6.4. POTENTIAL FOREST FIRE DANGER OVER NORTHERN EURASIA: CHANGES DURING THE 20TH CENTURY

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1. INTRODUCTION

There is a consensus among the scientific community that during the past century there were significant climatic changes documented in various meteorological variables, first of all in temperature and precipitation (IPCC 2001). The temperature changes have been most prominent in high latitudes and in the cold season and (as recent studies show) more during the nighttime than in the daytime (Karl et al. 1991; Folland and Karl 2001). Significant climatic changes over the high latitudes in the 20th century have been reflected in many atmospheric, oceanic, and terrestrial variables. A growing concern is that the changes in the mean values will transpire into changes in weather extremes that will directly impact society (IPCC 1998). In particular, changes in surface air temperature, precipitation, growing season duration, and snow cover cause changes in numerous derived variables of economic, social and ecological interest, including the natural frequency of forest fires. The following rationale for changes in this frequency for high- and mid-latitudes (thus, for Northern Eurasia) can be formulated as follows. Warming, spring snow cover retreat, extension of the growing season and a reduction of the "warm temperatures deficit" acting together promote vegetation growth and, therefore transpiration. At the same time, warmer surface air temperatures themselves increase the "atmospheric demand" for water vapor and increase of potential evaporation. If precipitation increases insufficiently to match this growing demand, we should witness drier surface conditions and so called "summer dryness" (Manabe et al. 1981) and thus, an increase in potential forest fire danger. This scenario is, however, not inevitable. It well can be that in some regions changes in the atmospheric circulation pattern and/or changes in local factors may increase precipitation "sufficiently" to oppose summer dryness (e.g., Groisman et al. 2004; Robock et al. 2005).

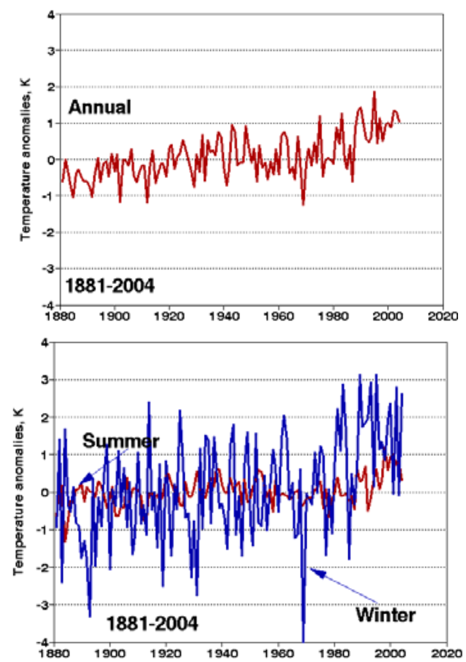

Figure 1. Changes of the surface air temperature during the period of instrumental observations over Northern Eurasia (continent north of 40°N and east of 15°E). Annual and seasonal temperature variations are presented in anomalies from the mean values for the 1951-1975 reference period. Linear trends of these time series are all statistically significant at the 0.01 level or higher and constitute 2.0 K, 1.2 K, and 0.5 K per 124 years for winter, year, and summer respectively. Data source: Archive of Lugina et al. (2005).

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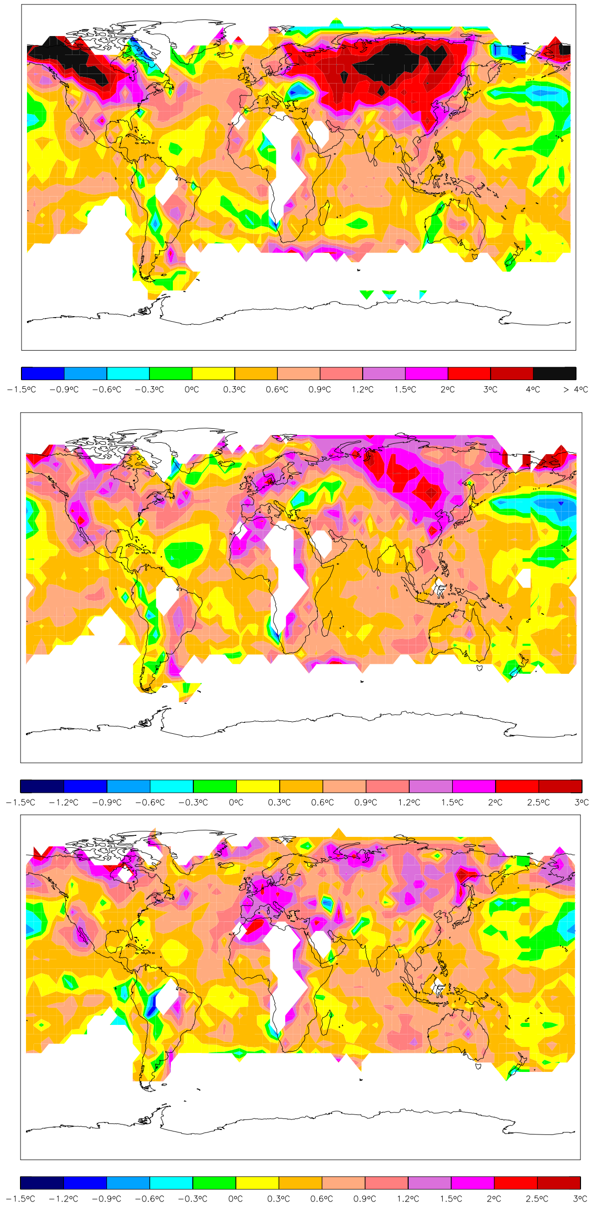

Figure 2. Mean seasonal temperature changes 1965 to 2004 over the globe. From top to the bottom: winter, spring, and summer. The change estimates were made by fitting linear trend lines. Data source: (Jones and Moberg 2003, updated). Processed by the NCDC Global Climate at the Glance Mapping System. More information is available at: http://www.ncdc.noaa.gov/oa/climate/monitoring/gcag/gcag.html.

Fire is one of nature's primary carbon-cycling mechanisms but human activity interferes with the natural component of this mechanism causing by some estimates more than half of the occurrences of boreal forest fires. When the weather conditions are conducive to the expansion of forest fires, this anthropogenic effect becomes especially pronounced. In this paper we target only the meteorological component of the changes in potential forest fire danger. After a brief overview of climatic changes in the region (below) and the Data Section, the two following sections examine this possibility using meteorological data for the northern extratropics and comparing them with available information about the forest fire areas and frequency. Discussion and Conclusion Sections conclude the paper

1.1. Overview of climatic changes in Northern Eurasia during the past century.

In the 20th century, Northern Eurasia was the region with the largest and steadiest increase of surface air temperature which became the most pronounced during the second half of the 20th century (Figure 1). The changes in the past 40 years have one more peculiarity that deserves to be noted. While in previous decades (at least during the period of instrumental observations), we mostly observed changes in the cold season, the recent warming became prominent in the warm season also (Figures 1 and 2). This warming should manifest itself in changes of environmental characteristics affecting both terrestrial ecosystems dynamics and human activity. Groisman et al. (2003a, 2005b) assessed changes in several such characteristics over Northern Extratropics during the past 50 years including frequency of extremes in precipitation and temperature, frequency of thaws; heating degree days, growing season duration, sum of temperatures above/below a given threshold; days without frost, and day-to-day temperature variability. Each of these characteristics has substantially changed over Northern Eurasia. The update of this assessment is briefly summarized below.

Extreme events. Significant changes in heavy precipitation events were reported over Fennoscandia and Russia (cf., also Groisman et al. 2005a,b) while over the Asian part of Russia no discernable increase in total precipitation has been seen in the past five decades (cf., also Gruza et al. 1999). The frequency of unusually cold nights and days (based on T_{min} and T_{max} daily data) decreased while the frequency of unusually warm nights and days increased (at nighttime, the changes were more prominent than in the daytime (cf., also Frich et al. 2002).

Days with thaw. A day with thaw (snowmelt) can be defined as a day with snow on the ground when the daily mean temperature is above –2ºC (Brown 2000). During these days snow deteriorates, changes its physical properties, and eventually disappears. In winter and early spring in high latitudes, thaws negatively affect surface transportation, winter crops, and sustainability of the natural environment, including vegetation and animals. In late spring, intensification of thaw conditions leads to earlier snow retreat and the onset of spring (Groisman et al. 1994; Brown 2000). Gradual snowmelt during the cold season affects seasonal runoff of the northern rivers, reducing the peak flow of snowmelt origin and increasing the mid-winter low flow. The circumpolar change in the frequency of days with thaw north of 50°N during the past fifty years results in statistically significant increasing trends for winter and autumn of 1.5 to 2 days. This change constitutes a 20% (winter) to 40% (autumn) increase in the thaw frequency during the second half of the 20th century. Figure 3 presents an update of this study for Fennoscandia where the change has been especially large (a 45% increase during the past 50 years).

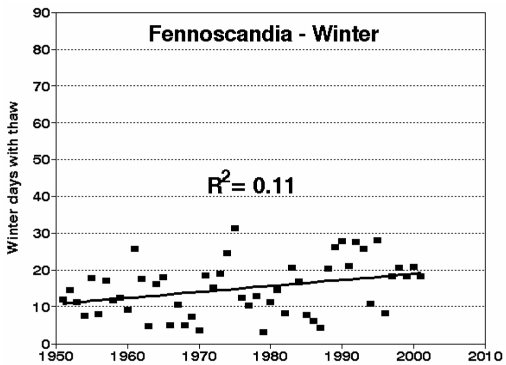

Figure 3. Frequency of winter days with thaw over Fennoscandia and their linear trend. A 45% increase during the past 50 years (by 8 days) is statistically significant at the 0.05 level (R^2 = 0.11). Definition of day with thaw used: presence of snow on the ground and mean daily temperature above –2°C. On average, 17 days per winter season were days with thaw.

Characteristic	Former USSR	Asian Russia
Heating-degree days	-7	-7
Degree-days below 0ºC	-15	-14
Degree-days above 15ºC	11	20
Duration of the growing season		
T> 10ºC	9	14
T> 5 ºC	8	12
Duration of the frost-free period	8	11

Table 1. Changes in derived-temperature characteristics over Northern Eurasia during the past 54 years (within the fUSSR boundaries; period 1951-2004). Linear trend estimates (% per 54 years) are presented for the entire former USSR and Siberia and Russian Far East south of the Polar Circle (Asian Russia). All trend estimates are statistically significant at 0.01 or higher levels.

Heating degree-days, duration of growing season, and sum of temperatures above/below a given threshold. Heating degree-days are the sum of positive mean daily temperature (T_{mean}) anomalies from the base temperature $(T_{base} – T_{mean})_+$. Heating degree-days closely correlate to energy consumption for heating and have numerous other practical implications (Guttman and Lehman 1992). The dates of steady (at least 5-day-long) transitions of mean daily temperatures across +5°C and/or +10°C are used to define "growing seasons" for various species in the high latitudes. Table 1 reports significant reductions in heating degree-days over the former USSR and Siberia in particular (7% per 54 years) and a significant increase in the growing season duration (a 10 days increase nationwide but a 17 days increase in Central Siberia during the past 54 years). To characterize the severity of the cold season, a sum of negative temperatures can be used. Time series of this characteristic for winter and for the entire cold season indicate that the annual "severity" of the cold season has substantially decreased over Northern Eurasia. Sums of mean daily temperatures above specific thresholds (5°C, 10°C, or 15° C) are used in bio- and agro-climatology to define the northernmost limits of expansion of different vegetation species including crops. The ongoing warming of the high latitudes causes shifts in these sums and, therefore, creates a potential to change the boundaries. Regional changes of the sums with mean daily temperature above 15° C (the tendencies for positive sums above those two other thresholds are similar) are shown in Table 1. This result supports the increase in "greenness" of the high latitudes (reported recently from satellites; Myneni et al. 1997), provides a longer time scale (compared to the remote sensing results), and quantifies the "greenness" changes.

Days without frost. The length of the frost-free period is among the most carefully monitored variables in the high latitudes. It can be very short in the Russian Arctic and reaches more than 150 days in Fennoscandia. The length of this period has increased over the eastern half of the continent only (by 11% per 54 years). It hints that this parameter continues to control the ecosystems in the western half of the continent and has not substantially changed during the past 50 years.

Spring snow cover retreat and days with unfrozen ground. Brown (2000) seamlessly blended in situ snow cover observations from a sparse network in Eurasia with satellite estimates of spring snow cover extent and reconstructed snow cover extent as far back as 1915. These data were extended to the present (cf., Figure 10 in Groisman and Bartalev 2005) and report a steady spring snow cover retreat with a rate of ~13% during the past 75-80 years. This is in line with increases in the growing season period and allows for a longer period with active evapotranspiration.

1.2. *Summarizing the above*, we can state that in Northern Eurasia (particularly in its eastern half) changes in surface air temperature during the past 50 years were especially significant. Thus, there should be additional water "demand" for evaporation and transpiration. This and moderate (or none) changes in precipitation over the eastern half of the continent may lead to the possibility of drier summer conditions and their detrimental consequences for society: an increase in potential forest fire danger (that leads to more frequent forest fires). These conditions were projected by some GCMs for the greenhouse gases enriched atmosphere (e.g., Manabe et al. 2004) and suggest reduced future water availability in high and mid-latitudes over the land (Folland and Karl 2001).

2. DATA

Data. Several global data sets were used in this study to assess climatic variations over Northern Eurasia and (for some types of analyses) for North America. Monthly temperature and precipitation data (Jones and Moberg 2003, Lugina et al. 2005, Groisman and Rankova 2001, and NCDC 2000) were used to provide background information about climatic variations in the region.

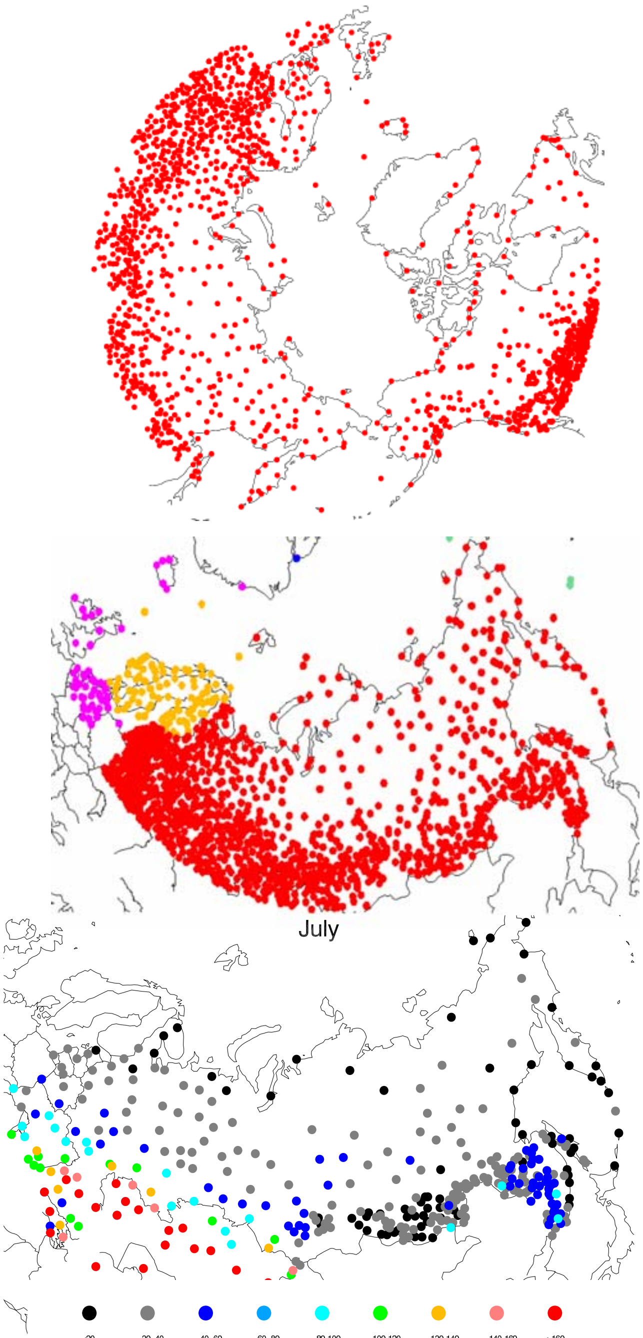

Figure 4. (Top). Map of GDCN stations north of 50°N with more than 25 years of valid daily precipitation data. Total coverage with daily precipitation (Middle) and temperature (Bottom) data in Northern Eurasia available for this study. Only stations with more than 25 years of valid daily precipitation and T_{max} data are shown. Colored code in the T_{max} availability map represents the KBDI climatology of the July Keech-Bayram drought index (KBDI) and is explained in Section 3.1.

Daily data were the primary time format used in this study. Mostly we employed an updated version of the Global Daily Climatology Network (GDCN, NCDC 2002; Groisman et al. 2005a; Figure 4). For this study, in Scandinavian countries, Finland, and in southern Siberia, GDCN was substantially expanded using national archives. Precipitation time series for the former USSR (fUSSR) were homogenized to account for changes in instrumentation and observational practice as described in Groisman and Rankova (2001). Figure 4 (upper panel) shows the GDCN stations with precipitation daily data. For North America and Northern Europe, the number of stations with available daily precipitation *and* temperature data is slightly less than shown in this Figure. For the former Soviet Union, there is a tenfold discrepancy between the number of stations with precipitation and temperature initially available in the GDCN Figure 4 (bottom panel). During the pilot step of the study, we found a significant long-term signal of increasing potential of forest fire danger in the southern regions of Siberia and Russian Far East (south of 55ºN). Therefore, additional efforts were made to collect, quality control, and use more than 200 stations with temperature data for this part of the world.

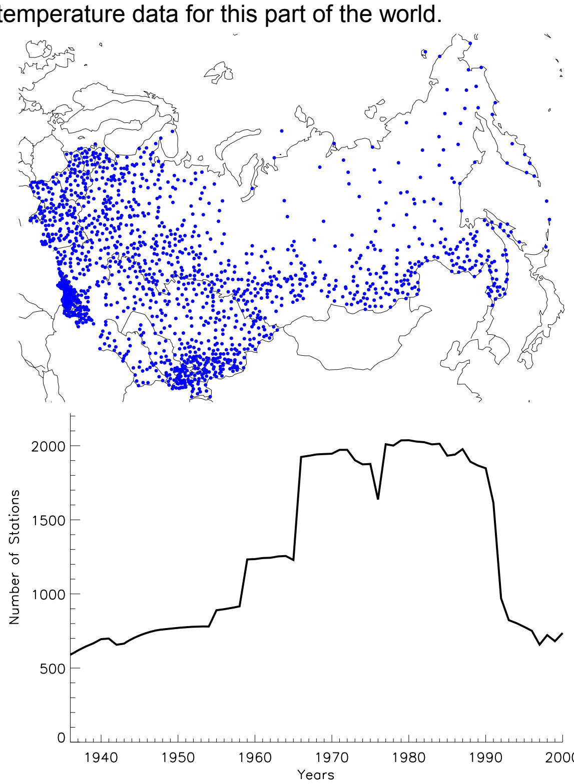

Figure 5. Data availability in the GSCN archive used for this study. (Top) Map of "long-term" stations with temperature data available at least at 80% of days during the 1961-1990 reference period (Bottom) The number of stations with data per year. After 1991 mostly Russian stations are available in this archive (NCDC 2005b).

For Northern Eurasia (within the fUSSR boundaries) and Canada we used a new Global Synoptic Climatology Network (GSCN) created jointly by the U.S. National Climatic Data Center (NCDC), Russian Institute for Hydrometeorological Information, and Meteorological Service of Canada. Within the boundaries of the former Soviet Union, GSCN consists of 2095 stations (NCDC 2005b; Figure 5) currently updated up to 2000 and includes the entire suite of synoptic observations with 8-hourly (prior to 1936), 6-hourly (prior to 1966), and 3-hourly (1966 and after) resolution. GSCN was used to assess changes in the indices that require synoptic information (daytime temperatures and humidity) for their calculations (Section 4.2). Approximately 1520 GSCN stations within 1026 1ºx1º grid cells have more than 80% of the data during the 1961-1990 reference period. Only these stations were used in subsequent analyses for this paper. We had an opportunity to compare our results based upon GDCN and GSCN to assure that they provide similar results (Section 3.4.2). Except for southern Siberia and the Russian Far East, GSCN has more temperature data than GDCN but there is very little humidity information prior to 1936. This made it impossible for construction and analysis of indices that use synoptic information prior to that year.

One of the analyses of this paper includes Canadian data. When considering temperature variations over Canada, we included a subset of 210 Canadian stations with homogenized temperature time series (Vincent and Gullett 1999). A priority was given to these high-quality data instead of the observations in the GDCN. Precipitation time series for Canada were homogenized to account for changes in instrumentation and observational practice as described in Groisman (2002). GSCN for Canada includes 768 stations mostly located in the southern part of the country (NCDC 2005a).

Area averaging. Most of results of the following sections are presented in the form of regionally averaged quantities. Administrative regions (states and provinces, group of countries) were used for North America and Fennoscandia, while climatologically-motivated regionalization was selected for the former USSR. Eleven regions of the former USSR used throughout this paper are the same as in Groisman et al. (1995a) and schematically represent climatic regions of the former USSR according to Alisov (1957) and Shver (1976) with additional consideration of differences in data availability (e.g., in Siberia south and north of 55ºN). Area-averaging over the regions was performed as follows: First, station data anomalies from the long-term mean for the reference 1961-1990 period (or statistics) were averaged within each 1º x 1º gridcell. This step allows for suppression of unduly impacts of station clusters on the area mean values. The gridcell values (those with at least 1 valid station value within) were then averaged further over the region with weights proportional to the gridcell latitude cosine. Area-averaging over mega-regions (e.g., Siberia or the former USSR) is then conducted by averaging the regional mean values with the weights proportional to the areas of the regions that compose the mega-region. This averaging routine was tested many times for different meteorological elements, is robust, and represents a reasonable compromise compared to the optimal area-averaging routines when we are lacking sufficient information about the spatial covariance function of the averaged meteorological field. It does not claim to cover the entire region but focuses on the data-elucidated regions where people live and maintain meteorological observations for sufficiently long periods of time.

3. INDICES OF POTENTIAL FOREST FIRE DANGER

Each summer, forest and tundra in high latitudes suffer from numerous naturally caused fires that are difficult to fight due to their remote locations. Among meteorological variables that affect the potential fire danger are surface air temperature, soil moisture, humidity deficit, probability of lightning, and atmospheric stability (Turner and Lawson 1978; Keetch and Byram 1968; Zhdanko 1965; Gillett et al. 2004). To characterize the level of potential fire danger, numerous indices have been suggested. In this study, we used four indices to assess the potential forest fire danger:

(1) Keetch-Byram Drought Index (KBDI). This index uses daily data of maximum temperature and precipitation and was developed and used in the U.S.; and (2) Nesterov (NI), Modified Nesterov (MNI) and Zhdanko (ZhI) Indices. These indices use synoptic daytime data of temperature and humidity and daily precipitation and snow on the ground and were developed and used in Russia.

Nesterov Index of fire danger, G, based on the humidity deficit, temperature, and information about the days with precipitation below 3 mm day^{-1} is calculated according to the formula:

$$G = \Sigma\ (T \times d), \qquad (1)$$

where T is the mid-day temperature, d is the dew point deficit ($d = T - T_d$, where T_d is the dew point), and totals are calculated for positive temperatures for a sequence of days with precipitation less than 3 mm (Sherstyukov 2002). Rainfall above 3 mm resets G to zero. For Central Russia, days with G below 300 are the days without substantial forest fire danger while days with G above 1000 are characterized as days with high forest fire danger. Index G and several other indices require sub-daily meteorological information that is not easy to access on a century time scale. Therefore, we used a simplified index (KBDI) but tested two other indices based on sub-daily synoptic information: modified Nesterov and Zhdanko indices.

3.1. Keetch-Byram Drought Index

The Keetch-Byram Drought Index (KBDI; Keetch and Byram 1968) is a measure of meteorological conditions conducive to forest fires. It uses only daily maximum temperature and precipitation information and estimates soil moisture deficiency on a scale ranging from 0 to 800. Zero is the point of no moisture deficiency and corresponds to no danger of forest fire, and 800 is the most severe drought that is possible and corresponds to extreme forest fire danger. The logic behind the index is that wet soil suppresses wild fires while dry soil organic matter enhances these fires and makes them difficult to control. Certainly, factors in addition to soil moisture influence the occurrence and behavior of forest fires. However, in the USA, experience over the years has established the close association of extremely difficult fire suppression with cumulative dryness, or drought.

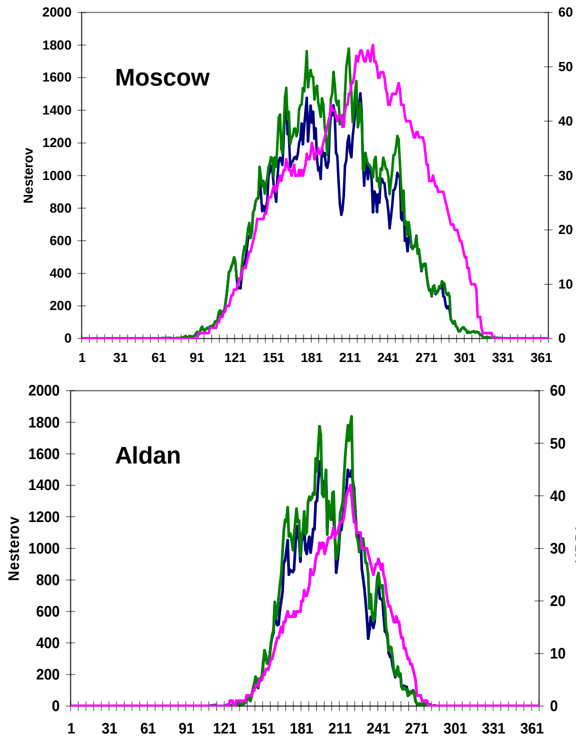

Figure 6. KBDI (pink lines), Nesterov indices NI (black lines) and MNI (green lines). Long-term mean values for the 1936-1999 period. Moscow and Aldan, Yakutia.

For these reasons, we have chosen the KBDI to study changes in forest fire potential. Below is a short summary of the algorithm of the KBDI evaluation:

Begin calculations at the point when soil is close to saturation (e.g., after snowmelt) and KBDI ≈ 0. Then

- Increase KBDI by an amount of evapotranspiration, E (a function of the current KBDI, T_{max} values, and mean annual P)
- Reduce KBDI by the amount of "net" rain, if any. In the sequence of humid days with non-zero precipitation, the "net" rain is the actual rainfall on the second day and days thereafter, but is reduced by 5 mm (0.2 inch) during the first day of the sequence.

In Figure 4 (bottom), the KBDI index is presented for Northern Eurasian stations with daily maximum temperature and precipitation available for the past fifty years. This is a July climatology of the index (the long-term mean values). Note the difference in the ranges of the index between high and mid-latitudinal stations.

3.2. Zhdanko and modified Nesterov indices

Zhdanko (1965) suggested a recurrent index of potential forest fire danger during the warm snow free period of the year similar to G (Eq. 1):

$$Zh\,(N) = [Zh\,(N-1) + d] \times K(N), \qquad (2)$$

where d is the dew point deficit and K(N) is a scale coefficient in a [0,1] that controls the index change when precipitation occurs on day N (Table 2). This reduction factor is equal to 1 when no rainfall occurs, is equal to 0 when daily rainfall is 20 mm or more, and gradually decreases between these thresholds (e.g., it is equal to 0.4 when daily rainfall is in the range of 3 to 5 mm, Table 2). Thus, the differences between Eqs. 1 and 2 arise from a steeper temperature dependence used in G and the introduction of a more relaxed

R [mm]	0	0.1-0.9	1.0-2.9	3.0 - 5.9	6.0-14.9	15.0-19.0	>19
K	1	0.8	0.6	0.4	0.2	0.1	0

Table 2. Scale coefficient K used to in Eq. 2 to account for daily precipitation impact on accumulated drought indices.

influence of rainfall on the forest fire index in Eq. 2 (Nesterov index assumes K(N)=0 for rainfall as low as 3 mm without accounting for the level of dry conditions prior to this rain event). In our further analyses we used a modified Nesterov Index (MNI) by introducing to its values a K(N) reduction factor similar to that used by Zhdanko in Eq. 2. Figure 6 shows examples of climatology for three indices, NI, MNI, and KBDI. The differences between NI and MNI are not large (although NI shows less stable behavior). Differences between KBDI and Nesterov indices are large in the autumn but, keeping in mind that over Northern Eurasia forest fires occur mostly in spring-summer, both indices are applicable.

A comparison of the remaining differences between both indices (Zhdanko and MNI) shows that their application delivers similar results (Section 3.4.1).

3.3. Normalization

Fires occur in tundra and forest steppe zones and, in a quest to use the same indices throughout the climatic zones, they should somehow be normalized. For example, the only regional adjustment in the KBDI computation depends on the long-term annual precipitation, P, that is assumed to be proportional to the total regional vegetation density (that adjusts itself to P) and thus controls E. Surface radiation balance is not used for this control which implies that the KBDI should be regionalized. The reason being that the actual vegetation density is a function of (at least) surface radiation balance (that can be associated with potential evapotranspiration) and precipitation (Budyko 1971).

In regionalizing the KBDI (as well as MNI and ZhI), we did not change the calculation schemes but instead, we abandoned a direct relationship between the KBDI and soil moisture in the upper soil and duff layers. The authors of the KBDI wrote: "For forest fire control, a useful concept of drought is one which treats it as a continuous quantity which can be described in numerical terms. The values would range from zero (soil and duff saturated with water) up to some maximum value which corresponds to an absence of available moisture in the soil and duff. The upper part of the scale corresponds to those conditions for which many definitions of drought require that the dryness or moisture deficiency be abnormal or unusual" (Keetch and Byram 1968). Therefore, we fully employ this peculiarity of KBDI by using the upper frequency part of this scale in our analyses to select the days with abnormally dry soil conditions, i.e., the days particularly conducive to forest fire. Specifically, at each point for the entire period of record, we calculated KBDI and then estimated its distribution for the part of the year (season, month) when KBDI was above zero. We estimated its distribution for the reference period 1961-1990 (when a majority of stations have the data available). Upper percentiles of this distribution were defined at each station (upper 10^{th} percentile, upper 1^{st} percentile, etc). Then we calculated the number of days above these percentiles. No matter what the absolute values of KBDI actually are or whether forest fires do or do not actually occur in the region, we assume these days as potentially dangerous for forest fires (i.e., more conducive for fire). The count of these days was performed for each season and year and area averaged to present the time series of "regionally-averaged" conditions that are conducive to forest fire. In this approach, however, locations in swampy areas that would never be able to burn (at present climate conditions) are included in the analyses and participate in the area-averaging process as well as locations with dry soils that have a great chance to catch fire from natural and anthropogenic causes. For area-averaged characteristics based on all forest fire indices, we used the normalization procedure described above.

Therefore, in our analyses, all these indices were regionalized (normalized) by using the upper frequency part of their scale to select the days with abnormally dry conditions, i.e., the days conducive to forest fire. Specifically, for each index at each point and month, we estimated its distribution, defined upper percentiles of this distribution (e.g., upper 10^{th} percentile), and then calculated the number of days above these percentiles.

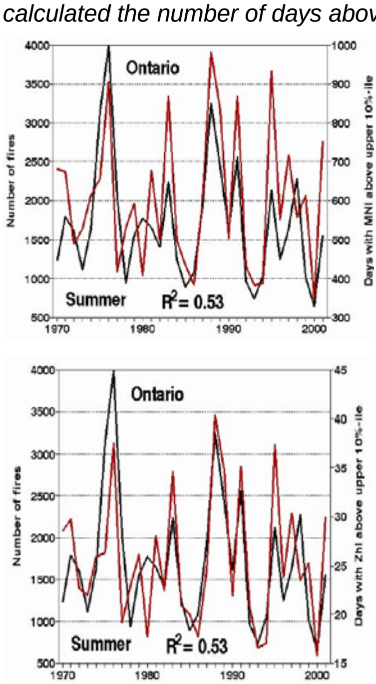

Figure 7. Comparison of Modified Nesterov (Top) and Zhdanko (Bottom) Indices with the count of forest fires over Ontario Province in Canada. Both indices were normalized (i.e., number of days with indices above the upper 10^{th} percentile were area-averaged over the province). Black lines: Number of fires in the province. Red lines: Days with high MNI and ZhI. R is the correlation coefficient.

3.4. Testing of different potential forest fire indices based on daily and synoptic data sets versus statistics of forest fire

3.4.1. Tests versus forest fire statistics. To test the performance of the forest fire indices that characterize the climatic component of the forest fire danger, we need to have reliable statistics of actual forest fires and information that most (or at least a stable fraction) of these fires are a result of "natural" origin. For several reasons, this is not the case for most of the former USSR (Georgiy Korovin, Director, Center for Problems of Forest Ecology and Productivity, Moscow, Russia, Personal Communication, 2005; Conard et al. 2002). It is also impossible to use forest fire statistics for the conterminous U.S. and Europe where forest management, fire suppression, and increasing anthropogenic influence substantially predetermine trends in forest and brush fire occurrences (cf., http://www.ncdc.noaa.gov/img/climate/research/2004/fire04/usminusalaska-wildlandfires-1960to2004.gif).

Therefore, we select the northern part of North America to assess the performance of our forest fire indices to characterize regionally averaged time series of actual forest fire occurrence and areas burned. The southern provinces of Canada were especially interesting, because in addition to several decades of forest fire statistics, we have there dense daily and synoptic networks (in GDCN and GSCN) for use. For Alaska,

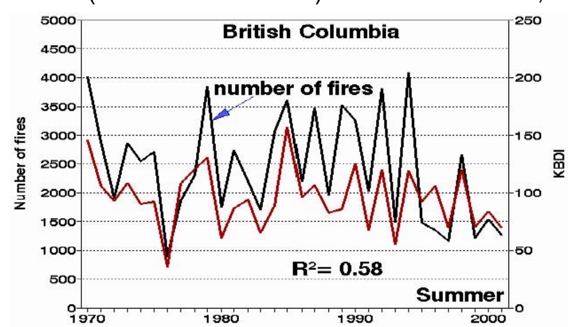

Figure 8. Time series of total annual forest fire counts in British Columbia and summer KBDI values. Decreasing tendencies in KBDI and forest fire counts over the province during the past 30 years indicate increasing humidity conditions and corroborate with similar KBDI changes in the northwestern part of the conterminous United States (Groisman et al. 2004) and a general increase in precipitation over British Columbia in the 20^{th} century (Stone et al. 2000). R is the correlation coefficient.

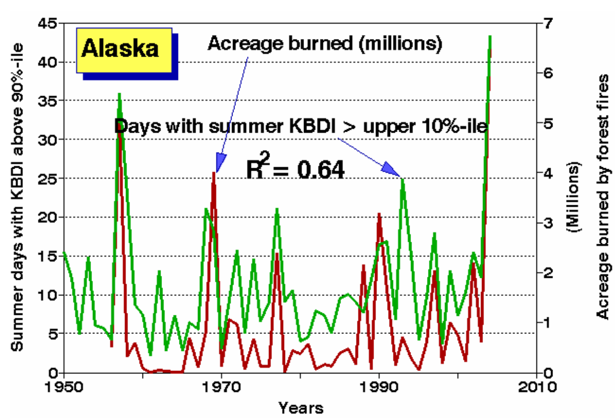

Figure 9. Frequency of high KBDI values in Alaska (dotted lines) versus actual areas burned by forest fires (solid lines). R is the correlation coefficient.

most of meteorological stations are located in the southern half of the State, and only daily data were ready for use at the time when this study was conducted. Therefore, for Canada we compared all forest fire indices among themselves and with forest fire statistics, while for Alaska only KBDI was tested against the statewide forest fire counts and areas burned. The pattern of the seasonal cycle of two types of indices, KBDI and those based on synoptic information, over Canada resembles that for Northern Eurasia. For example, in Canada as well as in Russia the atmospheric dryness (better described by the dew point deficit accumulated values, i.e., by NI, ZhI, MNI) occurs earlier than dryness associated with soil and duff moisture deficit associated with KBDI. Area averaged time series of NI, MNI, and ZhI are very close and moderately well correlated with statistics of actual forest fires (e.g., Figure 7). A similar level of association with statistics of forest fires in western North America is demonstrated by KBDI (Figures 8 and 9) where it reasonably well reproduces both interannual variability and trends (when the trends exist) of observed fire statistics.

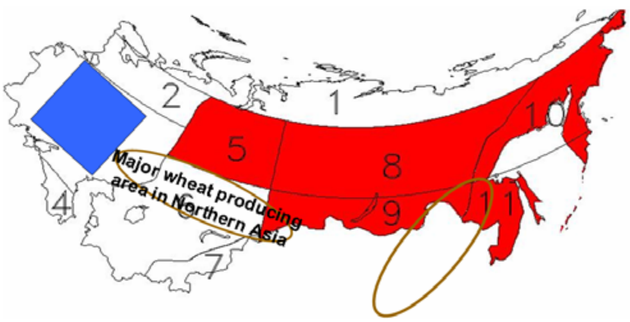

Figure 10. Five regions in Siberia where a potential forest fire danger increase in the 20th century was reported (red-colored; Groisman et al. 2003b), the regions where agricultural droughts have increased (brown ovals; Mescherskaya and Blazhevich 1997; Zhai et al. 2004), and the region where improved humidity conditions have been observed in the past 50 years (blue; Figure 11; Shiklomanov and Georgievsky 2003; Robock et al. 2005).

3.4.2. Test of conclusions based on different indices and/or data sets. Because, ZhI, NI, and MNI are very close, this test is presented only for MNI and KBDI for the former USSR territory. Both indices were normalized by selection of the number of days with indices above the upper 10th percentile and area-averaged over the regions shown in Figure 10.

Whatever trends were in place, an increase of wet conditions (as over the Great Russian Plain; Figure 11) or the progression of dry conditions (as over West Siberia and Russian Far East; Figure 12), normalized time series of various "fire" indices are reasonably well correlated and support conclusions about the regional tendencies of change in potential forest fire danger based on each of them. They also deliver similar conclusions about changes in potential forest fire danger whatever data source we used (e.g., Figure 13 where two different independently collected temperature data sets were used to calculate KBDI). *In summary, after normalization, all potential forest fire indices correlate reasonably well with actual regional statistics of forest fires and with each other*. Knowing this information, in the next Section we present only results based on KBDI.

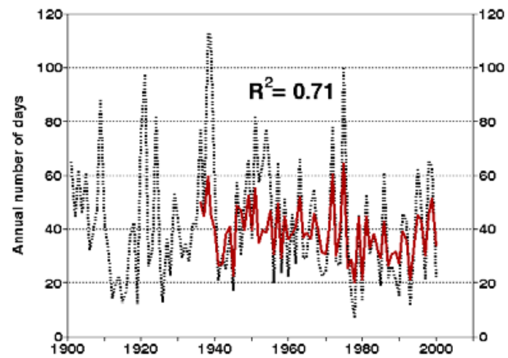

Figure 11. Number of days with KBDI (dotted black lines) and MNI (solid red lines) above the upper 10th percentile of their annual distribution area-averaged over the European part of the former USSR south of 60°N. R is the correlation coefficient. During the common period (1936-2000), both indices show statistically significant decreases in the annual frequency of dry days. Note: From 1992-2000 the regions of fUSSR outside of the Russian Federation were not as well represented in terms of station counts as had been in the past.

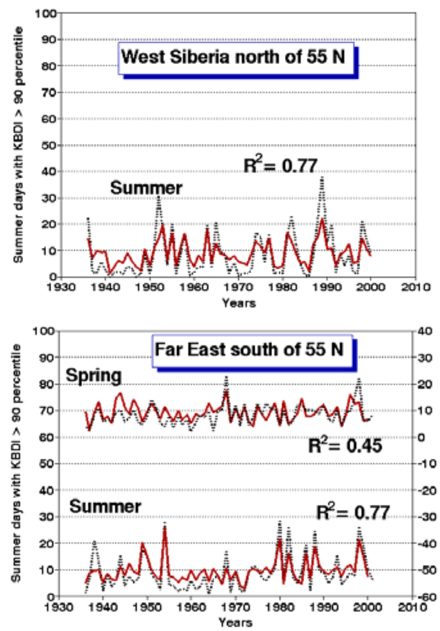

Figure 12. Number of days with KBDI (solid black lines) and MNI (dotted red lines) above the upper 10th percentile of their summer and spring distribution area-averaged over West Siberia north of 55°N and Russian Far East south of 55°N. R is the correlation coefficient.

4. POTENTIAL FOREST FIRE DANGER CHANGES OVER NORTHERN EURASIA

Our analysis did not reveal statistically significant changes in potential forest fire danger over northern Europe (Fennoscandia and northwestern Russia north of 60°N) during the past 50 years. Significant warming in these regions was mostly alleviated by an increase in precipitation (cf., Hanssen-Bauer and Førland 1994; Heino et al. 1999; Groisman et al. 2005a). We found some increase in spring KBDI outbreaks over Fennoscandia south of 64°N (Figure 14) that mostly can

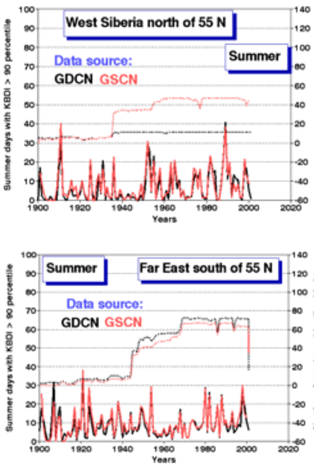

Figure 13. Comparison of summer KBDI estimates calculated using two different archives, GDCN and GSCN and area-averaged over the West Siberia north of 55°N and Russian Far East south of 55°N. Black lines represent calculations based on T_{max} from GDCN and red lines, estimates based on daytime temperatures from GSCN. In both cases, time series are closely correlated (R^2 = 0.86). Dotted lines show the annual number of 1°x1° gridcells with data availability.

be explained by strong spring warming (cf., Figure 2) and earlier snowmelt (cf. Figure 3). In this part of the world, spring is usually not a fire season and an increase in spring dryness indicated by KBDI here has not had a discernable (so far) impact on forest fires.

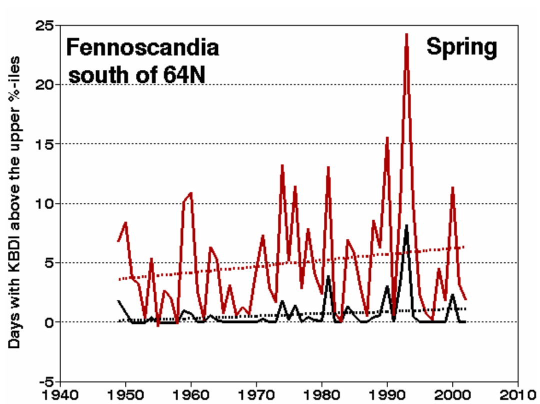

Figure 14. Number of days with KBDI above the upper 10th (red lines) and 1st (black lines) percentiles of their spring distribution area-averaged over southern Fennoscandia. Linear trends are shown by dotted lines. Only linear trend for the number of spring days with KBDI above the upper 1st percentile is statistically significant at the 0.10 level. During the 54-year-long period (1949-2002) the frequency of these days has increased more than threefold.

Over the European part of the fUSSR south of 60°N, we observe some increase in humidity conditions during the past 65 years (Figure 11; cf., also Shiklomanov and Georgievsky 2003; Robock et al. 2005; Groisman and Rankova 2001). East of the Ural Mountains, a tendency towards drier summer conditions prevails during the 20th century (Figures 12, 13, and 15).

Siberia is a region that is prone to forest fires (by some estimates: ~10^7 ha/yr are burned) but the KBDI is always below 200 (Figure 4, bottom panel). Most of Siberia is in the permafrost zone and, thus, has a shallow active soil layer. Low precipitation and rough terrain of Eastern Siberia (that assists runoff) leave soil above the permafrost relatively dry. Our pilot study (Groisman et al. 2003b) shows that over *all* of Siberia, the frequency of summer days with KBDI above the "non-zero" 90th percentile has increased during the past century (Figure 10). In Figures 12 and 15, and Table 3, we present our "final" estimates of changes of potential forest fire danger over the eastern part of Northern Eurasia during the past 65 years when (a) our data sets have the best spatial coverage and (b) we were able to verify and compare several indices with one another. The time series shown in these figures were evaluated three times. First, they were estimated using high-quality daily temperature and precipitation data of the long-term but sparse network of 223 stations of international exchange (Razuvaev et al. 1993). Secondly, we repeated our estimates using GDCN saturated for Siberian regions south of 55°N with additional daily data of approximately 200 Russian stations. Thirdly, we verified (confirmed) conclusions based on KBDI with computations of changes in MNI (e.g., Figures 12 and 13) and KDBI derived using an alternative source of daytime temperature information (e.g., Figure 13).

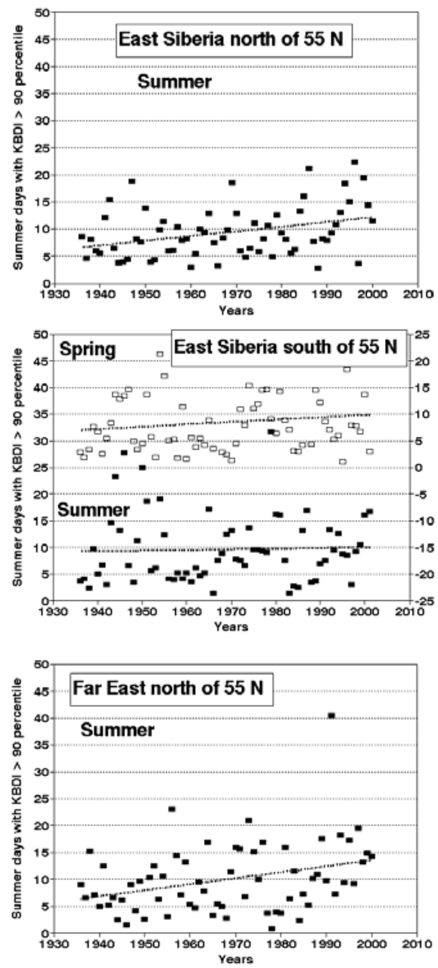

Figure 15. Number of days with KBDI above the upper 10th percentile of their summer (filled squares) and spring (open squares) distributions area-averaged over the residual three of five regions (red color coded in Figure 10). West Siberia and Far East south of 55°N are shown in Figures 12 and 13. Linear trends are shown by dotted lines.

Table 3 provides linear trend estimates for time series of summer and spring (for southern regions only) days above the upper 10th percentiles of seasonal KBDI values and estimates of their statistical significance using the two-tailed t-test. For one of the regions initially color-coded in red in Figure 10 (South of Eastern

Siberia), cross-validation and the use of more detailed data show no statistically significant summer dryness during the past 65 years (cf., Figure 15). It is worth noting that an earlier spring onset accompanied by a significant warming and an earlier snow cover retreat (Brown 2000; Groisman et al. 1994, 2003b) also cause an increasing KBDI in the spring season in southern parts of Siberia and the Russian Far East during the past 65 years (Table 3).

In addition to regional averaging, we also assessed patterns of individual (station-based) trends of potential forest fire danger over the eastern part of Northern Eurasia for the past 50 years (not shown). The assessment indicated that the areas of the strongest increase of KBDI and MNI are located in the Yenisey River Basin and surrounding areas of Western and Central Siberia. In the western Yakutia and Transbaikal area, the increase was less prominent and further eastward (including Far East Regions of Northern Eurasia) potential forest fire danger has increased again.

5. DISCUSSION

Global warming, which has been especially pronounced during recent decades in extratropical land areas and particularly in minimum temperatures (Karl et al. 1991; Folland and Karl 2001), is related to a reduction in spring snow cover extent (Brown 2000, Groisman et al. 1994, 2003b), and thus to an earlier onset of spring- and summer-like weather conditions (Easterling 2002). Warming also relates to a higher water vapor content in the atmosphere (Douville et al. 2002; Trenberth et al. 2003), which has been documented in many regions of the world (Sun et al. 2000; Ross and Elliott 2001). This in turn results in an increase in the frequency of *Cumulonimbus* clouds (documented for the former USSR and the contiguous United States by Sun et al. 2001), which is related to the general increase in convective and thunderstorm activity and an observed widespread increase in very heavy precipitation in the extratropics (Groisman et al. 2005a,b). During the past century, global temperature and particularly temperature in high latitudes has increased dramatically. This is associated with a retreat in spring snow cover, changes in the length of the growing season period and, therefore, an increase in the precipitation needed to be spent on evapotranspiration (if available). In high latitudes, most of the evapotranspiration occurs in a narrow interval of early summer. For example, according to Rauner (1972), up to half of the evapotranspiration in the forest-steppe zone of the European part of Russia and Western Siberia occurs in June-July. If the precipitation increase (which is also occurring in high latitudes during the past 50 years) does not match the "needs" of evapotranspiration, the summer dryness will increase and potential forest fire danger will also increase. It appears that this is the case for Alaska and Siberia south of the Arctic Circle (Groisman et al. 2005b). In Siberia, we do not observe a substantial increase in summer precipitation during the past 50 years (Gruza et al. 1999; Sun and Groisman 2000). Furthermore, a redistribution of precipitation (increase of heavy rainfall and decrease in days with precipitation) was found over the Asian part of Russia (Sun and Groisman 2000). Heavy rainfall (which is increasing in frequency in Siberia) usually comes in thunderstorms from *Cumulonimbus* clouds (Sun et al. 2001). The accompanying lightning produces an additional (and independent) factor that acts to increase the forest fire danger. This explains why, using meteorological information for the past century, *we found a significant (sometimes a twofold) increase in indices that characterize the weather conditions conducive to forest fires. The areas where this increase was statistically significant coincide with the areas of most significant warming during the past several decades in Alaska (Figure 9) and Siberia south of the Arctic Circle (Table 3).*

Two major agricultural regions in Northern Eurasia are Western Siberia and Northern Kazakhstan (summer wheat crop) and Northern China (rice crop). In both these regions humidity deficit is a critical factor that controls agricultural production and, if adverse drought conditions persist, may lead to desertification, soil erosion, and dust storms. Recent studies (Mestcherskaya and Blazhevich 1997; Zhai et al. 2004; and Dai et al. 2004) show the tendencies to more dry conditions over these regions. For example, Figure 16 presents an updated drought index time series for West Siberia and Northern Kazakhstan by Mescherskaya and Blazhevich (1997, bottom panel of their Figure 2). It clearly indicates that the century-long trend to drier conditions has continued through year 2004 in this region. Our findings corroborate with these results because various meteorological indices of potential forest fire danger and droughts are siblings. They all report drier soil and vegetation conditions.

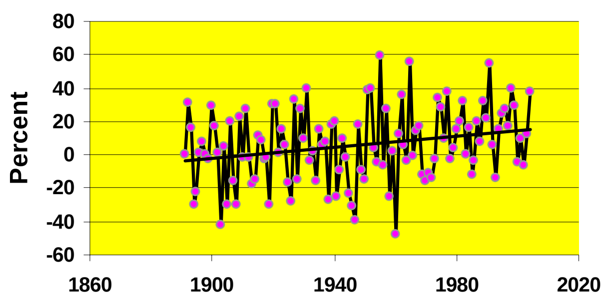

Figure 16. Early summer (MJJ) drought index over the major cereals-producing region of western Siberia and northern Kazakhstan (update of Mestcherskaya and Blazhevich 1997) and its linear trend for the 1881-2004 period. This index represents the area differences between unusually dry and unusually wet divisions of the region in percent for the period 1891-1995 and characterizes the spread of dry conditions over the region. The observed linear trend (16%/100yrs) is statistically significant at the 0.05 level.

6. CONCLUSIONS

Theoretical projections of increasing summer dryness in the interior of the continents as a result of the CO_2-induced global warming were first suggested 25 years ago (Manabe et al. 1981, 2004). Our findings show that during the past 65 years this scenario is upheld in dry regions of northern Eurasia (as well as in Alaska during the past 50 years despite a total precipitation increase). In these regions, changes in surface air temperature were especially important as they caused additional water "demand" for evaporation and transpiration. East of the Ural Mountains we observe:

- Up to two-digit (%) increases in temperature derivatives (e.g., the "warm season" duration and sum of temperatures above the phenologically-important thresholds of 5°C and 10°C, etc.) which suggest that evapotranspiration may increase;
- Earlier snowmelt and more frequent thaws which suggest that more cold season precipitation may go into runoff and become unavailable for vegetation in the warm season;
- A moderate (or none) increase in precipitation but a larger increase in thunderstorm activity (thus, lightning frequency may also be on ascent) which suggest that a larger fraction of warm season precipitation may also go into runoff;
- All the above factors do increase the possibility of drier summer conditions and their detrimental consequences for society: an increase in potential forest fire danger (that leads to more frequent forest fires) and an increase in the probability of the extremely dry weather conditions (droughts).

Thus, the tendency for "summer dryness" in Northern Eurasia is supported (in addition to the GCM's simulations) by observational evidence for more than a half of the continent from the Ural Mountains eastward (this study; Mescherskaya and Blazhevich 1997; Dai et al. 2004; Korovin and Zukkert 2003; Mokhov et al. 2003; Zhai et al. 1999, 2004). However, this tendency competes with other factors that drive contemporary climatic changes. Further studies are needed to ascertain whether this tendency continues to prevail throughout the continent (or its eastern part).

Scenarios of the possible future climatic change in Northern Eurasia indicate that the changes will be most prominent in this region. The superposition of these scenarios with the present characteristics of the potential forest fire danger in the Eastern half of Northern Eurasia, show that forest fires themselves may be an important feedback mechanism affecting both the rate and magnitude of the continental climatic changes. An unfortunate corollary is the need to reassess the existing scenarios of future climatic change in Northern Eurasia, that presently fail to account for the feedback between the biosphere and the atmosphere.

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Regions south of 66.7° N	Season	Frequency changes %/65yr	S (%)
European part of the fUSSR	Annual	-70	98
south of 55N	Spring	-50	90
West Siberia, north of 55° N	Summer	85	95
East Siberia, north of 55° N	Summer	60	99
Far East, north of 55° N	Summer	80	99
East Siberia, south of 55° N	Summer	-	-
	Spring	30	80
Far East, south of 55° N	Summer	50	90
	Spring	40	95

Table 3. Changes in mean regional frequency during the 1936-2000(2001) period when seasonal (summer or spring) KBDI exceeds the "non-zero" 90th percentile of its distribution for the reference period 1961-1990. Statistical significance (S) of all linear trend estimates was tested using the two-tailed t-test.