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An assessment of fire occurrence regime and performance of Canadian fire weather index in south central Siberian boreal region

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Abstract

Wildfire is the dominant natural disturbance in Eurasian boreal region, which acts as a major driver of the global carbon cycle. An effectiveness of wildfire management requires suitable tools for fire prevention and fire risk assessment. This study aims to investigate fire occurrence patterns in relation to fire weather conditions in the remote south central Siberia region. The Canadian Fire Weather Index derived from large-scale meteorological reanalysis data was evaluated with respects to fire regimes during 14 consecutive fire seasons in south central Siberian environment. All the fire weather codes and indices, including the Fine Fuel Moisture Code (FFMC), the Duff Moisture Code (DMC), the Drought Code (DC), the Buildup Index (BUI), the Initial Spread Index (ISI), and the Fire Weather Index (FWI), were highly reflected inter-annual variation of fire activity in south central Siberia. Even though human-caused fires were major events in Russian boreal forest including south central Siberia, extreme fire years were strongly correlated with ambient weather conditions (e.g. Arctic Oscillation, air temperature, relative humidity and wind), showing by in-phase (or positive linear relationship) and significant wavelet coherence between fire activity and DMC, ISI, BUI, and FWI. Time series observation of 14 fire seasons showed that there was an average of about 3 months lags between the peaks of fire weather conditions and fire activity, which should take into account when using coarse scale fire weather indices in the assessment of fire danger in the study area. The results are expected to contribute to a better reconstruction and prediction of fire activity using large-scale reanalysis data in remote regions in which station data are very few.

1 Introduction

The global boreal zone covers about 1.3 billion ha across Eurasia and North America representing the largest forest biome and one third of global forest cover (FAO, 2010). Boreal regions store more carbon in trees, soil and peat than any other terrestrial ecosystem (Goldammer and Furyaev, 1996). However, wildland fire is a major disturbance in boreal forest regions which in turn can lead to considerable ecological and economic losses as well as global CO_2 emissions comparable to other fuel combustion (Bowman et al., 2009). Fire activity is projected to increase in boreal regions due to changes in the climate system and human activity (Moritz et al., 2012; Flannigan et al., 2009). According to Flannigan et al. (2009), an average of 10–15 million ha burn annually in boreal forests, primarily in Siberia, Canada, and Alaska, and there is a growing awareness of the effectiveness of fire management in the circumboreal forest under future climate change. Thus, the selection of suitable tools for fire prevention and assessment becomes an important component of land management over the region.

Fire danger is described as the results of both constant and variable factors of the fire environment which influence the ignition, spread and difficulty controlling wildland fires (Dimitrakopoulos et al., 2011). Fire danger rating is a system that integrates the effects of selected fire danger factors in order to produce qualitative or numerical indices of fire potential that are used as guides in fire management activities (Stocks et al., 1989). Within a number of influence factors, weather, vegetation properties, and human play crucial roles in determining the fire danger, and thus almost all forest fire danger rating systems try to integrate meteorological data with both the bio-physical properties of natural fuels and human activity to predict the probability of fire occurrence as well as the potential damage of fire (Chuvieco et al., 2010; Dimitrakopoulos et al., 2011). Description of various existing systems around the world can be found in Viegas et al. (2000), Carvalho et al. (2008), Dimitrakopoulos et al. (2011), and Chuvieco et al. (2010). In the countries of Eurasia and North America that belong to the boreal region, there is also a multiplicity of methods in use for the evaluation of the fire danger, including the Canadian Forest Fire Danger Rating System (CFFDRS) used in Canada (Van Wagner, 1987), the National Fire Danger Rating System (NFDRS) used in the USA (Bradshaw et al., 1984), and Nesterov Fire Index (NFI) used in Russia (Stocks and Lynham, 1996; Rubtsov et al., 2011). The Canadian Forest Fire Weather Index

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(FWI) System is a sub-system of the CFFDRS and has been in its present form since 1970 (De Groot, 1987). The FWI system is not only widely applied to assess forest fire danger in boreal forests (Stocks et al., 1989; de Groot et al., 2012; Rubtsov et al., 2011; Soja et al., 2011) but also in many other ecoregions in southern Europe (Viegas et al., 2000; Carvalho et al., 2008; Dimitrakopoulos et al., 2011; Padilla and Vega-García, 2011; Šturm et al., 2012; Holsten et al., 2013), Australia and New Zealand (Arpaci et al., 2013; Fogarty et al., 1998), and China (Tian et al., 2012). Because of its simplicity and its strong interpretive product, the FWI system is now operated nationally in many countries and is being adapted to monitor wildfire danger globally (Dimitrakopoulos et al., 2011).

In the calculation of the FWI's codes and indices, four weather variables including rain accumulated over 24 h, air temperature, relative humidity, and wind speed are needed and generally taken daily at noon local standard time (LST) or 13:00 local daylight time (LDT) at weather stations (Lawson and Armitage, 2008). The accuracy and precision of estimation of the FWI's codes and indices are strongly depends on the observation of weather elements from local weather stations. Ideally, the standards and locations of fire weather stations should conform to those recommended by the World Meteorological Organization (WMO) for agrometeorologic observations in forest areas (Lawson and Armitage, 2008). For examples, the location of fire weather station should represent the general area of concern with respect to distance, topography, vegetative cover, and local weather patterns. Unfortunately, however, it is not usually possible to meet all of these standards in practice, particular in remote regions where weather stations are sparse. Thus, large-scale reanalysis meteorological data such as products of the National Centers for Environmental Prediction (NCEP), the European Centre for Medium-Range Weather Forecasts (ECMWF), and the NASA Goddard Earth Observing System version 4 (GEOS-4) could be alternative inputs for the calculation of surrogate fire danger codes and indices (Soja et al., 2011; Bedia et al., 2012). A reanalysis project consists of the assimilation of observational data through numerical simulation models to produce atmospheric variables and

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meteorological data that covers globally over several decades or more (Kalnay et al., 1996). Applications of reanalysis data are manifold in different scientific and technical fields such as agriculture, water resources, energy and natural hazards (Bedia et al., 2012). However, models based reanalysis data may present spatial and temporal inconsistencies and deviations from ground-station observed climate because of their relative coarse spatial resolution. Although some important works have been done on testing the performance of reanalysis data in reproducing FWI values (e.g. Bedia et al., 2012), the agreement between reanalysis data based fire weather variables and actual fire regimes remains an open question to be addressed in many ecoregions around the world (Bedia et al., 2012).

Since Russian boreal forests play an important role in greenhouse gases emissions and the global carbon balance (Kukavskaya et al., 2012; Kasischke et al., 2005), there is an urgent need to obtain accurate forest fires related information of this ecozone (Rubtsov et al., 2011; Kukavskaya et al., 2012). In terms of management of fire activity, there are several existing systems of fire danger assessment being widely applied in Russia such as a relative simple ignition index developed by Nesterov (Stocks and Lynham, 1996), Russian moisture indcies (MI1 and MI2) (Rubtsov et al., 2011), and the Canadian Forest Fire Weather Index (FWI) system (Van Wagner, 1987). Rubtsov et al. (2011) found a positive correlation ($R^2 = 0.45$) between the cumulative area of local fires and the local weather stations based BUI and DMC indices in Siberian forests. Compared with the Russian moisture indices (MI1 and MI2), the ISI and FWI indices described better the diurnal dynamics of fire areas in Siberia region. In addition, Soja et al. (2011) found that the Canadian fire weather index based on the large-scale ($1^{\circ} \times 1^{\circ}$) data of GEOS-4 product showed consistent result with the FWI derived from ground-station interpolated meteorological data in eastern Siberian forest. Soja et al.'s results also revealed that the large-scale GEOS-4 weather data can be used to accurately assess fire weather and danger at local and regional scales. All these evaluations of the FWI system by Rubtsov et al. (2011) and Soja et al. (2011) in Siberia have not fully quantified the performance of all large-scale FWI's codes and indices in predicting fire regimes (e.g. fire season, number of fires, area burned, extreme fire years, etc.) at different temporal and spatial scales. In other words, the suitability of a particular system to be used in a given geographical area should be evaluated for long time period in order to properly apply to capture temporal and spatial variability of climate and fire risk.

The FWI system of the CFFDRS was designed for Canadian fuel and weather conditions measured at local weather stations. In other countries, such as Russia, where environmental conditions and fire regimes may be quite different, all components of the FWI system may be neither necessary nor appropriate. In addition, weather stations are sparse in many remote boreal regions. Therefore, testing the ability of reanalysis data based fire weather indices to correctly detect critical periods of fire risk and evaluate their performance against historical fire records is very important to improve the prediction of fire activity by the fire management agencies. The overall objective of this study was to investigate the basis and underlying relationships between large-scale ($1.875^{\circ} \times 1.92^{\circ}$) reanalysis climate data based Canadian fire weather indices and Siberian fire regimes, in order to evaluate its potential use in south central Siberian fire environment. To this aim, we assessed characteristics of fire regime in south central Siberia region using fire and burned area records from MODIS products. All Canadian fire weather codes and indices were then calculated based on the NCEP reanalysis meteorological dataset. Finally, the performance of the FWI system components was assessed by means of wavelet analysis which determined to what extent the FWI components were able to monitor fire regimes and also to identify critical periods of fire risk. This study only used fire occurrence (number of fires) to represent of fire activity in relation to fire weather indices in the study area. Area burned was excluded in this relationship because of complexity of fire spread defined area burned that is highly sensitive to local fire-fighting policies and many other factors rather than weather conditions. Drivers of area burned within ecoregion across south central Siberia will be reported in another manuscript.

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2 Materials and methods

2.1 Study area

The study area is about 200 000 km^2, extending from 48 to 60° northern latitudes to 95 to 105° eastern longitudes (Fig. 1) and covers both south central Siberia and northern Mongolia. The forests in the study area are represented by northern, middle, and southern taiga and steppe-taiga ecozones. Low-productivity mature larch forest with moss and lichen ground cover dominates in the northern central Siberia taiga. In the middle taiga, Scots pine and larch are dominant species. The highest tree species diversity can be found in the forests of southern taiga in the study area and includes stands of both needleaf and broadleaf tree species (Kukavskaya et al., 2012). The climate of the central Siberia is extremely continental. The mean annual air temperature ranges from −4 °C in the south to −13.8 °C in the north. Total mean annual precipitation is about 300–400 mm in the southern part and gradually decreasing northwards to 180–250 mm (Zyryanova et al., 2010). The south central Siberia region is underlain by continuous and discontinuous permafrost in northwards and southwards, respectively. Wildfire is a major natural disturbance in the area in which southern boreal forest fires are responsible for up to 39 % of the total forest area burned in Russia (Kukavskaya et al., 2012).

2.2 Satellite and weather data

Two MODIS products (tile h23v03and tile h23v03) from 2000 to 2013 were used to evaluate fire frequency, fire season, and area burned in south central Siberia and northern Mongolia, including the 8 day MODIS active fire product (MOD14A2) (Giglio, 2010) and the standard monthly burned area product (MCD45A1) (Boschetti et al., 2009). All these products were downloaded from http://reverb.echo.nasa.gov and preprocessed using the MRT tool (Dwyer and Schmidt, 2006).

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Calculation of the Canadian fire weather indices was based on consecutive daily observations of air temperature, relative humidity, wind speed, and 24 h rainfall. We selected meteorological reanalysis data obtained from the National Centers for Environmental Prediction (NCEP) reanalysis-2 data (http://www.esrl.noaa.gov/psd/, accessed 12 February 2014) from 2000 to 2013 for our study area. The NCEP reanalysis is a joint product of the National Centers for Environmental Prediction (NCEP) and the National Center for Atmospheric Research (NCAR) (Kalnay et al., 1996). NCEP data have been available since 1948 and updated until present. The NCEP reanalysis-2 data have a spatial resolution of $1.875^{\circ} \times 1.92^{\circ}$. The daily meteorological data were extracted from a grid cell ($1.875^{\circ} \times 1.92^{\circ}$) that falls within our study area (Fig. 1). Reanalysis data for the four required variables to calculate fire weather indices at 13:00 LDT was gathered considering 24 h accumulated values for precipitation and instantaneous values for 2 m air temperature, 10 m wind speed, and surface relative humidity. In the case of precipitation, the 24 h rainfall was calculated from daily mean precipitation.

2.3 Characterizing fire regime and calculating fire weather indices

Fires between 2000 and 2013 were summarized from 8 day composite active fire MOD14A2 product to determine fire season and peak of fire season in the south central Siberia and northern Mongolia. Only hot spots with high-confidence level (fire mask equals 9) in MOD14A2 product were selected for this purpose. In addition, yearly burned area from MCD45A1 and yearly number of fires from MOD14A2 product were also summarized to clarify burn trend as well as fire occurrence tendencies for the last 14 years in the study area.

The FWI system includes six standard components. The three fuel moisture codes: (1) the Fine Fuel Moisture Code (FFMC) is a numerical rating of the moisture content of litter and other cured fuels less than 1 cm in diameter. This moisture code is an indicator of the relative ease of ignition and flammability of the top litter layer less than 1–2 cm in depth with typical fuel loading of about 5 t ha^{-1}. The FFMC fuels are affected

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by air temperature, wind speed, relative humidity, and rain. (2) The Duff Moisture Code (DMC) is a numerical rating of the average moisture content of loosely compacted organic layers that is 5–10 cm in depth, and has a fuel loading of about 50 t ha^{-1}. The DMC values are calculated by total daily rain, air temperature and relative humidity. (3) The Drought Code (DC) is a numerical rating of the average moisture content and an indication of seasonal drought effects on deep and compacted organic layers. It is representative of the fuel layer at 10–20 cm in depth and having a fuel loading of about 440 t ha^{-1}. The DC fuels are only affected by air temperature and rain because of the depth of this fuel layer. In addition, the three fire behavior indices: (1) the Initial Spread Index (ISI) is a numerical rating of the expected rate of fire spread. It combines effect of wind and the FFMC to indicate the expected rate of fire spread. (2) The Buildup Index (BUI) is a numerical rating of the total amount of fuel available for combustion. The index is a weighted combination of the DMC and DC in which the DMC has the most influence on the BUI value. (3) The Fire Weather Index (FWI) is a numerical rating of the potential frontal fire intensity that combines the rate of fire spread (ISI) with the amount of fuel being consumed (BUI). The three fuel moisture codes are highly correlated to fire occurrence, while the remaining three components of fire behavior indicate the rate of fire spread as well as the danger level of fire (Lawson and Armitage, 2008).

In this study, six daily fire weather indices between 2000 and 2013 were computed based on Van Wagner and Pickett (1985). The FWI components were calculated using 13:00 local daylight time (LDT) values of temperature, relative humidity and wind speed, and daily total precipitation. This study used 13:00 LDT observations from 20 hourly grid points in the NCEP reanalysis dataset distributed across the study area (Fig. 1). All fire weather indices were calculated for 14 year time series over the winters, except for the Drought Code (DC). The DC values need to be adjusted for low overwinter precipitation (Lawson and Armitage, 2008). However, adjusted parameters of low overwinter precipitation by regional fire weather authorities were not available in the study area. Thus, we used daily accumulated precipitation during winter months (October–March) to calculate DC values over the winter. All indices were

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then examined by average values of 8 day composites between 2000 and 2013 for an assessment of fire seasonality and periods in which extreme fire events occurred.

2.4 Wavelet analysis

A number of statistical methods exist that examine relationship between two time series of ecological processes or properties such as spectral coherency, codispersion coefficient of multivariate geostatistics, Fourier analysis, and wavelet analysis (Cazelles et al., 2008; Yates et al., 2007). The use of either first three methods is dependent on the assumption of stationary in the data that the statistical properties of the data do not vary with time or location (Cazelles et al., 2008). However, data of ecological processes typically violate the stationary assumption. For example, observations of number of fire and fire weather variables are commonly characterized by extreme values in peak fire season which may lead to unevenly distributed variance and nonstationarity. Thus, wavelet analysis that overcomes the problems of non-stationary in time series by performing a local time or space-scale decomposition of the signal (Torrence and Compo, 1998) would be a suitable tool to analyze temporal scale-dependent relationship between two or more ecological processes such as fire activity and fire weather conditions. Wavelet analysis has been widely applied in geosciences, particular in meteorology, climatology, oceanography, and hydrology (see review by Labat, 2005). However, very few contributions of wavelet analysis can be found in the field of fire sciences (e.g. Macias Fauria and Johnson, 2006; Girardin et al., 2006; Vargas et al., 2012).

Comprehensive reviews on the application of wavelet analysis are given by Torrence and Compo (1998), Labat (2005), and Cazelles et al. (2008). Wavelet analysis was developed from the Fourier transforms and defined as a function with zero mean and that is localized in both frequency and time (Grinsted et al., 2004). Depending on the algorithm, the wavelet analysis can be classified as continuous wavelets transform or discrete wavelets transform. The wavelet transform of a time-series $x(t)$ with respect to a chosen mother wavelet is defined by the linear integral operator as follow (Cazelles et al., 2008) (Eq. 1):

$$W_x(a,\tau) = \frac{1}{\sqrt{a}} \int_{-\infty}^{+\infty} x(t)\varphi^*(\frac{t-\tau}{a})\mathrm{d}t = \int_{-\infty}^{+\infty} x(t)\varphi^*_{a,\tau}(t)\mathrm{d}t, \quad (1)$$

where * denotes the complex conjugate form. Parameters a and τ denote the dilation (or scale factor) and translation (time position), respectively. The wavelet transform $W_x(a,\tau)$ can be seen as a cross-correlation of a time series $x(t)$ with a set of wavelets $\varphi(\frac{t-\tau}{a})$ of various scales a, at different time position τ. There are several considerations in making the choice of a wavelet and mother wavelet such as real vs. complex wavelets, continuous or discrete wavelets, orthogonal or redundant decompositions. In this study, the continuous wavelet transform (CWT) was selected to separate temporal series of fire occurrence and fire weather indices into continuous scales and temporal positions. This is because of CWT's ability to preserve all the information in original data series giving us the possibility of gaining insight about the original data series (Shu et al., 2008). For CWT, we used the Morlet wavelet function (Torrence and Compo, 1998; Grinsted et al., 2004) (Eq. 2, with dimensionless frequency, $\omega_0 = 6$) since it can provide a good balance between space and frequency localization (Shu et al., 2008).

$$\varphi(t) = \pi^{-1/4}\exp(-i2\omega_0 t)\exp\left(-\frac{t^2}{2}\right). \quad (2)$$

The wavelet transform (or wavelet coefficient, $W_x(a,\tau)$) is a measure of how the sample values of time series vary. The wavelet power spectrum at a location and scale, which defined as the square of the absolute value of the wavelet coefficient $|W_x(a,\tau)|^2$, is the local variance of the sample values. The sum of all wavelet power spectra is the total variance of the time series.

In addition, the wavelet cross spectrum and the wavelet coherence can be computed and analyzed in order to quantify the relationships between two time series. The

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wavelet cross spectrum (WCS) is given by

$$W_{x,y}(a,\tau) = W_x(a,\tau)W_y^*(a,\tau) \tag{3}$$

with * denoting the complex conjugate. Because WCS describes the common power of two processes without normalization to the single wavelet power spectrum, this can produce mis-interpreting the relationship between two time series (Maraun and Kurths, 2004). Therefore, the wavelet coherency (WCO), which is defined as the amplitude of the WCS normalized to the two single wavelet power spectrum (Maraun and Kurths, 2004) (Eq. 4), was used to measure for the relationship between fire occurrence and fire danger indices. It should be noted that analyses of cross wavelet spectrum and wavelet coherence have edge artifacts that accounted for by defining a cone of influence (COI) in which edge effects cannot be ignored (Grinsted et al., 2004). Therefore, wavelet power spectrum and wavelet coherence below the cone is lacking in accuracy and should be interpreted with caution (Cazelles et al., 2008).

$$R^2_{x,y}(a,\tau) = \frac{|W_{x,y}(a,\tau)|^2}{|W_x(a,\tau)|^2|W_y(a,\tau)|^2} \tag{4}$$

The wavelet coherence (Eq. 4) is similar to a traditional correlation coefficient of two datasets and it is used to evaluate a localized correlation of two processes in time frequency space (Grinsted et al., 2004). A value of 1 means a linear relationship between $x(t_i)$ and $y(t_i)$ around time t_i on a scale a, while value of zero is obtained for no correlation between $x(t_i)$ and $y(t_i)$. The statistical significance level of the wavelet coherence was estimated using Monte-Carlo methods using red noise to determine the 5 % significance level (Grinsted et al., 2004).

If the coherence of two series is high, the arrows in the coherence spectra can be used to show the possible delay in the relationship between two time series processes. Arrows at 0° (horizontal right) indicate that both phenomena are in-phase or a linear positive relation and arrows at 180° (horizontal left) indicate that they are in anti-phase or a linear negative relation. These can be also interpreted as a linear relation between two time series. On the other hand, arrows at 90 and 270° (vertical up and down, respectively) indicate an out of phase situation or a non-linear relation between the considered phenomena. In this study, the phase angle difference defined as $\tan^{-1}[\mathcal{I}\{W_{x,y}(a,\tau)\}/\mathcal{R}\{W_{x,y}(a,\tau)\}]$ (Torrence and Compo, 1998) was converted to time lag (or delay) to evaluate the effectiveness of fire weather index and its relation to fire occurrence in south central Siberia.

Both continuous wavelet transform and wavelet coherence were applied to evaluate the ability of large-scale Canadian fire weather indices and its relationships with fire activity. As noted by Grinsted et al. (2004) time series for wavelet analysis should not be too far from normally distributed, we tested the histograms of the time series and found that all variables were closed to normal distribution. In addition, time series data of fire occurrence and fire weather indices were standardized using mean and standard deviation for comparisons and were referred to the standardized versions as original time series data in the wavelet analysis.

3 Results

3.1 Characteristics of fire regime and fire weather indices

Wildfires in south central Siberia region were found to be severe for the last 14 years and showed several critical periods in 2003–2004, 2006–2008, and 2010–2012. Except for FFMC and DC, Canadian fire weather indices clearly identified patterns of temporal fire occurrence between 2000 and 2013 with some identical peaks within each fire-year (Fig. 2).

In terms of fire seasonality, the analysis of 14 years active fire detections and burned area over the south central Siberia region demonstrated that seasonal fire occurrence from March to October annually (Table 1 and Fig. 3). Spring (March–June) was the most severe fire season, while very few fires occurred in the late season (September–

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October), 80.4 and 3.1 % respectively. In the primary fire season, May was the most severe month of fire activity accounted for 48 % of total fires during fire season. Two other peaks of fire activity were in July and September annually (Fig. 3).

In relation to burned area, more than 30 000 km^2 of forest, cropland, and grassland were burnt between 2000 and 2013. More specifically, these burned areas comprised of 48 % of conifer forests, 37 % of grassland and cropland, 11 % of mixed forests, and 3 % of broadleaf forests (summarized from large burned areas (> 1000 ha) within the study area, data not shown). In general, higher number of fires resulted in larger burned area, except for fires in 2007 and 2008 (Fig. 4). Visual interpretation of fire activity during this period, almost all fires occurred in the flat and low elevation areas that resulted in the high rate of fire spread and thus larger burned patches even small number of fires. Both fire occurrence and burned area data showed a cyclic pattern of about 4–5 years interval in south central Siberia region with the severe fire/burn years in 2003, 2008 and 2012 (Fig. 4).

3.2 Relationships of fire weather indices and fire occurrence

3.2.1 Continuous wavelet analysis of fire occurrence and fire weather indices

The local wavelet power spectrum of fire weather indices and fire occurrence was shown in Fig. 5. Fire weather indices and fire occurrence showed high variance at scales of 8–16 months that indicates seasonal variation of these processes as shown from visual observation in Fig. 2. In particular, very high and significant variations of FFMC (Fig. 5b), DC (Fig. 5d), and ISI (Fig. 5e) were observed in all years between 2000 and 2013. Compared with the variance of number of fires, these indices did not represent critical periods of fire occurrence. On the other hand, continuous wavelet transform of DMC (Fig. 5c), BUI (Fig. 5f), and FWI (Fig. 5g) showed significant and high variance of these variables at scales of 8–16 months in the years similar to that of fire occurrence (Fig. 5a). Additionally, the continuous wavelet transforms of these fire weather indices also indicated some significant peaks of fire risk at smaller scales of

8 days to 4 months (Fig. 5c, f and g) that were overlapped with the significant regions of fire occurrence (Fig. 5a). These relationships between fire weather indices and fire occurrence between 2000 and 2013 at different time scales can be confirmed using wavelet coherence analysis in the next steps.

3.2.2 Wavelet coherence analysis of fire and fire weather indices interrelation

In general, the wavelet coherence analysis indicated that fire weather conditions were strong correlated with fire activity between 2000 and 2013, and the significant coherency varied at different temporal scales (Fig. 6). The strong coherency of fire weather indices and number of fires at a scale of 8–16 months was associated with the annual variations of fire weather indices and fire occurrence at the same scales as indicated in the continuous wavelet analysis (Fig. 5) and original dataset (Fig. 2). However, the phase difference showed that the process of fire activity was ahead (arrows pointing up and up right) of all fire weather indices at those large temporal scales, which indicated the highest values of fire weather indices and fire activity in each year between 2000 and 2013 were inconsistent. The calculation of average phase angle at scales of 8–16 months indicated the time lag of 3 months between FWI and fire activity in the study area. In other words, as the peak of fire activity was in May, the FWI values increased gradually and reached the maximum in August.

With respect to critical periods of fire occurrence, DMC (Fig. 6b), ISI (Fig. 6d), BUI (Fig. 6e), and FWI (Fig. 6f) indicated very well for extreme fire years as well as significant peaks of fire seasons at a scale of 8 days to 8 months depending on severity of fire activity, particular in 2002–2003 fire-years. This was also shown by the phase difference that fire weather indices were mainly in-phase with fire activity (arrows pointing right) at small scales of 8 days to 8 months. However, there was a peak of fire occurrence in 2008 (Figs. 2a and 5a) that could not distinguished from the analysis of wavelet coherence possibly because of that extreme fires in this year affected by other reasons rather than fire weather conditions. Even though FFMC and DC (Fig. 6a and c) can represent inter-annual variations of fire occurrence at a large scale of 8 months to 3 years, these fire weather codes did not clearly indicate all critical periods of fire occurrence as well as some peaks within a fire-year.

4 Discussion

Most fires in south central Siberia occurred in the spring (80.4 %), supporting previously reported estimates in Russia fire regime which are distinctly different with Canadian fire season that is peak in mid-summer (de Groot et al., 2012). The south central Siberian fire season was similar to that of boreal forest in northern China (Tian et al., 2012). Mollicone et al. (2006) indicated that more than 87 % of fires in boreal Russia are human-caused, which is consistent with the spring-dominated fire season found in this study. According to De Groot et al. (2012), the main reason for human-caused fires occurred in spring is existing of dead light surface fuels such as cured grass and leaf litter available for combustion before under-story plants green-up and trees leaf-out in summer. Additionally, the human impact on the forests through fires also owes to lack of control, ineffectual fire management policies and socioeconomic conditions in the region (Mollicone et al., 2006; Achard et al., 2008). This also might be a consequence of the oil exploitation in Siberia (Dienes, 2004). Even though human activities are responsible for seasonal fire occurrence in Russian boreal forests, there are more fires in years during which the weather is anomalous (Achard et al., 2008). We found that a cyclic pattern of both burn trend and fire occurrence (Fig. 4) between 2000 and 2013 was highly consistent with the pattern of Artic Oscillation Index (AOI) (Fig. 7). This is similar to the findings by Balzter et al. (2005) that inter-annual forest fire variability in central Siberia could best be explained by a combination of the Arctic Oscillation index and regional summer temperatures. As the AOI quantifies the difference in atmospheric pressure between the northern middle and high latitudes, a positive value of AOI indicates higher pressure at mid-latitudes. Consequently, higher pressure at mid-latitudes brings higher than normal temperatures to northern Eurasia, and that

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suggests a possible causal link between the Arctic Oscillation and south central Siberian fires (Balzter et al., 2005).

All Canadian fire weather indices showed statistically significant correlations with fire occurrence in south central Siberia (Fig. 6). However, strong coherency between number of fires and fire weather indices does not necessarily mean that of existing an effective index to represent fire danger levels. There are three case scenarios that could result in high coherencies of two processes at different scales and locations; (1) an in-phase or a linear positive relation, (2) an anti-phase or a linear negative relation, and (3) an out of phase of specific angle or non-linear relation. As the use of fire weather indices is to assess fire danger levels as well as predict real fire activity, these indices should be in-phase with the process of fire occurrence. Therefore, in coupling with an assessment of wavelet coherence, phase relationship is an important measure to evaluate the effectiveness of a fire danger system. The phase differences showed that DMC (Fig. 6b), ISI (Fig. 6d), BUI (Fig. 6e), and FWI (Fig. 6f) were in-phase with fire activity (arrows pointing right) at small scales of 8 days to 8 months. This basically confirmed the conclusion that these indices were the suitable variables for prediction of critical periods of fire activity with higher their values indicate higher number of fires. The phase relationships between fire activity and FFMC and DC did not show strong linear positive relation at 8 days to 8 months scales (Fig. 6a and c). FFMC indicates the moisture content of dead fine fuels and is used as a general indicator of potential for human-caused fire starts (Wotton, 2009), while DC represents the moisture content of deep compact soil organic matter. As indicated in the causal link between Artic Oscillation and fire activity, those suggest that extreme fire years in south central Siberia were more dependent on ambient weather conditions (relative humidity, air temperature, wind) than on drought conditions.

Observations at larger scales of 8–16 months showed that the process of fire activity was ahead (arrows pointing up and up right) of all fire weather indices, with the average time lag of 3 month at scale of 12 months. This indicates the performance of Canadian fire weather indices for seasonal observations of fire activity within a year in south

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central Siberia. More specifically, the calculation of the fire weather indices started in early April after snow has essentially left the area (see Lawson and Armitage, 2008). Thus, the values of the fire weather indices increased gradually due to a decrease of soil and fuels moisture after spring and reached the maximum in autumn as a dry season. However, the fire activity in south central Siberia region was primary in spring with the peak in May (Table 1 and Fig. 3). As a result, the seasonal or intra-annual patterns of the fire weather indices were inconsistent with that of the fire occurrence. This argument of the phase difference between fire activity and fire weather indices mentioned other physical mechanisms (e.g. vegetation types and topography) affected fire seasonality in south central Siberia region that should take into account in the application of Canadian fire weather indices to the area.

Many studies noted that analyzing both the frequency of fires and spatial extent of burned areas can give us a clearer understanding of the relationship between fire regimes and weather conditions (Pricope and Binford, 2012). However, our results (data not shown) indicated that elevation and density of resident places in south central Siberia have higher impact than fire weather indices in determining area burned. This is similar to the performance of Canadian fire weather indices in Mediterranean (Dimitrakopoulos et al., 2011), northern Chinese boreal (Tian et al., 2012), and even Canadian boreal (Harrington et al., 1983; Flannigan et al., 2005) environments in which correlation between FWI components and burned areas was poor and varied depending on ecozone. Therefore, this study excluded wavelet coherency analysis of time series burned areas and fire weather indices. According to Dimitrakopoulos et al. (2011) it could be anticipated that the fire weather indices would explain a significant fraction of variance in burned area.

5 Conclusions

We analyzed several components of fire regimes in south central Siberia during the last decade using MODIS hotspot and burned area products in conjunction with

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climatological data. Fire occurrence was severe in the study area with three extreme fire periods in 2002–2003, 2006–2008, and 2011–2012. The annual patterns of both fire occurrence and burned area were highly consistent with the Arctic Oscillation indicated a possible causal link between the Arctic Oscillation and south central Siberian fires. This study also revealed fire seasonality in south central Siberia with the primary fire season in spring accounted for 80 % of fire occurrence annually.

The performance of large-scale reanalysis data based Canadian fire weather components in determining inter- and intra-annual variability of fire occurrence was also evaluated using wavelet analysis. The results demonstrated several aptitudes for their potential use as a fire danger system in remote regions of sparse weather stations. All fire weather indices were highly correlated with fire occurrence. However, only DMC, ISI, BUI, and FWI successfully reflected critical periods and extreme years of fire occurrence with in-phase processes at small observation scales of 8 days to 8 months data depending on severity of fire year. The phase difference of 14 year time series data showed that there was an average of about 3 months lags between the calculated fire weather conditions and fire activity at large observation scales of 8–16 months. This estimated time lag should be considered to have more accurate on using large-scale fire weather indices in the assessment of fire risk in the study area.

In general, despite the coarse spatial scales, NCEP reanalysis meteorological data in conjunction with Canadian fire weather system are able to accurately assess fire weather and danger at regional scales. This has an important implication for ability of coarse meteorological data to reconstruct historical fire weather as well as quantify future fire potential since those reanalysis data are always available to users, such as data from NCEP, ECMWF, GEOS-4, and IPCC weather and climate change scenarios.

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Table 1. Inter-annual and intra-annual characteristics of fire incidence in south central Siberia and northern Mongolia (2000–2013).

Year	Month								Σ Fire	Σ Area burned (km^2)
	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct		
2000	2	78	152	127	7	7	3	0	376	275
2001	0	32	1074	14	3	22	16	4	1165	342
2002	8	425	1615	151	884	445	428	0	3956	4844
2003	9	696	4318	3257	778	117	4	6	9185	5718
2004	0	5	712	94	18	7	4	4	844	346
2005	4	214	401	11	54	43	23	8	758	884
2006	8	75	1165	420	1729	111	8	0	3516	2121
2007	6	701	38	60	503	106	33	16	1463	2181
2008	86	153	3607	320	8	3	23	4	4204	6083
2009	1	138	510	39	13	1	10	8	720	1436
2010	0	71	803	163	15	24	9	3	1088	915
2011	7	404	1753	1378	536	21	426	6	4531	2533
2012	4	1063	1456	1596	541	72	71	4	4807	3518
2013	0	290	241	259	46	79	33	22	970	1266
Σ Monthly (%)	135 (0.4 %)	4345 (11.6 %)	17 845 (47.5 %)	7889 (21 %)	5135 (13.7 %)	1058 (2.8 %)	1091 (2.9 %)	85 (0.2 %)	37 583	32 459
Season fire (%)	Spring (80.4 %)				Summer (16.5 %)		Autumn (3.1 %)			

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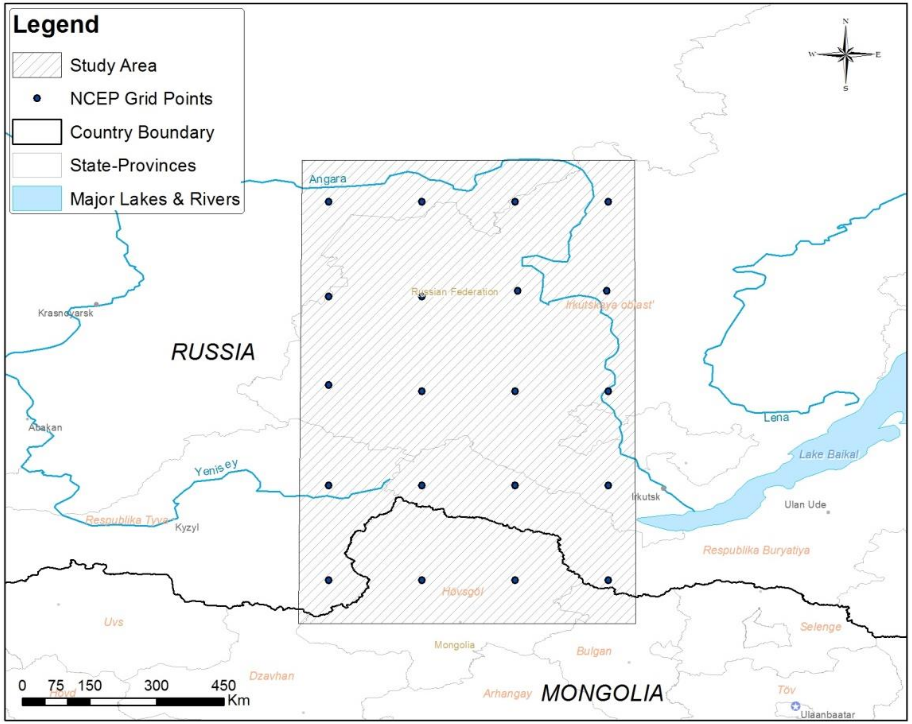

Figure 1. Study area in south central Siberia and northern Mongolia. The study area is covered by tile h23v03 and tile h24v03 of employed MODIS products. Black points indicated weather data grid points of NCEP reanalysis-2 data.

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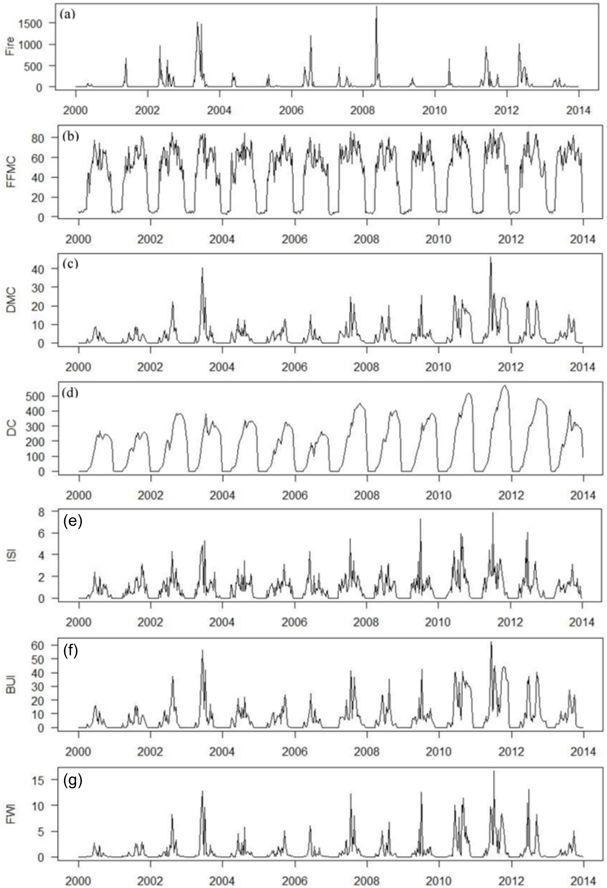

Figure 2. 8 day time series of **(a)** number of fires detected from MOD14A2, **(b)** Fine Fuel Moisture Code (FFMC), **(c)** Duff Moisture Code (DMC), **(d)** Drought Code (DC), **(e)** Initial Spread Index (ISI), **(f)** Buildup Index (BUI), and **(g)** Fire Weather Index (FWI). Fire weather indices were averaged over the region based on 20 NCEP reanalysis 2 grid points' data.

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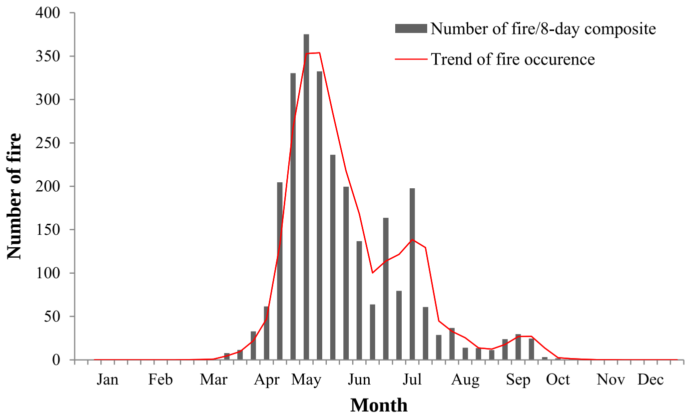

Figure 3. 14 year average number of fires which were calculated from total number of fires in each 8 day MOD14A2 composite between 2000 and 2013 in south central Siberia and northern Mongolia. The trend of fire occurrence showed three peaks of fire activity in May, July and September during fire season in the area.

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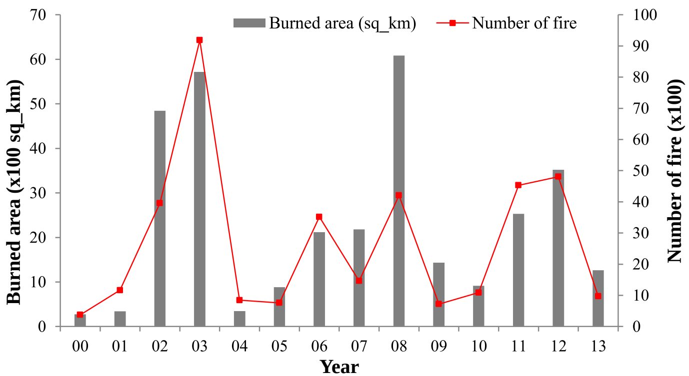

Figure 4. Total number of fires and burned area from 2000 to 2013 in south central Siberia region.

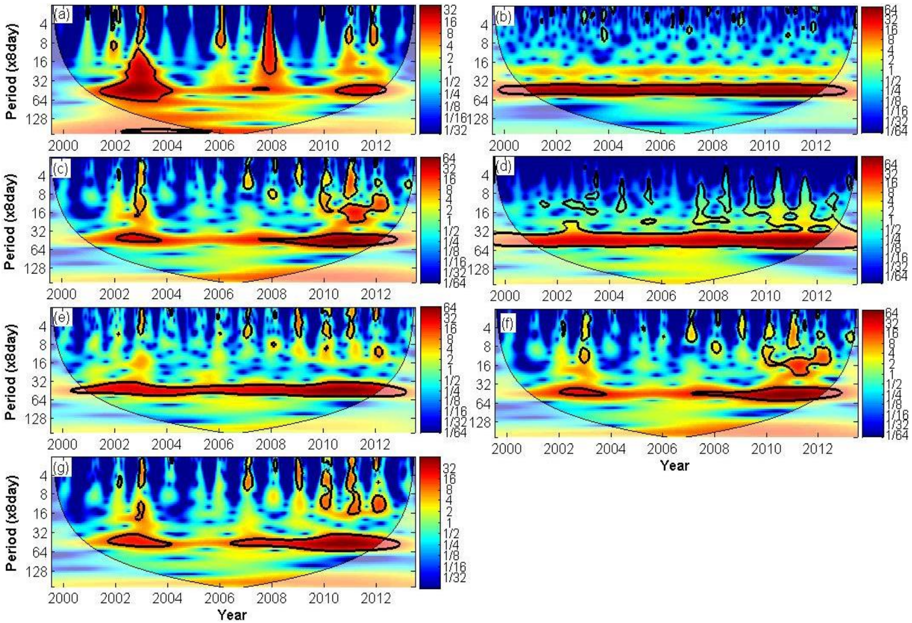

Figure 5. Wavelet power spectrum of standardized time series of **(a)** number of fires detected, **(b)** Fine Fuel Moisture Code (FFMC), **(c)** Duff Moisture Code (DMC), **(d)** Drought Code (DC), **(e)** Initial Spread Index (ISI), **(f)** Buildup Index (BUI), **(g)** Fire Weather Index (FWI). The thick black contour indicates the 5 % significance level against red noise, and the cone of influence (COI) is shown as a lighter shade. The color bars indicate wavelet spectral power.

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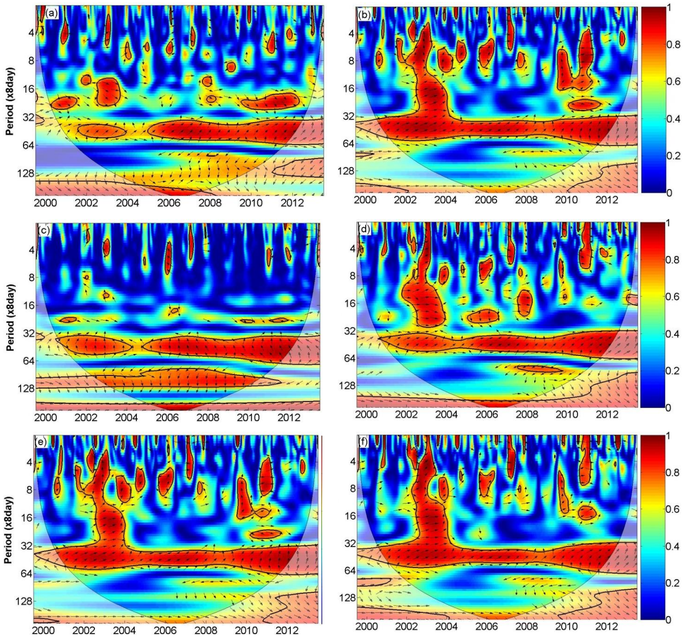

Figure 6. Wavelet coherence between **(a)** FFMC and fire, **(b)** DMC and fire, **(c)** DC and fire, **(d)** ISI and fire, **(e)** BUI and fire, and **(f)** FWI and fire. The 5 % significance level against red noise is shown as a black contour (red regions), and the cone of influence (COI) is shown as a lighter shade. Arrows indicate the phase differences between fire occurrence and fire weather indices (with in-phase pointing right, anti-phase pointing left, out of phase or non-linear relation pointing vertical up or down). Period (or scale) was converted to day/month unit in the results (e.g. period of 4 equals to 32 days or about one month). The color bars indicate correlation coefficients between two time series.

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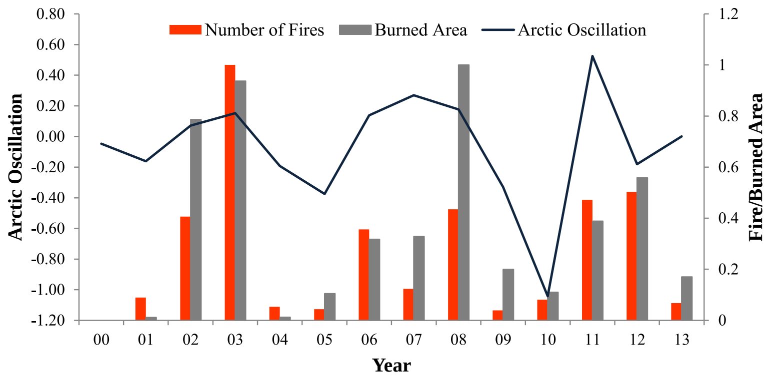

Figure 7. Relationship of annual fires and burned area with the Arctic Oscillation in south central Siberia. Arctic Oscillation Index was averaged from mean monthly values. 14 years number of fires and burned area were standardized using minimum and maximum values.

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