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Trends in global wildfire potential in a changing climate

Yongqiang Liu *, John Stanturf, Scott Goodrick

Center for Forest Disturbance Science, US Forest Service, 320 Green St., Athens, GA 30602, United States

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ABSTRACT

The trend in global wildfire potential under the climate change due to the greenhouse effect is investigated. Fire potential is measured by the Keetch-Byram Drought Index (KBDI), which is calculated using the observed maximum temperature and precipitation and projected changes at the end of this century (2070–2100) by general circulation models (GCMs) for present and future climate conditions, respectively. It is shown that future wildfire potential increases significantly in the United States, South America, central Asia, southern Europe, southern Africa, and Australia. Fire potential moves up by one level in these regions, from currently low to future moderate potential or from moderate to high potential. Relative changes are the largest and smallest in southern Europe and Australia, respectively. The period with the KBDI greater than 400 (a simple definition for fire season in this study) becomes a few months longer. The increased fire potential is mainly caused by warming in the U.S., South America, and Australia and by the combination of warming and drying in the other regions. Sensitivity analysis shows that future fire potential depends on many factors such as climate model and emission scenario used for climate change projection. The results suggest dramatic increases in wildfire potential that will require increased future resources and management efforts for disaster prevention and recovery.

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1. Introduction

Wildfire is a primary disturbance agent affecting the structure and composition of many forest ecosystems. The complex role that wildfire plays in shaping forests has been described in terms of vegetation responses as dependent on, sensitive to, independent of, or influenced by fire (Myers, 2006). For example, fire is largely absent where cold, wet, or dry conditions prevail (e.g., tundra, some rain forests, and desert). At the other extreme, fire is essential where species have evolved to withstand burning and facilitate fire spread. Notable fire-dependent ecosystems include many coniferous boreal, temperate, and tropical forests; eucalyptus forests; most vegetation types in Mediterranean climates; some oak-dominated forests; grasslands, savannas, and marshes; and palm forests. Fire-sensitive ecosystems have evolved without fire as a significant process but human activity has made them more vulnerable by fragmenting stands, altering fuels, and increasing ignitions. Fire-influenced ecosystems generally are adjacent to fire-dependent vegetation where wildfires originate and spread. Climate change that results in drier, warmer climates has the potential to increase fire occurrence and intensify fire behavior and thus may alter the distribution of fire-dependent, -sensitive and -influenced ecosystems.

Changes in fire occurrence and fire behavior are likely shorter term responses to changed climate and there are reports that this is already occurring (Piñol et al., 1998; Gillett et al., 2004; Reinhard et al., 2005; Westerling et al., 2006). The apparent increase in catastrophic wildfires globally (UNFAO, 2001) has multiple causes with human actors playing central roles. In the United States, for example, almost two-million ha of forest and other ecosystems were burned by hundreds of thousands of fires annually during 1992–2001, which cost billions of U.S. dollars (USFA, 2005). The 1997–1998 fires in Indonesia burned 8 million ha (Cochrane, 2003). In the latest catastrophic wildfires in southeastern Australia (AP, 2009), some 2200 square kilometers were burned out, 750 homes were destroyed on one day, and more than 200 people were killed. A recent phenomenon dubbed mega-fires (Williams, 2004) is the recognition that some fires are simply beyond our control, regardless of the type, kind, or number of firefighting resources deployed. In the U.S., large fires and mega-fires account for 90% of the area burned and 80% of suppression costs but together are less than 1% of all wildfires (Williams, 2004). Several converging factors are behind the increased frequency of catastrophic wildfires: extreme weather events such as extended drought, accumulation of fuels (often due to years of suppression activity), increasing human occupation of fire-dependent ecosystems, the so-called wildland-urban interface (Stewart et al., 2007; Sommers, 2008), unchecked biomass burning and escaped fires in tropical regions (Cochrane, 2003), and climate change (Goldhammer and Price, 1998; Stocks et al., 2002; Gillett et al., 2004; Westerling et al., 2006).

* Corresponding author. Tel.: +1 706 559 4240; fax: +1 706 559 4317.
E-mail address: yliu@fs.fed.us (Y. Liu).

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Catastrophic wildfire is a major natural disaster globally with severe environmental consequences. Emissions from wildfires are an important source for atmospheric carbon (Dixon and Krankina, 1993; Amiro et al., 2001; Page et al., 2002). The carbon emissions from the 1997–1998 Indonesian wildfires were the equivalent of the total global carbon uptake by the terrestrial biosphere in a typical year (Page et al., 2002; Tacconi et al., 2007). Furthermore, smoke particles are one of the sources of atmospheric aerosols, which affect atmospheric radiative transfer through scattering and absorbing solar radiation and through modifying cloud microphysics (Charlson et al., 1992; Randerson et al., 2006). These processes can further modify clouds and precipitation and atmospheric circulation (Ackerman et al., 2000; Liu, 2005a,b). In addition, wildfires release large amounts of particulate matter (PM) and other air pollutants, which can degrade air quality (Riebau and Fox, 2001). Wildland fires contribute an estimated 15% of total PM and 8% of CO emissions over the southeastern U.S. (Barnard and Sabo, 2003).

Weather and climate are determinants for wildfires along with fuel properties and topography (Pyne et al., 1996). Climate variability and fire weather influence wildfire behavior and account for the variability in fire severity at various time scales. The effects of climate variability are apparent as summer temperatures increase and many regions experience long-term droughts. Under warm and dry conditions, a fire season becomes longer, and fires are easier to ignite and spread. Several researchers have successfully correlated long-term atmospheric anomalies and wildfire activities (e.g., Swetnam and Betancourt, 1990 for the southwestern U.S.; Brenner, 1991 for southeastern U.S.; and Chu et al., 2002 for Hawaii; Skinner et al., 2002; Hoinka et al., 2009). Surface temperature, precipitation, surface relative humidity, and wind speed are the weather parameters used in some fire severity indices such as the Canadian forest fire weather index (FWI) (Van Wagner, 1987). A comparison of the relative importance of the first two parameters for the U.S. wildfires showed that the atmospheric condition more conducive for intense wildfires is dry weather; high temperatures also contribute to strong wildfire emissions in the western mountains of the U.S. (Liu, 2004).

Different methods and techniques have been used to simulate and project wildfire or fire potential based on meteorological conditions. Some studies used individual meteorological variables. For example, Flannigan and Harrington (1988) used precipitation amount and frequency, temperature, and relative humidity to simulate monthly fire burned areas in Canada during 1953–1980. Other have used weather indices. The Fire Weather Index is an important component of the Canadian Forest Fire Danger Rating System (CFFDRS) and one of the most widely used fire potential indices. Flannigan et al. (1998) used daily FWI based on general circulation model (GCM) simulations to establish relations with historical fires since 1850 in Canada. Flannigan and VanWagner (1991), Stocks et al. (1998), and Flannigan et al. (2000) used monthly and seasonal severity rating of FWI to project future fires in North America and Russia based on GCM climate projections. FWI has also been used in other regions of the world besides the boreal forests such as southern Europe (Moriondo et al., 2006; Good et al., 2008). The Keetch-Byram Drought Index (KBDI) (Keetch and Byram, 1968) is another fire potential index that is widely used in the United States. where it is part of the National Fire Danger Rating System (NFDRS). The KBDI was developed to evaluate the effects of long-term drying on litter and duff and subsequently on fire behavior. High values of the index relate to an increased flammability of organic material in the soil that contributes to increased fire intensity. Other indexed such as the energy releases component (ERC) were also used (e.g., Brown et al., 2004). The meteorological data needed to calculate FWI or KBDI were mostly obtained from observations and GCM simulations although some recent studies have used regional climate modeling techniques (e.g., Moriondo et al., 2006).

Many climate models have projected significant climate change by the end of this century due to the greenhouse effect (IPCC, 2007), including an overall increase in temperature worldwide and a drying trend in the subtropics. Thus, it is likely wildfires will increase in many regions. For example, climate change could spark more fires, and produce fires that burn more intensely and spread faster in northern California (Fried et al., 2004). Climate change impacts on boreal forests could result in a 50% increase in fire occurrence by the end of the century (Flannigan et al., 2009). Understanding of future wildfire trends under projected climate change is essential to assess potential impacts of wildfires including damage to humans and the environment. Understanding and the ability to predict wildfire occurrence and intensity is critical to designing and implementing necessary measures to mitigate these impacts.

A global picture of wildfire potential under a changing climate is much needed but presents several challenges. Because of the lack of historic wildfire data, researchers are forced to use surrogates for wildfire potential, such as the FWI and KBDI. This study investigates global wildfire potential and projects future trends under climate change due to greenhouse effects by interpreting changes in the calculated KBDI. Because the risk of wildfire events also depends on sufficient amounts and spatial continuity of fuels as well as ignition sources, we cannot model wildfire risk simply from climate change; hence we examine changed wildfire potential due to altered climate. This effort should be regarded as a first approximation of wildfire potential under climate change and our objective was to identify regions where changed climate potentially would increase wildfire occurrence.

Wildfire potential, as used in this study, is an expression of the possible severity of a fire season, or a portion of the fire season for a region. This definition therefore is focused on overall moisture conditions at the monthly to seasonal time scale. A regional fire season often coincides with a time of year characterized by significant drying of wildland fuels across all classes of dead and live fuels. Both Dimitrakopoulos and Bemmerzouk (2003) and Pellizzaro et al. (2007) found a strong relationship between the KBDI and live fuel moisture content in a number of species in the Mediterranean. Groisman et al. (2007) examined the use of four indices, including the KBDI, in evaluating potential fire danger across northern Eurasia and found that all of the indices delivered similar descriptions of conditions conducive to forest fires. While more detailed weather information is needed to assess the fire behavior of a specific fire event, a drought index such as the KBDI provides a good representation of the fuel conditions throughout a fire season.

2. Methodology

2.1. Keetch-Byram Drought Index

The KBDI is in essence an indicator of soil moisture deficit. The KBDI is based on a number of physical assumptions (Chu et al., 2002). Soil water transfer to the atmosphere through evapotranspiration is determined by temperature and annual precipitation which is used as a surrogate for the vegetation cover (areas with higher annual rainfall are assumed to support more vegetation). In addition, soil moisture is assumed to saturate at a water depth equivalent of 20 cm (8 in.) and the KBDI has a maximum value of 800. The corresponding mathematical formulas are

$$Q = Q_0 + \mathrm{d}Q - \mathrm{d}P, \tag{1}$$

$$\mathrm{d}Q = \frac{10^{-3}(800 - Q)(0.968\,\mathrm{e}^{0.0486T} - 8.3)\,\mathrm{d}\tau}{1 + 10.88\,\mathrm{e}^{-0.0441R}}, \tag{2}$$

where Q and Q_0 are the moisture deficiency (KBDI) of current and previous day, respectively, dQ is KBDI incremental rate, T is the daily maximum temperature at 2 m above the ground, dP is daily precipitation, R is the mean annual rainfall, and dτ is a time increment set equal to one day. Note that dQ = 0 when $T \leq 50$ F (10 °C) and only the portion of daily precipitation above the net accumulated precipitation of 0.5 cm (0.20 in.) is used.

Direct comparison of specific KBDI values for locations with different climate is often problematic as the drying rate in the index is a function of the mean annual precipitation for a location. This annual rainfall dependence was used as a simple surrogate for the amount of vegetation at a site (areas with more rainfall can support more vegetation and will therefore have higher rates of evapotranspiration). Because the index was developed for the southeastern U.S., the exact functional form of this relationship may not be valid for annual rainfall amounts that differ significantly from those of this region as was shown by Snyder et al. (2006) for arid grasslands in California; however, the KBDI still maintained respectable agreement with volumetric soil water content. Xanthopoulos et al. (2006) found that the KBDI reasonably reflected cumulative moisture deficits in the duff and upper soil layers in the vicinity of Athens, Greece, and also reflected to some extent water deficit in living plants and their potential flammability. Despite the potential limitations of the functional form used in the KBDI to parameterize evapotranspiration, the index is still a viable means of assessing the potential impacts of a changing climate on fire potential by focusing on the relative changes in KBDI produced by changes in temperature and precipitation.

KBDI was classified into 8 drought stages by an increment of 100 (Keetch and Byram, 1968). We combined two adjacent stages into one fire potential level, that is, low (KBDI below 200), moderate (200–400), high (400–600), and extreme potential (above 600). The range of a specific fire potential level could slightly vary with region and season (Goodrick, Regional/Seasonal KBDI Classification, Florida Department of Agriculture and Consumer Services, Division of Forestry, http://www.fl-dof.com/fire_weather/information/kbdi_seasonal.pdf), and fire type (Melton, 1989, 1996). The global wildfire patterns were first analyzed to identify the regions with large increases in wildfire potential under climate change conditions. Seasonal variability of fire potential, and changes in fire season length were then analyzed. Sensitivity analyses were used to examine the dependence of fire potential changes on daily fluctuation of meteorological variables, emission scenarios and choice of GCM model used, and to compare the relative importance of temperature and precipitation.

Melton (1989) provided guidelines on expected fire conditions and potential suppression problems for various ranges of the KBDI for the southeastern United States. When the KBDI exceeded 500, fires became much more intense and suppression/control of fires became increasingly difficult. But note that direct comparison of specific KBDI values for locations with different climate is often problematic as the drying rate in the index is a function of the mean annual precipitation for a location. This annual rainfall dependence was used as a simple surrogate for the amount of vegetation at a site (areas with more rainfall can support more vegetation and will therefore have higher rates of evapotranspiration). Because the index was developed for the southeastern U.S., the exact functional form of this relationship may not be valid for annual rainfall amounts that differ significantly from those of this region as was shown by Snyder et al. (2006) for arid grasslands in California; however, the KBDI still maintained respectable agreement with volumetric soil water content. Xanthopoulos et al. (2006) found that the KBDI reasonably reflected cumulative moisture deficits in the duff and upper soil layers in the vicinity of Athens, Greece, and also reflected to some extent water deficit in living plants and their potential flammability. Despite the potential limitations of the functional form used in the KBDI to parameterize evapotranspiration, the index is still a viable means of assessing the potential impacts of a changing climate on fire potential by focusing on the relative changes in KBDI produced by changes in temperature and precipitation.

2.2. Meteorological data

The maximum temperature and precipitation data for calculating the KBDI were obtained from the Data Distribution Centre of the Intergovernmental Panel on Climate Change (IPCCDDC, 2009). Two datasets of monthly means averaged over 30 years were used. One was the observed Climatic Research Unit (CRU) Global Climate Dataset averaged over 1961–1990. It consists of 0.5° latitude by 0.5° longitude resolution for global land areas, excluding Antarctica. The accuracy of the interpolations were assessed using cross-validation and by comparison with other climatologies (New et al., 1999). The other dataset was the projected future climate change averaged over 2070–2100 by four general circulation models. The basic features of these models used in these are given in Table 1.

GCM is a tool for simulating and projecting global weather and climate and their variability and change. Simulations of present and past climate with various GCMs have been extensively validated (IPCC, 2007). Simulations of precipitation, sea level pressure and surface temperature have been improved although many deficiencies mainly in tropical precipitation. GCMs are also able to reproduce low-frequency-like fluctuations. Advances have been made in modeling the observed changes in continental-scale surface temperatures and extremes and land precipitation over the 20th century. The HadCM3 model, whose projection of future climate will be used as a reference case in this study, represented well most aspects of the observed mean climate during the Atmospheric Model Intercomparison Project period (Pope et al., 2000). Also, the annual to decadal variability and spatial patterns of the global mean surface temperature simulated with HadCM3 were in good agreement with the observations (Collins et al., 2001). The validation results suggest a certain ability of GCMs in projecting future climate change. Nevertheless, large inconsistencies in regional features are found among various GCMs, especially in simulation and projection of precipitation (Zhang et al., 2007), suggesting a limitation in analyzing spatial patterns of KBDI within a given region when using GCM projected climate change.

Daily data have some advantages over monthly ones. For example, one previous study indicates the importance of precipitation frequency, which only can be identified in daily data, for fire severity analysis (Flannigan et al., 1998). We have used monthly data because this study investigates fire potential focused on overall moisture conditions at monthly to seasonal time

Table 1
GCMs whose projections of future climate change were used for the KBDI calculation.

GCM	Description	Spectral	Resolution	Grid cell	Reference
HadCM3	Hadley Centre climate model version 3	T42	2.5° × 3.75°	95 × 73	Pope et al. (2000)
CGCM2	Canada coupled global climate model	T32	3.7° × 3.7°	95 × 48	Flato et al. (2000)
CSIRO	Australia CSIRO climate model	R21	5.6 × 3.2	63 × 56	Hirst et al. (1996)
NIES	Japan climate model	T21	5.6° × 5.6°	63 × 32	Abe-Ouchi et al. (1996)

scale. In addition, KBDI, which was used to measure fire potential in this study, is basically determined by maximum temperature and precipitation with the latter to have more significant daily variability. In calculating KBDI, the role of precipitation is mainly accounted linearly from one day to the next and, therefore, the accumulated effect of daily fluctuation is relatively small at monthly to seasonal scale.

We used GCM simulation output for four emission scenarios defined in the Special Report on Emission Scenarios (SRES) (Nakicenovic et al., 2000). These scenarios combine two sets of divergent tendencies: one set varies between strong economic values and strong environmental values, the other set between increasing globalization and increasing regionalization. The A1 scenario describes a future of very rapid economic growth, global population that peaks in mid-century and declines thereafter, and the rapid introduction of new and more efficient technologies. The A2 scenario describes a very heterogeneous world with slower growth and greater regional disparity than the A1 scenario. The B1 scenario has the same global population growth as the A1 scenario but with reductions in material intensity and the introduction of clean and resource efficient technologies. The B2 scenario describes a world with continuously increasing global population, at a rate lower than A2, with moderate levels of economic development, and less rapid and more diverse technological change than in the B1 and A1 scenarios. The fossil intensive (A1FI) group was used for the A1 scenario, meaning that there remains a reliance on fossil fuels. Group "a" was used for other scenarios (that is, A2a, B1a, and B2a). The scenarios labeled A1 and A2 are cases of rapid global economic growth with and without more efficient global environmental technology applications, respectively, while the B1 and B2 scenarios are similar to A1 and A2 except for cases of regional economic growth. The fossil intensive (A1FI) group was used for A1 scenario and the group "a" for other scenarios (that is, A2a, B1a, and B2a).

2.3. KBDI calculation and analysis

Present and future KBDI values were calculated using observed and GCM simulated meteorological data, respectively. The observed data were interpolated to the corresponding grid cells of each GCM. The future maximum temperature and precipitation values were approximated as the sum of the present observed value and the projected change for each variable.

The monthly values were first converted to daily values by assuming no daily fluctuations within a specific month. Because actual daily precipitation was not used, the net accumulated precipitation of 0.5 cm was not removed. The initial KBDI was assumed to be zero everywhere on January 1. A two-step calculation was then conducted: (1) Values were calculated for each day over the 30-year averaged, year-long duration of the dataset, and (2) The same calculation was made starting from January 1, but using the KBDI on December 31 as the initial value. The two steps of calculation were repeated 30 times until the difference between two adjacent years became negligible.

The change in future KBDI produced by the projected climate change using the HadCM3 model (Pope et al., 2000) with the A2a scenario was used to analyze trends in wildfire potential. The uncertainty due to emission scenarios, GCMs, and daily fluctuations in temperature was investigated by analyzing the experimental calculations. The uncertainty due to the first two factors was examined by comparing the four emission scenarios of HadCM3 simulations and the simulations for A2a scenarios of the four GCMs.

The formulas 1 and 2 use daily maximum temperature and precipitation. However, monthly means of the two variables have been used in this study. To examine the resulting uncertainty, three experiments were conducted. We first estimated the magnitude of the standard deviation of daily maximum temperature using a dataset from a previous modeling study (Liu, 2005b) where regional climate modeling was conducted with the National Center for Atmospheric Research regional climate model, version 3 (RegCM3) (Giorgi et al., 1999) for June 1988. The domain covers the continental U.S. with a resolution of 60 km. The daily maximum temperatures at comparable grid spacing to that of HadCM3 were obtained by averaging the values at the RegCM3 grids within a HadCM3 grid spacing. The computed standard deviation varies with an average SD of 2.9 °C over the continental U.S.

Then, for a future change in monthly maximum temperature, dT, assume that the change in maximum temperature occurs at a pattern of $dT + SD$ on one day, 0 on the second day, and $dT - SD$ on the third day. This pattern repeats for the rest of a month. The projection of future wildfire potential with this fluctuation pattern is named experiment 2d. Similarly, we conducted experiment 3d for the alternate temperature change pattern of $dT + 2 \times SD$, 0, 0, and $dT - 2 \times SD$ and experiment 4d for the pattern of $dT + 3 \times SD$, 0, 0, 0, and $dT - 3 \times SD$. The calculation using monthly maximum temperature is named experiment 1d for comparison. Note that such daily fluctuations in precipitation would have no effect because precipitation is linearly related to the KBDI change in formula 2, hence we only examined the effect on our results of uncertainty of temperature.

3. Results

3.1. Global patterns

Several regions on the globe with large climate-related fire potential can be identified from the spatial distribution of current annual KBDI (Fig. 1). Among them is a cross-continent region consisting of northern Africa, the Middle East, India, and central Asia. The KBDI is above 600 in many areas, indicating extreme fire potential. Actual wildfires, however, are not very frequent because a majority of this region is covered by desert or dry lands. Nevertheless local areas of coniferous forests may suffer from arson-caused fires (J. Tsogtbaatar, Institute of Geoecology, Ulaanbaator, Mongolia, personal communication, 2006). Other regions, located between 45°S and 45°N within individual continents, are southern North America, northern South America, southern Africa, and Australia. The KBDI is 200–400 (moderate fire potential) in some areas and 400–600 (high potential) in other areas. Fire potential is low with the KBDI below 200 beyond 45°, and in East Asia despite the lower latitudes. The global pattern of fire potential measured using KBDI is generally similar to that obtained using a different approach (Krawchuk et al., 2009).

The projected climate change results in a widespread increase in global fire potential. The regions with the most significant increased potential in the future are basically the same as those with large fire potential at present. The KBDI increases by 300 in the Great Plains of United States (U.S.), Brazil and the adjacent countries, southeastern Europe and central Asia, and southern Africa, and by 100 in Australia. A large increase is found in southern Europe despite low current KBDI. In contrast, there is little change in northern Africa despite the highest current KBDI.

The geographic patterns of present fire potential are determined by several factors. In general, lower latitudes have higher fire potential because of more incoming solar energy and therefore higher maximum temperature (Fig. 2). Landscape type is another factor. Fire potential is higher in the desert and dry-land areas because of little rainfall and relatively high maximum temperature. In addition, climate regime also affects fire potential. East Asia is a typical monsoon climate regime where summer is hot but also extremely wet. As a result of this wetness, fire potential is

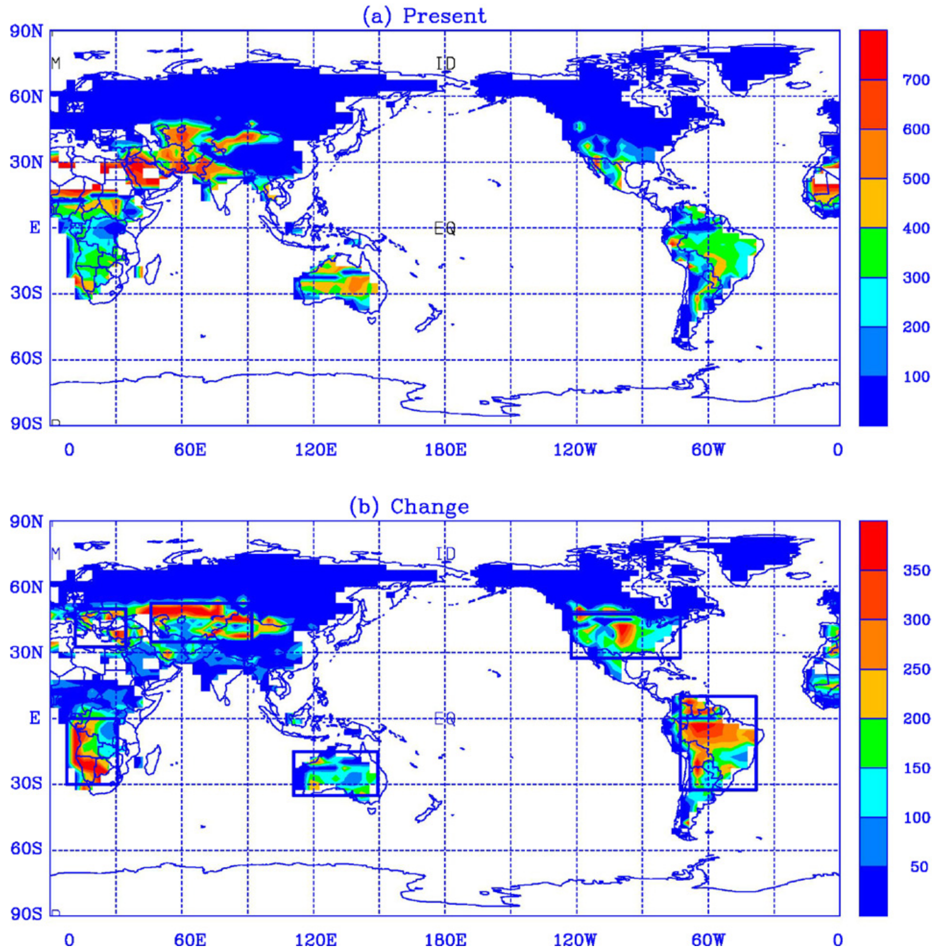

Fig. 1. The annual KBDI at present (a) and future change calculated using the climate change projected by HadCM3 with a2a scenario (b). The boxes in panel (b) are where the regional averages are made.

relatively low in East Asia compared to other regions within the same latitudes.

The large KBDI increases result from the combination of increased maximum temperature and decreased precipitation. Temperature increases by 4 °C and precipitation decreases by 0.25 mm/day in the regions where a large KBDI increase is found. Climate change is more significant in the Great Plains of U.S., Brazil, and southern Africa with temperature increasing by 6 °C in all three regions and precipitation decreasing by 0.75 mm/day in the first two regions.

3.2. Magnitude of fire potential changes

Averages over grid points were made to obtain more quantitative estimates of fire potential in the six regions with large future KBDI increase (see the boxes in Fig. 1). The U.S. region is further divided into four sub-regions of Southwest, Northwest, Southeast, and Northeast (approximately separated by 38°N parallel and 95°W meridian). Present KBDI is about 50 for southern Europe and 100 for the U.S., meaning low fire potential in the two regions; in contrast, it is above 200 for central Asia and the three southern hemisphere regions, meaning moderate fire potential (Fig. 3). The KBDI in Australia is above 300, the largest among the five regions. However, this region has the smallest KBDI increase in the future, less than 100. The KBDI increases by 150–200 in the other regions. The relative increase ranges from 30 to 300%, with the largest in southern Europe and the smallest in Australia.

Large variability among the U.S. sub-regions is found. At present, the Southwest has the largest KBDI of greater than 200, about twice as much as the U.S. average. The Southeast has a value of 150, also larger than the national average. The Northwest has about the same KBDI as the national average, while the Northeast has a very small KBDI. In the future, the KBDI increases by 100–200, largest in the Northwest and smallest in the Southwest. Relative KBDI increases range from 50% in the Southwest to over 600% in the Northeast. The dramatic increase for the Northeast results from its extremely small present KBDI value.

Fire potential in all regions moves up by one level, from low to moderate in the U.S. and southern Europe and from moderate to high in the other four regions. In the U.S., fire potential moves up by one level from low to moderate in the Southeast and Northwest, but remains the same in the other two sub-regions, that is, moderate in the Southwest and low in the Northeast.

3.3. Fire seasons

Wildfires in a region occur most frequently during a period of a few months called the fire season, when the atmospheric and fuel conditions are favorable for fire ignition and spread. As a consequence, fire potential is usually much larger during fire season than other times of a year. However, it is difficult to use a single KBDI value to define fire seasons across different regions. Here, fire season is compared by examining changes in the duration of contiguous periods with moderate or high fire

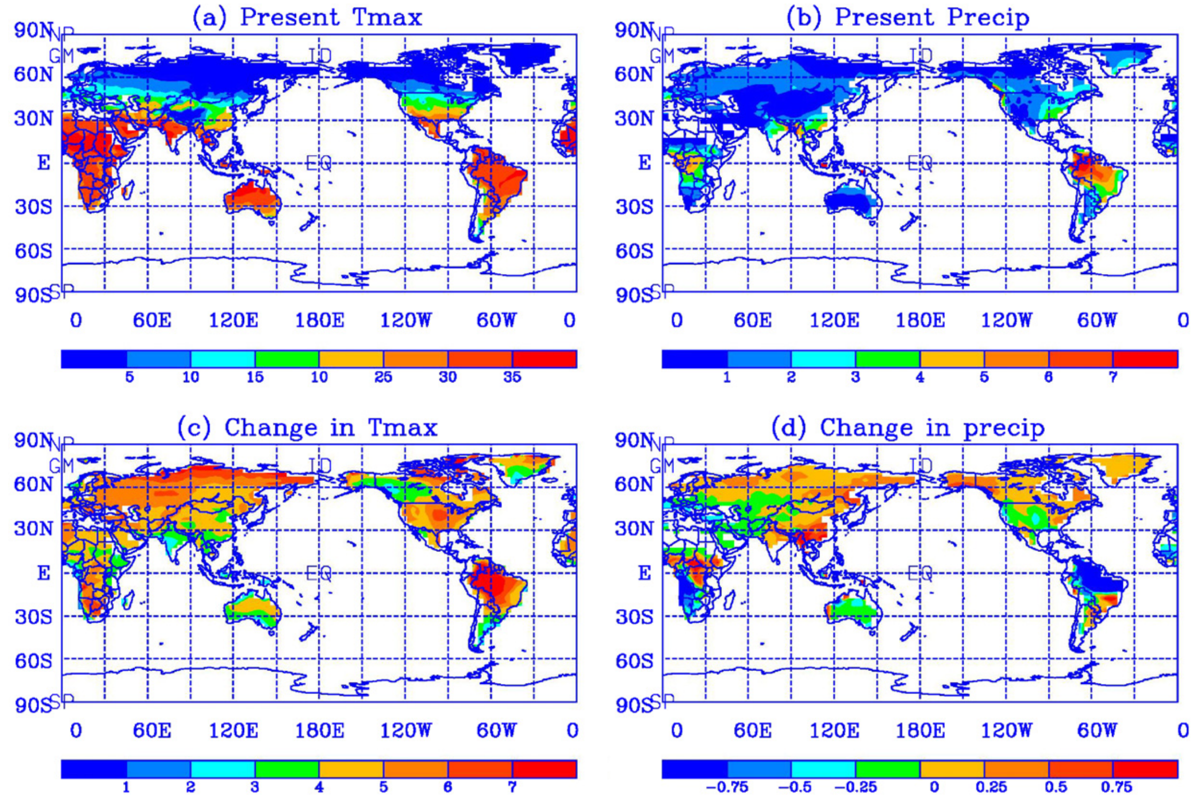

Fig. 2. The meteorological fields. Panels (a and b) are present maximum temperature (in °C) and precipitation (in mm/day), and panels (c and d) are the responding changes in the future projected by HadCM3 with a2a scenario.

potential. Changes in the length of these periods are compared between present and future conditions.

The period with moderate fire potential is already all year long at present in Australia and remains the same in the future (Fig. 4). It increases from nine months to all year long in the future in central Asia (June to next March), South America (May to next January), and southern Africa (May to November) at present. It increases to six months in southern Europe (June to November). In the U.S., the period changes from about half-a-year (May to November) to all year long in the Southwest, and from four months (July to October) to seven months (April to October) in the Southeast. There is no moderate fire potential at any time of the year in two other sub-regions at present, but a period of nine months (June to the following February) in the Northwest or four months (June to September) in the Northeast will emerge in the future.

Only South America and southern Africa experience periods of high fire potential at present, lasting for two months (August and September) and four months (July to October), respectively. In the future these periods will increase to 10 months (April to next January) and eight months (May to December), respectively. A short period of extreme potential is expected. Other regions will see a period of high fire potential in the future with the lengths ranging from two months (July and August) in the U.S., to eight months (June to next January) in central Asia, and to seven months (August to next February) in Australia. None of the U.S. sub-regions experience moderate fire potential at present. This will change in the future in all sub-regions except the Northeast, with a period for 2–4 months (between June and September).

These results indicate that most regions will face moderate fire potential for the entire year in the future. Also, all regions will see

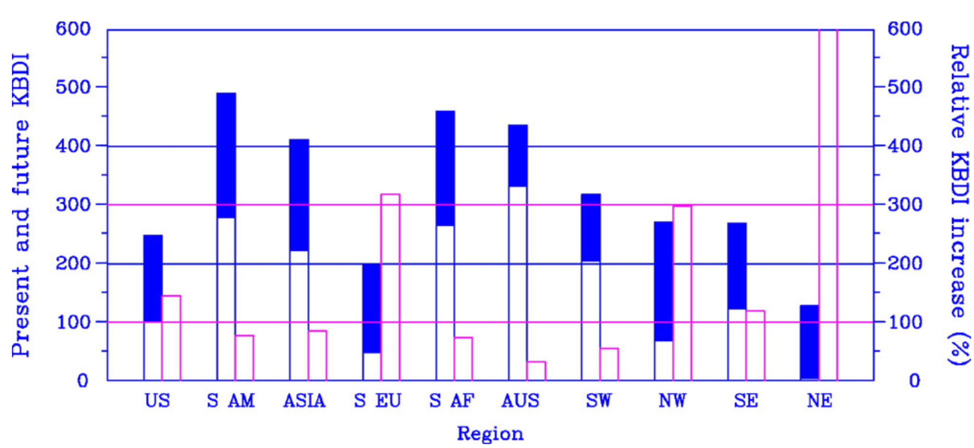

Fig. 3. Magnitude of regional KBDI for present and future change (the unfilled and filled parts, respectively) (a), and the change rate (in %) (b). The future KBDI changes are calculated using the climate change projected by HadCM3 with a2a scenario.

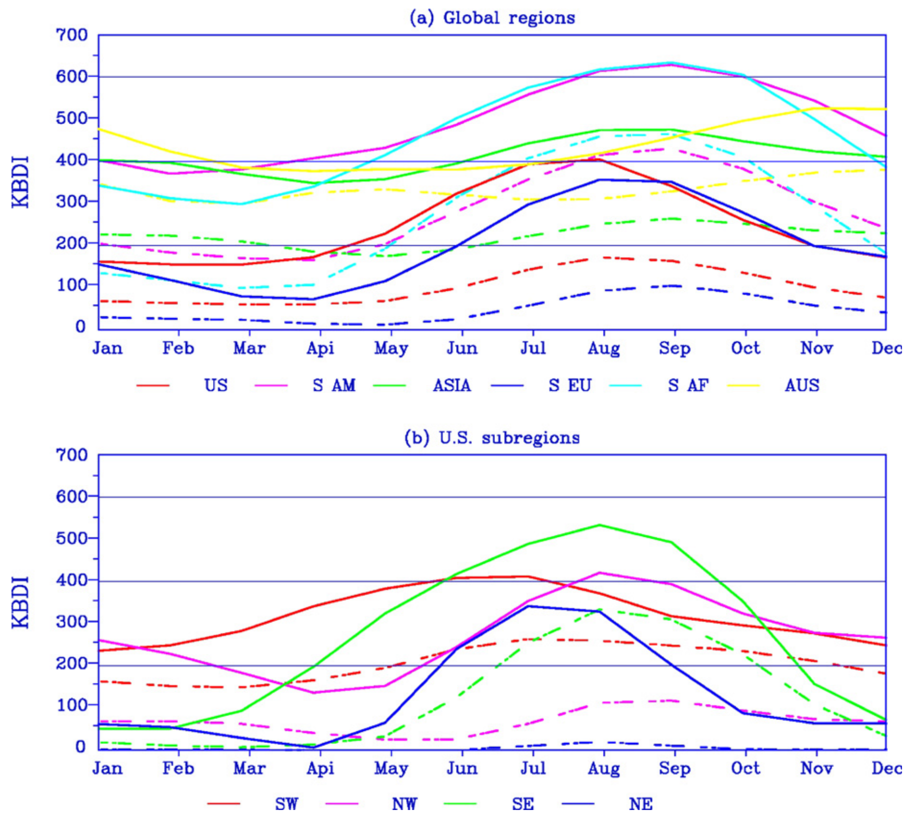

Fig. 4. Monthly variations of KBDI for present and future change for global regions (a) and U.S. sub-regions (b). Dashed and solid lines are present and future values, respectively. The future KBDI values are calculated using the climate change projected by HadCM3 with a2a scenario.

2–8 month longer period of high fire potential. Note that the largest fire potential in U.S., Eurasia, and Australia occurs in summer of the corresponding hemispheres, when temperature is the highest. But in South America and southern Africa, the largest fire potential occurs in the late winter and early spring of the southern hemisphere, which is the dry season of a year.

There is general similarity in geographic patterns between annual and seasonal KBDI for both present and future conditions. However, the extent and intensity of fire potential in many regions, especially those in middle latitudes, can vary significantly with season. In the U.S. (the contiguous United States), for example, moderate to high fire potentials are found presently in Texas and the southern Rocky Mountains in winter and spring. These areas are relatively warm and dry. In contrast, low fire potential is found in the Southeast and the southern Pacific coast because of moist conditions accompanying warm weather. But fire potential turns to moderate or higher in these two areas in summer and fall, mainly due to increased temperature.

Seasonal variability is also found in the future change in fire potential. However, its seasonal dependence is different from that of present fire potential. An increase in the KBDI by 200 or more is first found in the Great Plains and northwestern U.S.-Canada border in the winter (Fig. 5). It extends to southwestern U.S. in spring and to almost the entire U.S. in summer. It then retreats to the northern U.S. in by fall.

In winter, the projected maximum temperature increases by 4 °C from the northern Great Plains to the Southwest. Meanwhile, precipitation decreases from the Pacific coast to Texas to the southern Great Lakes while it increases elsewhere. In spring, the warming of 4 °C is found in entire U.S. except the Northwest. Precipitation decreases in the southwestern sub-region of the U.S. and increases in the northeastern sub-region. It seems the KBDI increase can be attributed to warming in the northern Great Plains in these two seasons. In summer, maximum temperature increases by 6 °C and precipitation decreases across most of the U.S., which corresponds to the nationwide KBDI increase. In fall, the magnitude of temperature increase reduces, with the largest increase found in the northern Great Plains and smallest increase in the Southwest. Precipitation decreases in the Northwest and the northern Great Plains while it increases in the other U.S. areas, explaining the KBDI increase in the northern U.S.

3.4. Sensitivity analyses

3.4.1. Contributions from temperature and precipitation

To examine the relative importance of the two meteorological variables in the future fire potential change, two more KBDI projections were made, one with only the future change in maximum temperature and the other with only future change in precipitation.

It is shown in Fig. 6 that future KBDI increases by about 35, 55, and 30 in U.S., South America, and Australia, respectively, with the change only in precipitation, but about three times as much with the change only in maximum temperature. This indicates the dominant contribution to the future KBDI increase in these regions comes from warming. The KBDI in the three other regions increases by about 70 and 100 without a change in maximum temperature, and close to these numbers without a change in precipitation, indicating comparable contributions from warming and drying. The result for the U.S. sub-regions is the same as that for the U.S. region showing a dominant contribution from warming.

3.4.2. Meteorological fluctuations

The magnitude of the future KBDI change is proportional to the interval of maximum temperature fluctuation (Fig. 7), meaning

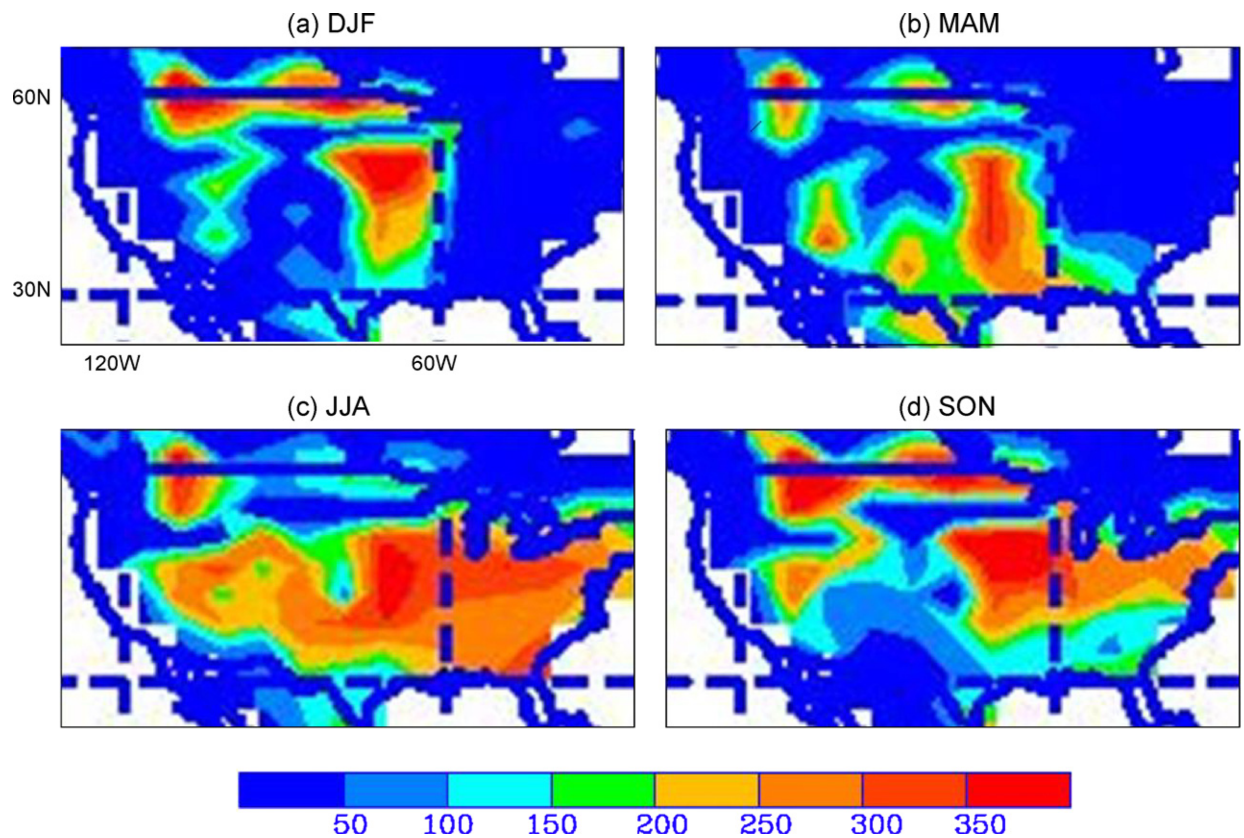

Fig. 5. The seasonal future KBDI changes in the United States. Panels (a–d) are winter, spring, summer and fall. The climate change is projected with HadCM3 with a2a scenario. The blue lines indicate latitudes and longitudes. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of the article.)

that the longer the fluctuation period and larger the fluctuation magnitude in maximum temperature, the larger the future KBDI increases. The differences in KBDI increase between the experiments 4d and 1d are about 50 at various regions. In addition, for some regions, the KBDI increase does not change much among the three experiments.

It is shown above that the future KBDI increase is 150 in most regions. Thus, a limited impact on the projected KBDI increase due to the uncertainty from daily fluctuations can be expected.

3.4.3. Emission scenario

The climate change projected by the HadCM3 model with the A1 and A2 scenarios produces the largest and second largest KBDI increases in all global regions, respectively (Fig. 8). The KBDI increase with the B2 scenario is larger than that with the B1scenario in all regions except Australia. The difference in the KBDI increase between A1 and B1 scenarios is from about 75 to 100. The relative difference is up to about 100%. The dependence of KBDI increase on emission scenarios is similar in the U.S. sub-

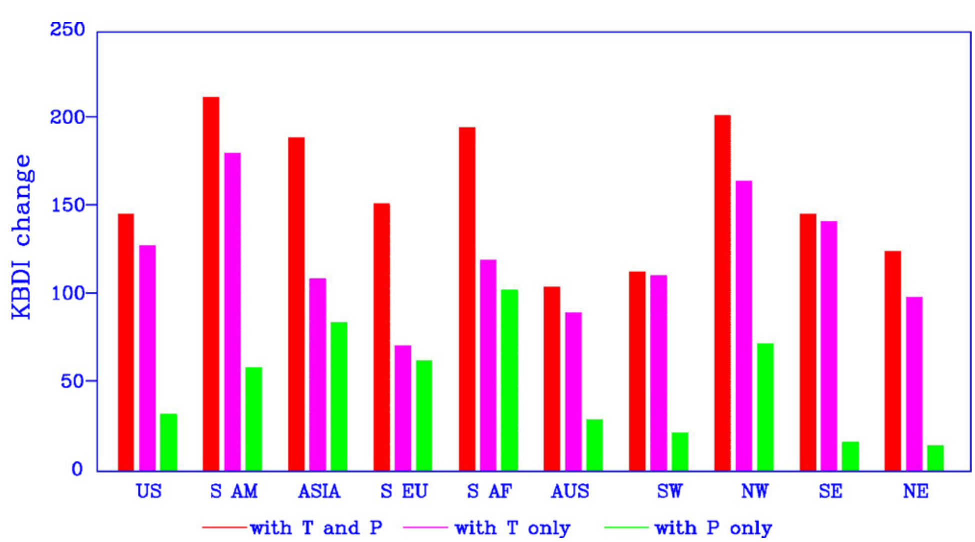

Fig. 6. The future KBDI increases due to the change in maximum temperature and in precipitation, respectively, projected by HadCM3 with a2a scenario. The bottom shows the global regions and U.S. sub-regions. The bars at each region or sub-region represent with changes in both meteorological variables, in maximum temperature only, and in precipitation only.

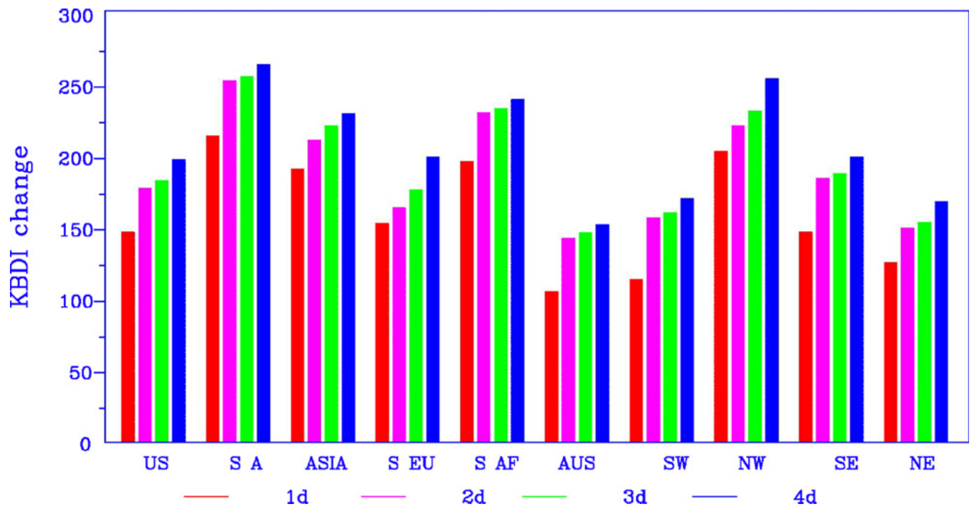

Fig. 7. Dependence of the KBDI increases in future on daily fluctuations in future maximum temperature change projected by HadCM3 with a2a scenario. The bottom shows the global regions and U.S. sub-regions. The bars at each region or sub-region represent the fluctuation interval of 1–4 days (see text for further explanation).

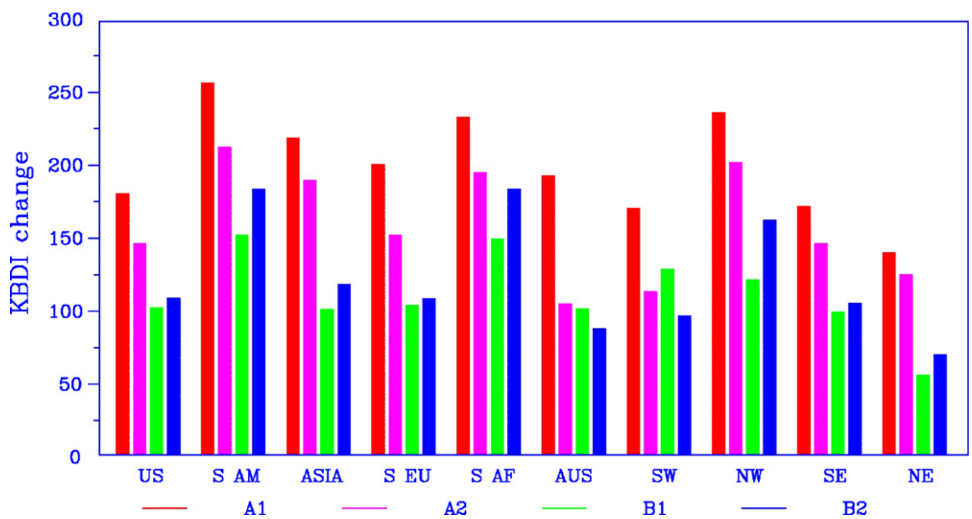

Fig. 8. Dependence of the KBDI increases in future on emission scenarios in the HadCM3 climate change projection. The bottom shows the global regions and U.S. sub-regions. The bars at each region or sub-region represent four emission scenarios.

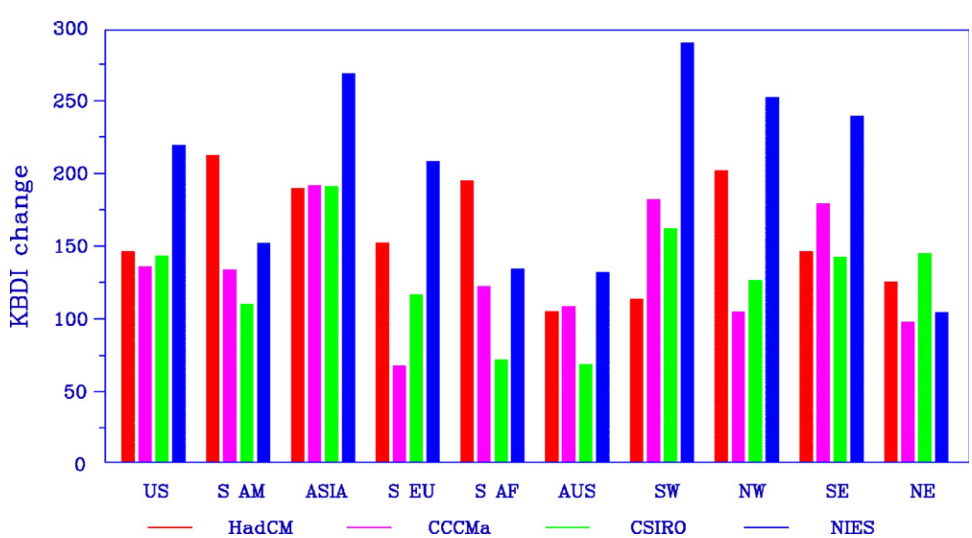

Fig. 9. Dependence of the KBDI increases in future on GCM. The bottom shows the global regions and U.S. sub-regions. The bars at each region or sub-region represent four GCMs. The a2a emission scenario is used in the projection of future climate change with these models.

regions except that the increase with B1 scenario is larger than that with A2 scenario in the Southwest.

This result indicates that the future KBDI increase is very sensitive to the emission scenario used in the projection. Climate change in response to rapid global economic growth and therefore large greenhouse gas emissions will lead to more significant fire potential increases than would be expected in response to more diverse regional economic growth.

3.4.4. GCM

Climate change projections with the NIES and HadCM3 models produce larger KBDI increases than those projected by the two other GCMs (Fig. 9). The difference between the largest and smallest increase among the four GCMs is from 50 to 125. The relative difference is from 30% to nearly 200%. NIES projected climate change also produces the largest KBDI increases in comparison with other GCMs in all U.S. sub-regions except the Northeast. In addition, the dependence of KBDI increase on GCM is more significant in all U.S. sub-regions except the Northeast than for the U.S. average. The Southwest has a difference of about 175 and relative difference of about 250% between the NIES and HadCM projections.

This result indicates that future KBDI increase induced by the climate change is sensitive to the GCM that is used. Increases produced by projected climate change from the HadCM is similar to that from NIES and larger than those by CCCMa and CSIRO models in most global regions and some U.S. sub-regions. Note that the four GCMs have different horizontal resolutions. Thus, the grid points used for each of the global regions and U.S. sub-regions are different. This may be account for some of the differences among the GCMs used here.

4. Discussion

The Intergovernmental Panel on Climate Change raised the possibility that changes in extreme weather and climate events due to greenhouse effects would increase the risk of wildfire (IPCC, 2007). Climate change can affect the number of fires occurring annually, the length of the fire season, the area burned by wildfires, and can increase fire intensity. The changes in these fire properties mean more frequent and higher intensity of seasonal wildfires and therefore larger fire potential. Changes in extreme weather and climate events can also increase the danger of severe wildfire seasons (IPCC, 2007). In our study, we examined the potential for increased fire occurrence globally due to climate change using an index of soil moisture deficit (KBDI) that has been used to indicate wildfire potential. We segmented the range of potential index values into fire potential classes and found significant increases in regions in the mid- and low-latitudes. Current low or moderate fire potential will increase one level (to moderate or high fire potential) by the end of this century. Some regions will face moderate fire potential year-round. The period of high fire potential will last longer each year. We found five regions where significant increases in fire potential could be expected; the U.S., South America, Eurasia, southern Africa, and Australia. Three of the regions, the U.S., Eurasia, and Australia, are located in mid-latitudes. These trends are mainly caused by warming in three regions and by the combination of warming and drying in the three other regions.

The KBDI is calculated based on temperature and precipitation, which are available from meteorological observations and from simulation with climate models. Thus, the KBDI is a practically useful index. It has been extensively used to indicate wildfire risk in the United States as well as other regions. The 1988 revision of the United States National Fire Danger Rating System (NFDRS) includes the KBDI as a means of increasing potential fire intensity during periods of prolonged dryness by adding a drought fuel load to the standard fuel loading of each fuel model (Burgan, 1988). Goodrick (2002) used the KBDI in a similar manner to enhance the performance of the Fosberg Fire Weather Index (Fosberg, 1978) as a tool for predicting the area burned by wildfires. Brolley et al. (2007) examined the potential of using the KBDI for seasonal forecasts of drought based on the state of the El Nino/Southern Oscillation (ENSO).

The exact functional form of the relationship between precipitation and vegetation used in the KBDI may not be valid for annual rainfall amounts that differ significantly from those of the Southeastern U.S. where the index was developed. Despite the potential limitations of the functional form used in the KBDI to parameterize evapotranspiration, the index is still a viable means of assessing the potential impacts of a changing climate on fire potential by focusing on the relative changes in KBDI produced by changes in temperature and precipitation. Of more concern is that vegetation itself will change as a result of climate change (Hansen et al., 2001) and it is not clear how well future precipitation can be used as a surrogate for future fuel conditions.

Not surprisingly, the assumptions of increased economic growth and accompanying carbon emissions (A1 and A2 scenarios) resulted in greater increases in fire potential. This indicates that the actual damage caused by future wildfire can be reduced somewhat by limiting carbon emissions and applying advanced environmental technologies. Similarly future fire potential also is sensitive to the particular GCM that is used. Generally GCMs are thought to provide reasonable projections of future temperature increases but are less able to project changes in precipitation (IPCC, 2007). This dependence of the results on the model used underscores the importance of improved climate modeling for more accurate projections of future fire potential. Specifically, improved projections of maximum temperature are important in the U.S., South America, and Australia, while improved projections of precipitation is important in all the regions.

Efforts have been made to evaluate past variations and to project future wildfire trends related to climate change. Prolonged drought in fire-sensitive tropical forests, combined with continuing deforestation and fragmentation (Malhi et al., 2008), will increase fire occurrence and the area of affected forests (Cochrane and Barber, 2009). The area burned in parts of the boreal forest is projected to double by the end of this century (Flannigan et al., 2009). For example wildfire in Canada is projected to increase by about 74–118% (Flannigan et al., 2005). In the western U.S. during the past three decades, temperature has trended higher and wildfire activity has increased accordingly (Westerling et al., 2006). Westerling et al. (2006) projected that wildfire activities would continue to increase in this century. Of particular concern is an increase in the frequency and distribution of extreme events (Mitchell et al., 2006) such as prolonged drought and high temperatures that lead to large wildfires driven by weather rather than by fuels.

Mesoscale climate modeling is a technique to simulate and predict atmospheric conditions, variability, and changes in a specific region of interest over a long period. These models were developed to solve the problems of low spatial resolution of the GCMs and to better represent the mesoscale systems responsible for convective precipitation events. We identified a number of regions with significant increases in future fire potential and applying regional climate models to these regions could reveal high-resolution spatial patterns of future fire potential. Mesoscale climate models already have been applied to projection of future wildfire change in southern Europe (Moriondo et al., 2006).

Changes in vegetation and land cover due to climate change can amplify the potential for increased fire occurrence. Our results indicate greater fire potential in most areas that currently have significant current fire potential for at least part of the year. In some areas of low current potential, this could mean an increase in fire occurrence. In areas where wildfire already is a factor to be considered in forest management, our results support the potential of extended fire seasons that possibly are more severe. With a hotter and drier climate vegetation communities will shift over time toward more fire-dependent species. Our results support the interpretation of an expansion over time of the current fire-dependent and fire-sensitive communities in response to on average, warmer and drier climate. A higher frequency of extreme weather events could accelerate this process and lead to abrupt community shifts. Increased weather anomalies such as prolonged droughts have been projected by GCMs for the mid-latitudes (Williams et al., 2007). In the Tropics, more frequent and severe droughts could result in a shift toward seasonally dry forests, which may burn with greater frequency than the present wet tropical forests (Cochrane and Barber, 2009) especially in areas where increased human pressure provides ignition sources otherwise lacking (Malhi et al., 2008). Only areas of low productivity that are not conducive to fuels buildup will be unaffected by changed fire potential. These results have several implications for climate modeling in general resulting from changes in land cover and effects of additional of smoke from increased fires.

Changes in land cover can affect regional climate not only through the global carbon cycle and release of anthropogenic CO_2 but also by changing biophysical processes (Foley et al., 2005). The primary biophysical mechanisms are changes in albedo, surface roughness, and the balance between sensible and latent heat loss (Field et al., 2007). Climate forcing from anthropogenic change in land cover can be substantial (Pielke and Avissar, 1990; Henderson-Sellers and McGuffie, 1995; Foley et al., 2005; Snyder et al., 2004; Brovkin et al., 2006) and current GCMs do not adequately account for these anthropogenic climate forcings (Pielke, 2005; Pielke et al., 2002). Increased wildfire in tropical forests will result in a net loss of carbon (Field et al., 2007). Thus, burning in these regions will contribute to more carbon loss into the atmosphere (Mahowald et al., 2005) and amplify the effects of climate change.

The atmosphere in the subtropics and mid-latitudes is often unstable. Smoke-atmosphere interactions can play a role in amplifying instability and the resulting anomalies. More extensive interactions with the atmosphere from increased future fire activity would cause more intense disturbances and variability in the regional weather and climate processes, with more severe effects locally than globally (Field et al., 2007). Regional alteration of landscape also affects global climate through teleconnections (Chase et al., 2000; Feddema et al., 2005). Mesoscale climate models suggest that precipitation and temperature in distant regions are affected by smoke plumes from severe wildfires. For example, smoke from the wildfires in Yellowstone National Park in the western U.S. exacerbated the severe northern drought in 1988 in the northern U.S. (Liu, 2005b). In addition, the monsoon in the South America was weakened due to the feedback of smoke emitted from burning to the atmosphere (Liu et al., 2005).

Climate change, increased human populations, land-use change, and responses to these changes pose the complex challenge of global change. Population increases and changes in land-use to support a larger global population with higher standards of living for at least some portion of the population will occur regardless of climate change, and will have an impact on natural vegetation, fuels, and ignitions of wildfires. Adding more intense wildfire activity because of climate change to these challenges means dramatic increases in human fatalities and property loss and longer fire season means the need for more resources for disaster prevention and recovery. Because of these issues and the adverse environmental effects of catastrophic wildfires, one possible social response would be an effort to increase suppression activity. However, indications are that fire suppression resources are already stretched to their limit during extreme conditions (Flannigan et al., 2009), resulting in more fires escaping initial attack and growing into extreme events (Fried et al., 2004; Flannigan et al., 2009). Although it would appear that fire suppression has an additional positive impact on climate change by sequestering large amounts of carbon in biomass, this ignores the inevitability of wildfire in fire-dependent ecosystems and does not account for the total carbon footprint of transportation fuel use and other factors in suppression. An all-out effort to suppress wildfire ignores their inevitability in fire-dependent forests, where it is a matter of when it will burn, not if it will burn.

5. Conclusions

Wildfire potential is projected to increase globally under future climates. This trend is seen in areas that currently have significant wildfire occurrence and many fire-dependent forest types. Our results using the Keetch-Byram Drought Index (KBDI) indicate that fire potential will increase overall from low to moderate in the United States, central Asia and southern Europe, and from moderate to high in South America, southern Africa, and Australia. Perhaps the most significant impact we found of climate change on wildfire potential is the lengthening of the fire season, accompanied by an increased likelihood of more extreme weather events. Most regions will face moderate fire potential for the entire year in the future. All regions will see a longer period of high fire potential, from 2 to 8 months. The highest fire potential in U.S., Eurasia, and Australia occurs in summer of the corresponding hemispheres, when temperature is the highest. But in South America and southern Africa, the largest fire potential occurs in the late winter and early spring of the southern hemisphere, which is the dry season of a year. The combined effect of increased fire potential and longer fire seasons will seriously challenge already taxed fire suppression programs.

Several caveats must be considered in interpreting these results, however. We show that the increased fire potential is sensitive to the particular general circulation model used to project future climates, as well as the emission scenario used. Additionally, current GCMs under-represent the influence of land cover change as a climate forcing and our study did not include the probable adjustments that will be made by vegetation to changed climate. The current fire-dependent and fire-sensitive communities could expand in area in response to warmer and drier average climate with abrupt community shifts possible due to a higher frequency of extreme weather events such as prolonged drought or extremely high temperatures. Such vegetation shifts will amplify the effects of changes in climate and longer fire seasons. The limitation of current GCMs that focus primarily on CO_2 as a climate forcing may overstate the effect that emission controls would have as a mitigation strategy.

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