J9.1. CONTEMPORARY CLIMATE CHANGES IN HIGH LATITUDES OF THE NORTHERN HEMISPHERE CAUSE AN INCREASING POTENTIAL FOREST FIRE DANGER

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1. INTRODUCTION

Significant climatic changes over the high latitudes in the 20th century have been reflected in many atmospheric, oceanic, and terrestrial variables. 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. Fire is one of nature's primary carbon-cycling mechanisms but human activity interferes with 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 dangerous. 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 Central Alaska and in Siberia south of the Arctic Circle.

2. DATA

We performed our analysis using a subset of about 1500 stations north of 50ºN from the recently created Global Daily Climatology Network archive (GDCN, Gleason et al. 2002; Figure 1a). 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 the former USSR (fUSSR) and Canada were homogenized to account for changes in instrumentation and observational practice as described in Groisman and Rankova (2001) and NCDC (1998). Figure 1 (top) shows the GDCN stations with precipitation daily data. Generally, the number of stations with precipitation and temperature daily data is somewhat less than shown in Figure 1 for North America and Northern Europe. For the former Soviet Union, there is a tenfold discrepancy between the number of stations with precipitation and temperature initially available in the GDCN. During the pilot step of the study, we found a significant long-term signal of increasing potential forest 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 1b).

Figure 1. Top (a). Map of GDCN stations north of 50°N with more than 25 years of valid daily data. Bottom (b). Present coverage with temperature daily data in southern Siberia and Russian Far East after supplementary stations for the region south of 55°N were incorporated into the GDCN archive; 1-degree grid boxes are shown.

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

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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 (Condra 1944; Turner and Lawson 1978; Keetch and Byram 1968; Karl 1986). To characterize the level of potential fire danger, numerous indices have been suggested. Figure 2 shows one such index based on the humidity deficit, temperature, and information about the days with precipitation below 2.5 mm day^{-1} (Sherstyukov 2002). Specifically, this index of fire danger, G, is calculated according to the formula:

$$G = \Sigma\ (T\ d)$$

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 2.5 mm. Rainfall above 2.5 mm resets G to zero. Time series with the number of days with thusly defined G above two different thresholds are shown in Figure 2 for the Moscow region, Russia. Days with G below 300 are the days without substantial forest fire danger. Days with G above 1000 are characterized as days with high forest fire danger. The figure shows an increase in potential forest fire danger in the region during the past 40 years. Index G and several other indices require sub-daily meteorological information which is not easy to access on a century time scale. Therefore, we used a simplified index suggested by Keetch and Byram in the late 1960s.

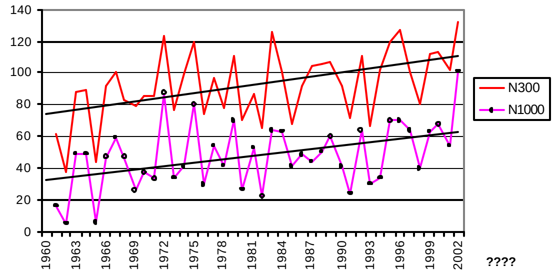

Figure 2. Interannual variability of the number of days with medium and above potential forest danger (G > 300) and high forest fire danger (G >1000) for the Moscow region (Sherstyukov 2002).

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

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 3, the KBDI index is presented for North American and North Eurasian (within the former USSR borders only) stations with daily temperature and precipitation available for the past fifty years. This is a climatology of the index for the month of July (the long-term mean values). Note a difference in the ranges of the index between high and mid-latitudinal stations.

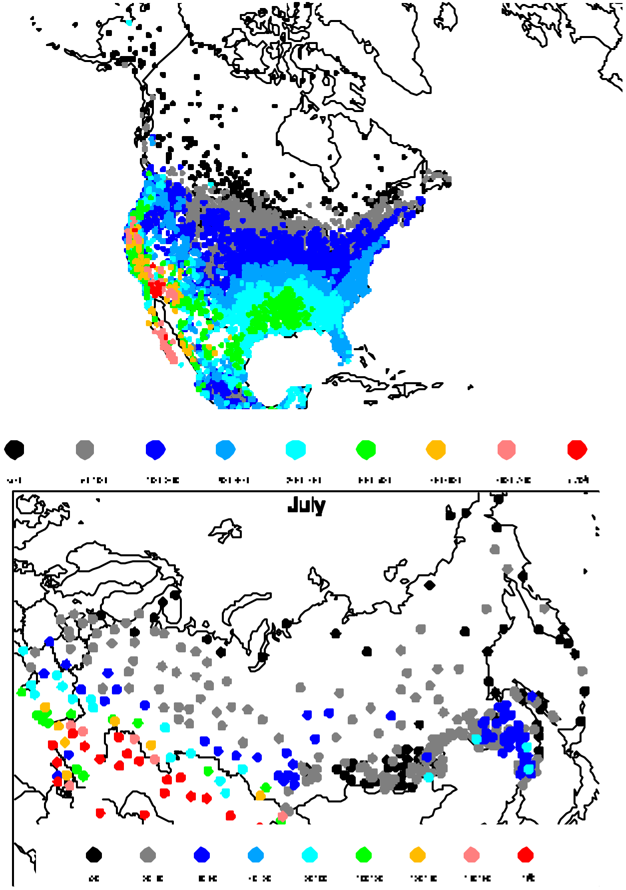

Figure 3. Climatology of July KBDI values for North America and Northern Eurasia. Note a different scale ranges used in these two plots.

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 (at least) of surface radiation balance (that can be associated with potential evapotranspiration) and precipitation (Figure 4).

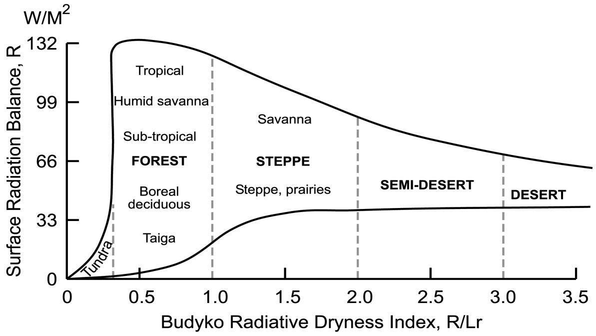

Figure 4. Geobotanical zones as a function of the surface radiation balance, R, and Budyko radiative dryness index (R/Lr). r is annual precipitation and L is specific latent heat of vaporization [Budyko 1971].

In regionalizing the KBDI, we did not change the calculation scheme but instead, we abandoned a direct relationship between the index and soil moisture in the upper soil and duff layers. The authors of the index 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 does correspond 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 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 percentile, upper 1 percentile, etc). Then we calculated the number of days above these percentiles. Keep in mind that, whatever 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., 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. We used fixed thresholds (e.g., 200, 300, and 400) for narrowly defined small regions where we can expect the KBDI variations to be relatively small.

4. TIME SERIES OF DAYS WITH KBDI ABOVE SELECTED THRESHOLDS

4.1. Central Alaska (between 62ºN and 66.7ºN) and Canada north of 55 N

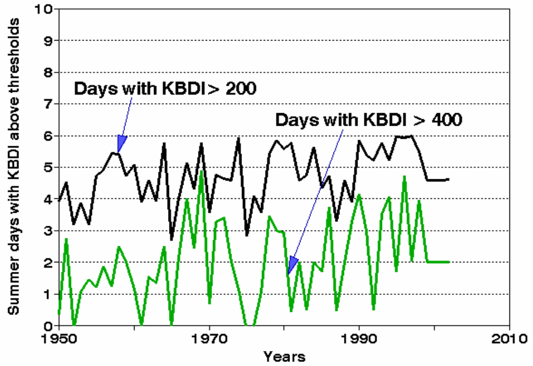

Figure 5. Frequency of summer days with KBDI above 200 and 400 in Central Alaska.

Only 52 years having a relatively dense station network are available for North America north of 55°N and south of the polar circle. Furthermore, when analyzing Alaskan data, we removed from consideration the very humid southernmost part of the state south of 62°N. After this removal a regional count of the number of days with high daily KBDI values above the fixed thresholds of 200 and 400 (shown in Figure 5) revealed an increasing trend of 22% to 70% per 50 years, respectively.

In northern Canada, we observed “some” increase in the number of days with high KBDI values, but high variability (compared to the signal strength) made the trend estimates statistically insignificant (cf., Figure 6).

4.2. Siberia south of the polar circle

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 3). 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. Figure 7 shows that over the entire Siberia study area, frequency of the summer days with KBDI above the “non-zero” 90th percentile has increased during the past century in the range of 70% to 115% (Table 1). It is worth

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[**] Area-averaging 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 gridcells. 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. This approach does not pretend 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.

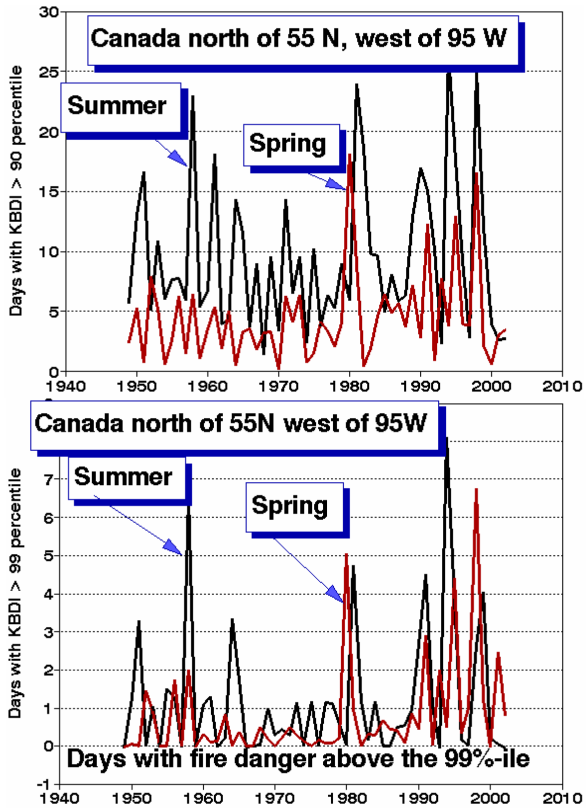


Figure 6. Changes in the frequency of high KBDI values in western Canada north of 55ºN (1949-2002). Number of summer and spring days with daily KBDI values above the upper 10 and 1 percentiles of its seasonal distribution.

noting that earlier spring onset accompanied by a significant warming and an earlier snow cover retreat (Groisman et al. 1994, 2001; Brown 2000) also cause an increasing KBDI in the spring season, especially in southern parts of Siberia and Russian Far East during the past two decades.

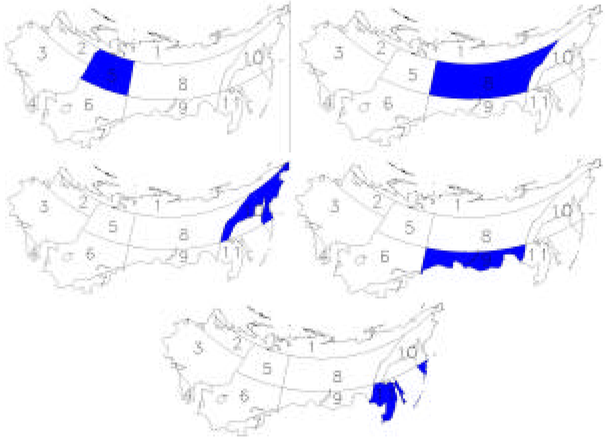
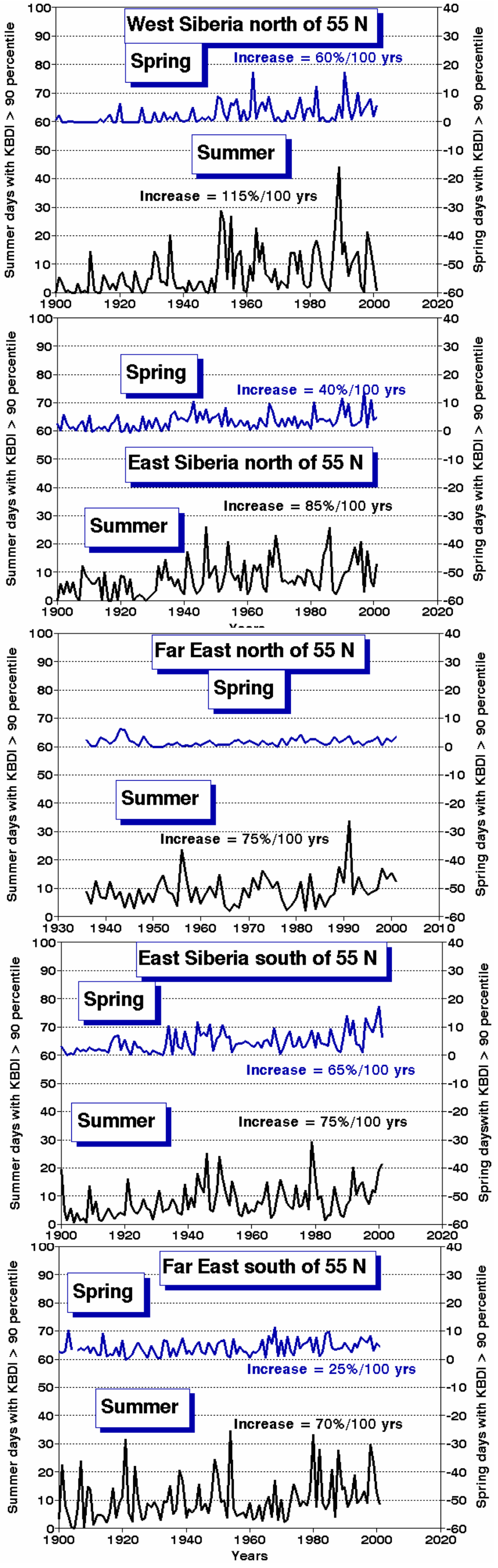


Figure 7. Top. 5-region partition of Siberia and the Russian Far East used in this analysis. Right. Time series of the number of summer and spring days with daily KBDI values above the upper 10 percentile of its seasonal distribution.



5. SUPPLEMENTARY SUPPORTING INFORMATION

During the past century, temperature in high latitudes has increased dramatically (IPCC 2001, Lugina et al. 2001; Figures 8 and 9). This is associated with a retreat in spring snow cover extent (Figure 10), changes in the length of growing season period (Groisman et al. 2003) 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 a 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 central Alaska and most of Siberia. 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*

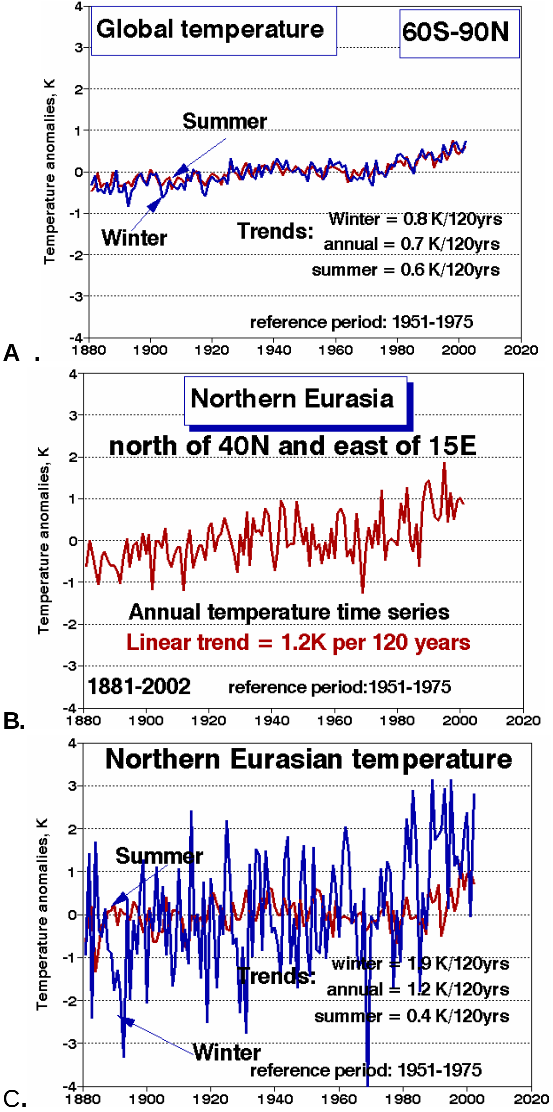


Figure 8. Global and North Eurasian surface air temperature changes during the past 120 years. (a) global (for zone from 60ºS to 90ºN); and regional surface air temperature area-averaged over Northern Eurasia: (b) annual and (c) seasonal time series. [Data source: CDIAC; Archive of work of Lugina et al. 2001; updated].

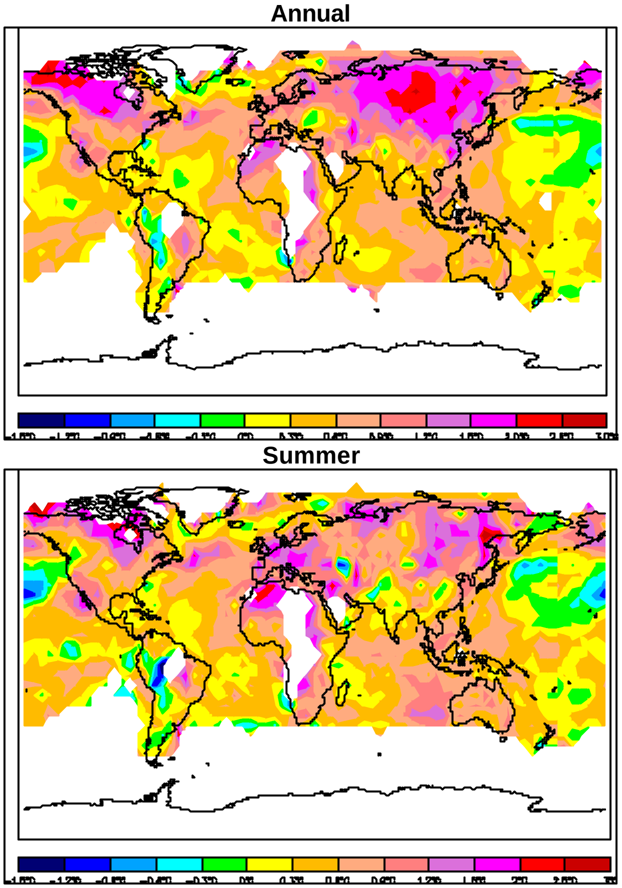


Figure 9. Mean Temperature Change 1965 to 2002 over the globe. Data source: (Jones and Moberg 2003). Processed by the U.S. NCDC Global Climate at the Glance Mapping System.

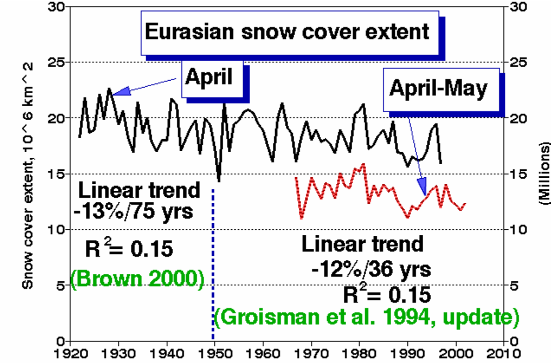


Figure 10. Eurasian snow cover extent in late spring (April, April-May) according to reconstruction by Brown (2000) and satellite visual imagery (Robinson et al. 1993; Groisman et al. 1994, updated).

clouds (Sun et al. 2001). The accompanying lightning produces an additional (and independent) factor that acts to increase the forest fire danger.

6. CONCLUSIONS

Our analysis indicates that the frequency of unusually dry summer and spring conditions (days with anomalously high KBDI values) has increased in Siberia and Alaska during the past century (50 years in Alaska). These changes, when overlapping with anthropogenic factors (such as reckless behavior in the forest, logging, and agricultural burning), have already aggravated the negative consequences of forest fires and (if continued) may be devastating in the future.

7. REFERENCES

Brown, R.D., 2000: Northern Hemisphere snow cover variability and change, 1915-1997, *J. Climate*, **13**, 2339-2355.

Budyko, M.I., 1971: *The Climate and Li*fe, Gidrometeoizdat, 470 pp. (in Russian; English translation: 1974, Academic Press, 508 pp.)

Condra, G.E., 1944: Drought: Its effect and measures of control in Nebraska. Nebraska Conservation Bulletin No. 25, Univ. of Nebraska, Conservation and Survey Div., Lincoln, Nebraska.

Gleason, B. E., T.C. Peterson, P.Ya. Groisman, D.R. Easterling, R.S. Vose, and D.S. Ezell, 2002: A new global daily temperature and precipitation data set. Presented at the 13th AMS Symposium On Global Change Studies, Orlando, FL, 13-17 January, 2002.

Groisman, P.Ya. and E. Ya. Rankova, 2001: Precipitation trends over the Russian permafrost-free zone: removing the artifacts of pre-processing. *Internat. J. Climatol.,* **21**, 657-678.

Groisman, P. Ya., T.R. Karl and T.W. Knight, 1994: Observed impact of snow cover on the heat balance and the rise of continental spring temperatures, *Science*, **263**, 198-200.

Groisman, P.Ya. R.W. Knight , and T.R. Karl, 2001: Heavy precipitation and high streamflow in the contiguous United States: Trends in the 20th century. *Bull. Amer. Meteorol. Soc*., **82**, 219-246.

Groisman, P.Ya. and 9 others, 2003: Contemporary climate changes in high latitudes of the Northern Hemisphere: Daily time resolution. CD ROM of papers presented at the 14th AMS Symposium on Global Change and Climate Variations, Long Beach, California (9-13 February, 2003).

Gruza, G.V., Rankova, E.Ya., Razuvaev, V.N. and Bulygina,O.A. 1999: Indicators of climatic change for the Russian Federation. *Climatic Change*, **42**, 219-242.

IPCC, 2001: *Climate Change 2001: The Scientific Basis. Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change* [Houghton, J. T., Y. Ding, D. J. Griggs, M. Noguer, P. J. van der Linden, X. Dai, K. Maskell, and C. A. Johnson (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 881 pp.

Jones, P.D. and Moberg, A. 2003: Hemispheric and large-scale surface air temperature variations: An extensive revision and an update to 2001. *J. Climate,* **16**, 206-223.

Karl, T.R., 1986: The sensitivity of the Palmer Drought Severity Index and Palmer's Z-Index to their calibration coefficients including potential evapotranspiration. *J. Climate Appl. Meteor*., **25**, 77-86.

Keetch, J.J. and G.M. Byram, 1968: A drought index for forest fire control. U.S.D.A. Forest Service Research Paper SE-38. 35 pp. [Available from: http://www.srs.fs.fed.us/pubs/]

Lugina, K.M. P.Ya. Groisman, K.Ya. Vinnikov, V.V. Koknaeva, and N.A. Speranskaya, 2001: Monthly surface air temperature time series area-averaged over the 30-degree latitudinal belts of the globe, 1881-1999. In Trends: A Compendium of Data on Global Change. Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory, U.S. Department of Energy, Oak Ridge, Tenn., USA.

National Climatic Data Center (NCDC), 1998: Data Documentation For Archive TD-9816, Canadian Monthly Precipitation, November 18, 1998. 21 pp. [Available from http://lwf.ncdc.noaa.gov/oa/ncdc.html].

Rauner, Yu.L., 1972:Heat Balance of the plant Cover. Gidrometeoizdat, Leningrad, 210 pp. (in Russian).

Robinson, David A., Dewey, Kenneth F., Heim, Richard R. 1993: Global Snow Cover Monitoring: An Update. *Bull. Amer.Meteorol. Soc.,* **74**, 1689–1696.

Sherstyukov, B.G., 2002: Index of forest fire. Yearbook of weather, climate and ecology of Moscow. Issue 1 for Year 2000. Moscow Moscow State Univ. Publ., 83-84.

Sun B. and P. Ya. Groisman, 2000: Cloudiness variations over the former Soviet Union. *Internat. J. Climatol.,* **20**, 1097-1111.

Sun, B., Groisman, P.Ya., and I. I. Mokhov, 2001: Recent changes in cloud type frequency and inferred increases in convection over the United States and the former USSR. *J. Climate*,**14**, 1864-1880.

Turner, J.A.; Lawson, B.D. 1978. Weather in the Canadian Forest Fire Danger Rating System. A user guide to national standards and practices. Environment Canada, Pacific Forest Research Centre, Victoria, BC. BC-X-177.

Vincent, L.A., and D. W. Gullett, 1999: Canadian historical and homogeneous temperature datasets for climate change analyses. *Int. J. Climatol*., **19**, 1375-1388.

Table 1. Increase in mean regional frequency when summer KBDI exceeds the "non-zero" 90th percentile of its distribution during the reference period 1961-1990. All linear trend estimates are statistically significant at the 0.05 or above levels. Asterisk (*) marks a different period for which trend has been estimated.

Regions south of 66.7° N	Period assessed	Frequency changes, %/100yr
West Siberia, north of 55° N	1900-2001	115
East Siberia, north of 55° N	1900-2001	85
Far East, north of 55° N	1936-2001	75*
East Siberia, south of 55° N	1900-2001	75
Far East, south of 55° N	1900-2001	70