal vegetation. SiBCliM uses three bioclimatic indices: (1) growing degree days above 5 °C, GDD₅; (2) negative degree days below 0 °C, NDD₀; and (3) an annual moisture index (ratio of growing degree days above 5 °C to annual precipitation), AMI, to predict vegetation zones/subzones. SiBCliM has been updated (Tchebakova *et al* 2009), primarily to include permafrost at the active layer depth, a critical ecosystem determinant in the extremely cold continental climates of Siberia (Shumilova 1962).

In SiBCliM, vegetation is separated by growing degree days into latitudinal subzones from north to south: tundra; forest–tundra; northern, middle and southern taiga; and forest–steppe. The annual moisture index separates vegetation into two large types, forest and steppe, and further subdivides the forest into dark (shade-tolerant and water-loving) and light (shade-intolerant and water-stress-resistant) conifers as described by Russian geobotany classifications. The cold

parameter, negative degree days equal to 3500–4000 °C, corresponds well to the permafrost borders and also tends to separate dark-and light-needed coniferous tree species, which grow in relatively mild or more severe winters, respectively. Four temperate vegetation classes (broadleaf forest, forest–steppe, steppe, and semidesert) that do not exist in the current Siberian climates are included in SiBCliM because of their potential importance in future climates. Therefore, in total, the current version of SiBCliM includes 14 vegetation classes, 10 boreal and four temperate vegetation classes.

Permafrost covers 80% of Siberia and is the primary factor controlling the distribution and composition of forests, particularly in interior Siberia. Larch forests, composed of *L. dahurica* (including the sister species *L. gmelini* and *L. cajanderii*), have the ability to grow in continuous permafrost where winter temperatures customarily drop below –40 °C. These larch species have evolved in the extreme continental climate of Central and East Siberia, and only *L. dahurica* is capable of growing on soils with the active layer depth as little as 10–30 cm (Abaimov *et al* 2002). In the summer, the moisture in the active layer that thaws from permafrost provides necessary moisture for the forest growth in this dry environment, and without this moisture, steppe or potentially semidesert would exist (Shumilova 1962).

Permafrost also limits the northward and eastward progression of dark conifers (*Picea obovata*, *Pinus sibirica* and *Abies sibirica*) and light conifers (*L. sibirica* and *P. sylvestris*), although these tree species can occur in the permafrost zone on sandy soils along river valleys and other sites where permafrost may thaw to a depth of 1.5–2 m (Shumilova 1962, Pozdnyakov 1993). Nevertheless, the dominant forest biome is light *L. dahurica* taiga. SiBCliM is consistent with these empirical relationships: dark coniferous forests only occur beyond the permafrost zone, and forest rather than steppe occurs in dry climate (annual moisture index greater than 3.3) within permafrost in Yakutia, East Siberia (Tchebakova and Parfenova 2006, Tchebakova *et al* 2009). In SiBCliM, the current permafrost border was derived from Malevsky-Malevich *et al* (2001, 2005), and the future permafrost border is modeled using Stefan's theoretical formula (Dostavalov and Kudryavtsev 1967). However, in the West Siberia lowlands (west of 90°E), which lies in a basin between two major rivers (Ob and Yenisei), valleys dissected by streams tend to have relatively warm soils. On them, *Picea obovata* and *Larix sibirica* are found on permafrost due to their ability to develop shallow root systems (Pozdnyakov 1993). In our study, SiBCliM was updated for this eventuality by allowing for the occurrence of dark taiga on permafrost in the north of West Siberia.

SiBCliM verification. To verify the ability of SiBCliM to model vegetation, modeled vegetation (figure 1(a)) was compared to the digitized actual vegetation map (figure 1(b)) of Isachenko *et al* (1988) within our Siberian window: 60–140°E and 48–72°N. We excluded mountains in southern Siberia because mountain vegetation classes are dissimilar to those on plains. Sixty Siberian vegetation classes in the actual map were aggregated into ten current classes of SiBCliM using the correspondence table (see Tchebakova *et al* 1994). Kappa

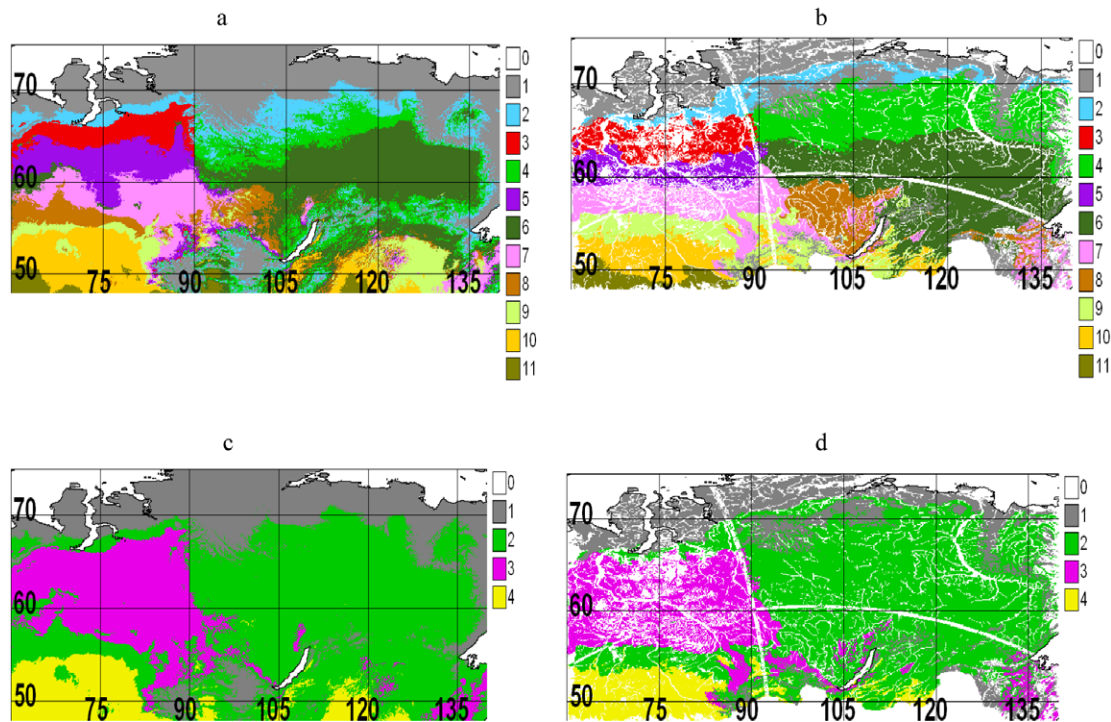


Figure 1. Vegetation distribution in Siberia mapped by coupling our SiBCLiM with maps of bioclimatic indices and of the permafrost driving the model (a). The digitized actual vegetation map of Isachenko (b). Vegetation class key: 0—water; boreal: 1—tundra; 2—forest—tundra; northern taiga: 3—dark, 4—light; middle taiga: 5—dark, 6—light; southern taiga: 7—dark, 8—light; 9—subtaiga, forest—steppe; 10—steppe; 11—semidesert; vegetation distribution aggregated by four aggregated types in the model map (c) and in the Isachenko amp (d). Vegetation type key: 1—tundra, 2—dark taiga, 3—light taiga, 4—grassland. Here, and in all figures, the vertical axis is latitude, the horizontal axis is longitude.

statistics were used to compare these maps. The Kappa statistic is an index which compares the agreement against that which may be expected by chance. Possible values range over: 1, perfect agreement; 0, no agreement; -1, complete disagreement (Landis and Koch 1977). The maps were compared overall and by separate vegetation classes. The overall agreement between these two maps was a 'fair' match (kappa 0.53) according to qualitative descriptors of Monserud and Leemans (1992). The agreement between ten contemporary vegetation classes varied between 'very good' and 'excellent' (kappa > 0.7) for tundra and steppe, to 'good' (kappa 0.55–0.7) for middle dark and light taiga, to 'fair' (kappa 0.4–0.55) for northern and southern dark taiga, southern light taiga and semidesert, to poor (kappa is <0.4) for forest—tundra, northern light taiga, and forest—steppe. When vegetation classes were combined into four vegetation types, tundra, forests (dark and light coniferous) and grasslands, the overall agreement between the maps increase to 'very good' with kappa = 0.74 (figures 1(c) and (d)); 'excellent' (kappa 0.86 and 0.95) for tundra and steppe; 'very good' (kappa 0.78) for light taiga; and 'good' (kappa 0.59) for dark taiga.

Wildfire is a catalyst for maintaining stability and diversity in boreal forests in synchronization with the climate. Wildfire is also a mechanism by which forests move more rapidly towards equilibrium with a new climate. Satellite and ground data show an increase in extreme fire seasons in Siberia, which coincides with the warmer and longer fire seasons of the contemporary climate. Nine of the last eleven years (updated

since Soja *et al* 2007) have resulted in extreme fire seasons, which would change the definition of a normal fire season. Three crucial factors control the potential for fires: (1) an ignition source, (2) fuel load and (3) fire weather. Yet, severe fires and extreme fire seasons are largely under the control of fuel load and fire weather, including relative humidity, wind speed and cumulative precipitation and temperature. Figure 2 shows examples of the coincidence in large-scale patterns of low to high fire weather and active fire.

We investigate fire potential based on two factors: fire weather and fuel load. High probability fire weather is characterized by a Nesterov fire index (NFI) of greater than 4000. The number of high fire danger days for each month was calculated from a moisture coefficient (a ratio of a positive monthly temperature to monthly precipitation) using the model of Malevsky-Malevich *et al* (2005). A linear regression model (with a determination coefficient 0.52) was designed to relate the annual number of high fire danger days, summed for all months, with positive temperature, from an annual moisture index. With this relationship, we estimated potential high fire danger days for current and future climates.

Climate data from more than 1000 weather stations across Siberia are used to map current climate variables. The current January and July temperatures and annual precipitation are mapped using Hutchinson's (2000) thin plate splines on a base DEM grid at a 1 km resolution. Bioclimatic indices, GDD₅ and NDD₀, are calculated from linear regressions derived from contemporary data: GDD₅ is calculated from

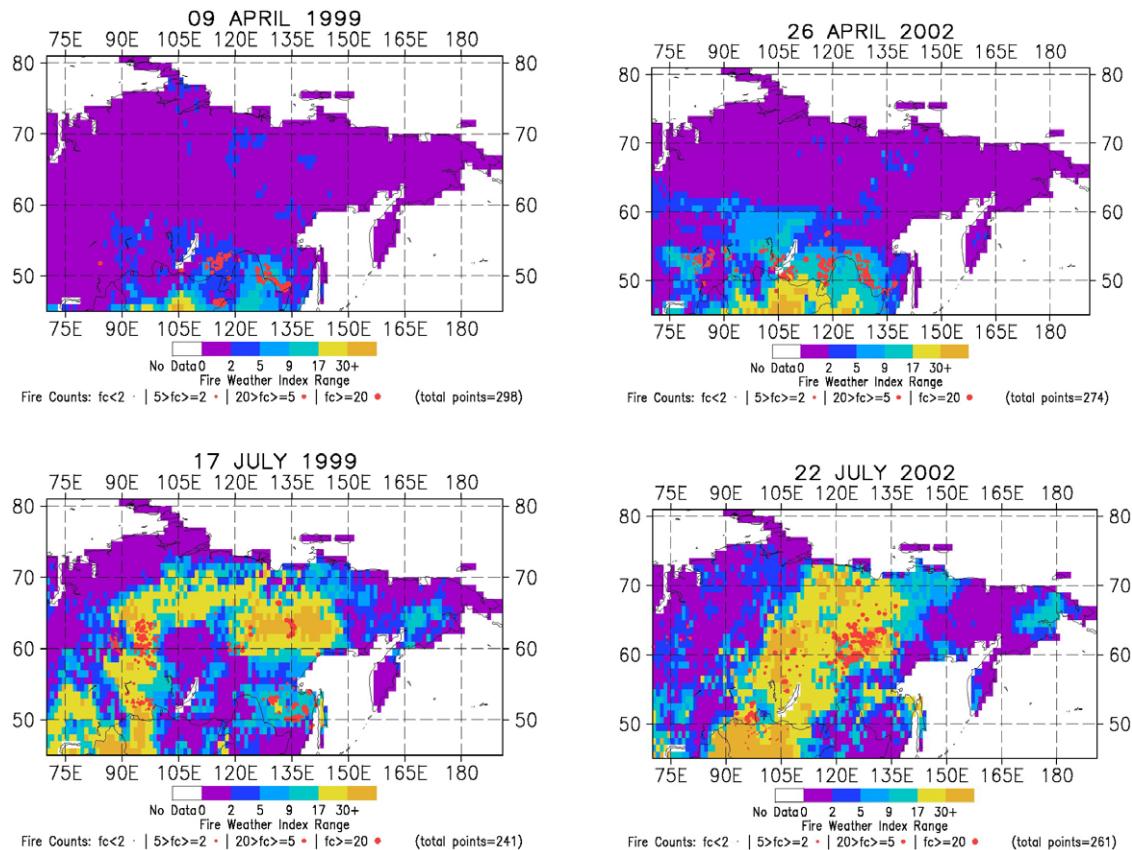


Figure 2. Canadian Fire Weather Indices (FWI) derived using one-degree weather reanalysis data overlain with fire data. High fire weather (cumulative temperature and precipitation, wind speed and relative humidity) is directly related to the ability of large fires to be sustained. These maps are examples used to demonstrate the coincidence in fire activity and severe fire weather and the converse, low fire weather and low fire activity. The ability of large-scale, satellite-based data to define extreme fire activity, as opposed to local weather station data, is new work.

July temperature ($R^2 = 0.90$) and NDD_0 is calculated from January temperature ($R^2 = 0.96$). The AMI surface is calculated by dividing the growing degree days, base 5°C , surface by the annual precipitation surface. Bioclimatic indices for the future are calculated using climatic anomalies for 2020, 2050, and 2080, the Hadley Centre HadCM3A1FI and HadCM3B1, derived from two Special Report on Emission Scenarios (SRES) that reflect opposite ends of the SRES range (IPCC 2000). Temperature increases across Siberia in both the A1FI and B1 scenarios do not differ greatly for 2020 but the difference doubles for 2080 scenarios, with the A1FI burning $8\text{--}9^\circ\text{C}$ versus $4\text{--}5^\circ\text{C}$ in the B1 scenario. These Hadley Centre scenarios, A1FI and B1, are also used to calculate future fire projections at 2080. To calculate fire weather indices from the model of Malevsky-Malevich *et al* (2005), we used climate data from 35 Siberian weather stations located in different vegetation zones for different periods from 1950 to 2000.

3. Results

Climate interactions. Siberian vegetation distribution is simulated and mapped for the current climate, 2020, 2050 and 2080 by coupling SiBCLiM with maps of bioclimatic indices and of the permafrost driving the SiBCLiM simulations under both the A1FI and B1 climate change scenarios (only

2080 is shown in figure 3; for 2020 and 2050 vegetation distributions see Tchebakova *et al* 2009). Simulations indicate that Siberian vegetation would be altered before 2020, and vegetation zones would be severely altered by 2080. The impact on the vegetation is unique for each time slice, being dependent on the scenario: a moderate change in vegetation is predicted from the B1 scenario, but dramatic changes are predicted from the A1FI scenario (figure 3(a)). According to the moderate scenario, habitats for northern vegetation classes (tundra, forest–tundra, and taiga) would decrease from 81.5% to 52.5% enabling southern habitats (forest–steppe, steppe and semidesert) to expand from 18.5% to 47.5%. According to the harsh scenario, northern vegetation types would decrease from 81.5% to less than 30%, with temperate southern vegetation prevailing on 50% of Siberia (figure 3(a)). Biomes could shift northwards as far as 600–1000 km by substitution or complete replacement of northern ecosystems.

These analyses on disparate species thus demonstrate the far-reaching effects of a changing climate on the ecologic distribution and genetic composition of future forests. Forest zones and species boundaries are expected to change at the same time as genotypes within species are redistributed (Tchebakova *et al* 2003, Rehfeldt *et al* 2004). Because analogs of the future forests of Siberia exist currently, one can

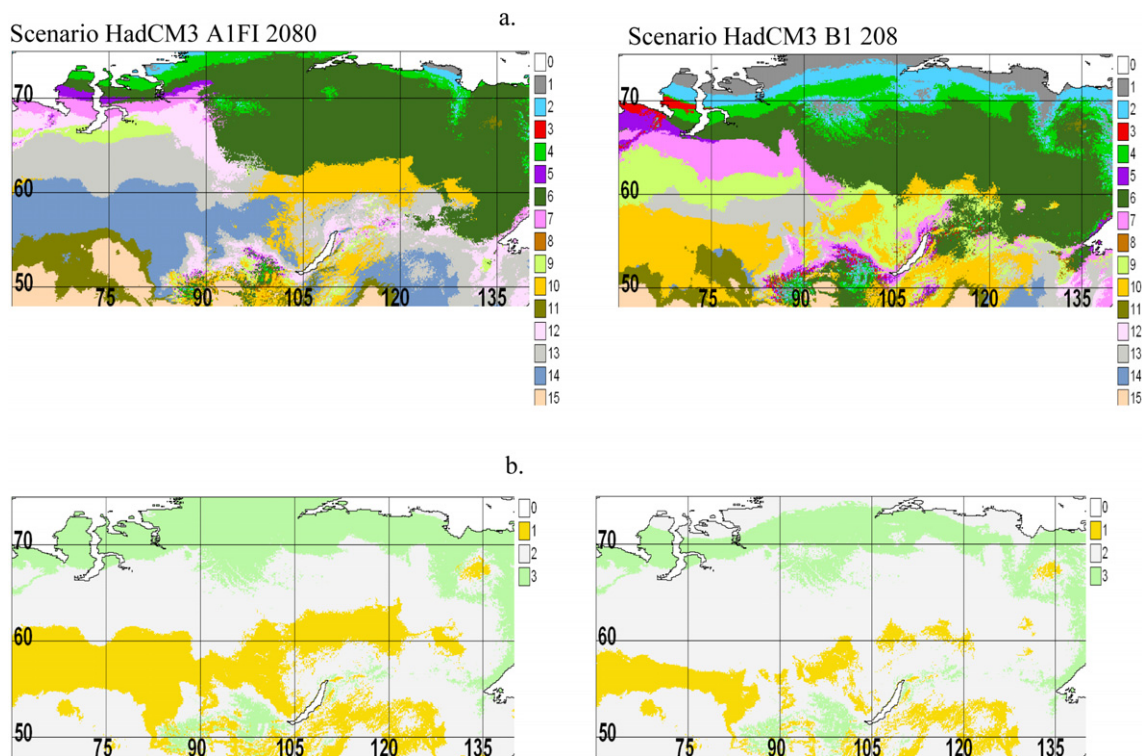


Figure 3. Vegetation distribution in Siberia in 2080 from HadCM3 A1FI and B1 climate change scenarios (a). The boreal vegetation key (1–11 classes) is as in figure 1. The temperate vegetation key (12–15 classes) is: 12—broadleaf; 13—forest–steppe; 14—steppe, 15—desert. Simulated hot spots of forest-to-steppe change (1—yellow), tundra-to-forest change (3—green) and ‘no change’ in major vegetation classes (2—light gray) in 2080 (b). 0—water.

confidently assume that the vegetation is capable of adjusting to the predicted changes. Current estimates, however, suggest that redistribution of forest zones, tree species and their climatypes will require long periods to adjust to the amount of change being predicted. From the ecological perspective, therefore, it is the speed of warming rather than the absolute amount of warming that is the most worrying.

Because the future climate is predicted to be dryer, forest–steppe and steppe, rather than forests, would be the dominate vegetation type over half of Siberia. These lands could also be suitable for agriculture, both traditional crops in the north and new crops in the south, or for biofuel production, but this topic would require extensive research. Desertification is expected in extreme southern Siberia as a result of a decrease in precipitation while temperatures are increasing dramatically. SiBCLiM also predicts new habitats suited to temperate vegetation (broadleaf forest and forest–steppe) by 2080.

Permafrost interactions. Permafrost effects on vegetation change will result from an increased thawing of the active layer depth, and the permafrost boundary is expected to retreat to the north and east. Regeneration of dark conifers beneath the larch shelter is expected to result in a northward expansion of their distributions (Kharuk *et al* 2005). However, despite predicted increases in temperatures, permafrost will not thaw deep enough across Siberia to support dark coniferous taiga. The expansive East Siberian landscape is expected to be populated with larch (*Larix dahurica*), which

is a taiga that is able to withstand shallow active layer depths, and this deciduous–coniferous species will continue to dominate the zonobiome. Permafrost thawing also changes hydrology (e.g. greater river discharge, disappearing lakes) and geomorphology (solifluction and thermokarst processes) across broad expanses of the contemporary permafrost zone. In a warmer and drier climate, larger areas will be affected by solifluction, thermokarst (Abaimov *et al* 2002) and windthrow (Vygodskaya *et al* 2004) modified by frequent catastrophic fires and deeper active layer thaw. As a whole, retreating permafrost should cause a reduction in the area of forests and their replacement by steppe on well-drained, tilted geomorphology (Lawrence and Slater 2005) or by bogs on poorly drained, flat geomorphology (Velichko and Nechaev 2000).

Fire interactions. Fire danger is predicted to increase as climate warms (Stocks *et al* 1998), and SiBCLiM model simulations support this assertion. When coupled with annual moisture index maps for current and future climate change scenarios, our regression model produces distributions of an annual number of high fire danger days in a warmer climate (figure 4). In the current climate, the period of high fire danger is as long as 40–50 days in southern Siberia and 50–60 days in Yakutia (figure 4(a)). In a warmer climate, by the end of the century, those periods will increase on average by 10 and 20–30 days, respectively, under the moderate B1 and severe A1FI scenarios, with the greatest increase (40–50 days) in the current forest–steppe and southern taiga (figure 4(b)).

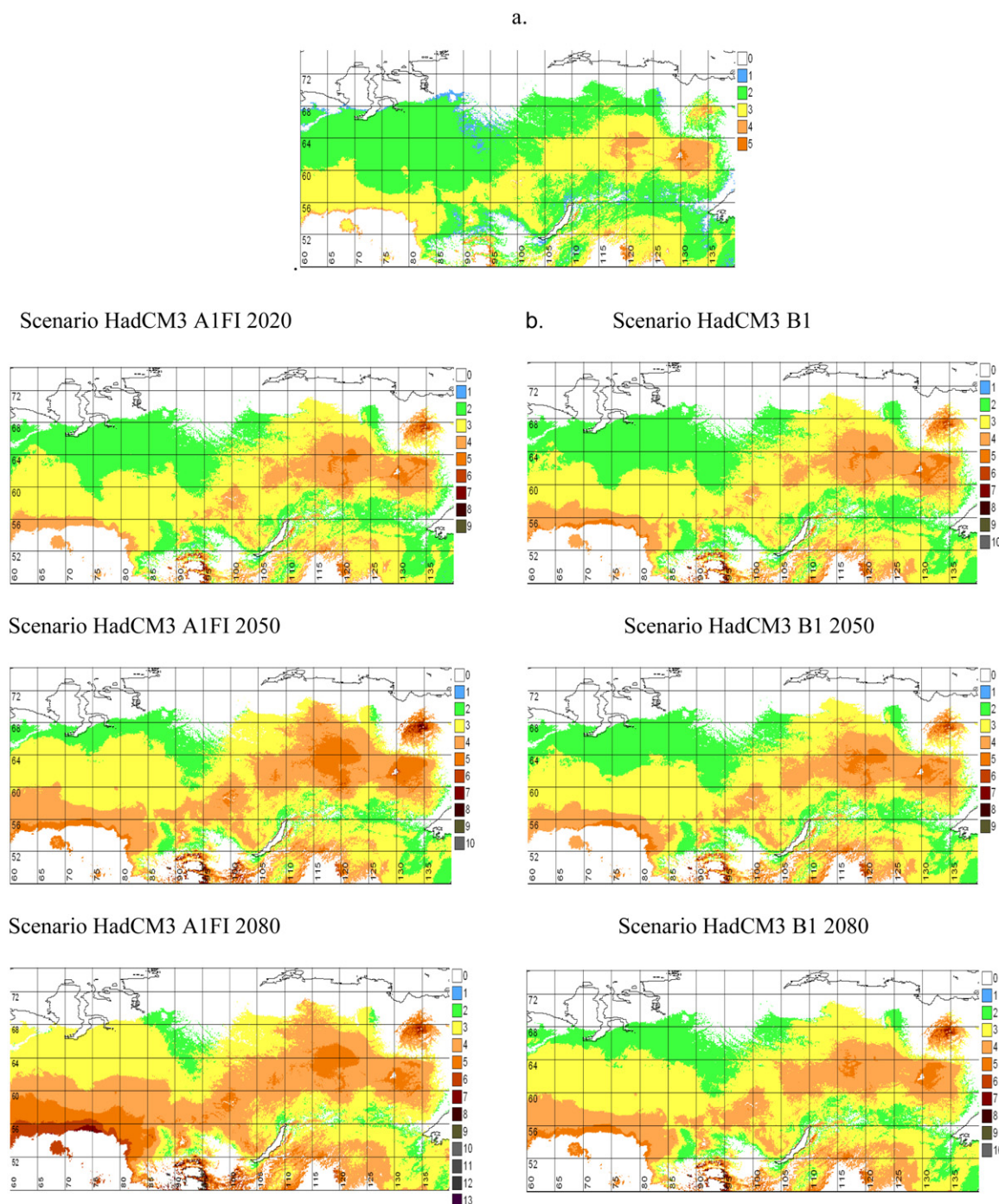


Figure 4. Modeled distributions of annual number of high fire danger days across Siberia in the current climate (a) and during the 21st century (b) from HadCM3 A1FI and B1 climate change scenarios. Fire danger days key: 0—non-forest area; 1—<30 days; 2—40 days; 3—50 days; 4—60 days; 5—70 days; 6—80 days; 7—90 days; 8—100 days; 9—110 days; 10—120 days; 11—>120 days.

Potential hot spots of forest-to-steppe vegetation change (figure 3(b)) in southern Siberia can be interpreted as a large fire load ripe to burn under any ignition source. A dryer climate would result in increased tree mortality in the southern taiga, thus increasing fire fuel accumulation. When superimposed, the two factors, fuel load (figure 3(b)) and fire weather (figure 4), show that risks of large fires would significantly escalate in southern Siberia and in central Yakutia promoting new habitats for steppe and forest–steppe rather than forests.

4. Discussion

Future vegetation predicted from climate change scenarios is motivating us to identify whether there were analogs of these in the past. Shorter or longer periods of different climates were reconstructed during the Holocene worldwide based on records from marine sediments, tree rings, fossil pollen and seed etc. The mid-Holocene (5000–6000 BP) is usually considered as an analog of future climate warming by the current mid-century

(Borzenkova and Zubakov 1984, Budyko 1986). There is growing evidence that the mid-Holocene climate in different parts of Siberia and Siberia as a whole was warmer (Khotinsky 1977, Koshkarova 1986, Tarasov *et al* 1999, MacDonald *et al* 2000, Andreev *et al* 2002). On the basis of the mid-Holocene vegetation distribution of Khotinsky (1984), Monserud *et al* (1998) reconstructed the mid-Holocene climate in Siberia as being warmer and wetter than the present climate. The climate of the 21st century is predicted from GCMs to be warm and dry. Thus, the mid-Holocene and future climates are likely to be dissimilar.

In a future warm and dry climate in Siberia, biomes could shift northwards as far as 600 km. Trees at the northern treeline can move only by means of migration, which is a complex and long-term process characterized by consecutive steps: seed dispersal and establishing of seedlings; growth and reproductive maturity of seedlings; and finally formation of closed canopy forests (Kirilenko and Solomon 1998). Migration of boreal tree species as estimated from paleoecological evidence suggests an average rate of only 300–500 m/year (King and Herstrom 1997). In the mountains, tundra may be replaced by forest more rapidly because migration rates upslope are comparable with the tundra belt width, 500 m. This distance may be covered by tree individuals in a historic timeframe. However, tree movement upslope may be tempered by poorly developed and thin soils in high mountains. In the plains, vegetation zones are hundreds of kilometers wide, rather than hundreds of meters wide as in the mountains. Consequently, it may take a millennium for a tundra zone this broad to be completely replaced by forest under climate warming. Species with broad climatic niches and high migration rates conceivably could adjust to a rapidly warming climate while species with a restricted range of suitable habitats and limited dispersal are likely to disappear first (Solomon and Leemans 1990).

The southern treeline is being shaped by forest fire, which rapidly promotes equilibrium between the vegetation and the climate. Extreme and severe fire seasons have already occurred in about 80% of the years between 1998 and 2006 in Siberia, which is an early indicator of the predicted change (Soja *et al* 2007). Tree decline in the southern taiga border in a dryer climate would facilitate the accumulation of woody debris. This accumulation, paired with increased fire weather, would result in a decreased fire return interval (time between fires) and an increased potential for severe and large fires. As a result, climate-induced fires may account for as much as 30 million ha of area burned annually in Siberian forests (Furyaev *et al* 2001).

In a warmer climate, following forest fire, forest regeneration may not be possible due to increased temperature and evapotranspiration and decreased precipitation. It is reported that the relic pine forest in mountains of Tuva is currently being converted to steppe at the lower tree line (Buryak *et al* 2009), and this could be an initial sign of climate change. In this scenario, grasses would replace forest (Rizzo and Wilken 1992, Smith and Shugart 1993). Characteristics that would permit steppe to thrive are a short life cycle, adaptation to minimal precipitation and to droughts, and ability

to recover after frequent fires. Both climate-induced tundra-to-forest and forest-to-steppe transitions are followed by changes in hydrology and carbon cycles; however soil transformation across landscapes would take time.

One of the major climate effects on vegetation in a changing climate would be vegetation shifts through transition zones between vegetation types or 'hot spots' where the first signs of vegetation change are expected to appear. Hot spots are of special interest for finding out how vegetation change may feed back to land surface albedo change. Hot spots of tundra-to-forest change in the north and highlands and forest-to-steppe change in the south and southern mountain foothills were modeled as the difference in vegetation in 2080 and current climate using our SiBCliM (figure 3(b)). Estimates of snow-free albedo change over Siberia due to vegetation shifts only showed that albedo would increase between the south and mid-latitudes due to the steppe advance with higher albedo compared to the forest which may cause regional cooling over the area. In the northern latitudes and highlands, tundra would be replaced by the forest with decreased albedo compared to the tundra which may cause additional warming at the high latitudes (Vygodskaya *et al* 2007). With consideration of changes in snow cover, tundra characterized by a high seasonal variation in albedo showed increased feedbacks (greater atmospheric heating) compared to forests characterized by less seasonal variation in albedo that showed lesser feedbacks (less atmospheric heating) (Chapin *et al* 2005). Thus, resulting warming due to effects of albedo and snow cover change would be greater at high latitudes and lesser warming or some cooling would occur at middle and low latitudes.

Fire and the thawing of permafrost are considered to be the principal mechanisms that will shape new vegetation physiognomies (Polikarpov *et al* 1998). In the dry climate in interior Siberia, frequent fires eliminate any of the dark conifer undergrowth that may have become established in suitable sites within the permafrost zone. The fire return interval in the light conifer (larch, *Larix spp.*, and pine, *Pinus sylvestris*) middle taiga in central Siberia is 20–30 years (Furyaev *et al* 2001) compared to 200–300 years in dark conifer (Siberian stone pine, *Pinus sibirica*, and fir, *Abies sibirica*) southern and mountain taiga in southern Siberia (Polikarpov *et al* 1986). Slowly growing dark conifers are not adapted to frequent fires and typically die; additionally, they are not light-tolerant, so they are not likely to be the first species to succeed following fire events. On the other hand, *Larix dahurica* is evolutionarily adapted to fire and successfully regenerates by opening of the cones after fire events. For East Siberia, Polikarpov *et al* (1998) speculated about modern post-fire succession. They predicted that dark conifers would be replaced by pine in southern dry climates and by larch on cold soils in a warmer climate. Dark conifers would shift northwards and eastwards following permafrost retreat; light-needed tree species (*Pinus sylvestris* and *Larix sibirica*) would follow them, expanding from the south. In the transition zone between dark-needed and light-needed tree species, birch and mixed conifer–hardwoods would dominate.

5. Conclusions

We investigated potential vegetation cover progression in the warming climate of Siberia during the current century using SiBCliM, the Siberian BioClimatic Model. With moderate (HadCM3 B1) and harsh (HadCM3 A1FI) climate change projections from the Hadley Centre we find that Siberian biomes would need to shift far to the north and east in order to reach an equilibrium with the change in climate. Because Siberian climate is predicted to be much warmer and drier, the future climate would be suitable for the forest–steppe ecotone and grasslands rather than forests. Water-stress-tolerant light taiga would remain the dominant Siberian forest. Thawing permafrost would change hydrology and increase forest disturbances through thermokarst and solifluction processes. However, permafrost will not retreat fast enough to make favorable habitats for dark taiga and *L. dahurica* taiga will remain the dominant forest type. Moreover, more frequent and severe wildfires in a drier climate would also eliminate dark undergrowth emerging in suitable habitats. Accumulated fire load due to increased tree mortality, especially in the southern forest border and central Yakutia, together with an increase in fire weather would also initiate large fires facilitating vegetation progression towards an equilibrium with the climate.

Climate, permafrost and wildfire are among the principal driving forces of vegetation establishment and successional change across Siberia in a rapidly changing climate. Permafrost and fire are directly influenced by climate; fire influences permafrost thawing; and all three factors influence vegetation cover change. Altered vegetation, permafrost and fire feed back to the climate system by altering the albedo of the landscape, changing the hydrologic and carbon cycles and producing altered direct and indirect emissions that could change the tropospheric chemistry, which in turn could alter patterns of precipitation and deposition of black carbon on ice; together these feedbacks could result in ‘a potential non-linear response to changes in climate’ (Soja et al 2007). Thus, there is a strong need to account for interactions at least between major environmental forces and terrestrial ecosystems in global and regional circulation models to get more reliable projections.

Acknowledgments

The authors thank G E Rehfeldt and R A Monserud for their helpful comments of the manuscript and D Westberg for figure 2.

References

- Abaimov A P, Zyryanova O A and Prokushkin S G 2002 *Eur. J. Forest Res.* **5** 2 95–106
- Andreev A A, Siegert C, Klimanov V A, Derevyagin A Y, Shilova G N and Melles M 2002 *Quat. Res.* **57** 138–50
- Borzenkova I I and Zubakov V A 1984 *Russ. J. Meteorol. Hydrol.* **8** 69–77
- Budyko M I 1986 *The Evolution of the Biosphere* (Dordrecht: Reidel) p 423
- Buryak L V, Kalenskaya O P, Sukhinin A I and Ponomarev E I 2009 *Proc. All-Russia Conf. Ecological Aspects of Forest-Forming Process* (Krasnoyarsk: V N Sukachev Forest Institute, Siberian Branch, Russian Academy of Sciences) pp 43–9
- Chapin F S III et al 2005 *Science* **310** 657–60
- Dostavalov B N and Kudryavtsev V A 1967 *Basic Permafrost Science* (Moscow: Moscow University Press) p 404
- Flannigan M D, Bergeron Y, Engelmark O and Wotton B 1998 *J. Veg. Sci.* **9** 468–76
- Flannigan M D, Cambell I, Wotton B M, Carcaillet C, Richard P and Bergeron Y 2001 *Can. J. Forest Res.* **31** 854–64
- Furyaev V V, Vaganov E A, Tchebakova N M and Valendik E N 2001 *Eur. J. Forest Res.* **2** 1–15
- Hutchinson M F 2000 *ANUSPLIN Version 4.1 User's Guide* (Canberra: Australian National University, Centre for Resource and Environmental Studies)
- IPCC 2000 Emissions scenarios *Special Report of the Intergovernmental Panel on Climate Change* ed N Nakicenovic and R Swart (Cambridge: Cambridge University Press) p 570
- Isachenko A G, Shlyapnikov A A, Robozertseva O D and Filipetskaya A Z 1988 *The Landscape Map of the USSR* (Moscow: General Ministry of Geodesy and Cartography of the USSR) 4 plates
- Kharuk V I, Dvinskaya M L, Panson K G and Im S T 2005 *Russ. J. Ecol.* **3** 186–92 (in Russian)
- Khotinsky N A 1977 *Holocene of the Northern Eurasia* (Moscow: Nauka) p 200
- Khotinsky N A 1984 *Late Quaternary Environments of the Soviet Union* ed A A Velichko (Minneapolis, MN: University of Minnesota Press) pp 179–200
- King G A and Herstrom A A 1997 *Past and Future Rapid Environmental Changes: The Spatial and Evolutionary Responses of Terrestrial Biota* ed B Huntley et al (New York: Springer) pp 91–101
- Kirilenko A P and Solomon A M 1998 *Clim. Change* **38** 15–49
- Koshkarova V L 1986 *Carpological Flora of Peatbogs in Siberia* (Novosibirsk: Nauka) p 121
- Landis J R and Koch G G 1977 *Biometrics* **33** 159–74
- Lawrence D M and Slater A G 2005 *Geophys. Res. Lett.* **32** L24401
- MacDonald G M et al 2000 *Quat. Res.* **3** 302–11
- Malevsky-Malevich S P, Molkentin E K, Nadyozhina E D and Slyarevich O B 2001 *Cold Reg. Sci. Technol.* **32** 1–11
- Malevsky-Malevich S P, Molkentin E K, Nadezhina E D and Shklyarevich O B 2005 *Russ. J. Meteorol. Hydrol.* **3** 36–44
- Milkov F N 1977 *Natural Zones of the USSR* (Moscow: Mysl) p 294
- Monserud R A and Leemans R 1992 *Ecol. Modell.* **62** 275–93
- Monserud R A, Tchebakova N M and Denissenko O V 1998 *Palaeogeogr. Palaeoclimatol. Palaeoecol.* **139** 15–36
- Peng C 2000 *Ecol. Modell.* **135** 33–55
- Polikarpov N P, Andreeva N M, Nazimova D I, Sirotinina M A and Sofronov M A 1998 *Russ. J. Forest Sci.* **5** 3–11
- Polikarpov N P, Tchebakova N M and Nazimova D I 1986 *Climate and Mountain Forests in Southern Siberia* (Novosibirsk: Nauka) p 225
- Pozdnyakov L K 1993 *Forestry on Permafrost* (Novosibirsk: Nauka) p 192
- Rehfeldt G E, Tchebakova M N and Parfenova E I 2004 *Recent Res. Dev. Genet. Breed.* **1** 113–30
- Rizzo B and Wilken E 1992 *Clim. Change* **21** 37–55
- Shumilova L V 1962 *Botanical Geography of Siberia* (Tomsk: Tomsk University Press) p 440
- Smith T M and Shugart H H 1993 *Nature* **361** 523–6
- Soja A J, Tchebakova N M, French N F, Flannigan M D, Shugart H H, Stocks B J, Sukhinin A I, Parfenova E I, Chapin F S III and Stauckhouse P W Jr 2007 *Glob. Planet. Change* **56** 274–96
- Soja A J et al 2009 *Environ. Res. Lett.* **4** submitted

- Solomon A M and Leemans R 1990 *Landscape Ecological Impacts of Climate Change* ed M M Boer and R S de Groot (Amsterdam: IOS Press) pp 239–316
- Stocks B J et al 1998 *Clim. Change* **38** 1–13
- Tarasov P E, Guiot J, Cheddadi R, Andreev A A, Bezusko L G, Blyakharchuk T A, Dorofeyuk N I, Filimonova L V, Volkova V S and Zernitskaya V P 1999 *Earth Planet. Lett.* **171** 635–45
- Tchebakova N M, Monserud R and Nazimova D I 1994 *Can. J. Forest Res.* **24** 1597–607
- Tchebakova N M and Parfenova E I 2006 *Comput. Tech.* **11** 77–86 (in Russian)
- Tchebakova N M, Parfenova E I and Soja A J 2009 *iLEAPS Rep. Ser.* **1** at press
- Tchebakova N M, Rehfeldt G E and Parfenova E I 2003 *Sib. Ecol. J.* **6** 677–86
- Velichko A A and Nechaev V P 2000 *Trans. Russ. Acad. Sci. Geograp. Ser.* **324** 667–71 (in Russian)
- Vygodskaya N N, Groisman P Y, Tchebakova N M, Kurbatova J A, Panfyorov O, Parfenova E I and Sogachev A F 2007 *Environ. Res. Lett.* **2** 045033
- Vygodskaya N N, Groisman P Y and Tchebakova N N 2004 Ecosystems and climate interactions *NEESPI Science Plan* chapter 3.5 <http://neespi.gsfc.nasa.gov>
- Weber M G and Flannigan M 1997 *Environ. Rev.* **5** 145–66
- Woodward F I 1987 *Climate and Plant Distribution* (Cambridge: Cambridge University Press) p 174