Regional model assessments of forest fire risks in the Asian part of Russia under climate change

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Abstract

Presented are the results from analyzing the changes in the fire danger conditions in the Asian part of Russia within the context of prospective climate change in the 21st century. It is found that with a rise in temperature, a substantial influence on the general increase of fire danger is exerted by the distribution function of precipitation. With general warming by the end of the 21st century, the middle and subtropical latitudes will see, along with increasing fire danger risk, an extension of the fire-hazardous period, whereas the high latitudes will undergo more limited changes in the risk.

Keywords: forest fires, climate models, climate changes, regional consequences.

Introduction

Among the most hazardous consequences of general warming of climate are droughts and fires [1–10]. Over the last several decades, climatic changes have manifested themselves as strong temperature, circulation and hydrological anomalies leading to a number of occurrences, including fires, as was the case, for example, in Russia in 2002, and in Western Europe in 2003 and 2007. Long-lasting anomalies of this sort, characterized by drouthy conditions during summer seasons in mid-latitudes, are associated with blocking anticyclones (blockings) in the troposphere. The occurrence of the regimes of droughts and fires is favored by the fact that during the warm months of a year, specifically in mid-latitudes of Northern Eurasia, with a rise in temperature, there is a general decrease of the total amount of precipitation [11, 12]. Under general warming, associated with the increase of CO₂ content, the role of continental blockings can be enhanced considerably in the atmosphere [13].

Fires lead to regional changes in biosphere, changes in albedo of underlying surface, evapotranspiration and radiative balance, and in the carbon exchange between atmosphere and terrestrial ecosystems [14, 15]. Because of an ever increasing fire incidence, a considerable change in albedo of underlying surface is expected to occur by the end of the 21st century [8].

In 2006, using the Nesterov fire danger index $I_f$ [16] we assessed, for the first time on the basis of calculations using the regional model, the forest fire risk for Russia’s regions, specifically for the European territory of Russia (ETR), having regard to potential changes of climate in the 21st century [3]. In 2007–2008, corresponding assessments were made for the Asian territory of Russia (ATR) [7, 9, 10]. This paper presents the results of the aforementioned assessment as obtained using $I_f$, as well as other criteria which are employed for the territory of Northern Eurasia (for the ATR in particular), based on results of numerical calculations in terms of the regional climate model.

Research methods

We analyzed the results from numerical calculations done in terms of the MGO regional climate model [17], with a horizontal resolution of 50 km, using scenario SRES-A2 [18] for the increase in greenhouse gas emissions in the 21st century. For the ATR, a detailed analysis of daily data from calculations using the regional model was carried out for three decades: in the late 20th century (1991–2000) as well as in the mid- (2041–2050) and late (2091–2100) 21st century.
The analysis of the fire risk utilized the Nesterov index as suggested for assessing the potential of forest fire danger [16]:

\[ I_{f} = \sum \left( T_{m} - T_{d} \right) \cdot T_{d}, \]

where \( T_{m} \) is maximum diurnal air temperature at the ground, °C, and \( T_{d} \) is dew point temperature dependent on relative humidity and temperature, °C. A modification to the index was also used [3, 6, 7, 19–21]. Summation is made with respect to the days when the precipitation amount \( P \) per 24 hours does not exceed 3 mm. When \( P > 3 \) mm, the value of \( I_{f} \) is reduced to zero. As in [3, 7], the conditions with \( I_{f} \) less than 300 (regime I) were regarded as non-fire-hazardous or as ones with very weak fire danger, while the conditions with \( I_{f} \) within the ranges 300–1000, 1000–4000, 4000–10 000 and more than 10 000, respectively, were taken as the regimes with a small (II), moderate (III), high (IV) and extremely high (V) fire danger level.

This study has also used a modified fire danger index:

\[ I_{FM} = \sum k \cdot \left( T_{m} - T_{d} \right) \cdot T_{d}, \tag{2} \]

where \( k = k(p) \). In contrast to (1), the coefficient \( k \) allows for the influence of precipitation in a more differentiated fashion is introduced in (2).

\[
\begin{array}{|c|c|c|c|c|c|c|}
\hline
P, \text{mm} & 0 & 0.1–0.9 & 1–2.9 & 3–5.9 & 6–14.9 & 15–19.9 & \geq 20 \\
\hline
k & 1.0 & 0.8 & 0.6 & 0.4 & 0.2 & 0.1 & 0 \\
\hline
\end{array}
\]

In addition to taking into consideration atmospheric precipitation in a differentiated fashion, the more detailed fire danger indices can take account of a wind-velocity dependence and other factors for example.

Results of model assessments of the fire danger level in different regions were compared with satellite data [22] for forest occurrence boundaries.

**Research results**

On the basis of the results derived from the investigations above, we generated a diagram for the distribution of the values of the mean summertime fire danger index \((I_{FM}(0))\) for the end of the 20th century (1991–2000) \((I_{FM}(0))\) on the ATR (Fig. 1, a, b). The boundaries of regions with a presence of forests on the territory of Russia were identified using satellite data [22]. Lower latitudes on the ATR are generally characterized by a higher forest fire risk. As with the ETR (see Fig. 1, b) [3], the forest boundary on the ATR (see Fig. 1, a) is within the zones of high gradient of the fire danger index, matching reasonably well the boundaries of regions with a moderate fire danger risk (regime III), exclusive of some regions. In particular, a high fire danger level under current climate corresponds to a significant number of forest regions in the Transbaikalia. This is also supported by data on forest fires [23]. In general, however, forests in mid- and high latitudes of Northern Eurasia exist predominantly under conditions of low summer fire danger (regimes I and II). Model calculations of the fire danger index are generally in a good agreement with similar calculations using ground-based observational data, and with satellite information on the actual fire situation [9].

An analysis of the potential changes of the forest fire risk in the 21st century using model calculations for Northern Eurasia’s regions revealed a significant spatial inhomogeneity. Fig. 2 presents the ratios of \( I_{FM} \) and \( I_{FM}\mid_{A} \) for the mid-21st century (2041–2050) to \( I_{FM}(0) \) and \( I_{FM}(0) \) in terms of anthropogenic scenario SRES-A2: a) \( \Delta I_{FM} / I_{FM}(0) \), and b) \( \Delta I_{FM}\mid_{A} / I_{FM}(0) \). Not only regional differences in the changes of forest fire risk, but also significant distinctive features show up for different fire danger criteria. A standard fire danger index \( I_{FM} \) (see Fig. 2, a) was used to obtain a strong increase of the forest fire risk in the middle part of the ATR (up to a three-fold level when compared with the end of the 20th century). Maximum values of the relative increase of the modified index \( I_{FM}\mid_{A} \) (see Fig. 2, b) in the middle part of the ATR are substantially smaller, down to a local decrease of the fire risk.

Fig. 2 intimates qualitative differences in the model tendencies of atmospheric precipitation depending on its intensity. This is borne out by the changes (to the mean) of the number of days with precipitation amount smaller and larger than 3 mm/day (the threshold value for calculating the index \( I_{FM} \)), as forecasted into 2041–2050. Over a significant portion of the ATR (especially its middle and eastern parts) there will occur an increase of the amount of weak precipitation (less than 3 mm/day). This will be accompanied by a decrease of the strong precipitation level over most of the ATR (especially in its middle and eastern parts). In the case of...
Fig. 2. The ratio of the mean summertime fire danger index (a) $I_{fa}$ in the mid-21st century to the mean summertime fire danger index in the late 20th century (b) $I_{fa}(0)$, and the ratio of the mean summertime modified fire danger index (b) $I_{fa}m$ in the mid-21st century to the mean summertime modified fire danger index in the late 20th century (b) $I_{fa}m(0)$.

For the boundaries of the regions with percentages of forests, see Fig. 1.

A more differentiated account for the precipitation effects on the summer forest fire risk assessment, there will be a substantial attenuation of the anomalously strong increase of fire danger in the middle part of the ATR.

It should be noted that if the influence of atmospheric precipitation on the summer forest fire risk assessment is accounted for in a more differentiated fashion, it is possible to adjust the nonlinear effect arising in the comparison of relative changes of mean standard summer fire danger indices $I_{fa}$ by the mid-21st century (see Fig. 2, a), and by the end of the 21st century in the case of anthropogenic scenario SRES-A2. For the end of the 21st century, no serious differences were revealed between the different fire danger indices used in the analysis. Also, as is the case with the mid-21st century, the principal determining factor of spatial inhomogeneity of fire risk changes will be represented, as before, by the inhomogeneity in atmospheric precipitation. In southern regions, with a decrease of the summer precipitation amount (having an intensity both larger and smaller than 3 mm/day), the fire emergence risk is enhanced, namely: it can exceed by a factor of 2.5 the respective values characteristic for the end of the 21st century. According to model calculations, the summer-averaged maximum daytime temperature here can increase by 4–5 °C, whereas its rise does not exceed 2–3 °C in northern regions. Besides, most northern regions show an increase of the precipitation amount; therefore, the fire danger risk here is poorly pronounced and even decreases in some of the regions. The sole exception is provided by Northern Ural where both a rise in temperature and a decrease in precipitation and humidity is expected. Here, according to model calculations, the fire risk by the end of the 21st century can increase two-fold. Furthermore, no substantial changes of the fire danger risks in the north of Ural are forecasted for the mid-21st century, as contrasted to the late 20th century.

Along with a general tendency toward an enhancement of the summer forest fire risk in Northern Eurasia, specifically on the ATR, a substantial increase in the duration of the fire-hazardous period makes it evident under warming in the 21st century. In particular, intra-annual distributions of $I_f$ and $I_{fa}$ were analyzed for the Transbaikalia (for the region 51–53° N, 110–115° W) (Fig. 3). At the end of the 20th century the fire-hazardous period in the aforementioned region lasted from July to September. In the 21st century, according to model calculations, this period can set in one month earlier. Moreover, the fire danger indices, both standard and modified, show a relative increase. Specifically, the standard fire danger index (see Fig. 3, a) can increase by a factor of 3.5 before the mid-21st century against its mean annual values in the later 20th century. In this case, the peak of fire danger will correspond to mid-August. Changes of this sort are associated with the expected abrupt reduction in strong atmospheric precipitation (over 3 mm/day) in this region at the time mentioned above. No substantial increase of the relative values of the standard index is forecasted for the end of the 21st century. The fire danger peak will shift, compared with the end of the 20th century, from August to July, while in September the fire danger risk can decrease to a non-fire danger level, which is due to the increase of days with strong atmospheric precipitation in the region. No such feature was revealed by calculations based on using a modified index that accounts for precipitation in a differentiated fashion. It is anticipated that the fire danger risk will be increasing against its present-day values also by the mid- and late 21st century.
Furthermore, the fire danger peak shifts from August to July, and the period increases virtually by one month, starting not in June but in May.

Conclusions

The findings reported in this paper indicate that a substantial enhancement in the potential emergence of extreme natural phenomena, such as forest fires, should be forthcoming across the ATR under global warming in the 21st century. In some regions, primarily in the south, the fire danger risk, with a reasonably aggressive anthropogenic scenario, can increase three-fold as early as the mid-21st century against the end of the 20th century. In addition to an enhancement in the mean summertime fire danger level, evidence indicates that there is taking place an increase in the duration of the fire-hazardous period, with a tendency toward a shift of the fire danger peak from the end of summer to mid-summer.

The decisive factor of the fire danger risk, along with the rise of temperature, is provided by a change of the humidification regime. Specifically, model calculations indicate that because of a reduction in intense atmospheric precipitation in the southeastern and middle parts of the ATR, a strong increase of the Nesterov standard fire danger index is forecasted to occur by the mid-21st century (in excess of that expected by the end of the 21st century). No such nonlinear effect is observed when a modified fire danger index is employed.

It is worth noting that the analysis was made on the basis of model calculations using a reasonably aggressive anthropogenic scenario, SRES-A2. With milder scenarios, the fire danger risk for the ATR would be increasing markedly more weakly.

The analysis made in this study suggests that assessments of the potential change in the fire-hazardous situation in the 21st century must utilize, along with relatively simple fire danger characteristics, such as the Nesterov standard index, detailed indices, specifically those which take into account the atmospheric precipitation distribution in a more differentiated fashion.

In a detailed analysis, there is good reason to take into consideration not only the characteristics of the meteorological regime but also the various regimes of underlying surface and vegetation as well as their transformations under climatic changes. In addition to allowing for the characteristics of potential fire danger, account must be taken of the influence of local anthropogenic [19] and natural (lightning activity) impacts on the likelihood of fire emergence.

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