Simulation of long-term dynamics of forest wildfires in Russia with Marcovian model

Andrei P. Kirilenko

European Forest Institute
Internal Report No. 10, 2002

EFI Internal Report 10, 2002
Simulation of long-term dynamics of forest wildfires in Russia with Marcovian model

Andrei P. Kirilenko

Publisher: European Forest Institute
Torikatu 34, FI-80100 Joensuu Finland
Tel. + 358 13 252 020
Fax. + 358 13 124 393
Email. publications@efi.fi
http://www.efi.fi/

Editor-in-Chief: Risto Päivinen

ABSTRACT

Warmer climate can lead to numerous changes in forests. One of the expected effects is an increased number of wildfires as a consequence of longer fire danger period and lower fuel moisture. A counteracting, yet a more volatile factor is increasing summer precipitation and changing precipitation pattern. To estimate quantitatively the changes in the long-term dynamics of area and number of wildfires, a probabilistic model of forest wildfires is suggested. The model simulates the events of fire ignition and fuel burning in a 0.5×0.5^o geographical latitude and longitude grid, covering the territory of Russia. Data for model identification were extracted from a forest fire database, covering a large part of Russian forest territory. Simulations are based on CRU historical climate database and on IMAGE future climate scenarios.

Keywords: Climate change, forest fires, Marcovian model

CONTENTS

1. PROBLEM

The continuous progress in scientific research of possible global climate change caused by anthropogenic emissions of greenhouse gases (GHG), and of the social, economic, and environmental consequences of global warming has resulted in a public and political awareness of the problem. The Kyoto Protocol (1997) has set up a framework of international co-operation to mitigate greenhouse emissions. The signatory countries have agreed to limit their overall emissions of CO_2 (varying between countries from –8 ~ +10%) in the first commitment period 2008–2012 as compared to the year 1990. The goals of the Protocol can be met by a country through direct or indirect investments in energy saving, new technologies, public transportation, etc., or by using an international GHG emission trading system, as permitted by Article 17 of the Protocol. Though some CO_2 emissions from agriculture and forestry are considered, the improvement in soil-saving technologies, fire control, logging and reforestation have either very limited or no significance at all when counted by countries towards meeting their obligations. Non-existence of the reliable regional forecasts of future carbon flows from forest disturbances is a barrier for the quantification of forest carbon sinks. Wildfires in the boreal forests zone have a significant detrimental effect on the vegetation carbon pool and emissions. Isaev et al. (1995) assessed the volume of forest wildfire carbon emissions in Russia as 24–66 million tons annually, which equals to 10 to 25% of the forest carbon sink. It was also found that a 1 ha decrease of burned area has the same effect on the vegetation carbon stock as 5 ha increase of forest area. Global warming and change in the precipitation patterns can alter the frequency of fires and thus the emissions considerably.

Numerous results of global circulation models show that within the next 50 years temperatures in the boreal forest zone can increase by 1–2^{o}C in the summer and 2–3^{o}C in the winter (IPCC 1996). Recently the IPCC adopted a corrected set of climate change scenarios with somewhat greater warming effect, mainly due to lower expectations of the cooling influence of sulphates. The global average surface temperature is expected to increase by 1.4 to 5.8^{o}C by the year 2100 (Climate Change 2001). According to the Climatic Research Unit of the University of Eastern Anglia´s analysis of temperature measurements from 1856 to 2000 (Jones et al. 1999), the 1990s were the warmest decade in the series. The seven warmest years globally have now occurred in the 1990s and 2000. They are, in descending order, 1998, 1997, 1995, 1990 and 1999, 1991 and 2000. The same analysis based on data from tree rings, corals, ice cores, and historical records show that the 1990s is the warmest decade of the millennium and the 20th century the warmest century. This trend is likely to continue. A widely used IPCC set of six emission scenarios IS92 would result in a 1^o to 3.5^o global temperature increase. However, a recent update in IPCC scenarios corrected this estimate significantly – mainly due to lower projected sulphur emissions. In the Third Assessment Report (Climate Change 2001), the globally averaged surface temperature is projected to increase by 1.4 to 5.8°C over the period from year 1990 to 2100.

One of the possible effects of the increasing summer temperatures and longer vegetation period is the change in the frequency and area of wildfires in the boreal forest zone. The assessments of consequent impact carbon emissions from burned biomass are rather high. For example, Kurz at al. (1992) assessed that an increase in wildfires in Canada between 1986 and 1989 has resulted in 86% increase in carbon emission. Another investigation of possible effect of global warming on wildfires was done by Kasischke et al. (1995). For Russia, Dixon and Krankina (1993) predicted an additional 7–12 million hectares of boreal forests to burn within the 50-years period of warmer climate, an increase of about 100%. However, the quantitative predictions of this increase are yet to be done.

Simulation modelling seems to be an advantageous tool for assessing the climate change impact on wildfires and is discussed in a number of publications (for discussion of the theory of fire history simulation see Johnson and van Wagner 1985). Sohngen and Haynes (1997) built a model, which linked forest fires with the forestry economy model and then applied it for the US forests. Their goal was to make projections of the monetary effects of the changing frequency of forest fires, and to project the dynamics of fire and post-fire carbon release. They also made projections of carbon stored in the US forests for a period of up to year 2040, using scenarios of decreasing amount of forest fires. Venevsky et al. (in preparation) and Thonicke et al. (in preparation) built a stochastic model of forest fires, and applied it for the territory of Spain. The model will be further integrated into the framework of Potsdam Institute of Climatology Global Vegetation Model. It should be noted that modelling warming impact on forest fires on the regional and global levels is a considerably different approach than landscape-level models (e.g. Hong and Mladenoff 1999), first of all differing in representation of spatial heterogeneity of fires. At a lower scale, cellular automata seems to be a tool of choice for many researchers. There is a large number of cellular automata models of forest fires and simple models of fire propagation are often used for teaching the cellular automata conception. A more complicated example here is an EMBYR (Ecological Model for Burning the Yellowstone Region) by the Oak Ridge National Laboratory (Hargrove et al. 2000), designed specifically to research fire impact on vegetation. The model simulates fire burning and propagation in a network of 50x50 m cells with different fuel moisture and load, controlled by landscape topography and by wind speed and direction (simulation animation is available online at EMBYR 2001). Additional effects taken into account include occasional random events of ignition, controlled by wind.

In a number of simulation models, climate change impact on various fire weather severity indices has been investigated. Stocks et al. (1998) applied integrations of two General Circulation models (CGMs) to find seasonal changes in fire weather in circumboreal forests and compared the results with current climate. 7% increase in days of high and very high fire danger and a 4% increase in days of extreme fire danger was found assuming doubled CO_2-concentration in the atmosphere. Flannigan and van Wagner (1991) found a total increase of 46% in seasonal fire severity rating for Canada in a $2xCO_2$ climate, although their later publication cite a more moderate change, with significant regions of boreal forests with reduced fire danger (Flannigan et al. 1998). Wotton and Flannigan (1993) also found a significant increase in the length of fire season, with average expansion of 22 days for Canadian forests.

2. PROJECT

The purposes of the project were to:

- Evaluate the main factors that determines the long-term statistics of wildfires on the territory of Russia,
- Make an assessment of possible changes in average annual wildfire number and area in boreal forests of Russia in warmer climates, according to the main climate change scenarios, recommended by the IPCC,
- Extend the forecast for longer time period, using the stochastic model of vegetation migration MOVES, and
- Assess the correspondent change in carbon emissions with forest wildfires.

To achieve the goals of the project, the following steps have been taken:

1. Building a database of forest wildfire history and climatology of the boreal forests zone of Russia. This database incorporated a subset of Dr. Korovin's computer database (Pokrivaylo et al. 1976) of the history of forest wildfires in Russia (date, coordinates, class of fire danger, and fire area) and current climate for Russia, on a $0.5^o x 0.5^o$ grid of geographical coordinates. After the project started, it was found that the existing database does not completely satisfy the project requirements due to considerable amount of errors in data (e.g. wrong latitude/longitude information) and long time of query processing. Also, more data describing the fires was included into the final database. The final subset of data was uploaded into Microsoft Access database. An additional problem with the data used was found: the fires occurred in the European part of Russia are significantly underrepresented. This is to be corrected at a later stage of the study by including oblast-based data from annual forest fire reports.

2. Using the database, to find the correlation between the average annual forest fire number and area and parameters of climate, for different latitudes, and to determine the most relevant parameters to be used in further research.

3. In the original project plan, it was intended to generate the projections of future climate, based on the runs of the UKMO, MPI, and GFDL models (Cubasch et al. 1992, Manabe et al. 1992, Murphy and Mitchell, 1995) with the IS92A scenario. The scenarios were adjusted as Greco et al. (1994). In the course of the project, it was decided to use Baseline – A climate change scenario, generated in the IMAGE2.1 project. IMAGE model calculates the surface temperature and precipitation for 10° latitudinal bands, and then scales the projection down into 0.5x0.5 grid cells using the IS92a calculations of the ECHAM1/LSG model from the Max Planck Institute (MPI projections). We believe that the chosen approach has the advantage of including the historical climate variability into the projections of future climate, which seems to be very important for fire simulations. It was also found necessary to include a weather generator into the model framework, and to generate patterns of fire weather for 1941–2100 time period.

4. To use the correlation found and the generated parameters of climate to find the projections of possible changes in forest wildfire amount and area in warmer climate. As a first step, to take into account the change in the length of the fire danger period and in summer temperatures and to use the GLDF climate changes scenario. The projections should correspond to the decades of 2040–2050 and 2060–2070 of global temperature rise. To find the corresponding change in the CO_2 release. Again, this step was modified due to different climate change scenario used. The calculations of CO_2 release have not been completed yet due to considerable increase of work projected for steps 1 and 3. However, the simulations of fire number and area take into account not only variations in fire season and summer temperature, but also the whole pattern of change in fire weather predictions.

3. DATA

Base map

In the model, the whole territory of the country is divided into 0.5x0.5 degree cells with a geographical grid, chosen to be compatible with the grid used in the IMAGE model (Alcamo 1994), version 2.1. The reason we needed this compatibility is that we intend to use the IMAGE synthesized climate for the projections of climate impact on wildfires. The advantage of the IMAGE climate is that it encompasses the GCM projections of future climatic averages with historical climate variability. The base map used is extremely sensitive to water bodies: cells with a moderate amount of water bodies are marked as water. Due to this fact, a big land area in the Volga river delta is marked as water. This will not affect model behavior since this area is not covered with forests, but nevertheless this area was edited for correct presentation of administrative units of the country. The original base map represents the current administrative structure of Russia with 89 subjects of the Federation. Since the pre-1990 regional data reflects the administrative structure of the time with smaller number of units, base map was changed accordingly.

Forest fires database

The data, describing about 200 000 forest fires occurred in 1987–1995, has been compiled by Dr. Georgii Korovin from the official reports of the Russian Federal airborne forest fire protection service Avialesookhrana. This data covers a large part of the territory of Russia (see Figure 1), some fires occurred on the territory of other FSU countries were also included. Seventy fields described each of the fires included into the dataset. For the purposes of the project, we extracted 22 parameters that characterised fire location, time, area, forest type, weather conditions, and distances from the nearest town and road (see Appendix 1). This data was then uploaded into the MS Access database. Next, entries with fields containing errors where excluded from the database, including the fires with geographical latitude and longitude falling outside of country boundaries, fires with wrong time records (e.g. date of fire extinguishing earlier than the data of fire start), area records (e.g. fires extinguished within 1 day of reporting with big difference between the areas at time of reporting and final burned area), and data falling beyond the limits of its category (e.g. 0 class of fire danger). Also there a strong peak in number of fires of 31–34, 62–66, and 92–97 days duration was noticed. A possible explanation for this phenomena are the errors in the ‘month of fire report’ field in the original data (e.g. a fire active 1 day, from the 12th June till the 12th June, mistakenly marked as a fire active from the 12th June till the 12th July, i.e. 32 days). Since 85% of forest fires included into the data set were extinguished with 3 days of their detection, with more than 50% extinguished within the day of detection, such kind of mistake produced a considerable amount of “long-lasting fires”, which were actually fires lasting only a few days. Yet this kind of mistake was easy to correct by plain exclusion of all fires of long duration with extremely small area. Finally, geographical locations of fires were aggregated into the grid of 0.5x0.5 geographical degree cells, consistent with the model basemap, and only the fires with location within the window of 43–69.5 East longitude and 27.5–172.5 North latitude were left in the database. This window includes more than 99% of the whole volume of the data.

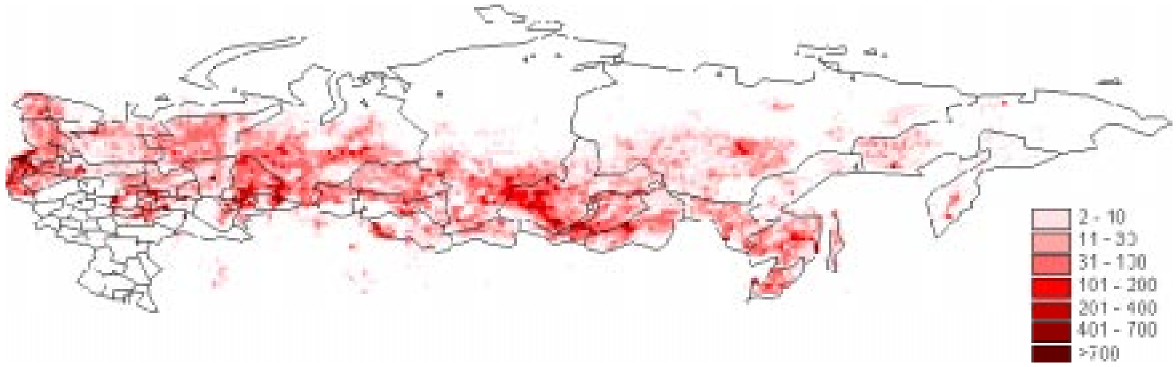

Figure 1. Spatial distribution of forest fires, according to fire forest protection database, 1987–1995. Each dot represents number of fires registered in one 0.5x0.5 geographical degree cell (approximately 1500 km^2) within 9-years time frame. Maximum number of fires per cell was 1400.

Region-based data on fires

It can be seen easily from the data on Figure 1 that the coverage of many areas is not adequate. A reason for that is that not all the fires in forest areas are registered with the Avialesookhrana service. In order to make a decision on the relevancy of aerial forest protection data in context with the project purposes, we had to compare the data with other forest fire statistics, collected independently.

An additional resource used is historical annual data on the number and area of reported forest fires, based on the regions of the Russian Federation. We compared this data with the Avialesookhrana data described above to select the regions where the quality of the latter was acceptable for the model (see Figure 2). For comparison, we used the total amount of fires during 1987–1995, summarized for subjects of the Russian Federation. It should be noted that the number of regions of Russia has changed since 1987; data presented in the figure reflect 1987 the administrative structure of (further referred as oblast-based; the contemporary structure will be referred as subjects-based). The same rule was applied for other data: it was recalculated based on oblasts.

Both sources of information give quite similar data for the majority of regions of the Asian part of the country. However, for the European part of Russia the situation is quite distinctive. Only northern and north-eastern oblasts are adequately presented in the forest protection service database. Other regions are significantly underrepresented or not covered by the database at all. This is especially true for dense-populated, high-urbanized areas. Obviously the inadequate coverage will not lead to a big error in the estimate of burned area due to smaller average fire area in those regions, however total number of fires will deviate significantly.

The current version of the model is solely based on the forest fire database and does not include aggregated region-based information. In the next version, this additional information will be used to complement the data on underrepresented regions.

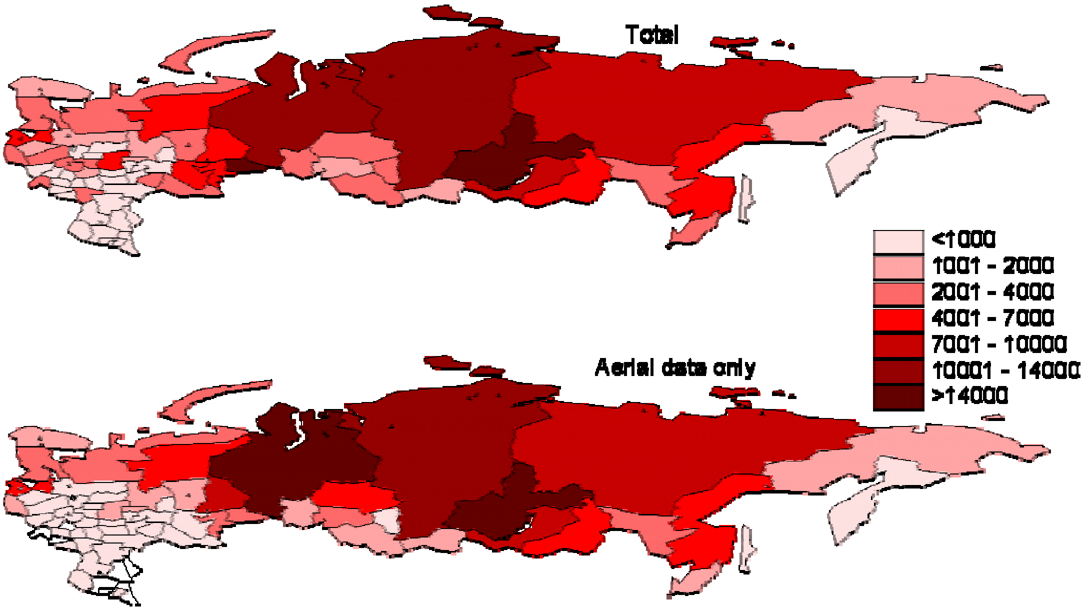

Figure 2. Comparison between the Avialesookhrana data of forest aerial protection service of Russia and total reported number of fires for aggregated regions of the Russian Federation. Total number of fires per region is presented. It can be seen that while in many regions two sources of information give quite similar data, densely populated regions, especially in the South European part of the country, are underrepresented in the Availesookhrana data, or not covered at all.

Climate database

Climate database describes the current climate on the territory of Russia on a base of 0.5x0.5 grid. It was generated from the IIASA Climate Database. The original database was developed at the International Institute of Applied Systems Analyses by Leemans and Cramer (1990) and represents the global distribution of average monthly cloudiness, precipitation and temperature over land at a 0.5x0.5 grid resolution. We also use the CRU climate baseline data (New et al. 2000) for annual historical values of climatic parameters. The data is available from the Climatic Research Unit of the University of East Anglia and describes monthly average climatic variables at a spatial resolution of 0.5° latitude by 0.5° longitude, covering all land excluding Antarctic. The data set describes 1901–1995 observed ground air temperature, diurnal temperature range, and precipitation. It also contains estimated wet-day frequency, vapour pressure, cloud cover and ground-frost frequency. This dataset was extended with the Baseline – A projections of the future climate for 1996–2100 from the IMAGE2.1 model framework. The IMAGE projections incorporate the IS92a integrations of the ECHAM1/LSG GCM by the Max Planck Institute. Since these projections include only temperature and precipitation, we used current climate data to emulate monthly course of air humidity. Monthly climatology was further transformed into daily values using stochastic weather generator. For current climate simulations (1987–1998), ten different realisations of weather pattern were synthesised and stored. We also synthesised series of daily values representing the 1941–2100 climate.

Population database

Additional database describing the current human population on the territory of Russia on a base of 0.5x0.5 grid was generated from the CIESIN (the Center for International Earth Science Info Network) population database, in particular their Global Demographic Dataset. This dataset provides the current data on global distribution of human population, approximated into 2.5’x2.5’ minute grid of geographical coordinates. We scaled the dataset into the model 0.5^ox0.5^o grid, reformatted, and stored it in the MS Access database.

4. RUSSIAN FOREST FIRES (RF) MODEL

Overview of the approach

In the model, the entire territory of the country is divided into 0.5x0.5 degree cells. Since the extreme Northern and Southern parts of Russia have none or very few registered forest fires (due to lack of fire protection, or due to lack of forest itself), the model simulates forest fires in a window inside 69.5–43.0 degrees of North latitude and 27.5–172.5 degrees of East longitude. Due to small latitude variation, comparing with the variation of longitude, the current version of the model supposes that all the cells have the same area (approximately 150 000 ha). This simplification was not crucial for the model, yet we plan to use actual area of a cell in the next version of the model. Each of the cells has its own unique identifier and all the data are stored on a per-cell basis, as opposed to grid basis, which is used for the base map only. Time step of the model is one day. Time frame of one model integration is ten years.

Each of the model cells is supposed to be heterogeneous and is described by a number of parameters. These characteristics of each cell can be separated into two classes: slow ones, which are supposed to stay unchanged within the time frame of one model integration, e.g. population (further referred as model parameters), and fast ones – those that have significant variation, e.g. weather. For each of the cell, the following model parameters are stored: type of forest – 10 types (see Appendix 1), share of land occupied by forest in a cell (0–1), and population density (per km^2). The next version of the model will also include the shares of slope grades for each cell, determined on a base of a 5’ scale digital elevation map.

Each of the cells is also characterized by a certain climate. Since fires are controlled by high-frequency components of the climate, here we used a 1-day time step. The inherited huge volume of stored data (storing just one component per each cell of the Russian territory would take at least 46 Mb), a separate model computes fire weather indices with daily resolution from monthly climatology. To generate weather from the monthly CRU climate, the fire weather model uses a stochastic weather generator. The scheme of model functioning is briefly described below:

- Fire model run starts with data input and initial variables assignments.
- Multiple iterations are run, each covering the entire simulation period. Input data are reset to the initial data for all iterations. The results of each iteration are different, although they all use the same monthly climate, because we used a stochastic weather generator and the fires are simulated as stochastic processes.
- Each year, model provides monthly climate. Then, the stochastic weather generator computes components of weather on a daily basis that are further used to compute fire weather indices.

Within a year, each 1-day model time step comprises the following evaluations:

Fire ignition submodel – works on per-cell basis

1. In each cell, a new fire source can appear as a result of a random ignition. The probability that a fire source appeared in a forest on a specific day depends of the population density.
2. For each fire source, a check is performed to determine if there is enough fuel build-up to support fire spread. A critical amount of fuel is determined on a per-cell basis and is reduced by fires.
3. For each fire source, a check is performed to find if the current weather permits fire self-support.
4. If all the three conditions are met, a new fire is registered into the fire records that are modified further by the fire life cycle submodel.

Fire burn submodel – works on per-record basis

1. For each fire, a test is run to determine if it burns out.
2. For each fire present in the records, a test is run to determine if a fire is detected and reported to the fire service protection service.
3. If a fire is registered, it is verified if it is extinguished by the forest fire protection service.
4. Area burnt by each of the fires is updated.
5. At the end of each year, annual statistics are accumulated from the fire records and all fire records are reset. For each cell, fuel buildup is changed according to the area burnt in this cell. This is not coded yet.
6. At the end of each iteration, multi-year average is computed and stored. At the end of model run, final statistics is computed and sent to visualization module or saved into a file.

The whole structure of the model framework is illustrated in Figure 3.

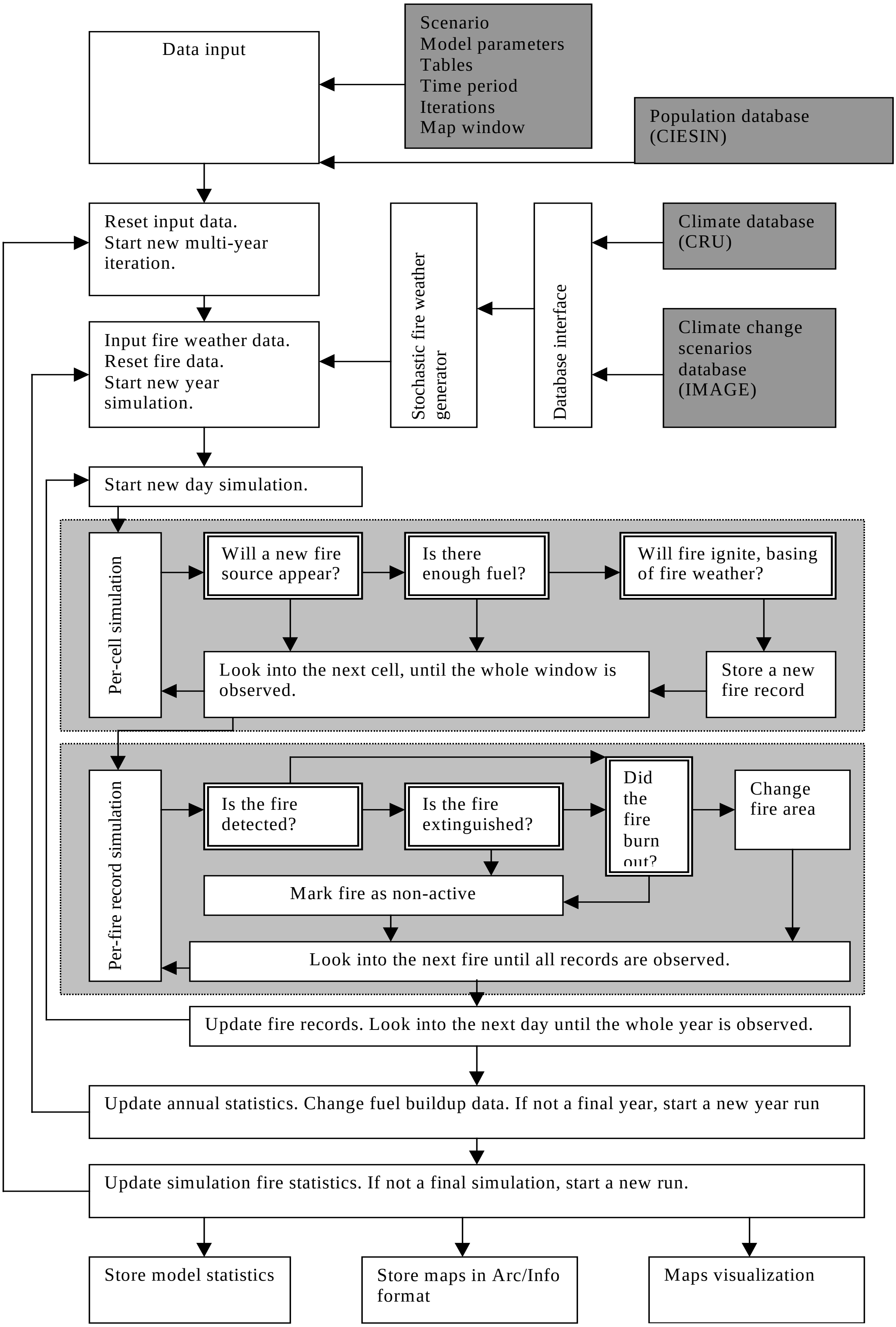

Figure 3. Structure of the RF model framework

Input data

The first group of model parameters describes the process of fire ignition. This group includes three tables and one map. An additional table describing fuel build-up in different groups of forests will be included when the next model version is ready.

The table describing number of fire ignitions occurred in a cell as a function of population density has been produced from the forest fire database and the population database. The table contains percentile values of number of fires occurred in one cell, for selected groups of population density (0–1, 1–2, 2–3, 3–4, above 4 persons/km^2). We have had difficulties obtaining enough wildfire data covering population density above 5 persons/km^2, since the most of the area presented in the database is sparsely inhabited. It can be seen easily from Figure 2 that the Availesookhrana data does not include the densely populated territories of central and south parts of the European part of the country. We presumed that denser population produces the same amount of fires per area as population of 5 persons/km^2, yet we will correct this in the future, when we supplement the data with oblast-based annual reports.

An additional factor to be considered here is the strong correlation between the population density and climate (e.g. see Figure 4). To negotiate the influence of the variations in climatic conditions, we initially restricted the dataset to the fires which occurred during the days with 4th and 5th classes of fire danger only, and then adjusted the table to real fire weather data. Here and further we used the percentiles to generate appropriate random sequences from uniformly distributed random values.

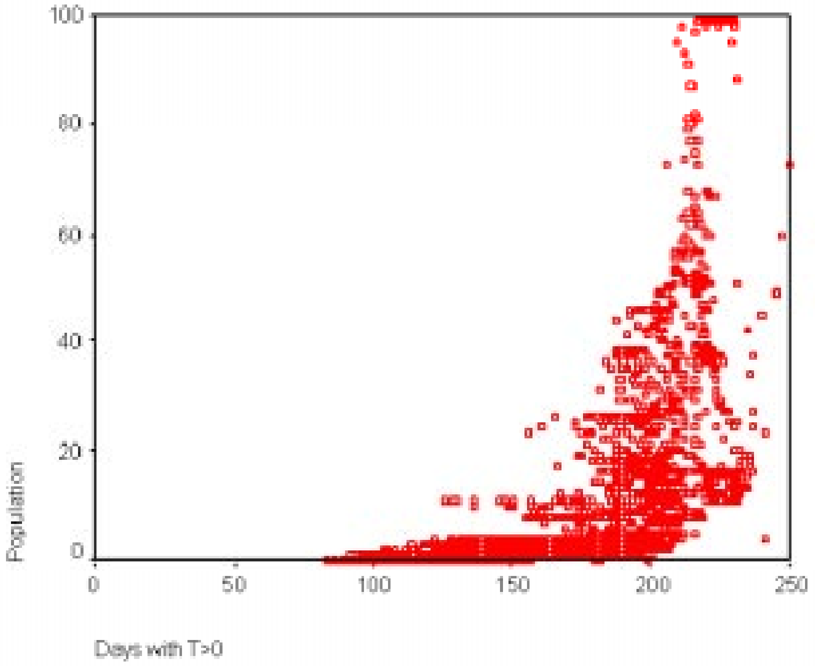

Figure 4. Population density is strongly correlated with climate. This factor complicates modeling of fire ignitions due to human activity. Spatial distribution of population is retrieved from the CIESIN world gridded dataset, climate is retrieved from the IIASA current observed climate data. Both sets are referenced with 0.5x0.5 grid, covered the whole territory of Russia.

To take into account the variations in the coverage of forests through the territory of the country, we used a forest density map. The map of distribution of forests on the territory of Russia shows the relative area covered with forests for each of the model cells. The map was generated using the data based on administrative units, and was used with the courtesy of Remote Sensing and Geographical Information Systems Laboratory of the International Forest Institute, Moscow, Russia (Remote Sensing … 2001).

The table describing the influence of weather conditions on the number of fires was produced from the information about number of fires and fire danger class at the time of fire detection, extracted from the forest fire database. According to data by Korovin (1984), if the average amount of fires ignited during a day with the 4th to the 5th fire danger class is taken for 1 unit, then the number of fires during a day with the 3rd fire danger class is 0.5, during a day with the 2nd fire danger class – 0.25, and during a day with the 1st fire danger class – 0.03. The database of forest fires provides similar data, with higher influence of dry weather on number of fires: 1 : 0.4 : 0.16 : 0.007. The number of fires occurred during days with the 4th and the 5th fire danger classes are similar and so the data for these fire danger classes were aggregated.

The second group of model parameters describes the process of fire spread and extinction. To take into consideration the influence of population on the time of fire detection we are using the table of percentile values of fire area at the time of detection, for the same classes of population density we used in the table of fire ignition. We cannot explain this effect from the method of data collection (according to the Avialesookhrana data, only few percent of fires are reported by local people), yet Figure 5 shows a strong effect of population density on initial fire area.

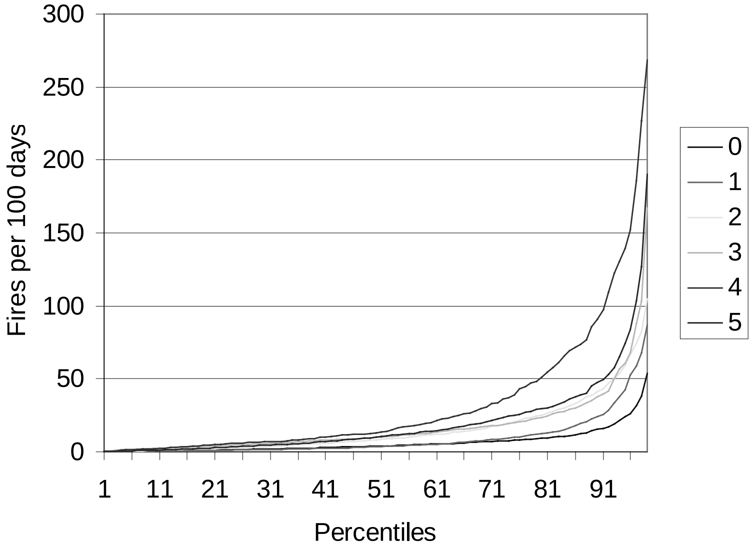

Figure 5. Fire ignitions per day with the 4th and the 5th fire danger class, per 0.5x0.5 cell, as a function of population density. Meaning of population classes: 0 – population less than 1 per/km^2; 1 – population 1–2 per/km^2; 2 – population 2–3 per/km^2; 4 – population 4–5 per/km^2; 5 – population more than 5 per/km^2. Possible reason for decreasing number of fires in the last class of population density is insignificant amount of forested cells with population larger than 5 persons/km^2.

In the model it was supposed that the daily change of fire area (ha/day) is a random value with probability distribution function distorted by the achieved area of fire and fire weather. A correspondent 3-dimensional table describes the distribution function. The data shows that for fires lasting less than 20 days, an average daily increase of fire area can be approximated by a linear function of time (i.e. fire area is a square function of time). We have not considered the influence of wind on the rate of fire spread due to lack of data in the climate database, but plan to include this data into the model in the future.

Fire weather generator

The high variability of daily weather was the reason why we had to use a stochastic weather generator. Global weather generator of The Institute of Terrestrial Ecology (Friend 1998) uses monthly averages for relative sunshine duration, precipitation, and temperature to generate 24-hour short-wave irradiance, precipitation, maximum temperature, minimum temperature, and mean water vapour pressure. The generator is based on a widely used approach (Richardson and Wright 1984, Richardson 1981). The code of the weather generator is available for download at the ITE web site (The ITE … 2001). We adjusted the original code in such a way that it could use the CRU input data as an input and, on the other hand, would produce the needed climatic variable, i.e. fire weather. For the current version we have chosen Nesterov fire weather indices (see description below). For a future version, it is also possible to use a more explicit index PV-1 “Humidity Index-1” (Korovin 1977). Both indices are accepted in Russia and both use the same climatic variables: maximum ground air temperature, dew point temperature, and precipitation, at a daily basis. The original software provides temperature and precipitation values. To generate dew temperature T_{dew} (C°) from air water vapour pressure E (mbar) we employed the following formula:

$$T_{dew} = 237.7 \frac{\lg(E/6.112)}{7.5 - (\lg E/6.112)} \ .$$

Nesterov index is a function of daily weather components with values from 0 to above 10000. The values correspond as presented below.

≤ 300	1st class	no fire danger
301–1000	2nd class	low fire danger
1001–4000	3rd class	average fire danger
4001–10 000 (or 12 000)	4th class	high fire danger
10 001–12 000	5th class	extreme fire danger

Fire ignition

In each cell, a new fire source can appear as a result of a random ignition. The event of ignition episode is simulated as a random event, based on population density. The procedure we apply here to synthesize random values is an analog of probability integral transformation. A uniformly distributed from 0 to 1 random number is used to find a percentile in the frequency table to determine number of fires in a given cell in a 100-day-period. Then, another random number is compared with the found number of fires divided by 100; we assume that the fire starts during this day if the random number does not exceed the number of fires divided by 100. We use four different frequency tables defined for population density 0, 1, 2, 3, and 4 per/km^2. For higher than 4 per/km^2 population density we use the 4 per/km^2

frequency table. The reason is that with higher than 4 per/km^2 population density number of fires drops sharply and then rebound again to its 4 per/km^2 value. A possible explanation is that there are not enough data for denser populated territories in the fire database to provide reliable statistics, a shortcoming we intend to correct in the future model version.
In totally, the fire database includes 8 classes of forest fire causes, including the “unknown” class. Of the other 7 classes only “thunderstorms” is attributed to nature, the other six are connected with various kind of anthropogenic activity in fire region. Totally, 69% of all forest fires are clearly attributed to humans, and 16% is attributed to thunderstorms, according to forest fire database. The cause of the remaining 15% is unknown.

Fuel build-up

An existance of a fire source is only one of the prerequisites of the development of a fire. Another requirement is the availability of an amount of fuel, enough to support the continuous spread of fire. An expert estimate (here and further, estimates made by Dr. Korovin are used if not mentioned otherwise) is that critical fuel build-up is 200 g/m^2.

The current model does not have a fuel build-up module, but a constant per-year rate of fuel build-up specific for each type of forest, reduced by fires will be included in the next version. We believe that this feature will help us to resolve the problem with the less-than-observed variability of the annual number of fires.

Fire self-support

The final requirement of fire development, used in the model, is the possibility of fire to provide enough energy for self-support. The potential of a territory to burn is referred to as fire danger. A share of the territory that has flammable materials with moisture less than some critical fire self-support moisture influences fire danger. Since fallen wooden material is the most important fuel for fire spread, the ability of fire self-support is determined by litter moisture. A very simplified differential equation from (Korovin et al. 1977) can be an example of formulas used in such approach:

$$\dot{w} = (w - w_c + P)\rho$$

Here, w – soil moisture; w_c – hygroscopic water contents, P(t) – precipitation dynamics, ρ – evapotranspiration coefficient.

However in applications, instead of direct computing of fuel moisture, synthetic meteorological indexes are frequently used. Our model RF employs Nesterov index, computed according to the following formula (Directives on forest ... 1973):

$$F_i = F_{I-1}\delta_i + t_i(t_i - \tau_i).$$

Here,
F_i – fire danger index at day *i*;
δ_i – delta-function, equal 1 if daily precipitation is less than 3 mm and 0, otherwise;
t_i – air temperature in ^{o}C, measured at 1–3 a.m.;
τ_i – dew temperature.

This method of fire danger assessment assumes that the expected number of fires λ_i at a day with fire danger class $c_i = c(F_i)$ and with number of fire sources n is: $\lambda_i = nP(c_i)$, where probability of fire ignition at a day with fire danger class c_i $P(c_i)$ is calculated from 5-years fire statistics.

Fire registration

In the model, a cell may have any number of current or already burned out fires. Each new fire is registered into fire records, if all three preconditions of fire ignition described above are met. In the current version of the model, a fire record consists of the following fields:

- location of fire (cell identifier),
- current burnt area (km^2),
- amount of fuel,
- day the fire started (a chronological number, starting from January, 1st),
- day the fire was reported and
- day the fire burnt out or was extinguished.

Fire end

For each fire, a test is run to determine if it burns out due to unfavorable weather conditions. It is supposed that a fire stops if weather conditions in the cell increase fuel humidity above a critical level that permits fire self-support. For simplification purposes, the model assumes that decreasing the Nesterov index to 0 (i.e. daily amount of precipitation exceeding 3 mm) stops the fire. The day fire ends is stored in the fire record. Otherwise, probability of fire termination at a given day is found on the basis of the current fire area and current fire danger. The algorithm is similar as discussed above.

Fire reporting

For each fire present in the records, a test is run to determine if a fire is detected and reported to the fire service protection service. A stochastic process with parameters dependent on population density simulates fire reporting. It is assumed that the higher population density, the sooner the fires are reported to the authorities. It is also assumed that the sooner a fire is reported, the sooner it will be extinguished. The day when a fire is reported is stored in the fire records.

Forest fire database states clearly that the local population plays a very limited role in forest fire detection: during 1987–1998, only 4% of forest fires were reported by local people, foresters, and other forest users, including the fires that were also independently detected by forest fire protection service. The majority of fires, 70% were detected by the air forest protectionservices. However, fire statistics show clearly that the population density affects the time needed to detect forest fires. It can be best estimated through the area of forest fires when fires are reported (see Figure 6). In the current version of the model we do not implement this algorithm. Instead, each fire is issued immediately after it starts, based on statistical data. Therefore, date of fire ignition is considered to be the same as the date of fire detection.

Fire dynamics

Area burnt by each of the fires is updated, and a new area is found as a random value. It is assumed that the average rate of daily incremented fire area is a linear function of time. We also consider fire danger index as a factor contributing to fire spread (see above for detailed information on the algorithm).

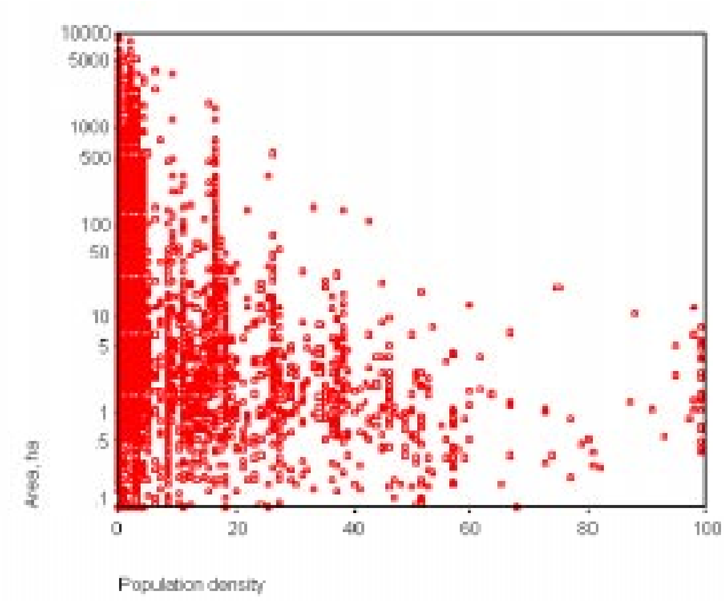

Figure 6. Effect of population density on the area of forest fire at the time fire is detected.

Fire statistics and iterative simulations

At the end of each year, annual statistics are accumulated from the fire records and all fire records are reset. Before this, all statistics on fires active during the year are stored for each cell over land. Average totals are also calculated and stored. At the end of each 10-year iteration, a multi-year average of the annual number of fires and of annual area of fires is computed and stored for each cell. These numbers are again averaged across the entire amount of model iterations. Finally, the decade averages of the total number of fires and total area burnt are computed for the whole territory of Russia. Each iteration modifies these mean values. Model iterations stop when a new iteration modifies the mean annual burnt area by less than some pre-set parameter. The experiments show that one iteration is enough to provide mean data describing the whole territory of the country during one decade. However, more iterations are needed to provide consistent data describing lesser territory or shorter time periods. In our experiments, we used up to 10 iterations to generate enough data to describe one simulated year.

Data storage and visualization module

At the end of model run, final statistics are computed and transferred to files for post-processing by other software. For data storage we use the Arc/Info Grid ASCII format; most of the post-processing is done using the Arc/Info and ArcView GIS software. Another option is data visualization. For this purpose, we built a model interface to the Digital Array Analyzer (Fortran-95 add-on from Digital), which provides basic routines for data visualization, manipulation, storage, and analysis. This choice of options for data storage permits the user two different alternatives for analysis of data, generated by the model: quick and easy on-the-fly check of model results and thorough analysis inside a business-standard GIS.

5. MODEL RESULTS

To compare the model results with actual data on the annual dynamics of fire number and area, we used a total number of fires for each year within 1987–1998 time frame, as recorded in the forest fire database. To provide consistency in comparison of simulations with these data, we masked the territory of the country, not covered by the forest fire database. We used historical climate for 1987–1995 years and the IMAGE projections for 1996–1998. Model simulations show a good correspondence with the reported average number of fires. However, the area of fires, according to the model, is less than estimated from the database. A possible explanation is that the model does not reproduce infrequent events of very large fires well enough, a feature which is to be corrected in the next version of the model. The model also reproduces the interannual course of amount wildfires, though the simulation results have considerably less variability (see Figure 7). This can be explained by the particular features of the model, and also by the nature of the data used. Some existing variability can be attributed to the fact that a considerable amount of smaller fires in the Asian part of the Russian territory is probably not detected and hence not recorded in the database. Then, the model itself does not have an implemented algorithm, simulating amount of fuel. This reduces the negative feedback of high-flammability years on future fires. However, the goal of the model is to estimate the change in the multiyear average number of fires, hence less-than-expected variability is not a concern here.

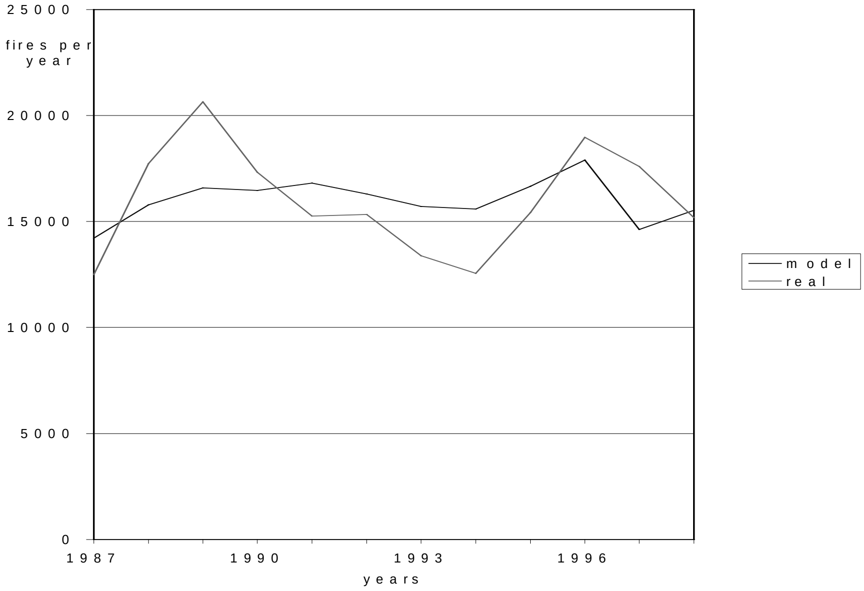

Figure 7. Comparison between model results and data retrieved from the forest fire database. Dynamics of annual number of fires is shown. Model demonstrates less variability in reproduced dynamics.

The daily climate we synthesised with the fire weather generator shows considerable change in the amount and distribution of weather patterns with increased fire danger. Table 1 lists the decade average number of fire danger days, representing the 1940s, 1990s, 2050s, and 2090s. It was found that some growth in the amount of days with higher than average fire danger can be seen already from the data representing the second half of last century: average amount of days with the 2nd class of fire danger in the 1990s is greater than in the 1940s by 1.5 days, and for the 3rd class by 2.3 days. However, we have not found any significant increase in the length of the high and extreme fire danger periods, meaning that only a moderate increase of the number of fires can be attributed to climate change. On the contrary, the forecasted climate for this century shows quite a significant increase in the weather patterns with high and extremely high fire danger: an increase by 1.5 days by the 2050s, and by 5.5 days by the 2090s, as compared with the contemporary climate. An even greater increase can be noticed in the number of days with low and moderate fire danger.

Table 1. Average number of days with specified class of fire danger in one year, for specified decades.

Years	**Days with specified fire danger class, according to climate database**		
	Class 2	**Class 3**	**Class 4–5**
1941–1950	33.1	40	23.2
1986–1995	34.6	42.3	23.5
2046–2055	36.8	47.3	25
2091–2100	40.2	52.8	28.7

This increase of fire danger is not evenly distributed through the territory of the country, yet it shows spatial correlation. Figure 8 illustrates these spatial variations by providing an annual sum of daily values of fire danger index, averaged for three decades of the 1990s, 2050s, and 2100. It can be seen that the main effect of the climate change impact on forest fires can be seen on the European part of the country and, later, in the Eastern Siberia. Since the average area of forest fires occurred in the Asian part of the country is significantly larger than in the European part, the increase in fire number will probably not be associated with the adequate increase in burned area, provided that the level of fire protection stays unchanged.

Since some parts of the model are not yet implemented, it is too early to make actual forecasts of the future wildfire dynamics in the changing climate. Some preliminary results, shown in Figure 9, show that we can expect growing number of fires – up to 24% increase by the year 2100. The picture shows the simulated running decadal mean value of fire number, reproducing climate data from 1941 till 2100.

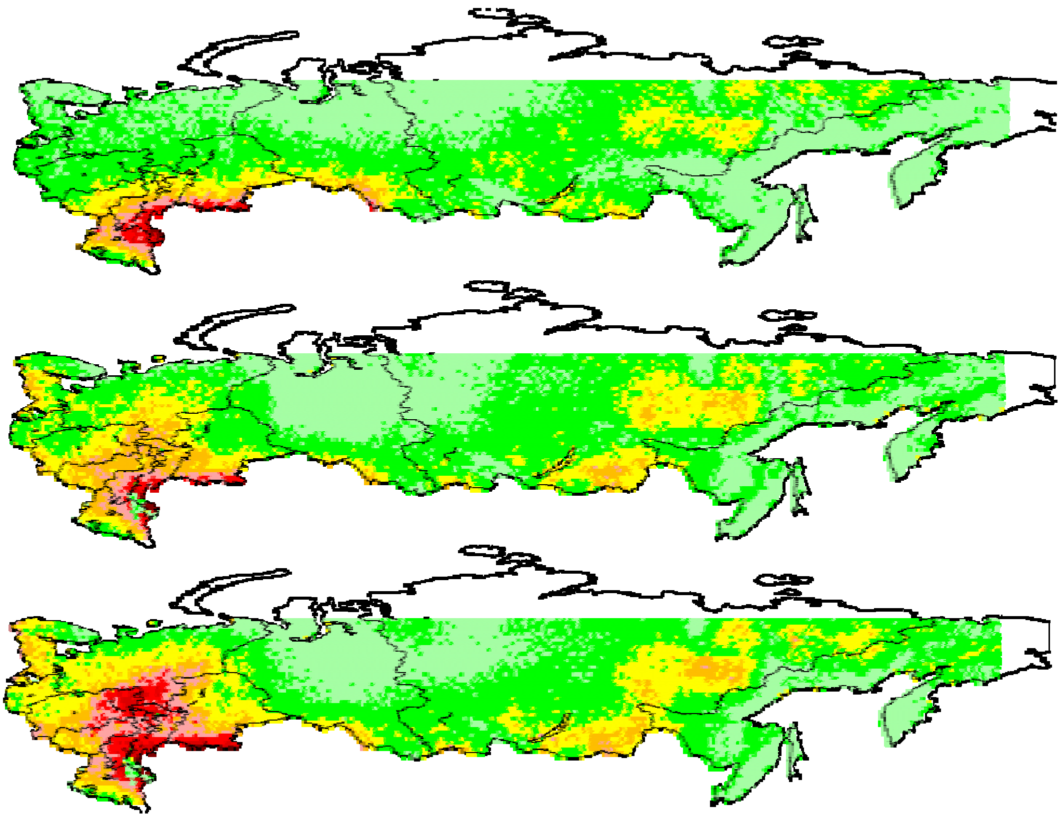

Figure 8. Effect of climate change on fire danger. Decade mean sum of daily values of Nesterov fire weather index for 1990, 2050, 2095 (top to bottom). Light green color corresponds to low fire danger and bright red color means extreme fire danger.

Figure 9. Preliminary model results. Long-term dynamics of forest fires.

Discussion

As the model development has just started and the results presented can be only considered as preliminary, used only for illustrative purpose to demonstrate the purpose of the modelling activity. Further research is necessary to provide enough confidence in the model results. Yet the main step in model enhancement should be connected not with improving in the model structure itself, but with better data used to compute model parameters. First of all, we should unify the data on forest fire statistics received from different sources, the more detailed data of aerial forest fire protection service should be complemented with the oblast-based data, which provides better area coverage.

The following features will be implemented in the next version of the model, which will permit to make first assessments of future amount and area of forest wildfires, suitable for analysis.

- The model will be extended to cover the whole territory of Russia. The current version covers only a part of the territory, described in the forest fire database. For this purpose we will additionally include region-based data from other sources;
- The algorithm of fuel dynamics will be fully implemented and included into the model. This will permit more interannual variability of the fire number and also will provide data to estimate the effect of fires on dynamics of stored carbon;
- The data will be differentiated between main forest species. Again, we will achieve more accurate reproduction of fire dynamics and better statistics for estimation of CO_2 release.

In the future, we also suppose to include the fire model into the stochastic model of tree species migration MOVES (Kirilenko and Solomon 1998) and to run joint simulations with the IPCC recommended climate change scenarios. The final goal is to assess how climate change is likely to affect the amount of carbon stored in the Russian boreal forests.

Acknowledgements

I would like to thank Dr. Korovin from the International Forest Institute, Moscow, Russia, for the data and discussions. This project was supported by a visiting scientist fellowship, granted by the European Forest Institute.

REFERENCES

Alcamo J. (ed.). 1994. Image 2.0. Integrated Modeling of Global Climate Change. Kluwer Academic Publishers. 318 p.

Cubasch, U., Hasselman, K., Hock, H., Maier-Reimer, E., Mikolajewicz, U., Samter, B. D. and Sausen, R. 1992. ‘Time-dependent Greenhouse Warming Computations with a Coupled Ocean-Atmosphere Model’. Climate Dynamics 8:55–69.

Climate Change 2001: The Scientific Basis. Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change (IPCC). 2001. Cambridge Univ. Press, Cambridge, UK. 944 p.

Directives on forest fire preventive works and regulations of forest fire protection units. 1973. Moscow, GosLesKhoz USSR, 183 p. (in Russian).

Dixon, R.K. and Krankina, O.N. 1993. Forest fires in Russia: carbon dioxide emissions to atmosphere. Can. J. For. Res. 23:700–705.

EMBYR, Ecological Model for Burning the Yellowstone Region. 2001. http://research.esd.ornl.gov/EMBYR/fire.mpg

Flannigan, M.D., Bergeron, Y., Engelmark, O. and Wotton, B.M. 1998. Future wildfire in circumboreal forests in relation to global warming. Journal of Vegetation Science 9:469–476.

Flannigan, M.D. and Van Wagner, C.E. 1991. Climate Change and wildfire in Canada. Can. J. For. Res 21:66–72.

Friend, A.D. 1998. Parameterisation of a global daily weather generator for terrestrial ecosystem modelling. Ecological Modelling 109:121–140.

Greco, S., Moss, R. H., Viner, D. and Jenne, R. 1994. Climate scenarios and socioeconomic projections for IPCC WG II assessment. material assembled for lead authors by IPCC WG II TSU, Washington, D.C. 12 p.

Hargrove, W.W., Gardner, R.H., Turner, M.G., Romme, W.H. and Despain, D.G. 2000. Simulating fire patterns in heterogeneous landscapes. Ecological modelling 135(2–3):243–263.

Hong, S.H. and Mladenoff, D.J. 1999. Spatially explicit and stochastic simulation of forest – landscape fire disturbance and succession. Ecology 80(1):81–99.

The ITE global daily weather generator. 2001. http://www.nbu.ac.uk/gwg/Files/w_gen.zip.

IPCC (Intergovernmental Panel on Climate Change). 1996. Climate Change 1995: Impacts, Adaptations and Mitigation of Climate Change. Cambridge Univ. Press, Cambridge, UK. 878 p.

Isaev, A.S., Korovin, G.N., Sukhikh, V.I., Titov, S.P., Utkin, A.I., Golub, A.A., Zamolodchikov, D.G. and Priazhnikov, A.A. 1995. Ecological problems of CO_2 assimilation through reforestation and afforestation in Russia. Centre for Ecological policy of Russia, Moscow. 87 p.

Johnson E.A. and van Vagner, C.E. 1985. The theory and use of two fire history models. Can. J. For. Res. 15:214–220.

Jones, P.D., New, M., Parker, D.E., Martin, S. and Rigor, I.G. 1999. Surface air temperature and its changes over the past 150 years. Reviews of Geophysics 37:173–199.

Kasischke, E.S., Christensen, N.L., Jr. and Stocks, B.J. 1995. Fire, global warming and the mass balance of carbon in boreal forests. Ecol. Appl. 5:437–451.

Kirilenko, A.P. and Solomon, A.M. 1998. Modeling dynamic vegetation response to rapid climate change using bioclimatic classification. Climatic Change 38:15–49.

Korovin, G.N. 1977. Estimation of forest fire danger and computing of characteristics of forest fires. LenNiiLKh, Leningrad. 64 p. (in Russian)

Korovin, G.N. 1984. Analysis and modeling of the statistical structure of the field of forest burning. LenNiiLKh, Leningrad. 84 p. (in Russian)

Kurz, W. A., Apps, M. J., Webb, T. M. and McNamee, P. J. 1992. The carbon budget of the Canadian forest sector: phase I. Forestry Canada, Information Report NOR-X-326. 93 p.

Leemans, R. and Cramer, W. P. 1990. The IIASA Database for Mean Monthly values of Temperature, Precipitation and Cloudiness of a Global Terrestrial Grid. WP-90-41. IIASA, Laxenburg, Austria. 64 p.

Manabe, S., Spelman, M.J. and Stouffer, R.J. 1992. Transient responses of a coupled ocean-atmosphere model to gradual changes of atmospheric CO_2. Part I: Seasonal Response. J. Climate 5:105–126.

Murphy, J.H. and Mitchell, J.F.B. 1995. Transient responce of the Hadley centre coupled model to increasing carbon dioxide. Part II: temporal and spatial evolution of patterns. J. Climate 8:57–80.

New, M., Hulme, M., and Jones, P. 2000. Representing twentieth-century space-time climate variability. Development of 1901–96 monthly grids of terrestrial surface climate. J. Climate 13:3317–2238.

Pokrivaylo, V.D., Korovin, G.N., Solodnikova, N.I. and Polomina, Z.S. 1976. Structure and functioning of ES-1020 computer database of forest fires. Leningrad, LenNIILKh, 60 p. (in Russian).

Remote Sensing and Geographical Information Systems Laboratory of International Forest Institute, Moscow Russia. 2001. http://www.ifi.rssi.ru/Web_Site/Eng/ENG_TIT.html.

Richardson, C. 1981. Stochastic simulation of daily precipitation, temperature, and solar radiation. Water Resources Research 17:182–190.

Richardson, C. W. and Wright, D. A. 1984. WGEN: A model for generating daily weather variables. U.S. Department of Agriculture, Agricultural Research Service. 83 p.

Sohngen, B. and Haynes, R. 1997. The potential for increasing carbon storage in United Utates unreserved timberlands by reducing forest fire frequency: an economic and ecological analysis. Climatic Change, 35(2):179–197.

Stocks, B.J., Fosberg, M.A., Lynham, T.J., Mearns, L., Wotton, B.M., Yang, Q., Jin, J-Z., Lawrence, K., Hartley, G.R., Mason, J.A. and McKenny, D.W. 1998. Climate change and forest fire potential in Russian and Canadian boreal forests. Climatic Change 38(1):1–13.

Thonicke, K., Venevsky, S., Sitch, S. and Cramer, W. 2001. The role of fire disturbance for global vegetation dynamics: coupling fire into a Dynamic Global Vegetation Model (in preparation).

Venevsky, S., Thonicke, K. and Cramer, W. 2001. A regional scale fire model (in preparation).

Wotton, B.M. and Flannigan, M.D. 1993. Length of the fire season in a changing climate. Forestry Chronicle. 69:187–192.

APPENDIX. The forest fires database, used in the project.

Code	Explanation	Units
YEAR	Year	Years
LATITUDE	Latitude	Degrees
LONGITUDE	Longitude	Degrees
DAY_DETECT	Day fire was detected (Jan, 1 is day 1)	Days, 1–366
CLA_SPOB	Method the fire was detected	1 – Towers; 2 – Ground fire protection units; 3 – Aviation; 4 – Forest cutters; 5 – Local people; 6 – Aviation & towers; 7 – Aviation & ground fire protection units; 8 – Local people & ground fire protection units; 9 – Local people & aviation.
CLA_PLOB	Area at time of fire detection	Ha
CLA_VETER	Wind speed at time of fire detection	m/s
CLA_KPOOB	Fire danger class at day of fire detection	1–5
CLA_PRICH	Source of fire	1 – Areas of forest cutting; 2 – Agricultural burning; 3 – Thunderstorms; 4 – Local people; 5 – Burning of wood left from forest clearcut; 6 – Expeditions; 7 – Railroads; 8 – Unknown.
CLA_RASTNP	Distance to the closest settlement	Km
CLA_RASTMV	Distance to the closest water body	Km
CLA_RASTPT	Distance to the closest road	Km
CLA_PORODA	Main forest species	0 – No forest; 1 – Pine; 2 – Fir, spruce; 3 – Larch; 4 – Cedar; 5 – Birch; 6 – Aspen; 7 – Hardwood deciduous; 8 – Dwarf cedar; 9 – Other.

CLA_POKROV	Ground vegetation	1 – Green moss ; 2 – Lichens; 3 – Heather; 4 – Grass; 5 – Sphagnum; 6 – Other.
DAY_EXTSTA	Day fire extinguishing started	Days
DAY_LOCALI	Day fire was localized	Days
DAY_EXTING	Day fire was extinguished	Days
CLA_KPOLIK	Fire danger class at day of fire extinction	1–5
CLA_PLLES	Area of fire, forest	Ha
CLA_PLVER	Area of fire, crown	Ha
CLA_PLPOD	Area of fire, ground	Ha
CLA_PLNLES	Area of fire, non-forest	Ha