Boreal forest fires burn less intensely in Russia than in North America

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[1] Around 5–20 million hectares of boreal forest burns annually, mainly in Russia and North America. However, there are reports of significant differences in predominant fire type between these regions, which may have major implications for overall emissions of carbon, gases and aerosols. We examine boreal forest fire intensities via MODIS observations of fire radiative energy release rate. Results support the contention of a consistent difference in fire intensity and mean fuel consumption in Russia and North America, due to differences in dominant fire type. North American fires have higher mean intensities, increasing in proportion to percentage tree cover, characteristics indicating likely crown fire dominance. Russian fires have lower mean intensities, independent of percentage tree cover, characteristics more indicative of surface fire activity. Per unit area burnt, the results suggest Russian fires may burn less fuel and emit fewer products to the atmosphere than do those in North America. *INDEX TERMS:* 1615 Global Change: Biogeochemical processes (4805); 1640 Global Change: Remote sensing; 1694 Global Change: Instruments and techniques; 0315 Atmospheric Composition and Structure: Biosphere/atmosphere interactions. **Citation:** Wooster, M. J., and Y. H. Zhang (2004), Boreal forest fires burn less intensely in Russia than in North America, *Geophys. Res. Lett.*, *31*, L20505, doi:10.1029/2004GL020805.

1. Introduction

[2] The Boreal forests (45–65°N) are key areas of current net terrestrial carbon sequestration, containing perhaps 25% of all terrestrially stored carbon [*Beerling*, 1999]. Around two thirds of Earth's closed boreal forest lies within the 17 million km^2 of the Russian Federation, with the majority of the rest in Canada and Alaska combined. Forest fires burn maybe 5–20 million hectares annually, and the annual area burned in Russian forests is many times that in North America [*Kasischke and Bruhwiler*, 2003; *Zhang et al.*, 2003]. Increases in boreal fire frequency and size are expected due to high latitude climate warming, and the boreal zone may ultimately become a net carbon source [*Stocks et al.*, 1998]. Boreal carbon budget studies are therefore a key element of global change research.

[3] An important point is the suggestion of a key difference in predominant fire type between Russian and North America boreal forests [e.g., *Kasischke et al.*, 1999; *Harden et al.*, 2000]. Russian fires are said to be largely lower intensity fires burning mainly surface fuels [*Furyaev*, 1996; *Conard and Ivanova*, 1997; *Lesresurs*, 1999], whereas in North America much higher intensity 'crown' fires predominate, these burning into the tree canopy [*Conny and Slater*, 2002]. Though essentially unproven, any such difference would have important implications since crown fires typically burn many times the fuel per unit area than do surface fires [*Kasischke et al.*, 1999]. This hypothesized difference is to some extent already reflected in boreal fire modeling efforts, where some models assume lower per-unit area fuel consumption in Russia than in North America [e.g., *Conard et al.*, 2002; *Kasischke and Bruhwiler*, 2003; *Zhang et al.*, 2003]. However, such parameterizations are based on limited pre- and post-fire field sampling, and their wider applicability remains uncertain. This limits current attempts at quantifying boreal zone carbon fluxes, and a method for assessing fire intensity (in terms of the rate of energy released by fires) and/or severity (in terms of the amount of fuel consumed) is considered key to reducing model uncertainty [*Global Terrestrial Observing Systems* (*GTOS*), 2000; *Kasischke and Bruhwiler*, 2003; *French et al.*, 2004].

[4] For the first time, new remote sensing data allows us to test for a systematic fire intensity difference between Russian and North American boreal forest fires using observations of the rate at which energy is radiated during combustion. These data are derived from infrared measurements made by the Moderate Resolution Imaging Spectroradiometer (MODIS) onboard the EOS-Terra and EOS-Aqua satellites.

2. Fire Radiative Power From MODIS

[5] MODIS builds on the fire detection and characterization capabilities of the long-standing Advanced Very High Resolution Radiometer (AVHRR) by (i) allowing unsaturated observations of even very large/hot fires via use of a dedicated middle infrared (MIR) 'fire' channel having a large dynamic range, and (ii) having this MIR channel centered at 3.9 μm, where the (unwanted) influence of solar-reflected radiation is half that in the AVHRR 3.7 μm channel and where atmospheric transmission is less variable [*Kaufman et al.*, 2003]. For most terrestrial regions, each MODIS instrument observes fires down to 100–500 m^2 in area (assuming flaming temperatures of 1000–800 K, respectively) twice per day at fixed local solar times.

[6] Fires radiate energy over a wide spectral range, and the rate of fire radiative energy (FRE) output relates directly to the rate at which chemical energy in the fuel is released and gas and aerosol emissions produced [*Kaufman et al.*, 1996]. Here we term this 'rate of FRE release' Fire Radiative Power (FRP, Joules per second or Watts), leaving Fire Radiative Energy (FRE, Joules) to correspond to temporal integration of FRP over the fire lifetime. *Kaufman et al.* [1996] developed an empirical non-linear relationship between the MODIS MIR channel brightness temperatures at an active fire pixel, and the fire FRP over all wavelengths.

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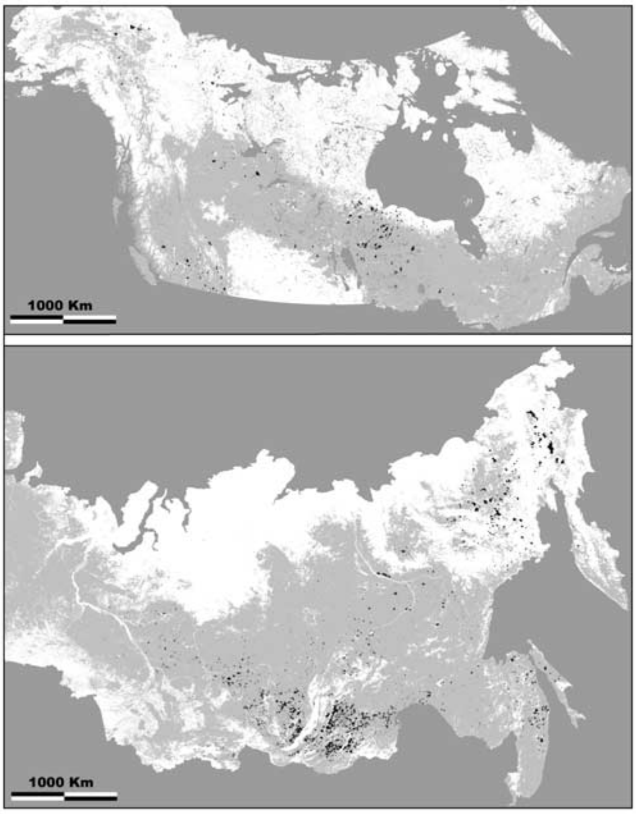

Figure 1. MODIS Terra and Aqua active fire detections (black) in the North American (45° to 70°N, 50 to 165°W) and Russian Siberia/Far East regions (45° to 70°N, 60 to 180°E) for June, July and August 2003, superimposed on forest cover (light gray). Far western (European) Russia is excluded as less than 5% of the 2001 Russian burned area noted by *Zhang et al.* [2003] occurred in this area, and the same pattern was confirmed for 1998 and 2002 during the current work. Active fire pixel locations are delineated as 3 × 3 pixel spots to aid clarity.

Wooster [2002] used small-scale experiments to show that FRE is indeed linearly related to the amount of fuel consumed, and *Wooster et al.* [2003] introduced an alternative linear method of FRP retrieval, based on MIR radiances. There is good agreement between the two alternative FRP retrieval methods, and they compare well to independent observations [*Wooster et al.*, 2003]. MODIS FRP data can therefore be taken as an indication of fire intensity at the time of observation, and are a key parameter in the MODIS fire product suite [*Kaufman et al.*, 2003].

3. Methodology and Results

[7] To test for systematic differences in fire intensity we used MODIS FRP data of June to August 2002 and 2003 collected over the Russian and North American boreal zones, when many thousands of MODIS fire pixel detections are made in both regions. Though *Kasischke et al.* [2003] highlight problems such as cloud obscuration when using certain active fire products to directly quantify emissions, such effects are common across the boreal zone and do not unduly hinder our fire intensity comparisons. FRP data of 2002 are available from EOS-Terra (~10:30 am/pm local equator crossing time), whereas the 2003 data are available from EOS-Terra and Aqua (~10:30 and 1:30 am/pm local equator crossing time respectively). Figure 1 shows the fire pixel distribution for 2003, with forests identified using the USGS Global Land Cover Database with the USGS Land Use and Land Cover Classification Legend [*Brown et al.*, 1999] (http://edcdaac.usgs.gov/glcc/glcc.html). Total numbers of fire pixel detections in forest cover types are reported in the caption of Figure 2.

[8] The available Forest fire FRP data from each MODIS instrument for each year were binned into 50 MW classes and the frequency-magnitude relationships examined. *Malamud et al.* [1998], *Zhang et al.* [2003], and others have shown that the frequency vs. burned area distributions of forest fires are well fitted by power-laws (i.e., are linear on a log-log plot) and Figure 2 indicates this is also true of FRP. However, a consistent difference is apparent between North American and Russian fires in each year, specifically that the relative frequency of the lowest FRP class (≤50 MW, arrowed in figure) is higher for Russian than for North American fires, whereas the relative frequency of the higher FRP classes (i.e., all classes greater than 50 MW) is higher for North American than for Russian fires. The same relationship is seen in the 2003 EOS-Terra data (not shown). Thus fires in the Russian boreal forest appear biased towards lower intensities compared to those in North America.

[9] Since reduced tree cover provides less crown fuel per unit area, such fire intensity differences might be explained by systematic variations in tree density between the two

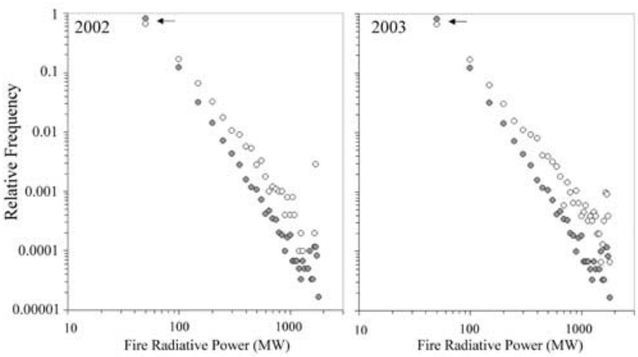

Figure 2. MODIS-derived fire radiative power comparisons for North American (open circles) and Russian (closed circles) boreal forest fires in 2002 (Terra) and 2003 (Aqua). Raw FRP data have been binned into 50 MW categories and frequencies are expressed relative to the total number of fire pixels in each region. The lowest FRP class (≤50 MW), the only one where Russian FRP plots at a higher relative frequency than North American FRP, is arrowed. Fire pixel counts for 2002/2003 are Russia (48,106/41,485) and North America (10,096/11,992) respectively. Departures from the generally linear trend on this log-log plot at the highest FRP are due to MODIS MIR 'fire' channel saturation over the very few fires observed at these extreme power outputs (>1650 MW). Assuming flaming temperatures of 1000–800 K, the active fires must be larger than 30,000–70,000 square meters to provide a saturated (500 K) signature in the MODIS 3.9 μm channel.

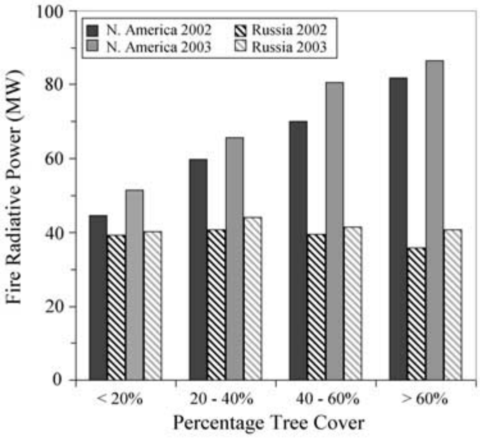

Figure 3. Mean fire radiative power stratified by % tree cover for boreal zone fires in 2002 and 2003. Results calculated from EOS-Terra observations of 54,618/13,837 fire pixels in Russia/North America respectively during 2002, and Eos-Aqua observations of 60,346/16,062 fire pixels in Russia/North America respectively during 2003. Percentage tree cover is taken from the MODIS Vegetation Continuous Fields products [*Hansen et al.*, 2003]. In each class, 2003 mean FRP is higher than 2002 by between 3 and 15%, perhaps because MODIS-Aqua observes closer to the peak time of the diurnally varying fire intensity.

boreal regions. Thus the FRP data of Figure 2 were stratified with respect to percentage tree cover, with the analysis including all boreal fire pixel detections and not just those in forests (fires in non-forest classes are confined to the lowest % tree cover class). Results (Figure 3) indicate that within each % tree cover class, mean FRP in Russia is systematically lower than in North America. Furthermore, mean FRP increases with % tree cover in North America, as would be expected if crown fires dominate, whereas no such increase is seen in Russia, which is suggestive of dominant surface fire activity where standing trees burn far less frequently.

4. Conclusions

[10] Using MODIS observations of fire radiative power, significant differences in boreal forest fire intensity are identified between Russia and North America, supporting the previously unproven contention of a consistent difference in mean fuel consumption rate due to systematic differences in dominant fire type. The area of boreal forest burned annually in Russia is many times that in North America, and the fire pixel count much greater. However, the significant fire intensity differences found here suggest that differences in direct pyrogenic carbon, gas and aerosol emission between the two regions are likely to be less significant than might be assumed when considering only active fire counts and/or burned area.

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