The Canadian Smoke Newsletter

Fall 2009

"Connecting diverse terrestrial, emissions, air quality and modelling communities."

Welcome to the Fall 2009 issue of ***The Canadian Smoke Newsletter***. I want to sincerely thank the contributors who made this issue possible. They have done a lot of hard work and the results show it. I invite all readers to consider contributing articles of their own for the benefit of the wider community.

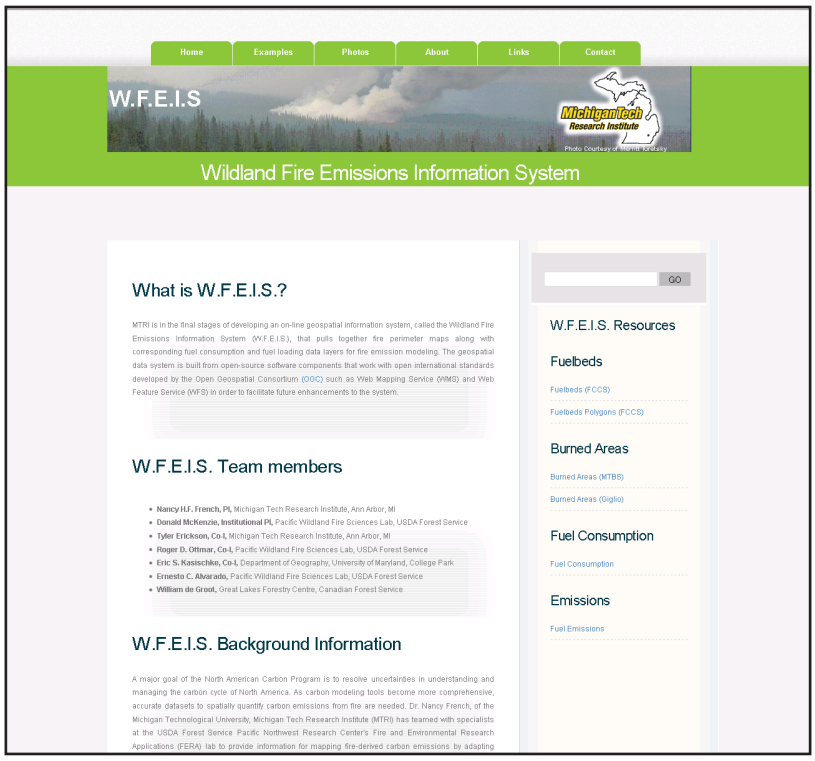
Prospective attendees and presenters have a number of interesting conferences to consider for 2010. Among them:

- Towards an Integrated Wildland Fire Management - Outcomes of the European Project "Fire Paradox", Freiburg, Germany, 23-26 February
- 2nd Human Dimensions of Wildland Fire Conference, San Antonio, Texas, USA, 26-29 April
- European Geosciences Union (EGU) General Assembly, ACV, Vienna, Austria, 2-7 May
- 2nd International Conference on Modelling, Monitoring and Management of Forest Fires, Kos, Greece, 23-25 June
- 11th Science Conference of the International Global Atmosphere Chemistry (IGAC) Project, Halifax, Nova Scotia, Canada, 11-16 July
- AMS 29th Conference on Agricultural and Forest Meteorology, Keystone, Colorado, USA, 2-6 August
- Wildland Fire Canada Conference, Kitchener/ Waterloo, Ontario, Canada, 5-7 October
- 3rd Fire Behaviour and Fuels Conference, Spokane, Washington, USA, 25-29 October
- 6th International Conference on Forest Fire Research, Coimbra, Portugal, 15-18 November
- American Geophysical Union (AGU) Fall Meeting, San Francisco, California, USA, 13-17 December

All the best for 2010.

Al Pankratz

Disclaimer: This informal newsletter is produced by the Air Quality section of Prairie and Northern region of Environment Canada on behalf of the smoke community. It does not represent the policies of Environment Canada.



Screenshot of the Wildland Fire Emissions Information System. The system is under development by a team at Michigan Tech Research Institute led by Nancy HF French.

In this issue:

Note: The article entitled "Air Quality Sampling during 2003 Prescribed Burns in Banff National Park; Part 2" originally slated for this issue will appear in the Spring 2010 issue. We apologise for any inconvenience.

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Quantifying wildfire emissions across North America with the Wildland Fire Emissions Information System

by Nancy HF French, Senior Scientist, Michigan Tech Research Institute, Ann Arbor, Michigan

How far does smoke from wildfires travel? Researchers in Canada and the US are working to understand wildfire emissions to better help with this question and understand how fire emissions influence the atmosphere. As part of the North American Carbon Program (NACP), the US National Aeronautics and Space Administration (NASA) has funded a project to develop information on fire emissions across North America. The information will be available through a user-friendly web-based system called the Wildland Fire Emissions Information System (WFEIS; see screenshot on page 1, this issue). Research by the late Dr. Richard Honrath and his team at the Michigan Technological University have shown from their measurements at a station on the Azores, an island chain in the Mid-Atlantic, that smoke is distributed around the globe (Figure 1). During the summer fire season in the boreal forests of Canada, Alaska, and Siberia, the Michigan Tech team has recorded high levels of carbon monoxide (CO) at the station, and has shown they originate from these extensive fires [Honrath et al., 2004].

In fact the question being asked is not where the smoke is from – that can be modelled using backward trajectories of dispersion models – but what quantities of CO and other critical atmospheric gases are actually emitted during these fires. Of interest to the NACP is quantification of total carbon emitted during wildland fire for carbon accounting purposes. This is where the work of the author, a member of the Michigan Tech Research Institute, a research center of Michigan Tech University based in Ann Arbor, comes in. Along with co-investigators at the US Forest Service and the University of Maryland as well as research partners at the Canadian Forest Service, the author is developing estimates of the amount of emissions produced during wildland fire burning. This NASA-sponsored program is designed to take the results of years of work by the project team on variables that drive emissions, and make this information available to interested parties via a new web-based system called the Wildland Fire Emissions Information System (WFEIS). Potential users of WFEIS include atmospheric scientists, who want to know the precise location of fires and level of emissions in order to better track where the emissions are going and how they interact in the atmosphere. Others include researchers

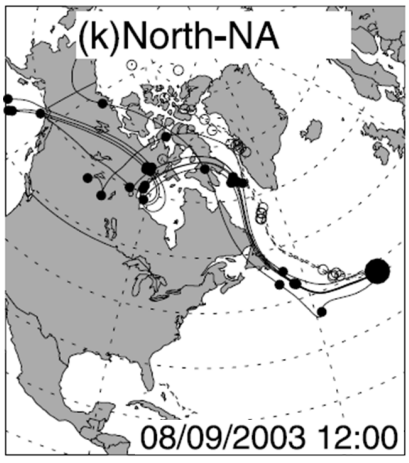

Figure 1. Typical backward trajectories (solid lines) showing the path of CO measured at the Azores station (black circle). This figure shows that atmospheric CO measured on Aug 9th, 2003 originated in fires across the boreal region of North America and possibly Russia. Copied from Figure 4k in Honrath et al. (2004).

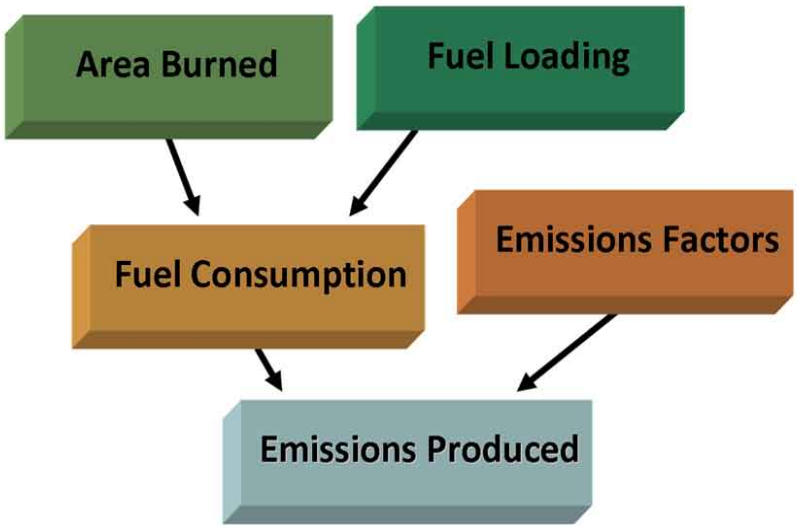

Figure 2. Four elements needed to estimate fire emissions.

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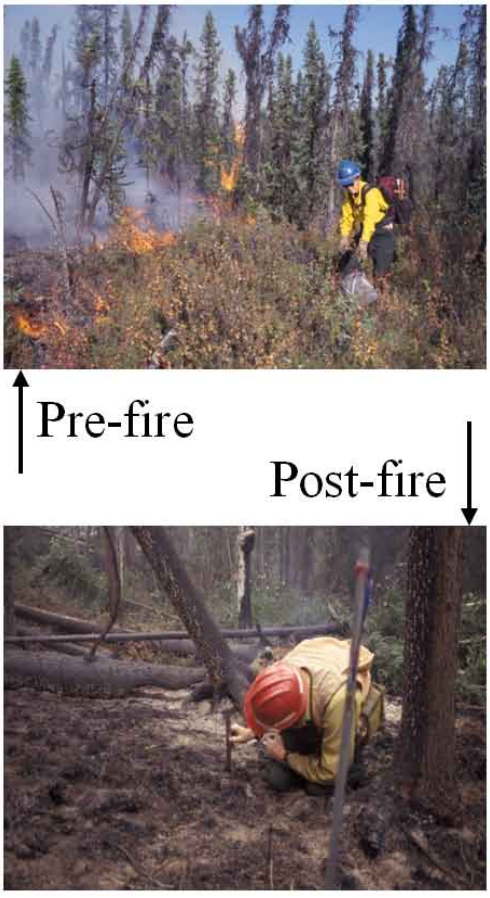
quantifying sources, sinks, and rates of carbon exchange throughout the earth system. An improved understanding of the natural sources of carbon to the atmosphere, such as fire, augments our accounting of carbon coming from industrial sectors (cars, smokestacks, etc). A third set of users comprises federal and local governmental groups who need to quantify emissions to better track air quality concerns and help mitigate the adverse health impacts of wildfire.

So, how can fire emissions be quantified? The answer lies in the extensive work carried out by US and Canadian forest service personnel along with university researchers, who have gone into the field to examine the effects of fire. To estimate emissions, four pieces of information are needed (Figure 2, previous page). For fuels and consumption, the most uncertain of the factors, some answers have been found through experimental burning, and others at sites burned in wildfire. Relationships between the forest type, condition of the fuels, and moisture conditions have been developed as a result of these field campaigns to determine under what conditions fires give off certain levels of carbon-based gas such as CO_2, CO, and hydrocarbons including methane (Figure 3). By measuring the material at the site before a fire and then quantifying post-fire material (what is left behind), the amount of biomass that is converted to smoke can be estimated. Although this sounds easy, it can be difficult to be at a place just before burning – to measure the various factors that influence level of burning – and then return to see the effects, especially for wildfires. Nevertheless this is done, along with other "forensic"-style methods, to obtain answers for a range of North American vegetation types [Kasischke and Johnstone, 2005; Ottmar et al., 2006; Ottmar and Baker, 2007; de Groot et al., 2009]. Once these relationships are obtained, they can be used to predict emissions for specific forest types under a variety of fuel moisture conditions. In some cases,



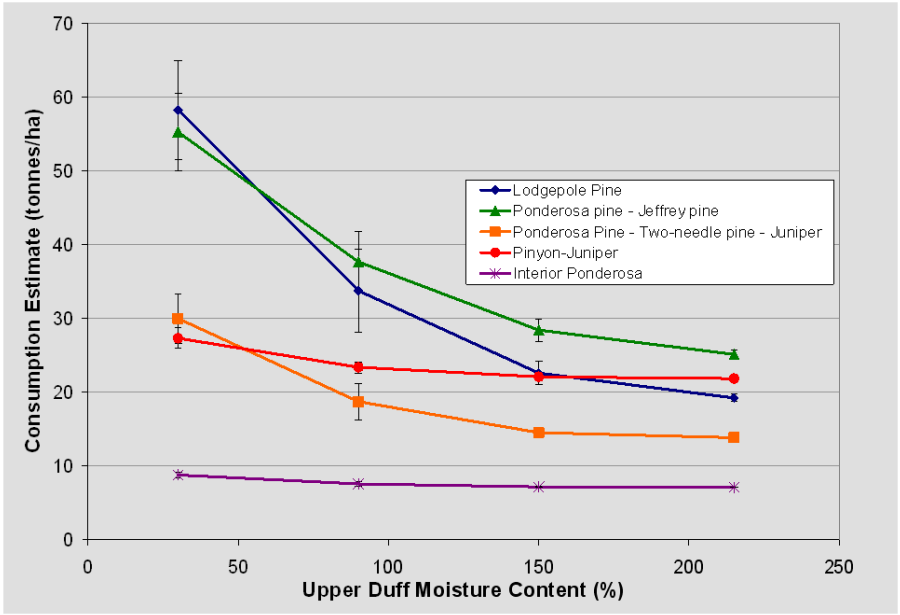


Figure 3. Fuel consumption is quantified with the US Forest Service's CONSUME model based on fuel type and condition. The graph shows emissions as a function of upper duff moisture – as a percentage of dry mass. Similar data has been collected by the Canadian Forest Service for their CanFIRE model. Using field-measured fuel conditions and the resulting fuel consumption after the burn, relationships between the forest type and moisture conditions are developed to determine fuel consumption and emission of carbon-based gas (CO2, CO, and hydrocarbons including methane).

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weather-based indices are developed to help determine the fuel moisture conditions. This includes the Canadian Fire Behavior Prediction (FBP) System's Fire Weather Index and the various codes that feed the index and can be computed from meteorological data to determine fuel moisture.

The WFEIS will use both the CONSUME and CanFIRE consumption/emissions models – CONSUME for the US and Mexico, and CanFIRE for Canada [de Groot et al., 2007]. Burn area maps from

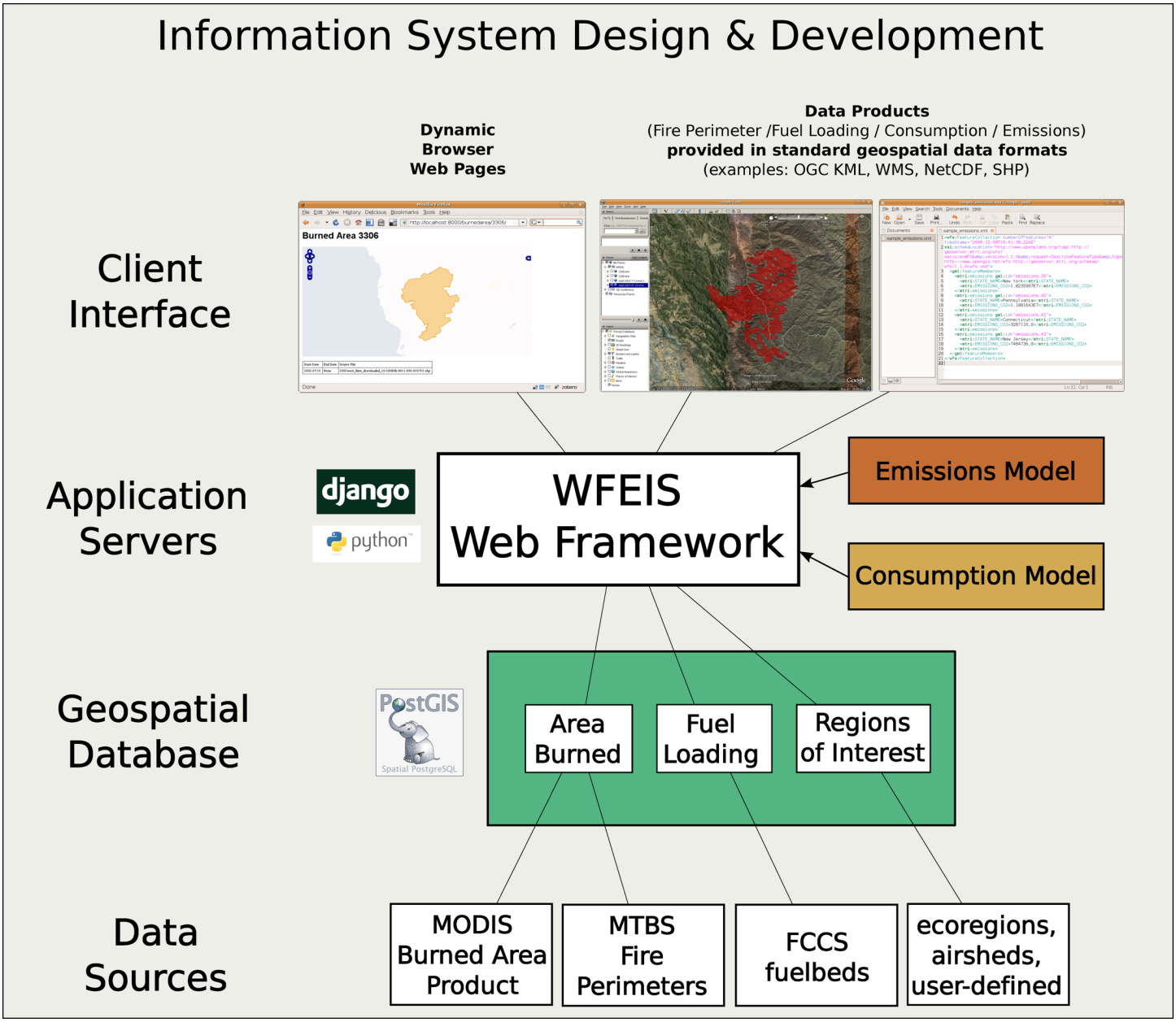

Figure 4. The WFEIS is developed as a web-based tool using an open-source GIS framework. Data sources are included in the WFEIS or are user-defined. The GIS database is used to compute emissions using the CONSUME or CanFIRE models. Results are served out to a client interface, either to visualize the result (in something like Google Earth) or to be used for model inputs. Users will be able to go onto the website to selectively map fire emissions or download GIS data layers of interest.

a variety of sources will be used for emissions estimation, including fire burn area products derived from the Moderate Resolution Imaging Spectroradiometer (MODIS) satellite instrument [Giglio et al., 2009] and Landsat (see http://mtbs.gov/) as well as record-derived maps, such as historic fire maps for Canada [Stocks et al., 2002] and the Alaska Large Fire Database [Kasischke et al., 2002]. Fuel information at 1-km grid scale will be available for the US and Mexico from the Fuel Characteristic Classification System-based map developed by the US Forest Service partners [McKenzie et al., 2007; see http://www.fs.fed.us/pnw/fera/fccs/; Ottmar et al., 2007]. Canadian FBP system fuels developed by the Canadian Forest Service have been mapped to a 1-km resolution using a satellite-derived vegetation map [Nadeau et al., 2005; http://cwfis.cfs.nrcan.gc.ca/en_CA/background/maps/fbpft]. In addition, the system provides emissions factors (EF) based on an extensive literature of measured emissions. These EF's relate consumed fuel to the type and amount of emitted particles and gases, and vary based on the type of fuel and the amount of moisture in the fuel. EF's are integrated into CONSUME and CanFIRE.

Once complete, the WFEIS will include access to several fire location data sets (burn area products) as well as fuel maps for North America. The system provides a geospatial view of fire emissions, which is important for understanding fuel conditions (type and weather) and for mapping emissions sources. The system is designed to work in retrospective mode, not in real time. The focus will be on providing more complete results on the impact of past fires on the carbon cycle. WFEIS will supply both map-based output for data visualization and tabular output for use in modelling frameworks (Figure 4, previous page). The author's development team will shortly release the initial version of the WFEIS, which is limited to emissions from the conterminous US, but which will eventually operate North America wide – for Alaska, Canada, and Mexico. In addition, the WFEIS is being used in two other projects also lead by the author. The first is to improve estimates of emissions from croplands and rangelands in the US and is funded by NASA's applied sciences program. The second is to conduct a study of wildfire and respiratory health under a grant provided by the US National Institutes of Health (NIH). Those interested can keep abreast of developments by visiting the project web site at http://wiki.mtri.org/display/firedss/Home or by contacting the author at nancy.french@mtu.edu. §

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Modelling the Interannual Variability of Black Carbon Emitted from Boreal and Temperate Wildland Fires

by David Lavoué, Consultant for the Air Quality Research Division, Environment Canada, Toronto

Over the past few years, the modelling section of the Air Quality Research Division at Environment Canada has carried out a comprehensive multi-year (1995-2004) modelling study of wildland fire smoke in the Northern Hemisphere. The purposes of this study were to estimate emissions of carbonaceous particles (black carbon and particulate organic carbon) from boreal and temperate wildland fires and to investigate the synoptic atmospheric transport of these aerosols over several consecutive years. These in turn enable assessment of the importance of natural aerosols in the atmosphere at regional scales, as well as their significant year-to-year variability. This article presents a short description of the hemispheric black carbon emissions inventories that were developed for this study and of the atmospheric transport simulations that were performed.

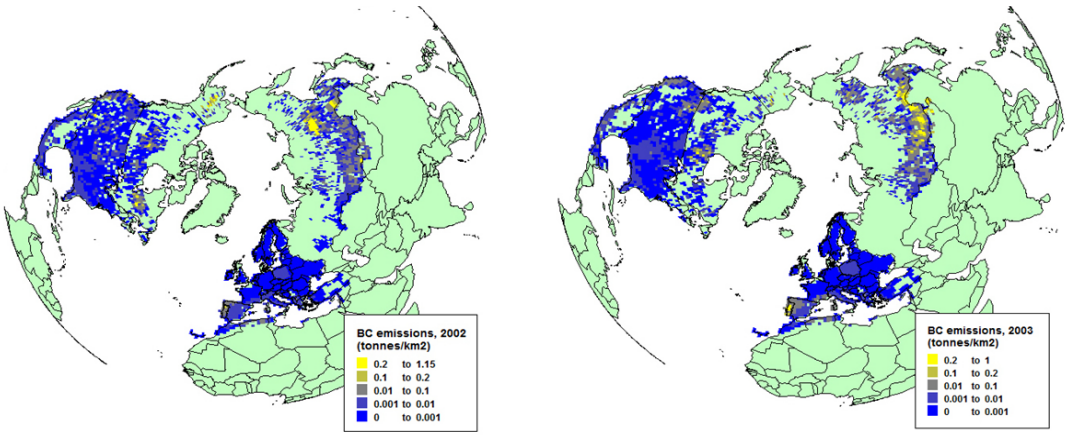

Figure 1. Geographical distribution in a regular 1 degree grid of black carbon (BC) emissions from boreal and temperate wildland fires in 2002 (left) and 2003 (right).

Emissions

Monthly emission inventories from boreal and temperate wildland fires were compiled from a combination of fire agencies' reports and satellite products following the method detailed in Lavoué et al. [2000]. For Canada, an emission model based on the Canadian Forest Fire Behaviour Prediction (FBP) System was applied to forest fires from 2000 through 2004 [Lavoué 2008]. For 1995-1999, the Large Fire Database (> 200 hectares) described by Stocks et al. [2003] was used. With respect to Alaska, Russia, and Mongolia, satellite-derived burn scars were used to map annual areas burned (e.g., Sukhinin et al. [2004]) and monthly variability was inferred from fire pixels detected by remote sensing, namely MODIS (http://modis.gsfc.nasa.gov/) and ATSR (http://www.atsr.rl.ac.uk/).

For Europe, North Africa, and the Middle East, areas burned were determined by country, and where possible for their internal jurisdictions, from a review of statistics available in the literature. These include fire statistic databases compiled by forest services and articles published in the International Forest Fire News by the Global Fire Monitoring Center (http://www.fire.uni-freiburg.de/).

Figure 1 depicts black carbon emissions from wildland fires in 2002 and 2003 in boreal and temperate regions. Large emissions from wildfires burning in central Quebec in 2002 are noticeable. The following year, fires were raging in northern Manitoba and to a lesser extent in the Interior of British Columbia. During both years, forest fires were active in the Russian Far East. Hotspots shifted from central Yakutia in 2002 to southern Siberia in 2003. Moreover, during the summer 2003 heat wave, fires in Europe were responsible for larger aerosol emissions than usual as hundreds of thousands of hectares were burned over by intense bush fires along the northern Mediterranean.

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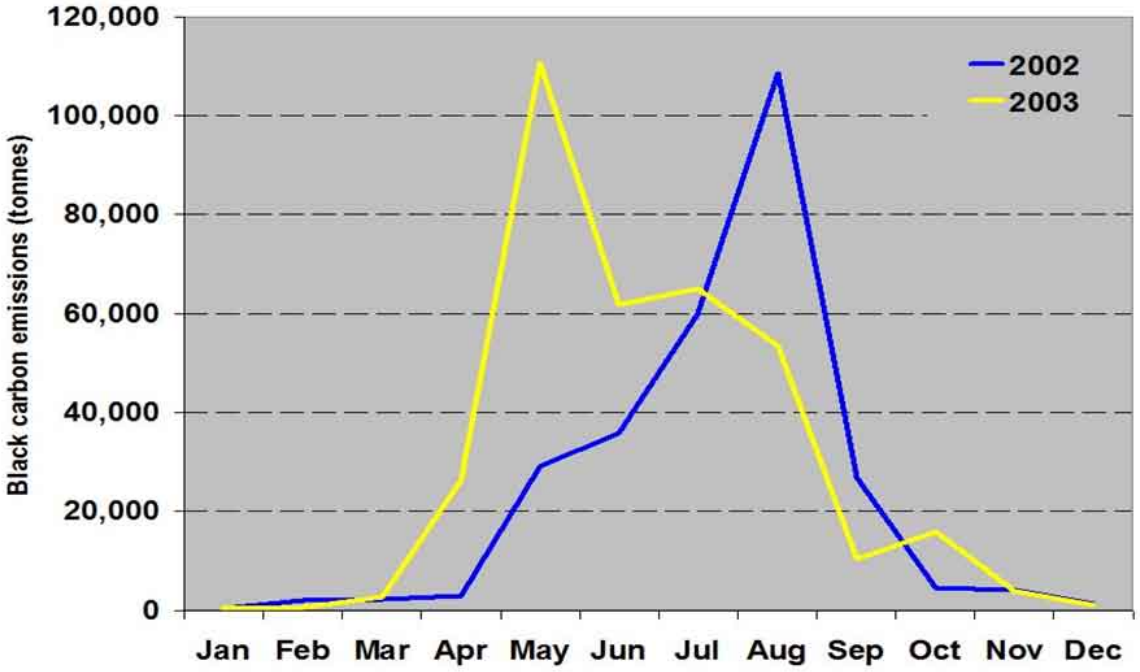

Figure 2. Monthly distributions of black carbon emissions from boreal and temperate wildfires in 2002 and 2003.

Figure 2 shows that seasonality of the emissions from wildland fires can vary significantly from year to year in the Northern Hemisphere. Both peaks were mainly due to Siberian forest fires but did not occur at the same time during the boreal fire season.

To study fire smoke dispersion and impact in chemical transport models, plume heights, also called injection heights in the atmospheric chemistry community, must be assigned to fire emissions [Dentener et al. 2006]. For instance, crown forest fires occurring in the Canadian boreal region release large amounts of energy and are characterized by very high convection columns that can reach the mid-troposphere. A few studies have documented the direct injection of Canadian smoke into the stratosphere [Fromm and Servranckx 2003]. On the other hand, Siberian smoke plumes produced by low intensity fires consuming surface forest fuels do not generally reach such altitudes.

Atmospheric Transport

Black carbon atmospheric transport from wildfires was simulated with the Environment Canada (EC) version of the multi-scale global air quality modelling system GEM-AQ (Global Environmental Multiscale-Air Quality). The Canadian operational weather forecast model GEM was coupled to an online chemical transport model integrating the gas-phase chemistry of 51 gaseous species and an aerosol package with 5 size-resolved aerosol types [Kaminski et al. 2008]. The aerosol treatment was performed with the Canadian Aerosol Module (CAM) and included wet removal and dry deposition schemes [Zhang et al. 2002; Gong et al. 2003]. GEM-AQ/EC was run for a 10 year period from 1995 to 2004 with a global uniform horizontal resolution of 1 degree. Wildland fire emissions were variable, but anthropogenic sources were kept constant. The study team evaluated the ability of the model to simulate seasonal variations and the regional distribution of carbonaceous aerosols. Monthly emissions and the horizontal resolution of 1 degree allowed transport patterns to southern populated areas and to the remote north to be studied.

Since year-specific wildland fire emissions were used, smoke transport was generally well reproduced. Pictures and animations created from daily modelled outputs emphasize the intercontinental transport of smoke in the Northern Hemisphere. For example, Figure 3a shows a smoke plume from the 2002 central Quebec fires crossing

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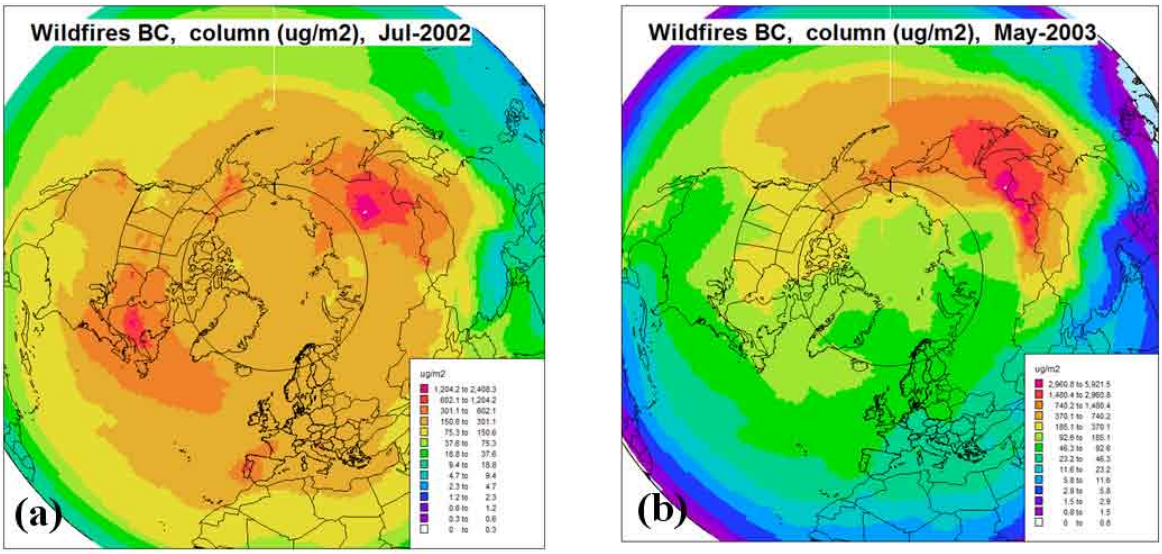

Figure 3. Simulated carbonaceous aerosol loading in µg/m2 for (a) July 2002 and (b) May 2003, from GEM-AQ/EC outputs (different color scales).

the east coast of North America and then being transported over the North Atlantic and Europe. In Figure 3b, a plume from the 2003 Siberian fires is transported over the North Pacific. This plume was also observed with MODIS imagery en route to North America, in mid-May.

The study team is currently in the process of assessing fire contributions to aerosol loading and deposition in the Arctic region and is also investigating transport pathways of Canadian smoke plumes to the north. GEM-AQ/EC simulation outputs will be compared to satellite observations and ground measurements. An oral presentation focusing on the transport of black carbon emitted by wildland fires to the Arctic is scheduled at the AGU Fall Meeting in San Francisco, CA in mid-December 2009.

Results from this study will be detailed in a series of papers presently being prepared for publication in peer-reviewed journals. This study also constitutes a preliminary step for integrating wildland fires into the new Canadian operational air quality model GEM-MACH [Moran et al. 2009]. It will also include numerous gaseous chemical species produced by fires.

Acknowledgments.

GEM-AQ/EC simulations were performed by Tianliang Zhao under the supervision of Sunling Gong at Environment Canada in Toronto. §

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Fire Emissions in Central Siberia

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Introduction

Wildfires in the Russian boreal forest zone are estimated to typically burn 12-14 million hectares (ha) annually [Cahoon et al. 1994; Conard and Ivanova 1997; Conard et al. 2002; Dixon and Krankina 1993; Kasischke et al. 1999]. Boreal forests contain about 21 percent of global forest area and 28 percent of global forest carbon [Dixon et al. 1994], yet data on the extent and impacts of fire in these forests related to actual burning conditions are scarce and often contradictory. While seemly very remote, smoke from Siberian biomass burning can easily reach North America via long range transport, and can at times constitute a significant amount of the pollution present in the Arctic (Amber et al. 2008).

Figure 1. A typical view of a dry site Scots pine forest growing close to 60° N latitude in central Siberia. Note the lack of conifer vegetation between the ground and the tree crowns, which would have acted as a ladder fuel for initiating a crown fire if present.

Fire is a highly variable phenomenon [Countryman 1972]. Depending upon burning conditions, the emissions from a fire can have a wide range of total gas and aerosol amounts as a result of variable consumption of biomass fuels. Another aspect of fire is its variation in intensity. If a fire is intense enough it can inject smoke to high altitudes, which benefits long-range emission transportation. To better understand fire in central Siberia, the Russian FIRE BEAR (Fire Effects in the Boreal Eurasia Region) Project was created as a forest fire research study to provide answers to basic questions on the management of fuels, fire and fire regimes, with the goal of enhancing carbon storage and forest sustainability in ways that minimize negative impacts of fire on global environment, wood production and ecosystem health [McRae et al. 2006]. Improved understanding of the extent and severity of fires and of factors affecting fire behavior, as well as the effects of fire on carbon storage, air chemistry, vegetation dynamics and structure, and forest health and productivity is essential for an improved understanding of the impacts of these fires.

This paper highlights some of the findings on fire emissions from the FIRE BEAR Project, which has been on-going since 1999. The discussion will center on data obtained from burning 200x200 m experimental plots on Scots pine (Pinus sylvestris)/ lichen (Cladonia sp.)/ feather moss (Pleurozeum schreberi) forest sites in the Krasnoyarsk Region of central Siberia. One site was 200 km northwest of where the Angara River empties into the Yenisey River, while two sites were near the Angara, 200 km east of this confluence. Study site latitudes ranged from 58 to 60 degrees north. Even this far north, these central Siberian forests support a commercially viable timber harvest (Fig. 1). Similar latitudinal locations in Canada are mostly above the treeline or support only dwarf-sized trees. Study

sites were multi-aged forests, with the oldest trees dating back to 1550. At the Yartsevo site, fires (dominated by early summer surface fires), occurred an average of once every 29 years between 1550 and 1956, the dates of the first and last recorded fires on the site. However, this does not consider the extensiveness of fires at different spatial scales [Swetnam and Baisan 1996]. Only twelve fires were recorded on at least 30 percent of the trees (including the 1550 date). The average mean interval between these fires was 36.9 years. Larger, landscape-scale fires recorded on at least 50 percent of the sample trees occurred 8 times (once every 58 years) over the same period [McRae et al. 2006].

Methodology

The research team set up a complete fire weather station on site for calculating the fire danger based on both the Russian Moisture Code [Vonsky 1975] and the fuel moisture codes and fire behavior indices of the Canadian Forest Fire Weather Index System [Canadian Forestry Service 1987; Van Wagner 1987]. These daily fire danger values are used as independent variables to portray burning conditions in models that were created to estimate expected fire behavior and fuel consumption. Biomass of all ground, surface, and aerial (tree) fuels was sampled before and after burning. The differences allowed the team to estimate the fuel or biomass consumption. This information was used to estimate total emissions for each fire. Experimental fires were carried out in June and July, which correspond to the main fire season for this region. Plots were burned under a wide range of fuel moisture and weather conditions to observe effects on fire behavior, fire severity, emissions, and other ecological factors. Protective firelines, ignition, and suppression were the responsibility of the Russian Aerial Forest Protection Service (Avialesookhrana) fire management personnel. All experimental plots were burned using line ignition along the windward side to quickly create equilibrium fire behavior that mimicked wildfires under similar burning conditions [Johansen 1987; McRae 1997].

Figure. 2. A Russian researcher using a filter probe held over an active portion of a fire to collect aerosols. A pump with a known flow rate collects smoke samples through the probe and deposits them onto filters for later analysis (apparatus on wheels to the left side of the image).

To measure patterns and speed (rates) of fire spread, electronic timers similar to those of Blank and Simard [1983] were used. These timers were buried at grid points in a 25x25-m sampling grid laid across each plot. Using times from 3 timers, an algorithm [Eenigenburg 1983] can be used to estimate direction and rate of spread of a fire. For several fires, researchers were fortunate to be able to estimate rates of spread using an infrared camera that was flown aerially over the fire [McRae et al. 2005]. Combining rate of spread and fuel consumption values allows the estimation of fireline intensity [Byram 1959], which can be used to estimate fire column height or potential injection altitude of the smoke into the atmosphere.

Carbon emission factors, in units of grams produced per kg of fuel burned for carbon dioxide, carbon monoxide, and methane, were determined using both ground and aerial emission sampling. The canister samples collected were analyzed in the laboratory for these gases and other hydrocarbons [McRae et al. 2006]. In addition, ground and air particulate sampling (Fig. 2) was carried out to enable quantitative determination of chemical elements comprising the aerosol particles [McRae et al. 2006, Samsonov et al. 2006].

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Results and discussion

All test fires were surface fires (Fig. 3) due mainly to the absence of ladder fuels that allow a fire an opportunity to shift from the surface to the crown of a tree. In fact, during a typical year in Russia, 80% of all fires are reported to be surface fires [Belov 1976; Furyaev 1996]. Total fuel consumption ranged from 1.0-3.2 kg/m^2, depth of burn into the organic forest floor ranged from 3.3-6.6 cm, rates of spreads ranged from 0.6-16.9 m/min, and fireline intensities ranged from 185-14,530 kW/m. Fire scenarios ranged from situations where personnel could easily approach and cross over the active fireline to ones where the fire was impossible to approach due to safety concerns (e.g., heat, fast fire spread).

Carbon (C) released by the fires (assuming that carbon comprises approximately 50 percent of the dry fuel consumed - [Levine and Cofer 2000]) ranged from 4.8 to 16.1 tonnes (t) C ha^{-1} depending upon the fire severity. This range of carbon release accurately reflects the variability of fire behaviour and fuel consumption experienced at actual fires throughout a normal fire season. It is this variability, along with the exact characteristics of individual fires, that emission modellers find difficult to incorporate into their simulations for a particular forest type. By combining data from experimental fire sites with regional weather data, the team has developed regression models that link fire emissions with both the Canadian and Russian Forest Fire Danger Rating Systems (Fig. 4). This

Figure 3. Images showing the typical range in Scots pine fire behavior on a dry site in central Siberia for a) a low-intensity (620 kW/m); b) a moderate (2259 kW/m); and c) a high-intensity (5220 kW/m) surface fire. Only the latter surface fire was severe enough to cause mortality of all trees on the site. The multiple fire whirls that were observed on the latter fire are good indicators of a high-intensity fire.

approach holds significant promise as a way of combining fuel and weather data with remote sensing-based fire severity estimates to calculate carbon sequestration and emission.

Emission factors of CO were between 98 g/kg and 135 g/kg, and the average emission factors of CH_4 and CO_2 for these fires were approximately 8 and 1650 g/kg, respectively. These data indicate a significant release of greenhouse gases (carbon dioxide and methane), from fires in central Siberia, given the total amount of biomass consumed annually. The emission factor value ranges are similar to those found for wildfires burning in pine forests in the western United States [Babbit et al. 1994] and for North American boreal and temperate forests [Cofer et al. 1996].

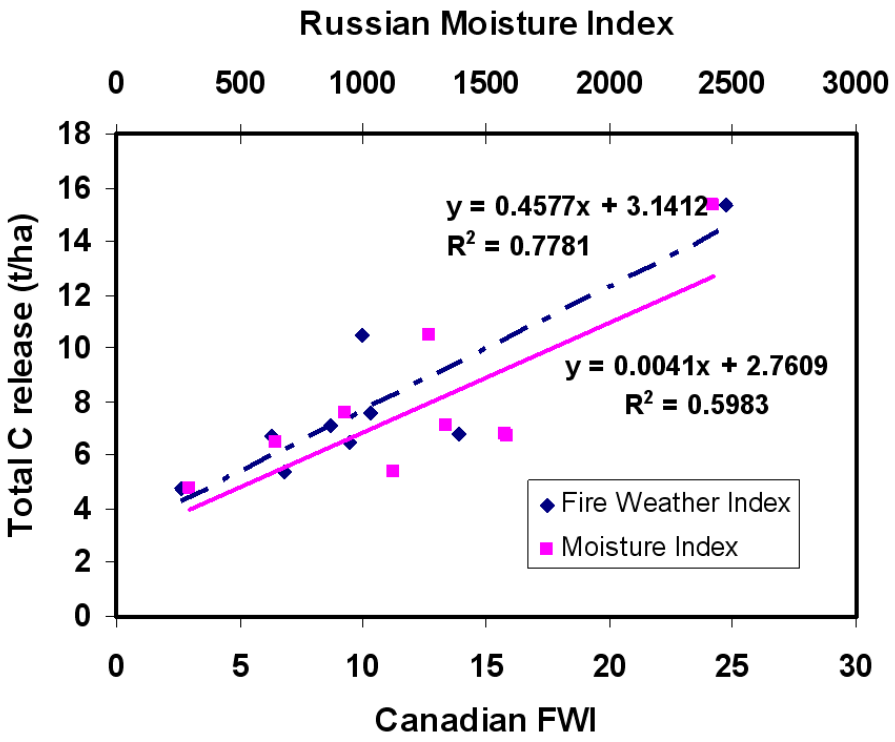

Figure 4. Models illustrating the relationships between carbon release from our experimental fires and Fire Weather Index (FWI) values of the Canadian Forest Fire Weather Index (Canadian, Forestry Service 1987) and the Russian Moisture Index (Vonsky et al. 1975).

The data indicate significant emissions of a wide range of aerosols in smoke [Samsonov et al. 2006; McRae et al. 2006], which have the potential to significantly affect both regional air quality and atmospheric chemistry and radiation fluxes. More specifically, in a typical year, where $12 \times 10^6 - 14 \times 10^6$ ha burn in Russia, we estimate that $3 \times 10^6 - 10 \times 10^6$ t of particulate matter may be emitted into the atmosphere [Samsonov et al. 2006]. About 90-95% of the particulate matter consists of fine smoke particles in the size range of 0.1- 5 mm in diameter. Such particles can strongly affect both the scattering and absorption of solar radiation in the atmosphere resulting in a decrease in the amount of solar energy which is able to reach the Earth's surface. Entrained aerosols include soil particles that have accumulated prior to the fire as dust on vegetation or on the surfaces of litter and ground fuels. This appears to be the primary means by which fire emissions acquire a significant quantity of chemical elements typically found only in soils (e.g., iron, calcium, aluminum, silicon, etc.).

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The ARCTAS Intensive Ozonesonde Network Study (ARC-IONS)

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In 2008, the ARC-IONS (ARCTAS Intensive Ozonesonde Network Study) campaign was undertaken in cooperation with the NASA project Arctic Research of the Composition of the Troposphere from Aircraft and Satellites (ARCTAS). ARCTAS was an extensive NASA airborne field campaign to investigate the chemistry of the Arctic lower atmosphere, with two phases (April and July 2008). It involved three aircraft with more than 30 instruments, flying a total of nearly 500 flight hours, as well as several NASA satellites, and was a major component of the International Polar Year project POLARCAT (Polar Study using Aircraft, Remote Sensing, Surface Measurements and Models, of Climate, Chemistry, Aerosols, and Transport). The July deployment of ARCTAS was particularly aimed at examining the contribution of forest fires to Arctic air pollution, and the impact of that pollution on Arctic climate. More details about ARCTAS can be found in Soja et al. [2008], in the Fall 2008 issue of The Canadian Smoke Newsletter.

ARC-IONS was a collaboration among Environment Canada, NASA and NOAA, creating a strategic ozone sounding network for North America in order to study budgets and sources of tropospheric ozone. This trans-continental network was patterned after the very successful IONS 2004 and 2006 networks [Thompson et al., 2007a], coordinated intensive ozone profile measurement campaigns that have provided valuable insight on ozone processes and their contribution to the tropospheric ozone budget [e.g. Cooper et al., 2006; 2007; Thompson et al., 2007b; Tarasick et al., 2007; Parrington et al., 2008, 2009]. The ARC-IONS network comprised sites in Canada, Alaska, Greenland and the northern U.S. (Figure 1). Mirroring ARCTAS, it consisted of two phases (April and July 2008) with most sites launching daily, generating a total of more than 380 profiles of ozone concentration, as well as pressure, temperature, humidity, wind speed and direction, from the ground to about 30 km altitude. Ancillary data on aerosol optical depth (AOD) was also available from CIMEL sunphotometers, operated at most of the Canadian sonde sites as part of the AEROCan network, and from Brewer UV measurements, also operated at most of the Canadian sonde sites. Surface ozone measurements were available for many sites.

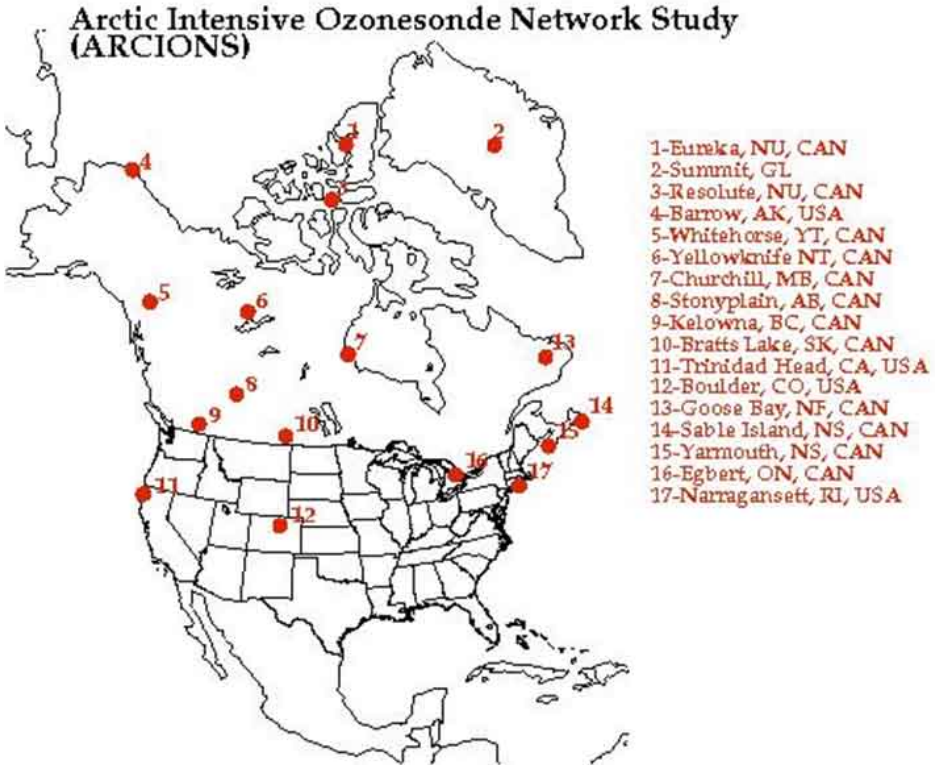

Figure 1. ARC-IONS ozone sounding measurement sites.

The aircraft, satellite, ozonesonde and other observations provide complementary information that permit scientific analysis beyond what can be obtained from a single measurement platform. For example, the effects of combustion aerosols on satellite UV measurements can be observed where fire plumes pass over Brewer sites. Profiles, trajectory plots and other images are available at http://croc.gsfc.nasa.gov/arcions/ and http://www.meteo.psu.edu/~smiller/amt/arcions, while data are available at http://www-air.larc.nasa.gov and http://www.woudc.org.

The objectives of ARC-IONS were:

1. evaluation of the role of stratosphere/troposphere exchange (STE) in the spring buildup of tropospheric ozone;
2. studies of boundary layer ozone depletions resulting from halogens released from sea salt deposited on Arctic sea ice;
3. the contribution to the tropospheric ozone budget from boreal forest fires and the extent of fire emission influence on a trans-continental scale and beyond;
4. validation of the Aura satellite instruments TES (Tropospheric Emission Spectrometer) and OMI (Ozone Monitoring Instrument) at high latitudes;
5. validation of the new Environment Canada air quality model GEM-MACH, for ozone and STE, and of forest fire models.

While ARC-IONS has achieved important results relevant to all of these objectives, it is, of course, the third that will most interest readers of The Canadian Smoke Newsletter. Expected to be an important aspect of the July campaign, the role of boreal forest fires turned out to be of primary importance to the April campaign as well, since the fire season started unexpectedly early in Siberia and smoke was detected in the Arctic during this period.

Ozone production from emissions from tropical biomass burning is well known, as it is observable from satellites [Fishman et al. 1990; Ziemke et al., 2001], and it has been the subject of intense study [e.g. Andreae et al., 1996; Fishman et al., 1996; Thompson et al., 1996; Thompson et al., 2001]. Ozone production from boreal fire emissions is less well quantified, although the potential atmospheric impact of boreal fires is larger, since both fuel consumption and intensity of boreal fires are typically an order of magnitude larger than for savanna fires [Stocks et al., 1997]. The higher intensity of boreal fires also carries emissions much higher into the troposphere and even into the stratosphere, making long-range transport an important consideration.

From late spring through autumn boreal forest fires can generate large amounts of ozone precursors and particulates [Andreae and Merlet, 2001; McKeen et al., 2002; Morris et al., 2006]. How these evolve photochemically to produce ozone within the Arctic and beyond is not well understood however, as the ozone production in smoke plumes seems to be quite variable [Mauzerall et al., 1998; Lapina et al., 2006; Pfister et al., 2006; Val Martín et al., 2006; Real et al., 2007]. Aircraft measurements of ozone in smoke plumes show highly variable concentrations, ranging from less than 35 to more than 75 ppbv [Val Martín et al., 2006].

During the spring phase of ARC-IONS, the early fire season in April 2008 led to extensive Arctic haze (similar to that in Figure 2), a phenomenon studied since the 1950s and thought to be due to emissions transported from Europe and Asia [Law and Stohl, 2007]. Arctic haze in April was shown to be due to biomass-burning plumes from forest fires in the southern Siberia-Lake Baikal area and by agricultural burning in Kazakhstan-southern Russia [Warneke et al., 2009].

The same biomass-burning events have been shown by Oltmans et al.

Figure 2. Arctic haze layer. Photo courtesy NOAA.

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[2009] to have led to enhanced ozone observed in ARC-IONS sonde profiles at a number of sites. Two examples, from Whitehorse, YK on April 20 and Kelowna, BC on April 17, are displayed in Figure 3. The Whitehorse profile shows a layer of enhanced ozone near 3 km altitude, with ozone values exceeding 70 ppbv. At Kelowna, the profile from 17 April shows a layer at 3.5 km with ozone values near 85 ppbv and another at 6 km, with ozone values near 110 ppbv. In all of these cases backtrajectories indicate that the source of the enhanced ozone was the biomass burning region in Siberia and Kazakhstan. At Kelowna, the AEROCan sunphotometer indicated a large enhancement in AOD on April 17. At the Barrow, Alaska ARC-IONS site on April 19, 2008, both ozonesonde and surface measurements indicated the highest hourly average surface ozone values (>55 ppbv) ever seen at this site in April, also traceable to the same biomass-burning activity.

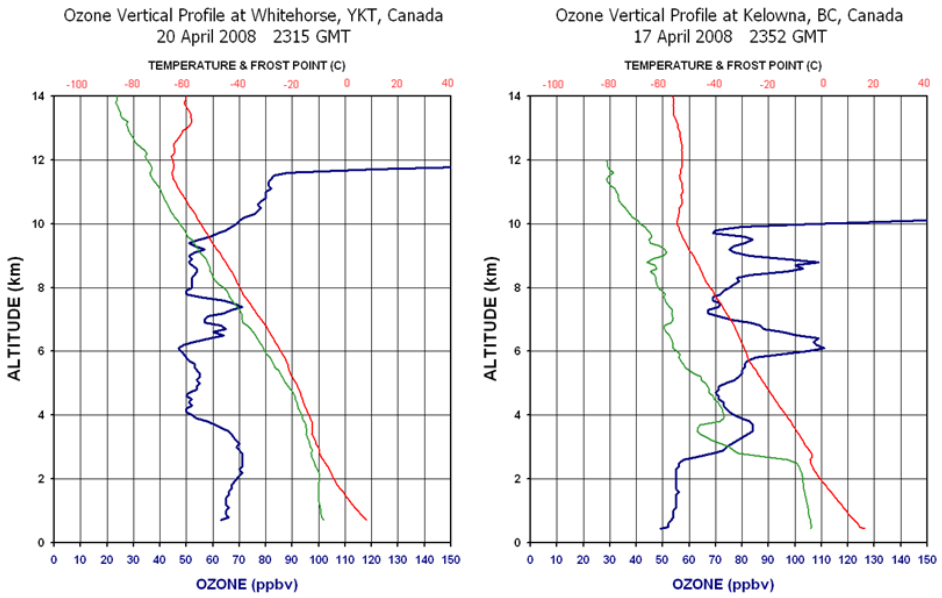

Figure 3. ARC-IONS ozone soundings at Whitehorse, YK (April 20, 2008) and Kelowna, BC (April 17, 2008). The layers of enhanced ozone near 3 km in both profiles, as well as that at 6 km in the Kelowna profile, are traceable to biomass burning in Siberia and Kazakhstan.

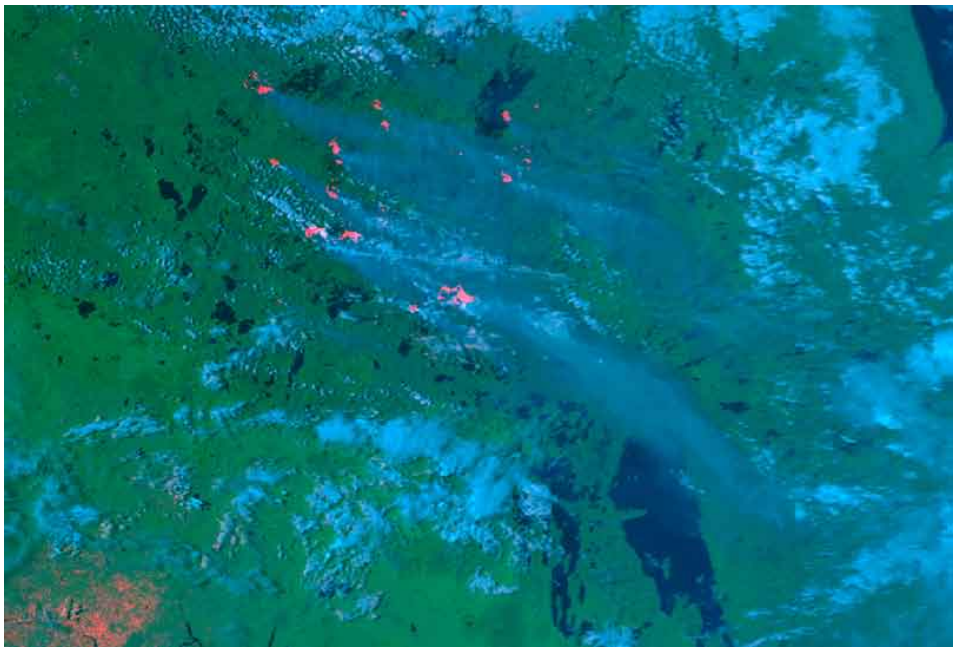

Figure 4. AVHRR image from June 30, 2008, at 2341 UTC, showing smoke plumes from Saskatchewan fires.

The July deployment of ARC-IONS was also an important period for fire activity, this time more locally (Figure 4). Fire activity in central Canada was similar to the 10-year average for July, with numerous intense surface fires and some crown fires. A focus of the July campaign was an attempt to quantify the contribution to the tropospheric ozone budget from boreal forest fires, and the extent to which fire emissions modify the mid-latitude ozone budget. This was accomplished by the application of lamina identification (LID) techniques to quantify the contribution from different sources [Thompson et al., 2007a, b]. The additional ozone attributed to boreal fire sources was quantified by comparison of laminae with recent active fire exposure (according to NOAA/Hysplit backtrajectories) to background ozone as determined from

each ozonesonde profile. Errors in trajectories can be fairly large after several days, leading to estimated uncertainties for this attribution of the order of 50%. Figure 5 shows the percentage enhancement of the Total Tropospheric Ozone Column (TTOC) due to boreal fires, at each of the summer ARC-IONS sites, estimated by this method [Luzik, 2009]. Figure 6 carries this calculation further, breaking down this enhancement at each site into separate contributions attributed to different geographical source regions.

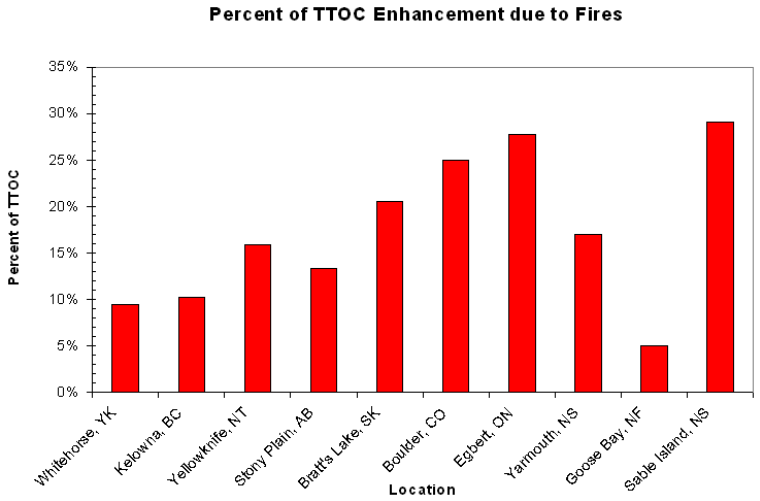

Figure 5. Percentage enhancement of Total Tropospheric Ozone Column (TTOC) due to boreal fires, at each of the summer ARC-IONS sites, estimated by the Lamina Identification (LID) method for each sounding [Thompson et al., 2007a,b], with additional ozone attributed by comparison of laminae with recent active fire exposure (according to NOAA/Hysplit trajectories) to background ozone. [from Luzik, 2009.]

Continuing work on analysis of ARC-IONS and related data, including further efforts at source attribution using the Lagrangian dispersion model FLEXPART (driven by meteorological analyses from the Canadian operational forecast model, GEM), and detailed photochemical modelling studies with the new Environment Canada air quality model GEM-MACH, will yield further insight into this interesting issue. Analysis of ARC-IONS data is, of course, ongoing, and will be so for some time. Preliminary results have been presented at the spring meeting of the American Geophysical Union (Toronto, May 23-27, 2009) and more will be presented at the fall meeting in San Francisco (December, 2009). A special issue of Atmospheric Chemistry and Physics, comprised of papers related to POLARCAT, is also in preparation.

A related field experiment in eastern Canada in July 2010 known as BORTAS (Quantifying the impact of BOReal forest fires on Tropospheric oxidants over the Atlantic using Aircraft and Satellites), will examine the outflow of boreal fires from North

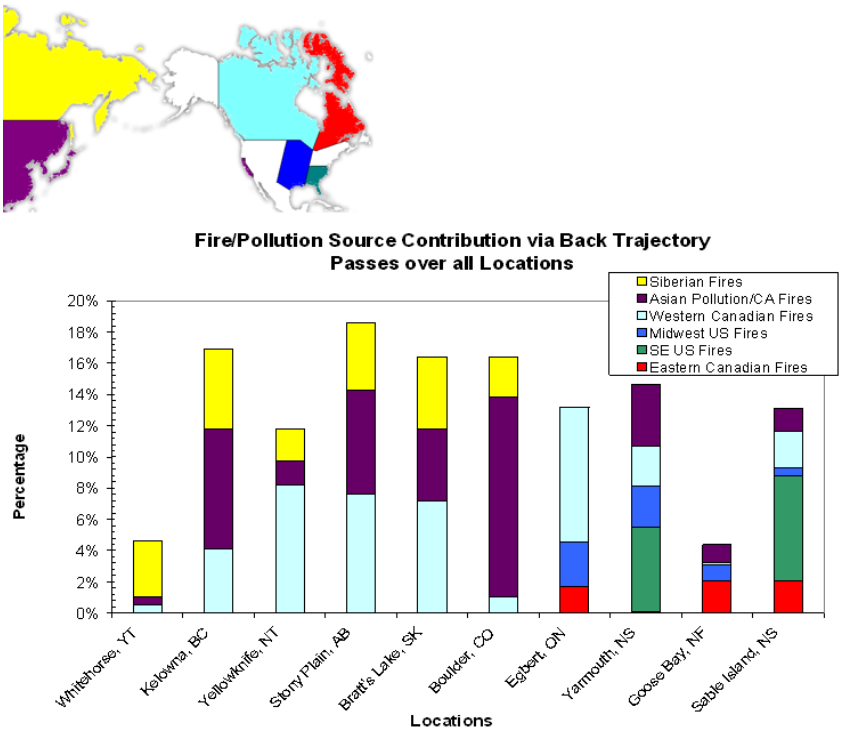

Figure 6. Attribution by geographical source region of percentage enhancement of Total Tropospheric Ozone Column (TTOC) due to boreal fires, at each of the summer ARC-IONS sites, estimated by NOAA/Hysplit backtrajectories. [From Luzik, 2009.]

America toward Europe. Led by the Universities of Edinburgh, York and Leeds, BORTAS is a collaboration with Environment Canada, NASA and several other European, Canadian and US universities. BORTAS proposes:

- to sample the biomass burning outflow from boreal North America over the western boundary of the North Atlantic using the FAAM146 aircraft (Figure 7);
- to use the measurements to derive a chemical mechanism that accurately describes chemistry within the plumes;
- to quantify the impact of boreal forest fires on oxidant chemistry over the temperate and subtropical Atlantic using a nested 3-D chemistry transport model, constrained by assimilated field measurements; and
- to detect, validate and quantify the impact of boreal biomass burning on global tropospheric composition using data from spaceborne sensors.

BORTAS will also be supported by an ozonesonde field study in Canada, although less extensive than ARC-IONS. The combined measurements will complement the ARCTAS/ARC-IONS results by providing a more complete look at the eventual fate of boreal biomass burning effluent, and by better quantifying its atmospheric impact. §

Figure 7. BAE 146-301 Large Atmospheric Research Aircraft

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The Canadian Smoke Newsletter

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"Connecting diverse terrestrial, emissions, air quality and modelling communities."

Papers of Interest

Smoke injection heights from fires in North America: analysis of 5 years of satellite observations

Discussion paper under review for the journal Atmospheric Chemistry and Physics; by M. Val Martin, J. A. Logan, R. Kahn, F. Y. Leung, D. Nelson, and D. Diner.

A five year dataset of Multi-angle Imaging Spectroradiometer (MISR) aerosol plume information over North America was investigated to determine the magnitude and variability of smoke plume heights under various conditions. Plumes were hand-analyzed using MISR Interactive Explorer (MINX) software and compared with simultaneous measurements of Fire Radiative Power (FRP) from the Moderate Resolution Imaging Spectroradiometer (MODIS) instrument onboard NASA's Terra spacecraft, and with assimilated meteorological observations from NASA's Goddard Earth Observing System (GEOS). In addition, smoke clouds not connected with any immediate ground source were analyzed. Five different definitions of heights were used in order to avoid dependency of results on any particular one. A screening procedure was applied to the dataset to remove pyro-cumulus plumes, digitized plumes of poor quality (e.g. those with a low number of height retrievals, or an excessive variability in the stereo-height values) and to remove stereo-height retrievals in the smoke clouds that MINX showed to be close to or at the surface. Heights were then assessed in combination with:

- Atmospheric stability conditions, specifically heights of stable layers aloft and of boundary layers, where stability was defined in terms of the change of potential temperature with height
- Instantaneous Fire Radiative Power
- Geographic distribution of the biomes in which the plumes were located
- Seasonal cycles

Taking into account bias due to MISR measurements occurring during late morning as a result of the Terra satellite overpass time, and the undersampling of the fires due to the spatial coverage of the MISR instrument, the following results were obtained:

- Using the median definition of plume height, 4-12% of plumes were found to exist in the free troposphere (>500m above the boundary layer), with a further 12-22% within 500 m above the boundary layer. A larger fraction of smoke clouds reached the free troposphere
- 86% of all plumes had associated stable layers, and those plumes not associated with stable layers had mean heights approximately 600 m higher than those associated with stable layers
- Plume heights were somewhat correlated with FRP under atmospheric conditions with deep boundary layers or with no stable layers at all. For plumes associated with shallow boundary layers or stable layers aloft, plume heights showed no relationship with FRP. This was true for all biomes. Plumes that did break through the boundary layer were associated with significantly larger FRP values (median difference approximately 500 MW) than those that remained trapped below.
- A pronounced seasonal cycle in plume heights and fire intensity (i.e., FRP values) was found for boreal and temperate biomes, with the boreal biome showing maxima for both heights and intensity during the period from May to July
- Seasonality of boundary layer height was not found to be the predominant influence on plume height, implying a significant role in this respect for fire intensity.

Overall this analysis demonstrated significant variability in plume heights, and the need to assess buoyancy of the fire in the context of local atmospheric stability. §

(summary by Al Pankratz, Air Quality section, Prairie and Northern region, Environment Canada)

Canadian Smoke Newsletter Notes

This informal newsletter is produced by the Air Quality section of Prairie and Northern region, Environment Canada, on behalf of the smoke forecasting community. If you wish to be on the email list for future issues or if you want to be taken off the list, please send a note to *al.pankratz***AT***ec.gc.ca*. You can use the same email address to contribute articles, news items, comments, suggestions or if you wish to receive CSN author guidelines.