The Canadian Smoke Newsletter

2014

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

Welcome to the 2014 issue of the Canadian Smoke Newsletter.

A long, cold winter delayed this summer's fire season over much of Canada. Using data from CIFFC (Canadian Interagency Forest Fire Centre), Natural Resources Canada (NRCan) reported on their website (http://cwfis.cfs.nrcan.gc.ca/report) that as of June 4, 2014, the number of fires across Canada was 1,302, compared to the 10-year average of 2,081 fires. This was 63% of normal. Area-wise, the contrast was even greater with only 39,919 hectares having burned up to that point, compared to the 10-year average of 164,274 hectares, 24% of normal.

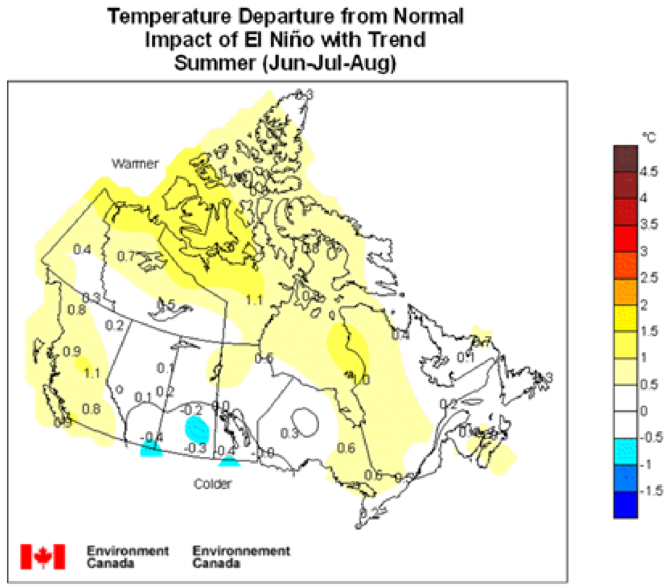
At the time of writing, NOAA's website (http://www.elnino.noaa.gov/) stated that a weak to moderate El Niño was expected to develop during late summer and fall. El Niños typically create significant deviations from normal temperature and precipitation conditions (see maps at right, courtesy of Environment Canada).

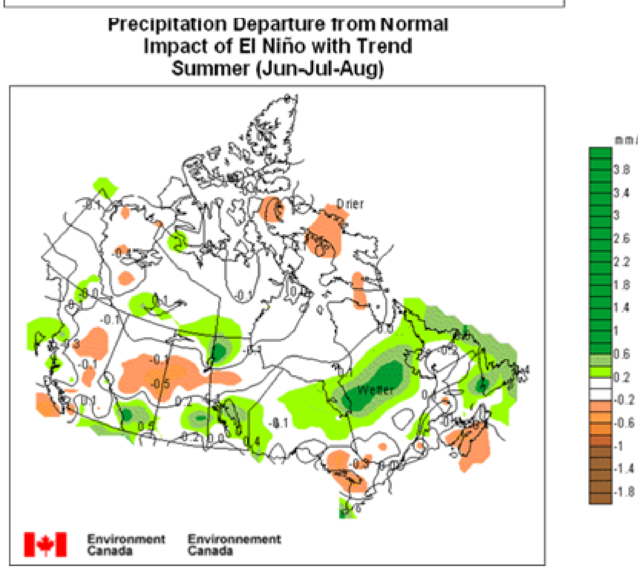
Fast forward to mid-August, and conditions appear to have jumped the gun on El Niño with huge fires occurring in the southern NWT, especially around Great Slave Lake. Yellowknife has been inundated with very high smoke concentrations for well over a month. According to the NRCan website mentioned above, as of August 6th, the number of fires across Canada jumped to 3,840, still only 78.3% of normal. However the area burned skyrocketed to over 3.5 million hectares, 183% of normal. Obviously the fires that are occurring are significantly larger than average.

On a different note, please consider attending the National Smoke Forum 2014, which will be held on Friday October 10th at the Marriott Harbourfront Hotel in Halifax, Nova Scotia. The Forum is being held immediately following Wildland Fire Canada 2014, which runs from October 7-9 at the same location. For details, see the preliminary agenda on pages 2 and 3.

Best regards,

Al Pankratz





Disclaimer: This informal newsletter is produced on behalf of the wildfire smoke community and has no affiliation with the government of Canada or any other agency. Articles from government, industry and academia, whether Canadian or international, are welcome. Please send emails to csn@uniserve.com for author guidelines. Views and comments in these articles are those of the authors or the organizations they represent, and do not necessarily reflect the views of the Canadian Smoke Newsletter.

In this issue:

Preliminary Agenda - National Smoke Forum, Halifax, Nova Scotia - October 10, 2014

Registration at: http://www.ualberta.ca/~wildfire/Wildland_Fire_Canada/2014.html

For more information: smoke@nrcan.gc.ca

AM – The importance of wildfire smoke, plus an overview of current technology and tools that help inform decision making

Welcome and Goals for the day (Bill Cole, Ontario Ministry of Natural Resources)

- broaden/strengthen the national smoke community of practice
- facilitate an understanding of the current science, tools and needs related to wildfire smoke in order to inform decision making
- identify knowledge gaps and suggest a path forward to address these gaps

Wildland fire smoke – why do we care?

Introduction and Impacts:

- Fire and Smoke: the basics (Brian Stocks, BJ Stocks Wildfire Investigations)
- Manitoba evacuation history/case studies (Darlene Oshanski/Barb Crumb, Manitoba Office of Disaster Management)
- Wildfire/woodsmoke case studies in the Maritimes (Mark Gibson, Dalhousie University)
- Wildfire Smoke and Health evidence (Sarah Henderson, British Columbia Centre for Disease Control)

--- Break ---

The State of Smoke Science, Information and Tools

Wildfire and Smoke Analysis:

- Initializing fire and smoke (Roland Schigas, University of British Columbia)

Forecast Smoke:

- BlueSky Canada (Kerry Anderson, Natural Resources Canada)
- BlueSky Canada Research (Rosie Howard, University of British Columbia)
- Canadian Meteorological Centre Smoke Forecasting System: Firework 2014 (Didier Davignon, Environment Canada)

Smoke Verification/Assessment:

- Smoke Model Performance Assessment (Steve Sakiyama, British Columbia Ministry of Environment)
- Ground-truthing BlueSky Playground (David Schroeder, Alberta Environment and Sustainable Resource Development)
- Smoke and Emissions Model Intercomparison Project and Implications (TBA)

--- Lunch---

PM – Next Steps and Discussion

Where do We Go From Here…

Projects for improving Smoke and Health Science

- Manitoba plans regarding smoke monitoring (Barb Crumb, Manitoba Office of Disaster Management)
- Manitoba plans regarding health messaging (Darlene Oshanski, Manitoba Office of Disaster Management)
- US perspectives on the future of smoke management (Pete Lahm, US Forest Service)
- Future of smoke science (TBA)
- Future of smoke-related health science (Sarah Henderson, British Columbia Centre for Disease Control)
- National Smoke Science Forum Proposal: Possible smoke/fire research organization models (Brian Stocks, BJ Stocks Wildfire Investigations)

--- Break ---

… and How Do We Get There?

Panel and Audience Discussion Session:

- moderator: Jeff Eyamie (Health Canada)
- panel members: Brian Stocks, Kerry Anderson, Pete Lahm, Barb Crumb, TBA

--- Summary, survey and thank yous ---

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Towards Establishing a National Forum on Smoke Forecasting in Canada

Brian Stocks
B.J. Stocks Wildfire Investigations Ltd.

[This article is made up of selected excerpts from a report to the BlueSky Canada CSSP (Canadian Safety and Security Program) project team. Funding for the project was provided by the CSSP, which is a federally-funded program designed to strengthen Canada's ability to anticipate, prevent/ mitigate, prepare for, respond to, and recover from natural disasters, serious accidents, crime and terrorism through the convergence of science and technology (S&T) with policy, operations and intelligence. Ed.]

Introduction

In recent decades wildland fire smoke has been increasingly recognized as a major environmental concern, with significant impacts on human health. There have been a number of international forums on this subject, calling for more research to improve both our understanding of smoke effects on human health, but also on our ability to mitigate or adapt to those impacts through improved modelling of smoke transport and dispersion. Canada has traditionally not conducted much smoke research in comparison to many countries, but this has changed in recent years, with the extension of the US BlueSky Smoke Forecasting framework into Canada and the inclusion of smoke in Environment Canada air quality modelling products.

This report briefly and generally summarizes growing smoke impacts internationally, past and current research activity in this area, including the expansion of BlueSky nationally in Canada. The report also discusses the need for a new fire research funding model in Canada similar to those being developed in the United States and Australia.

Background/Global Context

Vegetation fires are a very important disturbance in global vegetation cover worldwide, affecting ecosystems that are adapted to, tolerant of, dependent on, or susceptible to either natural or human-caused fires. An accurate assessment of the total global area affected by different fire regimes has not been determined, but it is estimated that vegetation fires burn from 3-6 million square kilometres annually, about half of this is in Africa.

The largest increases in fire activity over the past 3-4 decades have been occurring in tropical regions, primarily driven by land-use change/ deforestation in South and Central America, and in Southeast Asia. Large increases are also evident in Mediterranean Europe and Eurasia due to changing socio-economics and rural abandonment, but fire impacts are also increasing in many other regions of the world, including Australia and North America.

These increases in fire impacts are also associated with increases in social vulnerability to fire. Growing populations, public awareness, industrialization, the growth of infrastructure and disturbance-sensitive technologies are causing these increased vulnerabilities. This pattern will continue unabated due to (among others) climate change, wildland-urban interface (WUI) expansion (urban exodus), changing lifestyles, land abandonment (rural exodus), and economic development. As a result, society is becoming (and will continue to become) more vulnerable to vegetation fires in the future, particularly the effects of vegetation fire smoke on human health, both short-term and long-term. The most recent estimate is that exposure to wildfire smoke causes 339,000 deaths annually, with over 70% of those deaths occurring in Africa and Southeast Asia.

More frequent and extended smoke episodes associated with vegetation fires have attracted global attention in recent years, and raised awareness of the need for a better scientific understanding of health impacts if these impacts are to be prevented or mitigated. The transboundary effects of smoke pollution also make the development of international policies to address root causes and impacts an imperative. The bottom line is that the future, for a variety of reasons, will include more fires, more smoke, and more human exposure globally.

Two major fire smoke episodes (among many) did the most to raise international public and scientific awareness of the health issues associated with vegetation fire smoke:

1) Southeast Asia 1997/1998.

- Fires associated with forest clearing (2 million hectares annually since 1996) were coupled with an El Niño-Southern Oscillation (ENSO) event that exacerbated fire occurrence and severity. (http://en.wikipedia.org/wiki/1997_Indonesian_forest_fires)
- Deep-burning occurred in peat/swamp biomes, and was sustained over long periods.
- Low-level smoke was trapped in the region for weeks, mixing with urban smog.
- Huge health impacts occurred, with an estimated 650-1800 premature deaths in one week in 1997.

2) Western Russia 2010

- Extreme heat and drought exacerbated fires in agricultural and abandoned peatlands east of Moscow, as did rural abandonment (http://en.wikipedia.org/wiki/2010_Russian_wildfires).
- Over 1000 fires (200,000 hectares) burned, 50 people were killed by fires and $15 billion USD in losses were incurred.
- Smoke pollution in Moscow and region was extreme for extended periods with 350-700 daily Moscow deaths related to smoke/heat stress.
- The Munich Reinsurance Company estimated that the smoke/smog and heat wave caused 56,000 additional deaths (above long-term average) in the July/August period of 2010, with longer-term health impacts unknown.

International Collaborative Smoke Research

Rising concerns over the impact of land-use change-driven fire activity in the tropics on atmospheric chemistry arose in the 1980s, and the International Global Atmospheric Chemistry (IGAC) Project was formed within International Geosphere-Biosphere Program (IGBP) to, in part, address this issue. A number of international experiments have been conducted over the past 2-3 decades, focusing on South America, Africa, and Southeast Asia. The STARE-SAFARI 92 Experiment was one example, in which scientists from many countries conducted ground-, regional- and continental-scale measurements of emissions and emission transport from both South American and southern African fires to evaluate their impact on tropospheric ozone levels in the south Atlantic. Smoke chemistry measurements were also made on boreal forest fires in Siberia in 1993, eastern Canada (Ontario) in the late 1980s, and during the International Crown Fire Modelling Experiment (ICFME) in Canada's Northwest Territories during the late 1990s.

More recently, smoke chemistry and smoke transport measurements have been made during international campaigns focusing on boreal fire smoke transport. ARCTAS (Arctic Research on the Composition of the Troposphere from Aircraft and Satellites), sponsored by the National and Aeronautics and Space Administration (NASA) took place in Canada in 2008. ARCTAS focused on sampling the chemistry and plume dynamics of boreal fires, and tracked physical and chemical changes in smoke composition as smoke travelled downwind. In 2011 BORTAS (Quantifying the impact of BOReal forest fires on Tropospheric oxidants over the Atlantic using Aircraft and Satellites) took place over eastern Canada and the northern Atlantic, focusing on tracking physical and chemical changes in boreal fire smoke from central Canada.

These are just a few examples of international collaboration on smoke research in recent years. This work is continuing and is a strong indication of the importance the international science community places on better understanding smoke chemistry and transport modelling.

Wildland Fire Smoke Research in the United States

The establishment of the Clean Air Act in 1970, and its enforcement by the Environmental Protection Agency, required states to develop air quality management bureaus to monitor and maintain ambient air quality standards. In succeeding years subsequent amendments to the CAA resulted in tighter regulations on particulate matter and ozone levels.

Smoke management/emissions research began in the early 1970s, with a primary focus on prescribed burning in the Pacific Northwest and the Southeastern United States. These regions have extensive prescribed fire programs, including both slash burning and understory fuel reduction burning. Visibility and pollution impacts from smoke resulted in the formalization of smoke management programs. Over the ensuing decades fire researchers, particularly in the US Forest Service (USFS), and land managers in the United States have consistently addressed smoke issues in order to inform evolving policy decisions and increasing stringent air quality regulations. This has involved research aimed at modelling smoke transport, smoke effects on human health, and investigations into public understanding of wildland smoke issues.

BlueSky was developed during the 1990s and early 2000s by USFS scientists in the Pacific Northwest, along with many partners, and introduced in 2005 across 11 western US states. Since that time BlueSky has been improved and expanded, and has proven very useful as a tool to integrate fire occurrence, fuels and weather data to calculate smoke emissions, trajectories, and concentrations.

Still, resolving the need for sound fire management practices with the requirements for increasingly strict air quality regulations is an ongoing and difficult challenge. Much higher population densities and a plethora of air quality regulations and jurisdictions, along with the propensity for litigation, have to date made this a much higher profile issue in the United States than in Canada. However, with an expanding WUI and projected increases in climate change-driven wildland fire impacts, Canada is likely on a similar trajectory in terms of increasing smoke issues.

The Joint Fire Science Plan (JFSP). The JFSP was created in 1998 with funding from both the USFS and the Department of the Interior (DOI), and quickly became a force in wildland fire research in the US (http://www.firescience.gov/). The primary objectives of the JFSP were to develop new lines of fire research aimed directly at the needs of fire managers, and to streamline the delivery of fire science in a constantly changing ecological and social environment. The JFSP is a competitive, peer-reviewed grant process that supports projects that complement and build on other fire research, particularly that conducted by the USFS and DOI. An annual cycle of proposal solicitation, review, and funding ensures a timely response to evolving conditions, and positions the JFSP to tailor wildland fire research in response to the emerging needs of policymakers and fire managers. Currently the JFSP has an annual appropriation of $12 million USD.

The JFSP has funded an increasing number of proposals dealing with smoke science in recent years. These have included many proposals within the following research themes: smoke and emission model evaluations, smoke dispersion from low intensity fires, public perceptions of smoke management, megafire smoke and population impacts, assessments of fire emission inventory tools, effects of wildland fire smoke on human health, and the effects of climate change on wildfire activity impacts on air quality. Over 40 proposals related to smoke science have been funded since 2008.

In recent years the JFSP funded a proposal to develop a Smoke Science Plan (SSP) that would guide JFSP smoke-related research funding during the 2011-2015 period. After conducting workshops with key fire scientists and managers, and surveying the community of interest (NASA, NOAA, EPA, USFS, DOI) through a web-based questionnaire, four research themes emerged:

- smoke emissions inventory research
- fire and smoke model validation
- smoke and populations
- climate change and smoke

International Smoke Symposium. The International Association of Wildland Fire (IAWF) hosted an International Smoke Symposium in late 2013 that brought together research specialists, managers and policy-makers from government agencies, NGOs, tribes, and private institutions (http://www.iawfonline.org/2013SmokeSymposium/). The symposium was meant to serve as a nexus of interdisciplinary research, management and policy and definitely achieved that goal. Participants discussed and evaluated current practices, and the latest research and technological developments, and the meeting provided a critical sounding board for future needs and practical solutions to management challenges. Sessions at the Smoke Symposium dealt with smoke and air quality modelling, smoke and climate change, smoke and populations, smoke management and mitigation policies and practices, and wildland/agricultural fire activity, smoke emissions and inventory. These sessions closely mirror the Smoke Science Plan themes.

The foregoing illustrates strongly that, after conducting extensive research in smoke science in previous decades, US scientists and managers continue to view smoke management as a real current and future issue in the US, and they are taking steps to bring stakeholders together on this issue. While fire research in general continues to be reasonably well-funded in the US, the additional funding through JFSP is augmenting this funding in a very meaningful way, and ensuring that research products are timely and relevant.

Wildland Fire Research in Australia

For many decades wildland fire research in Australia followed a similar path to research programs in Canada and the United States, and indeed there was extensive communication between the countries in this subject area. As in Canada, much of the fire research conducted in Australia was carried out under the auspices of the federal government, specifically the Commonwealth Scientific and Industrial Research Organization (CSIRO). Diminishing resources and funding at CSIRO, and growing fire problems in Australia led to the development of a different model to deliver wildland fire research in that country.

The Bushfire Cooperative Research Centre (CRC) was established in 2003, during a year of major fire impacts in Australia, through a grant from the Australian Government's Cooperative Research Centres Program (www.bushfirecrc.com). The Bushfire CRC was extended, with renewed funding for the 2010-2013 period, following the disastrous Black Saturday fires near Melbourne in 2009, in which 179 people lost their lives.

The Australian CRC program supports medium to long-term, end user driven research collaborations to address major challenges facing Australia. CRCs are established to pursue solutions that are innovative, of high impact and capable of being effectively deployed by the end users. The Bushfire CRC is supported by 51 partner organizations, including all of the fire/land management agencies in Australia and New Zealand, as well as CSIRO, the Bureau of Meteorology, private enterprise and local governments.

Bushfire CRC research themes reflect a recognition of the high-impact fires in 2003 and 2009, and include an emphasis on prevention, preparation and suppression, management of fire in the landscape, community self-sufficiency for fire safety, and protection of people and property. The overarching theme is understanding and communicating the risk from wildfire, and managing the threat. However, the Bushfire CRC still conducts basic research on fire weather, fire danger rating, fire behavior modelling, fire and landscape ecology, fire economics, risk assessment, and smoke properties and impacts. Smoke-related research involves smoke emissions/composition and transportation modelling from both prescribed fires and wildfires, and the effect of smoke on public and firefighter health.

Client agencies are actively involved in setting research priorities, as they are major contributors of research funds. Research is carried out collaboratively, with government researchers working closely with academic colleagues and operational fire management agencies. For the 2003-2009 period the Bushfire CRC received $114 million ASD in direct funding and in-kind support from the Australian government and the fire industry. For the 2010-2013 period this support totalled $57 million ASD. Most recently a new Bushfire and Natural Hazards CRC has been created, with funding of $47 million ASD over the next 8 years from the Australian government.

Wildland Fire and Smoke Research in Canada

Over the past 80-90 years the Canadian Forest Service (CFS) and its predecessors have been responsible for much of the forest fire research in Canada, although academic institutions have also been involved in some aspects of fire research. At its peak 40-50 years ago the CFS fire research program covered fire research on fire weather, danger rating, fire behavior, fire ecology, fire economics, fire suppression, and fire management systems. No direct research was or has been undertaken on smoke science, although the CFS has actively participated in numerous international experiments dealing with smoke chemistry and transport, as mentioned earlier in this report. [*It should be noted that research on smoke and smoke prediction is currently being conducted within Environment Canada, for example in the Firework project at the Canadian Meteorological Centre. Ed.*]

In 2005 the Canadian Council of Forest Ministers (CCFM) released the Canadian Wildland Fire Strategy

(CWFS), a report endorsed by provincial and territorial governments in Canada, along with the federal government (http://www.ccmf.org/english/coreproducts-cwfs.asp). The CWFS laid out quite clearly the challenges currently facing fire management agencies in Canada, recognized the changing context and growing complexities in Canadian fire management, and identified the emerging issues, including:

- Managing risk and public expectation in association with an expanding WUI;
- Forests under stress due to insects, as well as fuel accumulation;
- Climate change with more frequent, severe and larger fires and longer fire seasons:
- Increasing competition for forest land base together with recreation and aboriginal issues;
- Declining fire management infrastructure - both equipment and personnel.

The CWFS has not been funded adequately to date, even after recent significant wildfire impacts such as the 2011 Slave Lake Fire which burned 500 homes and resulted in $700 million in insured losses, but some CWFS initiatives are being undertaken on a limited scale.

The first substantial discussion of Canadian wildland fire smoke issues took place in Edmonton in 2007 at the Smoke Forecasting Workshop hosted by Environment Canada and the governments of Alberta and British Columbia. Workshop participants included atmospheric and fire research scientists, environmental and resource managers from provincial and federal agencies, along with representatives from universities, health agencies, airshed zones and the environmental consulting industry. The main workshop objectives were to:

- identify users and document their needs with respect to smoke forecasts;
- identify the tools needed for smoke forecasting and their availability; and
- find partners who could work to implement a smoke forecasting system and identify the required resources.

The primary conclusion from this workshop was a recognition of the need for a national smoke forecasting framework in Canada that could be used at both local and regional levels. There was also a feeling that Canada lacked the support and required resources to build such a system at that time, and there was considerable interest in expanding the BlueSky model used in the western United States to include Alberta and British Columbia as a pilot project. There was a feeling that this could be accomplished with existing resources. Workshop participants also recognized the need for involvement from other sectors (e.g. agriculture, health, emergency response, municipalities etc.) as a national smoke forecasting system was developed.

Over the next few years an interagency working group collaborated on the extension of the US BlueSky system into British Columbia and Alberta, and a prototype system was established at the University of British Columbia. Smoke forecasts for BC and Alberta were initiated in 2010 (http://www.bcairquality.ca/bluesky/west/index.html). Subsequently BlueSky was expanded to eastern Canada (http://www.bcairquality.ca/bluesky/east/index.html), and smoke forecasts for this region began in 2013 at a lower resolution. At that time, funding from the Canadian Safety and Security Program (CSSP) provided the opportunity to develop a truly national smoke forecasting system for Canada. In 2014 BlueSky Canada will run twice daily for western and eastern Canada, with high resolution (4 km) runs planned for BC/Alberta and for Ontario/Quebec.

It is expected that, as user agencies become familiar with BlueSky products, there will be growing interest in supporting BlueSky operations and the further development of this smoke forecasting capability. With growing awareness of current and future fire and smoke impacts, it is also anticipated that other government sectors will see the benefit of BlueSky Canada products in anticipating and mitigating smoke impacts. With this in mind, those involved in the development of BlueSky Canada are interested in establishing a broader national forum on smoke issues in Canada. Smoke forecasting model outputs and improvements would be a part of this national forum, but it would also provide a platform for discussions on broader smoke/fire issues including public health, smoke inventories, and climate change. The forum members would identify research and policy needs through the development of a strategic plan, facilitate communication and collaboration among agencies, and seek funding opportunities.

Further Thoughts on the future of Wildland Fire/Smoke Impacts

The future of smoke modelling in Canada cannot be separated from the future of wildland fire research in this country. As discussed earlier, federal fire research capacity has declined in recent decades and there is no indication that this trend will be reversed. Other countries have found ways to continue to build their fire research programs through the development of new funding models that involve client agencies and their requirements in the development and funding of research. In Canada it seems an inescapable conclusion that provincial/territorial fire management agencies must be involved in future priority-setting and funding if fire research is to maintain relevance. Research on smoke management issues will be closely tied to this new approach. Perhaps the concept of a Fire Institute, with funding from provincial/territorial agencies, industry and the federal government, and with collaborative research undertaken by the CFS, agencies and academia, would be worth pursuing. §

Additional Reading

Smoke Science Plan. 2010. Prepared by A.R. Riebau and D.G. Fox (Nine Points South Technical Pty. Ltd.) for the USDA/USDOI Joint Fire Sciences Program (http://www.firescience.gov/)

World Health Organization/United Nations Environment Programme/World Meteorological Organization. 1999. Health Guidelines for Vegetation Fire Events. http://www.fire.uni-freiburg.de/vfe/WHO Health Guidelines Vegetation Fires/

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Stereoscopic Retrieval of Smoke Plume Heights and Motion from Space-Based Multi-angle Imaging, using the MISR INteractive eXplorer (MINX)

by David L. Nelson[1] and Ralph A. Kahn[2]

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Introduction

Airborne particles – desert dust, wildfire smoke, volcanic effluent, urban pollution – affect Earth's climate as well as air quality and health. They are found in the atmosphere all over the planet, but vary immensely in amount and properties with season and location. Most aerosol particles are injected into the near-surface "boundary layer," but some, especially wildfire smoke, desert dust and volcanic ash, can be injected higher into the atmosphere, where they can stay aloft longer, travel farther, produce larger climate effects, and possibly affect human and ecosystem health far downwind. For these reasons, monitoring aerosol injection height globally can make important contributions to climate science and air quality studies.

The Multi-angle Imaging Spectro-Radiometer (MISR) is a spaceborne instrument designed to study Earth's clouds, aerosols, and surface. Since late February 2000 it has been retrieving aerosol particle amount and properties, as well as cloud height and wind data, globally, about once per week. The MINX visualization and analysis tool complements the operational MISR data products, enabling users to retrieve heights and winds locally for detailed studies of smoke plumes, at higher spatial resolution and with greater precision than the operational product and other space-based, passive remote sensing techniques. MINX software is being used to provide plume height statistics for climatological studies as well as to investigate the dynamics of individual plumes, and to provide parameterizations for climate modeling.

MISR

In December 1999 NASA launched the TERRA satellite into Earth polar orbit. TERRA is the first of several large platforms in the Earth Observing System (EOS) fleet that are designed to study climate. The Terra satellite hosts five scientific instruments, including MODIS (Moderate Resolution Imaging Spectroradiometer), a familiar legacy instrument, and MISR [Diner et al., 1998], one of the first spaceborne instruments to acquire data globally using multiple cameras to view the Earth at multiple angles (Fig. 1).

Each of MISR's nine cameras images Earth roughly from pole-to-pole, north to south on the day-side, in four spectral channels, centered at blue, green, red and near-infrared wavelengths. Orbits always cross the equator around 10:30 AM and PM standard local time. At 50° N, overpasses occur at about 11:15 AM in

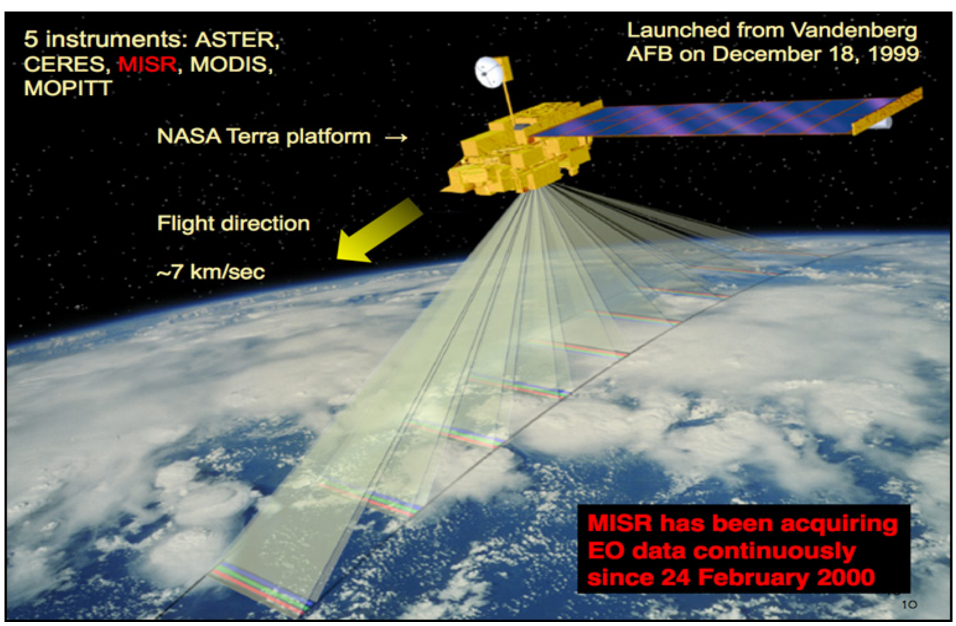

Figure 1. Illustration of the TERRA satellite with MISR aboard, and the nine-camera, four-wavelength MISR observing pattern. TERRA orbits at an altitude of 705 km and completes each orbit in 99 minutes.

most places. The additional time results from TERRA's tilted orbit, which causes a time zone to be crossed. Time zones that do not follow geographic meridians can be exceptions to these rules.

The nine camera zenith angles range from 70° looking forward, through nadir, to 70° looking aft, along the satellite ground track. This allows MISR to view every scene nine times within about seven minutes. The images have a pixel footprint of 275 m in 12 MISR channels and 1100 m in the remaining 24; all four spectral bands in the nadir camera and the red bands in the other eight cameras are acquired at the higher resolution. Global coverage is acquired every 9 days at the equator and every 4 days at 50° N.

Part of MISR's mission is to study clouds by retrieving their heights and motion vectors. Multiple viewing angles provide the capability to apply purely geometric, stereoscopic methods to this task. MISR heights are independent of radiometric calibration uncertainties and detailed knowledge of the atmospheric temperature structure required by instruments that rely on thermal infrared spectral bands to estimate feature height. MISR products can be downloaded from NASA's Atmospheric Sciences Data Center website (https://eosweb.larc.nasa.gov/order-data).

MINX

MISR's operational cloud height and wind products are generated automatically and are used primarily to provide global statistics for climate studies. The MINX software complements the operational product, taking advantage of human-in-the-loop analysis, and making it possible to tease out fine detail from smoke plumes and other features. Beginning in 2006, our group at JPL was funded by the EPA and NASA to develop the MISR Plume Height Project. It aimed to provide a wildfire-smoke-injection-height climatology to support climate change and air quality studies. This required a new approach to retrieving heights. MINX is our solution [Nelson et al., 2013].

MINX is an interactive, GUI-based program that displays a large viewing window in which the nine camera images from a portion of a MISR orbit can be displayed in an animation loop using conventional play/pause movie controls (Fig. 2).

Displaying successive camera images enables the user to study the 3D context of a scene and to detect relationships that would be difficult to discern in a single, nadir-view image. The animation window is also the workspace where a user digitizes a polygon, inside which heights and winds are retrieved on a grid of regularly spaced points. MINX is freely downloadable from the Open Channel

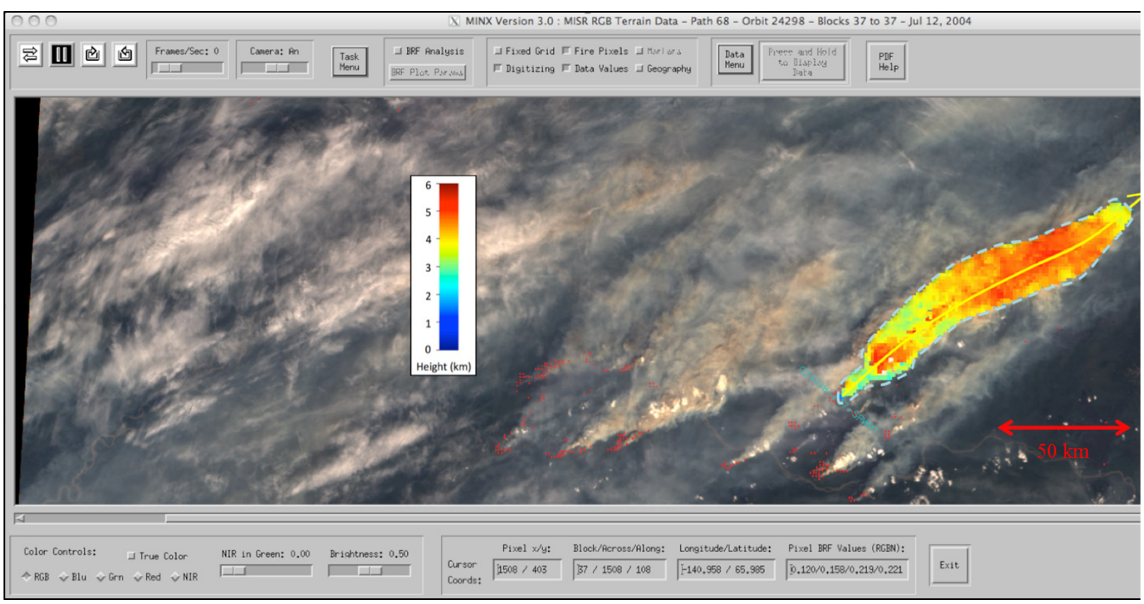

Figure 2. The MISR nadir camera image for orbit 24298 in the image pane of the MINX animation window after one block of MISR data has been loaded. The wildfire plumes on the right half of this image were captured over eastern Alaska on 12 July 2004. Five plumes in the image are associated with fires each producing from 3 to 6 gigawatts of radiative power as measured by MODIS. MODIS thermal detections are shown as red dots; MINX heights above sea level within the plume itself, between about 3 and 5 km, are represented according to the color bar; the dashed, aqua outline of the plume polygon and the yellow wind direction arrow were digitized manually.

Foundation website (https://www.openchannelsoftware.com/projects/MINX).

Retrieving heights stereoscopically from a smoke plume in a MISR scene depends on measuring the parallax observed between pairs of camera images, using an image-matcher. Then applying our knowledge of camera view angles, the height can be computed. This is complicated by the fact that the feature can move due to wind action; in the observed plume displacement, proper motion is conflated with apparent motion due to parallax. Our algorithms separate the contributions from true motion and parallax to produce heights as well as components of wind speed in both the along-swath direction and normal to it. One critical MINX innovation is the requirement that a human provide the wind direction. This reduces the problem of determining three unknowns at every point (height, wind speed along swath and wind speed across) to two and greatly improves retrieval precision (see Nelson et al., 2013, for details). The wind direction can usually be inferred, especially when a fire source is identified as a high-brightness-temperature anomaly in a MODIS thermal-infrared image, and it can be digitized at the same time as the polygon outlining the plume is defined.

All MISR cloud-height products and all versions of MINX before 2014 use MISR's red-band images to generate heights. Red-band retrievals are most successful when the background scene is dark in that spectral band (e.g., plumes over ocean or boreal forest), and when the aerosol being analyzed is optically dense. When one or both of these conditions are not met (e.g. thin plumes over grassland), the red-band might not see the smoke, or not detect the smoke at the highest level. A version of MINX to be released near the end of 2014 will greatly improve the retrieval of thin aerosols over bright surfaces, by using a combination of the red and blue bands in retrievals.

The MISR MINX Plume-Height Project

For the MISR Plume-Height Project, we initially retrieved heights for about 3,400 smoke plumes over North America over five years, 2002 and 2004-2007 [Val Martin et al., 2010]. This database of smoke plume heights has since expanded to include about 5000 plumes over North America for fire years 2001-2008, and more than 6500 plumes from other selected regions of the world. A small dataset of 85 plumes was also separately acquired to support the ARCTAS field campaign over Canada in 2008. All these data are available at http://misr.jpl.nasa.gov/getData/accessData/MisrMinxPlumes, in both graphical and digital form.

We are currently digitizing plumes for the entire world for the year 2008, and expect to make these data available before the end of 2014. This should add more than 15,000 smoke plumes to the database. A small number of volcanic plumes are also available on the website, and this is an area that will be expanded in the future.

When using the data on the Plume-Height Project database, several factors should be taken into account. First, the MISR swath seen by all cameras is about 380 km wide, significantly smaller than the MODIS swath. Therefore any location at 50° N latitude is observed by MISR once every four days on average, so many short-lived fire events are not seen by MISR. Second, plumes are seen only in late morning, before some fires have reached their maximum intensity. Third, only red-band retrievals are available for plumes digitized before 2014, so optically thin plumes might be underrepresented, or their heights might be underestimated. The global plume-height retrievals covering 2008 will be the first dataset to use the new red-and-blue-band algorithm. Additional information is available on the plume project website (Fig 3).

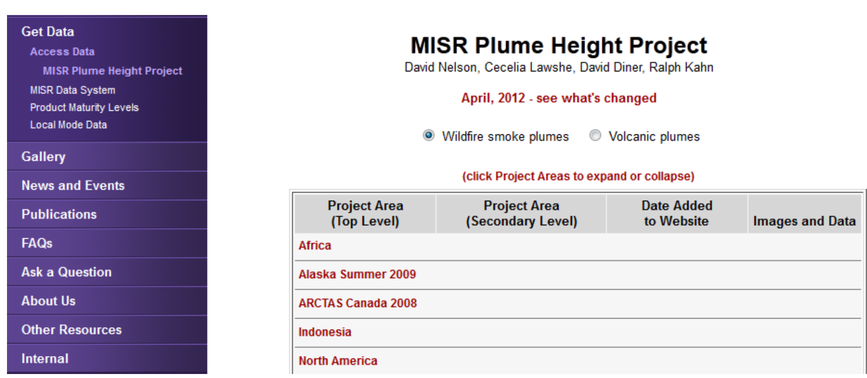

Fig 3. A portion of the project website at http://misr.jpl.nasa.gov/getData/accessData/MisrMinxPlumes

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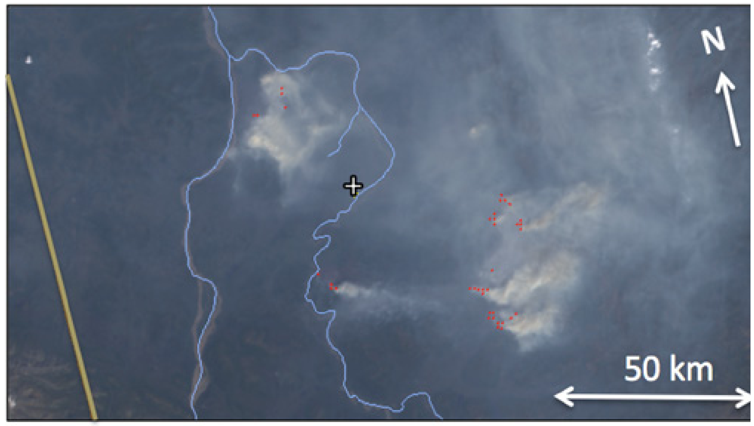
Examples from the smoke plume dataset

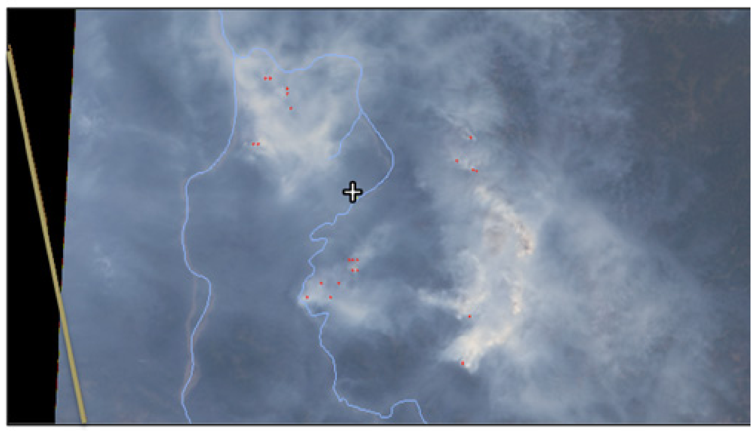
Canadian Smoke Plume Example 1. The 2004 fire year was particularly intense in Alaska and the Yukon. Numerous large fires burned in late June and early July, a few of which are shown in the images of Fig. 4 at right, as MISR passed over the area. Between June 23 and 25 (A and B), under clear skies, several slow-moving fires can be seen. The height of these plumes as determined by MINX is between 1.5 and 3 km on both the 23rd and 25th. The wind is generally from the WNW at 2 to 5 m/s on the 23rd but is relatively stagnant and undirected two days later.

By July 2 (C), under partly cloudy skies, most of the original fire fronts have diminished in strength, and a larger fire has developed between them. This new fire is a duplex structure – a low plume driven by southerly winds beneath a higher plume driven by easterly winds (red arrows). The higher humidity in the cloudy scene increases the potential for condensation of fire-generated water vapor as the plumes rise. The result is that two towering pyrocumulus clouds have formed over the fires (blue arrows), rising to over 9 km.

The MODIS 4-micron radiance associated with the plumes in Fig. 4C, interpreted as fire radiative power (FRP, e.g., Kaufman et al., 2003), is 5720 MWatt. Some of this power may be attributable to a fire beneath the pyrocumulus cloud nearer the fire pixels. However, it is likely that most if not all of the thermal radiation from the fire that generated the larger pyrocumulus cloud is shielded from



A. MISR orbit 24021, June 23, 2004


B. MISR orbit 24050, June 25, 2004

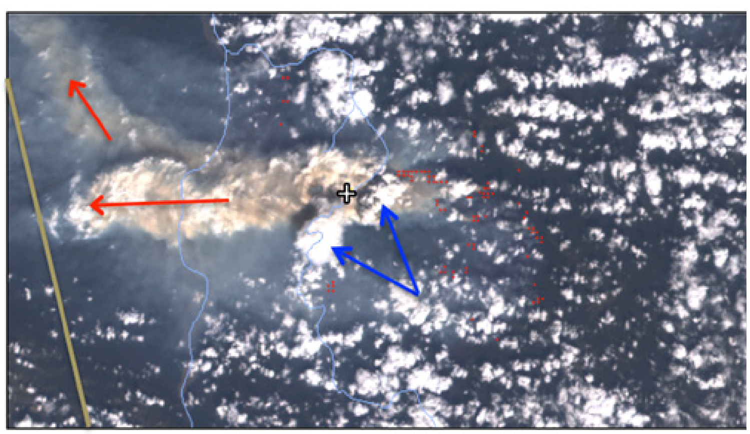

C. MISR orbit 24152, July 2, 2004

Figure 4. Three images of smoke plumes in the Yukon, Canada, in June and July 2004, captured by MISR's nadir camera, each showing the same geographic region. The brown line is the Canada/Alaska border, light blue lines are rivers and red dots are hot spots detected in the MODIS instrument's 4-micron images. The plus symbol represents a common location near the center of the fires in C (62.29° N, 139.61° W).

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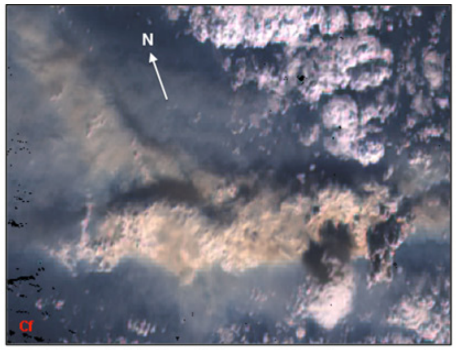
detection by thick smoke.

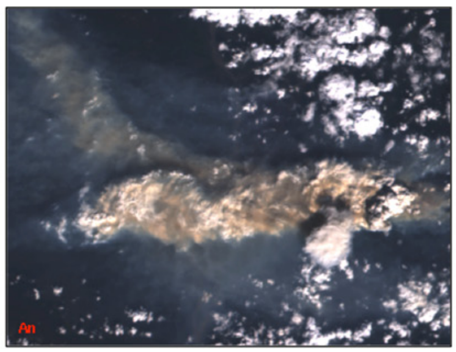
The three scenes in Fig. 5 at right show the duplex plume from Fig. 4C as imaged by MISR's 60˚ forward (Cf), nadir (An), and 60˚ aft (Ca) cameras. Nearly vertical columns of aerosol, largely in shadow, connect the pyrocumulus clouds to the plume below on the Cf camera image (Fig. 5A). The clouds' shadows on the underlying plume and their larger amount of parallax shift reinforce the conclusion that they are higher than the relatively flat mass of the plume. Similar evidence suggests that the north-trending plume lies beneath the other. We also observe that the tops of the pyrocumulus clouds are tilted toward the SW, because their position on the Cf camera is not symmetric with respect to the Ca camera. The top of the pyrocumulus clouds may have entered a regime with northeasterly winds.

The two C camera images in Fig. 5 demonstrate another advantage of multi-angle observations. The aerosol optical thickness is greater in these oblique views through the peripheral smoke than in the nadir view, because the optical path traversed through smoke is greater. This feature is especially useful when retrieving aerosol physical and optical properties (e.g., Martonchik et al., 2009; Kahn et al., 2010).

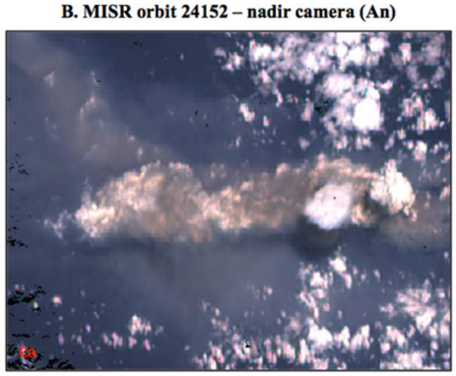
The MINX retrieval results for these plumes are shown in Figs. 6 and 7. Fig. 6 shows the color-coded heights for the plume in Fig. 5 in map view, and Fig. 7 shows the height and wind profiles. The digital data are also available in the MINX database.



A. MISR orbit 24152 – 60° forward-looking camera (Cf)



B. MISR orbit 24152 – nadir camera (An)



C. MISR orbit 24152 – 60° afterward-looking camera (Ca)

Figure 5. Views of the duplex smoke plume in Fig. 3C from three MISR cameras: A. Cf, B. An, and C. Ca.

Canadian Smoke Plume Example 2.

A pair of large smoke plumes captured by MISR during the ARCTAS field campaign on 30 June 2008 is shown in five camera images in Fig. 8 (next page). A total MODIS FRP of 6524 Mwatt was recorded for the larger plume to the north, and this plume was digitized for MINX height

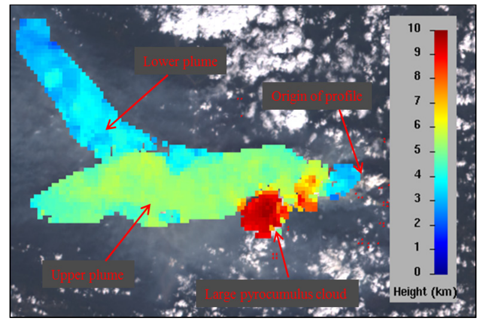


Figure 6. Color-coded, wind-corrected heights in km retrieved by MINX for the duplex plume in Figs. 4C and 5. This is a map-view version of the heights shown in blue in the profile of Fig. 7 (top panel).

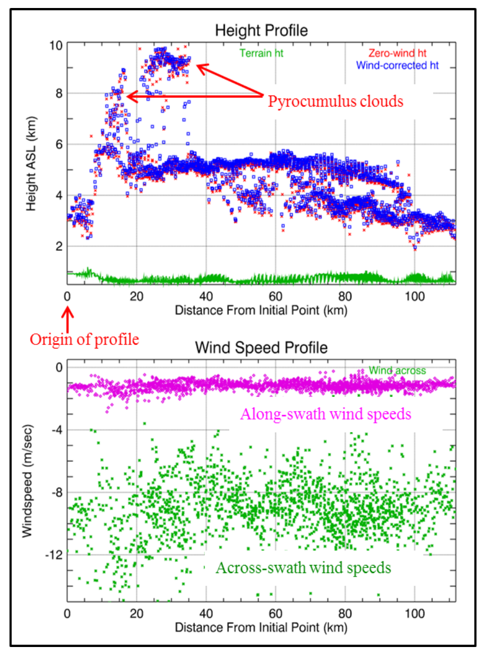


Figure 7. Profiles of height above sea level in km (A) and wind speed in m/s (B) for the duplex plume in Fig. 6 as a function of distance from the initial point digitized. On the height profile, red points are heights uncorrected for wind, blue points are heights corrected for wind and the green line represents the height of the underlying terrain. On the wind profile, green points are wind speeds across-swath and magenta points are wind speeds along-swath.

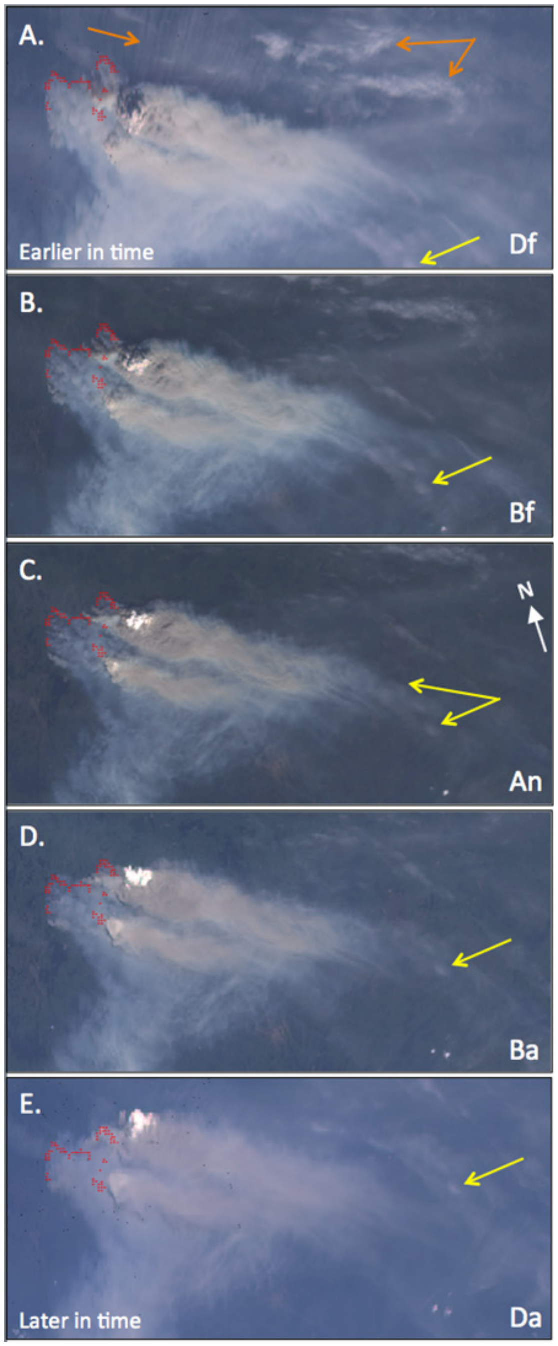


Figure 8. Large plumes on MISR orbit 45397 observed during the ARCTAS campaign in Canada on 30 June 2008. Images are from 5 of MISR's 9 cameras: A. Df, B. Bf (45° forward-looking), C. An, D. Ba (45° aft-looking) and E. Da. The turbulent clouds at the top of the larger plume are at 55.3 N, 102.50 W.

retrieval. A map of color-coded, wind-corrected heights for this plume is shown in Fig. 9A, and the height profile is given in 9B. Winds of 18 m/s tilt the individual columns of rising smoke about 60° from the vertical. A turbulent mass of smoke capped by a pyrocumulus cloud rises to a height of 6 km over the fire, while the bulk of the plume settles into an equilibrium height of 3 to 4 km. The contrast between the white, water-rich pyrocumulus cloud and the dirty smoke below it is best seen in the bottom two panels of Fig. 8 where reflected sunlight exposes the plume's southern side.

The absence of color-coded heights toward the SE end of the digitized region in Fig. 9A indicates that no retrievals were obtained there.

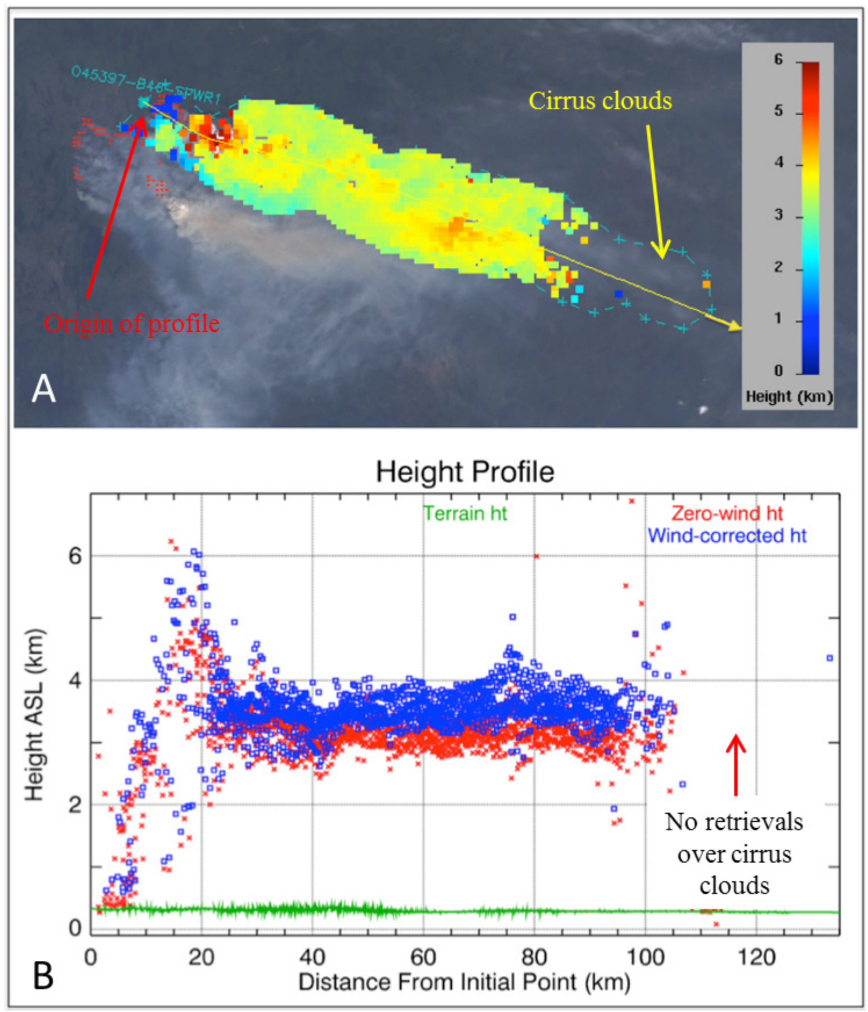


Figure 9. Wind-corrected height retrieval results for the larger plume in Fig. 7 in map view (A) and profile view (B).

Inspection of the camera images shows that what appears to be the tail of the plume on the nadir image (Fig. 8C) is actually cirrus cloud at 11 km altitude (yellow arrows). This altitude was determined in a second retrieval pass, after increasing the maximum height in the MINX height retrieval filter. (Documentation for operating the MINX software is available from the MINX web site.) Other cirrus clouds are indicated by orange arrows on the 70˚ forward (Df) camera image (Fig. 8A). Visual inspection of the multi-angle images is particularly useful in discriminating between signal and noise.

By following the progress of the cirrus cloud forward in time from the Df to the 70˚ aft (Da) camera, we see that it has a component of motion across-swath, toward the right. Parallax does not contribute to motion in the across-swath direction, so we conclude that there is a component of proper motion toward the right. But parallax does contribute in the along-swath direction, so we cannot determine the resultant direction of motion based solely on the changing position of a feature between camera pairs. Structural cues from the smoke are better indicators of true direction of motion, from which the MINX retrieval provides quantitative wind vector constraints.

Applications and Future Work

The five-year MINX North American smoke plume data set has been used to qualitatively assess the fraction of fires that inject smoke above the boundary layer, stratified by land cover type, year, month, boundary layer stability, and MODIS FRP (Val Martin et al., 2010). These data sets have also been applied to quantitatively evaluate the performance of a widely used 1-D plume-rise model, initialized with several common ways of estimating fire area and heat flux (Val Martin et al., 2012). A subset of these plumes was used to demonstrate the complementarity between near-source plume-height maps produced by MISR and downwind aerosol layer height derived from the space-based CALIPSO lidar instrument [Kahn et al., 2008]. MINX plume heights combined with CALIPSO layer heights were also used to assess the inter-annual variations in fire plume height over Borneo and Sumatra, and their correlation with El Niño events [Tosca et al., 2011].

Volcanic plumes and dust plumes have been studied with the help of MINX as well. For example, MINX was used to map the heights of the 2010 Iceland volcanic plume eruption [Kahn and Limbacher, 2012], to study the variations in Mt. Etna ash plume injections [Scollo et al., 2012] and to evaluate volcanic plume height determinations by thermal infrared methods [Ekstrand et al., 2013].

Much more extensive application of the MINX tool is possible, and some additional work is planned. For example, the 2008 global plume data, when it is completed, will be used to constrain the AeroCom aerosol transport models (http://aerocom.met.no/Welcome.html), and determine the degree to which applying the observed heights rather than the injection heights commonly assumed in climate models affects the derived smoke aerosol climate forcing. But a primary effort must be made to digitize a larger fraction of the smoke, volcanic, and dust plumes in the more-than-14-year MISR data record. To encourage this, we are developing training tools, so others can contribute to the effort. §

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The Canadian Smoke Newsletter

2014

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Wildfire Smoke From Start To Finish

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Over the past few years, the Canadian Smoke Newsletter has focused on articles about the measurement, modelling and forecasting of smoke from fires which are for the most part located within the boreal forest. Although we have talked about specific aspects of smoke and have sometimes defined what it is in terms of some of its chemical constituents, we have not dealt with it comprehensively from start to finish. This article is an attempt to remedy that omission.

Fire

Because it is usually true that where there are fires there is smoke (to reverse the old adage), it makes sense to start our story of smoke by looking at fire. It is there that the aerosols that make up smoke get their start. For fire to occur we need a flammable/combustible material such as wood which is capable of reacting exothermically (i.e. the reaction releases energy). We need an oxidizer to participate in that reaction (atmospheric oxygen in the case of wildfires). We need an ignition source (e.g., lightning, cigarettes, sparks from trains or all-terrain vehicles) that raises the temperature at the fuel to a point where the exothermic reaction can start. Finally, the reaction must be able to be sustained over time.

The chemical reaction for complete combustion of hydrocarbons is :

$$O_2 + \text{hydrocarbons} \rightarrow CO_2 + H_2O$$

In the case of wildfires, it is vegetation (which is primarily made up of hydrocarbons) that provides the fuel which is capable of exothermic reactions, specifically cellulose, oils, waxes, lignins, fats, starches, tannins and resins [California Department of Public Health et al., 2008]. Complete combustion of all of these constituents of vegetation is rare. The general reaction for burning vegetation can therefore be depicted as:

$$\text{vegetation} + O_2 \rightarrow CO_2 + H_2O + CO + \text{trace gases} + \text{particles}$$

In the forest, it is a combination of convection (rising air currents over hot surfaces and compensating downward currents around it) together with the prevailing winds which carry the by-products of fire up and away, allowing fresh, oxygenated air to access the fire and keep the reaction going.

Flame. Distillation occurs when ignitable vapours composed of volatile organic compounds (VOCs) are driven from the fuel by heating. These gases, together with gases generated by reactions on the fuel, liquids created by pyrolysis (organic compounds changing composition due to heating) and ejected solid particles all react with each other above and around the fuel to form different chemical species. These reactions emit light (in characteristic ways for each reaction type) throughout the visible, infrared and UV portions of the spectrum. Visible light emitted by these reactions forms a bright, fluctuating structure which we call flame. In contrast, flame from alcohol-based

Figure 1. Visible flame engulfs a forest stand from the surface of the ground to the tops of the crowns. Source: Canadian Forest Service (Natural Resources Canada), reproduced with permission.

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fires can be barely visible (http://www.circletrack.com/enginetech/ctrp_1201_alcohol_fuel_basics/, accessed 1 June 2014). The colors of flame depend on the amount of oxygen present, the type of reaction as well as the temperature at which the light-emitting reactions take place. Color is an indicator of flame temperature: e.g., red (~700ºC), orange (~900ºC), yellow (~1200ºC) and blue (~1400ºC) (Figure 1).

Charring. Chemical processes which can start at temperatures as low as 75-150ºC but more typically between 200-300ºC, create changes in fuel which drive off gases from the combusting materials and leave behind a mix of carbon and other solids called char. By definition, therefore, these changes are the result of incomplete combustion. There may or may not be flame associated with charring [Boboulos, 2010].

Smouldering. Smouldering is a lower temperature oxidation process than that associated with open flame. It occurs relatively slowly on the surface of certain fuels (Figure 2). Smouldering areas on fuels appear

Figure 2. Smouldering lodgepole pine post-fire with isolated open flame. Image courtesy of US National Parks Service - Yellowstone Photo Collection.

to glow. There is no visible flame because the oxidation reactions are operating on solids, rather than on gases. Smouldering can sustain itself for long periods of time under the right conditions (even underground), propagating by conduction. Because of the lower temperatures during oxidation, smouldering is "dirtier" – releasing significantly more combustion by-products, including smoke. For materials that can support smouldering, smouldering always produces char.

Fuel

Fuels are any living or dead organic material that can ignite and burn. Fuels make up the most important

Fig 3. Leaf litter and duff. Image courtesty NOAA/NWS.

Fig 4. Closeup of duff layer. Image courtesy of NOAA/NWS.

component of the well-known fire behaviour triangle: fuel, topography and weather. The other two factors must always be considered in relation to fuels [Brown and Davis 1973].

Duff. An accumulation of leaf and/or needle material on the ground above the mineral soil, duff is usually the result of several years of shedding by trees or bushes, and ranges in thickness from several centimeters to as much as 30 or 40 centimeters in some regions (Figures 3,4). Duff is completely or partially decomposed, and is sometimes divided into two layers. The upper fermentation layer is where the original plant material is in various stages of breakdown, but is still recognizable. The lower humus layer comprises the layer in which the original plant material is not recognizable (Figure 5).

Litter layer. Litter is a layer of leaves, twigs or fine branches which has not decomposed and which lies on top of the duff (Figures 3,5).

Smaller plants. Smaller plants are vegetation whose tops are usually within a meter of the ground but are

Figure 5. Cross-section through litter/duff. Image courtesy Chelene Krezek-Hanes.

occasionally as high as 2-3 meters. This fuel category is mostly comprised of:

- grasses - plants with narrow leaves and non-woody stems (Figure 6), e.g., big bluestem, switchgrass
- forbs – plants that flower, have broad leaves and non-woody stems, e.g., chicory, sunflower; and
- shrubs – woody-stemmed plants that typically have multiple “trunks” (Figure 7), e.g., sagebrush, tumbleweed.

Live trees (trunks/crowns). These are large growing plants which have a single woody trunk and numerous woody branches growing outward

Figure 6. Grass fuel type. Source: Canadian Forest Service (Natural Resources Canada), reproduced with permission.

Figure 7. Oak brush fuel in Colorado. Image courtesy Colorado State University.

from the trunk, and whose tops are usually above 2-3 meters when mature (Figure 8). The branches above either the lowest live branch or the lowest branch that is still part of the canopy are called the crown. Live trees are harder to get burning, but once lit burn much hotter than grasses.

Figure 8. Live spruce trees. Source: Canadian Forest Service (Natural Resources Canada), reproduced with permission.

Figure 9. Mixed stand of spruce and dead balsam fir. Source: Canadian Forest Service (Natural Resources Canada), reproduced with permission.

Dead and dying trees. Live, dead and dying trees can be mixed together (Figure 9). There are several sub-categories within the dead or dying tree fuel type, namely:

- snags - dead and dying trees that are still standing on their own or being supported by trees around them (Figure 10),

Figure 10. Dead snag being propped up by trees around it. Image courtesy NOAA/NWS.

- downed trees - trees that are lying on the ground or partly buried in the ground. They may be toppled by a combination of age and disease, insects, wind events or fire. Downed trees can be in various stages of decomposition; and
- slash - composed of trunks, branches, twigs or pieces left behind by forest management, clearing or pruning operations (Figure 11). Slash is frequently collected together to form piles which are then burned.

Insects and disease can drastically alter the nature of fuels. Of special note is

Figure 11. British Columbia mixed conifer slash. Source: Canadian Forest Service (Natural Resources Canada), reproduced with permission.

the advance of the mountain pine beetle across the forests of British Columbia and Alberta. A greater than normal beetle infestation has affected millions of hectares of mostly lodgepole pines (Figure 12), resulting in large areas of dead standing trees which are more prone to wildfire, and which have different burning characteristics than normal live or dead pines.

Figure 12. Trees infested by the mountain pine beetle show as red within one year of infestation. Image courtesy of the Government of British Columbia.

Figure 13. Areas of burned and unburned peat. Photograph by Merritt Turetsky, University of Guelph.

Peat. Peat is a fuel composed of decomposed plant matter (Figure 13), packed into a layer just beneath the earth's surface (a layer of more than 40 cm of accumulated organic soil is defined as peat). Peat can be thought of as a precursor to coal (given the right conditions acting over long periods of time) and is used as domestic fuel in some areas of the world. When peat is ignited below the surface, the oxidation process proceeds slowly (up to ten times more slowly than with flaming combustion). Oxygen can be supplied through cracks, gaps and openings in the ground. Despite low concentrations, diffused oxygen is enough to enable smouldering to take place within the peat layers. The area of combustion moves slowly along as heat conducts its way into adjoining areas. Smouldering underground in peat can last for decades or in a few cases, centuries.

Fuel models. Fire research groups have built fuel classification systems based on various fuelbed characteristics in order to calculate fire danger indices and fire behaviour components with mathematical models . Examples of these systems include the Canadian Fire Danger Rating System (http://cwfis.cfs.nrcan.gc.ca/background/fueltypes/c1, accessed 27 June 2014) and the US Fuel Characteristic Classification System (http://www.fs.fed.us/pnw/fera/fccs/, accessed 27 June 2014). Fuelbeds are characterized by their fuel load, bulk density, fuel particle size and heat content. Fuel components are usually grouped by horizontal stratification, e.g., ground fuels, litter-lichen-moss, woody fuels, non-woody vegetation, shrubs and canopy.

Fire Behaviour

Ignition. According to Natural Resources Canada, 50% of fires in Canada are caused by lightning (Figure 14), with human activities responsible for the other half. In the more densely populated US, humans cause up to 90% of fires, while lightning causes the other 10%. There are other natural

Figure 14. Lightning strike. Credit: © UCAR, Photo by Carlye Calvin/NCU. The source of this material is the COMET® Website at http://meted.ucar.edu/ of the University Corporation for Atmospheric Research (UCAR), sponsored in part through cooperative agreement(s) with the National Oceanic and Atmospheric Administration (NOAA), U.S. Department of Commerce (DOC). ©1997-2014 University Corporation for Atmospheric Research. All Rights Reserved.

causes of wildfire, such as contact with lava or sparks from rock falls but their numbers are negligible. Humans start fires in many ways, namely:

- carrying out prescribed management burns
- failing to put out campfires
- operating vehicles that shed sparks
- carelessly discarding cigarettes
- losing control of debris fires, or
- setting fires deliberately.

The vast majority of lightning-caused fires are due to dry lightning which is lightning that is not accompanied by significant precipitation. This usually occurs with high-based thunderstorms in fairly low relative humidity environments. There are exceptions: Florida, for example, sees ignitions from thunderstorms even in cases where precipitation is significant. Lightning strikes that are sustained (multiple return strokes, in some cases lasting up to half a second) have a correspondingly higher chance of starting fires.

Fuel immediately ahead of existing wildfire is dried by exposure to radiative heating emitted by the fire, which drives off moisture. Ignition then occurs when the fuel is further heated to its combustion temperature, through radiative heat, convective heating, direct contact with flame or by spotting (contact with burning brands or embers blown ahead of the fire - Figure 15).

Weather. Temperature, relative humidity, precipitation and wind all influence fire behaviour, both in the short term and long term. For example, high temperatures promote the drying of fuel. High temperatures for long periods of time (i.e., drought) dry out even large logs, and create prime conditions for catastrophic, high intensity fires.

Fire is inhibited by the moisture content in fuel. High relative humidity therefore affects fire indirectly by decreasing the rate of evaporation of fuel moisture or by actually increasing the moisture content on and within fuels. Rain and snow also influence fuel moisture content by wetting fuels directly. Strong winds promote drying by wicking moisture away from fuels, and affect fire by creating turbulent eddies above tree canopies and down in the surface fuels. Wind also acts by determining the path fires take, and if fires are burning in the crowns, can carry glowing embers considerable distances to start new fires (spotting). Winds in the form of chaotic downdrafts from thunderstorms are particularly treacherous and have been known to trap and kill fire crews by altering the intensity and direction of the fire in a very short time.

Due to varying internal makeup, different fuel types have different drying rates. The diameter of the fuel (twig vs. branch vs. trunk) also affects how long the fuel will retain moisture and therefore how soon it will be ready to burn after a precipitation event. For

Figure 15. Spotting ahead of the main wildfire column. Credit: NIFC. The source of this material is the COMET® Website at http://meted.ucar.edu/ of the University Corporation for Atmospheric Research (UCAR), sponsored in part through cooperative agreement(s) with the National Oceanic and Atmospheric Administration (NOAA), U.S. Department of Commerce (DOC). ©1997-2014 University Corporation for Atmospheric Research. All Rights Reserved.

example, a twig that has been wetted (either by rain or by humid air) can be substantially dry within hours under the right conditions, whereas large logs may take a month or more to achieve the same proportion of drying.

Topography/aspect. Fire is significantly affected by the slope of the ground it is travelling over or toward. If the ground slopes up ahead of the fire, the radiant heat from the flame is closer to the fuel and has an easier time heating and drying the fuel and preparing it for ignition. On the other hand, if the ground slopes down ahead of the fire, this heating/drying effect is significantly reduced and the fire has more difficulty propagating. For this reason, fires tend to advance more quickly when they spread uphill [South Australian Country Fire Service, 2010].

Sunward facing slopes experience significantly more solar heating than shaded slopes. This acts to increase drying and makes fire propagation easier. Canyons funnel/accelerate winds and fire can therefore propagate rapidly through them. Fire is also affected by elevation indirectly, in that moisture content of fuels can be significantly different due to increased cloud and precipitation, later/earlier snow cover, altered vegetation density and plant species.

Fire behaviour influences on combustion and emissions. Factors that alter fire behaviour necessarily affect emissions as well. For example:

- fuel breaks act to retard fire by denying it fuel. In a similar manner, cutblocks can change how fire moves by altering the continuity and type of fuel. Firefighters make use of these behaviours to slow down, steer or stop fires by creating controlled fires to use up the fuel ahead of an advancing wildfire. In some cases however, fire can extend or spot over such barriers given sufficiently strong winds
- more pollutants are emitted when:
  a) fuels are moist, inhibiting combustion speed and temperature rise; and
  b) dry fuels burn so intensely that they can consume most of the available oxygen. If oxygen starvation occurs, combustion is incomplete resulting in higher emissions
- fast and intense fires are most associated with:
  a) coniferous trees, due to high amounts of fast burning sap in their branches, as well as the trees' tendency to grow close together
  b) deciduous trees in spring prior to leafout when they have a low moisture content
- fuels can burn differently depending on how they are arranged. Vertical vs. horizontal, compact vs. distributed, large amounts vs. small amounts, size, location, surroundings – all have some influence
- surface fuel fires are usually less intense than crown fires
- trees with dead branches below the crown, or crowns that extend down to the ground are termed "ladder fuels" because they provide a way for fire to move upward from the surface into the higher parts of the tree. For example, certain species of coniferous trees such as black spruce have branches close to the ground, or may be draped with mosses, and this can promote the transition from surface fire to crown fire
- there is a seasonal cycle to how fuels behave as grasses and foliage leaf out, grow, wither and die.

Fire behaviour prediction models. Fire models have been developed by various research groups to predict fire behaviour components; for instance the US BehavePlus [Andrews 2014] and the Canadian Fire Behaviour Prediction (FBP) System [Forestry Canada Fire Danger Group 1992]. In these models, fire behaviour is expressed in terms of fire spread (rate and direction), fuel consumption and fire intensity. Fire intensity is the rate of heat energy release per unit time per unit length of fire front (kW/m), and is equal to the product of the net heat of combustion, the quantity of fuel consumed in the flaming front and the linear rate of spread.

Smoke

Smoke colour. Colour is the outcome of a complex set of factors, but is usually a good indicator of efficiency of combustion. Since fuel type and fuel moisture affect the efficiency of combustion, they also have an effect on the colour. Typical colours for smoke are black, white, grey, brown or orange (in sunlight).

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According to a fact sheet from the Government of South Australia [South Australian Country Fire Service, 2010] smoke colour can provide clues as to the behaviour of a fire. Specifically smoke which is:

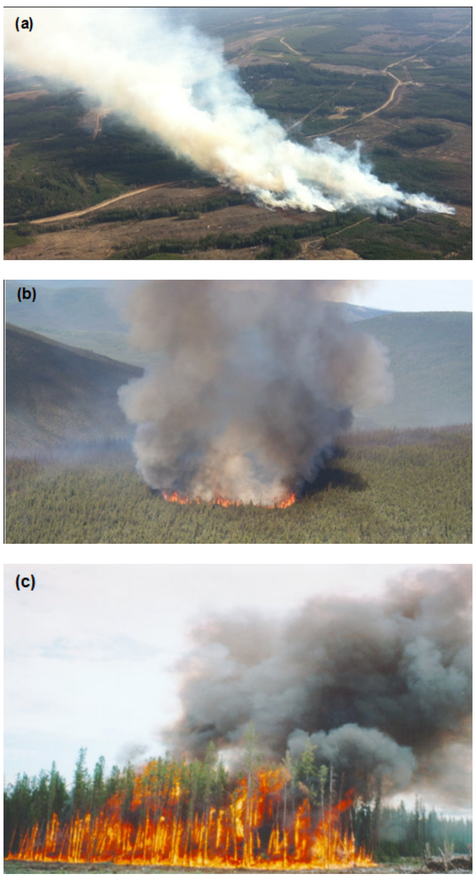

Figure 16: (a) White smoke from fire WWF#008 on May 9th, 2013 in Alberta (picture courtesy of Alberta Environment and Sustainable Resource Development); (b) gray/brown/black smoke from the Mayo#1 wildfire on June 14th, 2005 in the Yukon Territory (picture courtesy of David Milne from Yukon Territory Wildland Fire Management); (c) black smoke from a controlled fire on July 4th, 1998 near Fort Providence in the Northwest Territories, as part of the International Crown Fire Modeling Experiment (picture taken by David Lavoué).

- dense and white generally corresponds to very moist fuel and mild fire behaviour (*with the exception of white water clouds which form within and above intense, smoke-generated convective plumes such as pyrocumulus and pyrocumulonimbus [Ed]*), the white indicating water droplets
- pale grey/blue corresponds to moist fuel and mild to moderate fire behaviour
- black/dark brown corresponds to dry heavier fuel, high fire behaviour and inefficient combustion
- copper/bronze corresponds to very dry fuels and high to severe fire behaviour.

Figure 16 provides three examples of smoke color related to fire behaviour in Canada. Figure 16a shows white smoke from an early spring fire burning in northern Alberta. Meteorological records from a weather station 50 km away indicate that snow cover had just finished melting away, so fuel moisture was likely high. Fire danger at the time is estimated to be moderate (based on a comparison between this photo and pictures taken during experimental fires where the Fire Weather Index was known (http://cwfis.cfs.nrcan.gc.ca/background/examples/fwi, accessed 1 June 2014).

Figure 17. Orange sunlight through smoke. Image courtesy of US National Parks Service - Yellowstone Photo Collection.

Figure 16b shows crowning at a fire in the Yukon mountain forest in June 2005. The daily Yukon Wildfire Bulletin indicates that fire behaviour was extreme in that region by mid-June. The variety of colours are likely due to a mixture of black and brown smoke emitted during the flaming phase and light-coloured smoke which may be due to moisture driven from within the fuels or smouldering behind the flaming front.

Figure 16c shows black smoke emitted during the continuous crowning phase of a controlled burn in the Northwest Territories. Based on weather observations taken a few kilometers from the burn site, the FWI was 28 (Very High) and the fire intensity was approximately 15,000 kW/m.

One of the more common colours associated with smoke is orange (Figure 17). This is an optical effect which occurs relatively frequently when smoke containing a high proportion of very small particles interjects itself between the observer and the sun. In this situation, the particles deflect blue, green and yellow more strongly (but not totally) from the line of sight, allowing predominantly orange and red light to reach the observer's eye.

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Smoke composition. It must be reiterated that the formation of smoke is an incredibly complex process. The chemical constituents of fuel (which can vary wildly by region), moisture within and around the fuel, the temperature at which the burning or smouldering combustion occurs, the turbulent diffusion of heat and ventilation of oxygen imparted by wind, all influence the myriad chemical pathways that occur simultaneously when fire travels across the landscape, smoulders in duff and litter or creeps along underground. In addition, products such as herbicides or man-made chemicals can be added to the mix when treated plant material, garbage (e.g., tires) or stored industrial equipment and tanks (e.g., propane) burn.

Smoke can take a number of forms, from gases to tiny particles to clumps of large particles. An Australian study looked at the chemical soup that bushfire fighters are exposed to as they work to extinguish fire for extended periods of time. Contained in the soup were tar, silica particles, free radicals, toxics such as carbon monoxide, PAHs, VOCs, as well as irritants such as formaldehyde, sulphur dioxide and acetic acid. In fact, wildfires can produce thousands and thousands of chemical compounds. Table 1 lists some of the more predominant emitted and secondary compounds and places them into two broad categories, gases and particles [Urbanski et al., 2009]. Leaving aside debris launched into the air close to a fire, particle formation in fires is mainly due to condensation and coagulation (hitting and sticking). Intense fires tend to reduce the amount of oxygen available deep inside the flame, inhibiting oxidative reactions. As a result, the amount and size of particles produced is greater with more intense fire. Smoke particle shapes vary from roughly spherical

Gases	
Carbon dioxide (CO_2)	Greenhouse gas. Together with CO, it forms the bulk of total emissions from fires (92-95%)
Carbon monoxide (CO)	Photochemically reactive, colourless, odorless, produced by incomplete combustion, a concern in smouldering areas
Methane (CH_4)	Greenhouse gas. Fourth largest source of emissions from wildfires (after CO_2, CO and $PM_{2.5}$)
Nitrous oxide (N_2O)	Greenhouse gas. Multiplying its warming potential by its emission factor makes it as climatically important as CH_4
Non-methane volatile organic compounds (NMVOC)	Formaldehyde, acetic acid, formic acid, methanol… Photochemically reactive
Nitrogen oxides (NO_x)	Photochemically reactive
Ozone (O_3)	Produced in secondary VOC/ NO_x photochemistry reactions in the plume (not as part of the initial combustion), in some cases at considerable distances from the fire
Polycyclic Aromatic Hydrocarbons (PAHs)	A group of more than 100 chemicals such as fluorene, naphthaline, phenanthrene and pyrene, some of which are carcinogenic. PAH molecules act as condensation nuclei for other gases
Particles	
Black Carbon (BC)	Light absorbing aerosol made up of pure carbon
Organic Carbon (OC)	Light scattering aerosol composed of carbon mixed with other elements such as hydrogen
Secondary Organic Aerosols (SOA)	Gas to particle processes which occur mostly as a result of NMVOCs reacting with NO_x
Trace minerals	Silica, dust, soil. Given sufficiently strong updrafts and turbulence around the base of the fire, particles resting on or around fuels can be sucked up and form part of the plume
PAH micro particles	PAH and SOA molecules act as sites for pyrolized gases to condense onto, or for other particles to stick to (coagulation).
Ash	Large ash particles can be found 10's of kilometers downwind from large fires. In some cases, pyroCBs have lofted ash into the upper atmosphere, resulting in horizontal transport for hundreds or thousands of kilometers.

Table 1. Some major components of wildfire smoke.

liquids to irregularly shaped solids, to combinations of the above as a result of particles of various shapes sticking to each other. Particles can be partly liquid and partly solid when gases condense onto solid particles to form a liquid coating. Round liquid particles with no solid core also exist and are termed tarballs. Electron microscopy provides a superb up-close view of smoke particles (Figure 18).

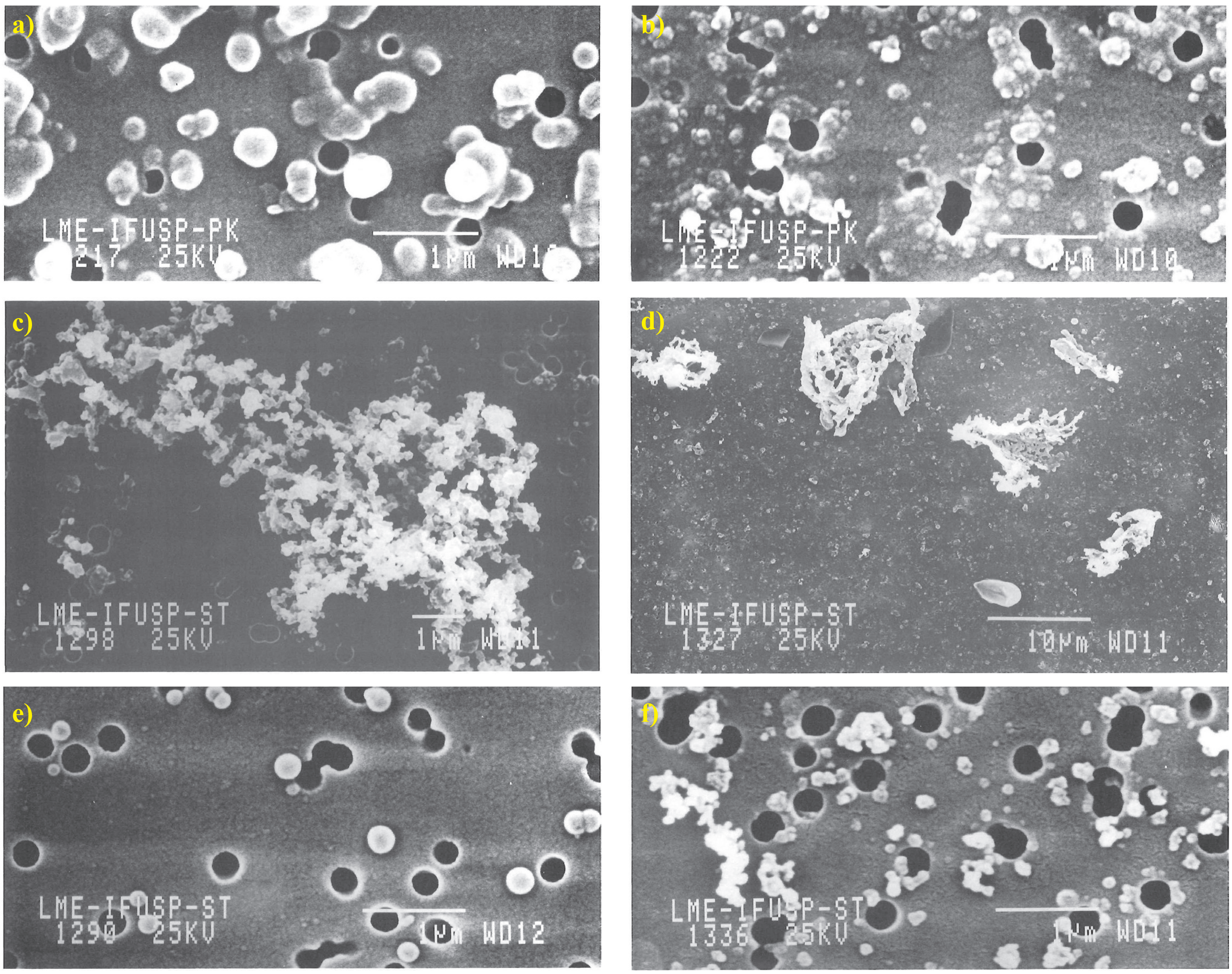

Figure 18. a) Particles resulting from flaming combustion, collected 7 minutes after fire ignition; b) Particles resulting from flaming combustion, collected 32 minutes after fire ignition; c) soot cluster, flaming combustion, 94 minutes after ignition; d) soot cluster, flaming combustion, 37 minutes after ignition; e) particles resulting from smoldering combustion; f) particles sampled 21.8 km downwind, 178 minutes after ignition. Photographs taken from article entitled "Particle size distributions, elemental compositions, carbon measurements, and optical properties of smoke from biomass burning in the Pacific Northwest of the Unites States" from 'Biomass Burning and Global Change, Volume 2, edited by Joel S. Levine, Cambridge, MA: The MIT Press, pp. 716–732, Figure 67.1 (http://mitpress.mit.edu/node/189387) (Image courtesy Vanderlei Martins and MIT Press).

Fine particles known as $PM_{2.5}$ (particles < 2.5 microns in aerodynamic diameter) are the third largest source of emissions (after CO_2 and CO). 50-60% of smoke particles are composed of organic carbon (roughly speaking, carbon bound to other elements, usually hydrogen) and 5-10 percent of smoke particles are composed of black carbon (pure or elemental carbon) [Reid, 2005]. As alluded to above, convective water clouds made up of fine water droplets occasionally form within and above wildfires (Figure 19).

Pollutants are often categorized as primary or secondary. Primary pollutants are emitted directly from sources such as wildfires whereas secondary pollutants are the result of reactions of various chemicals within the plume as it moves with the wind. The highly cited study by Andreae and Merlet, [2001] provides a comprehensive list of emission factors of chemical compounds measured in the laboratory or in the field. Some smoke pollutants have been classified as Criteria Air Contaminants (CACs) in Canada (https://www.ec.gc.ca/air/default.asp?lang=En&n=7C43740B-1, accessed 22 July 2014).

Chemical evolution of smoke plumes. Plumes from large fires can maintain their identity over long distances, in some cases for thousands of kilometers. Turbulent mixing and diffusion gradually act to disperse the particles within an air mass. How a smoke plume evolves with time and distance is called "plume aging" in atmospheric science. Aging is characterized by decreasing particulate concentration, increasing particulate size, and increasing particulate volume (e.g., Hobbs et al. [1996]) as coagulation and gas to particle conversion processes continue to operate within the plume.

For ozone, it appears that a significant proportion of the total ozone produced in smoke is generated within a few hours of the smoke being emitted (young smoke) by oxidation of alkenes and aldehydes in the presence of NO_x catalysts. Ozone concentrations can then remain high as smoke plumes are transported over hundreds or thousands of kilometers. On some occasions mixing to the surface occurs, creating high ozone episodes. In older smoke plumes travelling across long distances, the oxidation of CO and alkanes becomes dominant. Whether the overall amount of ozone produced is significant depends on a complex interaction of factors like temperature, the amount of solar radiation, the type of fuel burned, the amount of reacting chemicals emitted and their dispersion by turbulent mixing [Nikolov, 2008]. Carbon dioxide behaves somewhat differently. It is dominant close to a fire, but is depleted with time, and CO becomes dominant as the plume ages and travels with the wind [Matichuk, 2007].

Plume rise. Plume rise depends on both fire behaviour and atmospheric conditions at the surface and aloft. Buoyant, heated gases above wildfires rise and entrain surrounding cool air. Buoyancy is the means by which thermal energy released at the fire is converted to kinetic energy of motion within a vertical column.

Traditionally, fires are categorized either as wind-driven or as plume-dominated [Byram, 1959]. For the former, winds in the boundary layer are strong, and fire direction and rate of spread are primarily driven by wind direction and speed, respectively. These fires tend to have an elliptical shape, and their convection columns lean downwind and usually do not reach great heights.

Conversely, columns of plume-dominated fires tend to rise to their full

Figure 19. White cumulus water clouds condensing above smoke plume near Edra forestry tower, Alberta. Photo courtesy Alberta Environment and Sustainable Resource Development.

extent vertically when the winds are constant or decreasing immediately above the fires. Because these fires are influenced by their own convective circulation, their direction and rate of spread can suddenly change, which makes them very dangerous on the ground. Convection columns are usually well-developed and can reach 5000+ meters (the mid-troposphere). Such fires can produce a pyro-cumulus or even a pyro-cumulonimbus cloud (pyroCb), characterized by showers, lightning, and strong downburst winds.

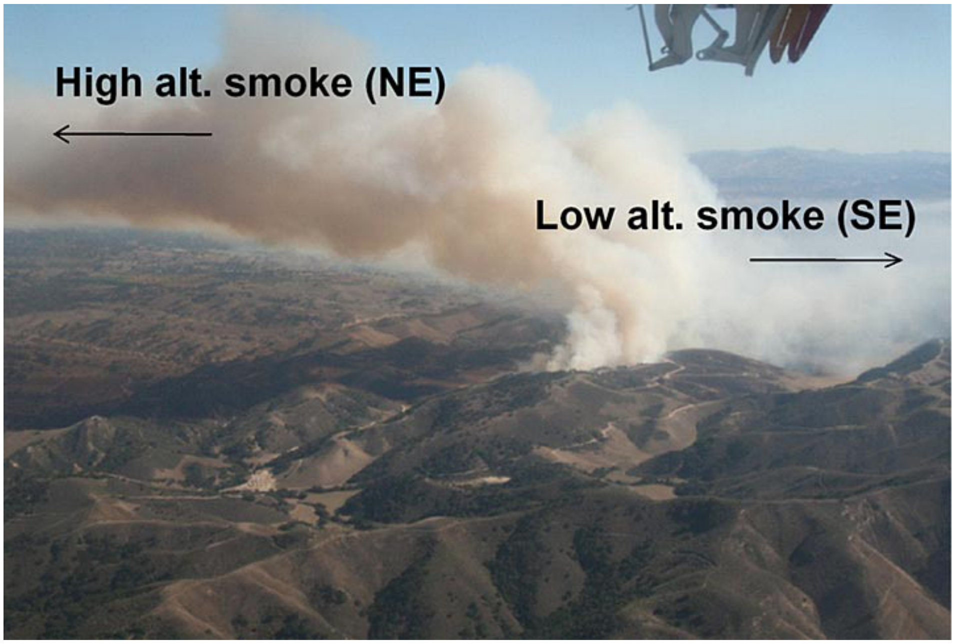

Figure 20. A chaparral fire plume in California. Low altitude smoke due to smouldering moves southeastward while the high altitude plume has lofted above the boundary layer and is blown in a northeasterly direction. Credit: Sheryl Akagi.

The exact height and dynamics of a smoke column are a function of the atmospheric lapse rate, turbulent flow in the environment around the fire and the size/intensity of the fire itself. The process can then feed back on itself. A plume behaves as a semi-solid barrier moving slowly across the landscape, partially blocking ambient wind and creating whirlwinds and vortices within itself and to the lee of the plume. The heat within the plume mixes with its surroundings via entrainment and the plume radiates energy as well, thereby changing the thermal environment around it. All of these processes which are set in motion by the presence of the fire in turn affect a fire's own evolution.

Figure 21. Smoke plume changing direction with height. Image taken from the Whitefish forestry tower in Alberta. Image courtesy Alberta Environment and Sustainable Resource Development.

Further complication ensues when winds change direction with height. Figures 20 and 21 each show a plume where wind flows within and above the boundary layer are drastically different, resulting in smoke being blown in different directions depending on how high the plume rises.

Two extremely destructive fires that occurred in Alberta 10 years apart provide us with examples of convective and wind-driven plumes.

a) In the summer of 2001, the Chisholm fire destroyed 120,000 hectares of forest (Figure 22). Its convection column reached the lower stratosphere [Fromm and Servranckx, 2003]. The plume was simulated with the numerical model ATHAM (Active Tracer High Resolution Atmospheric Model) [Trentmann et al. 2002]. ATHAM can simulate the three-dimensional evolution of very high energy smoke plumes from forest fires.

b) A good example of the bent-over, wind-driven plume type is the plume from the 2011 Slave Lake fire that destroyed almost half the town of the same name in northern Alberta on May 15th of that year. NASA satellites captured active fires and smoke plumes in the area of the town on May 15th at 1:45 pm local time. Smoke was blowing toward the northwest. By mid-afternoon, wind gusts up to 90 km/hour pushed the fire (identified as SWF065) towards the town. NASA imagery only shows a very light plume from SWF065 since the picture was taken before the "blow up" which happened by late afternoon. Fire management personnel were very concerned by the extreme fire behavior close to a populated area and by the dense smoke which was greatly decreasing air quality at the surface. ATHAM succeeds in simulating the bent-over plume for 10+ km downwind. Fire behaviour

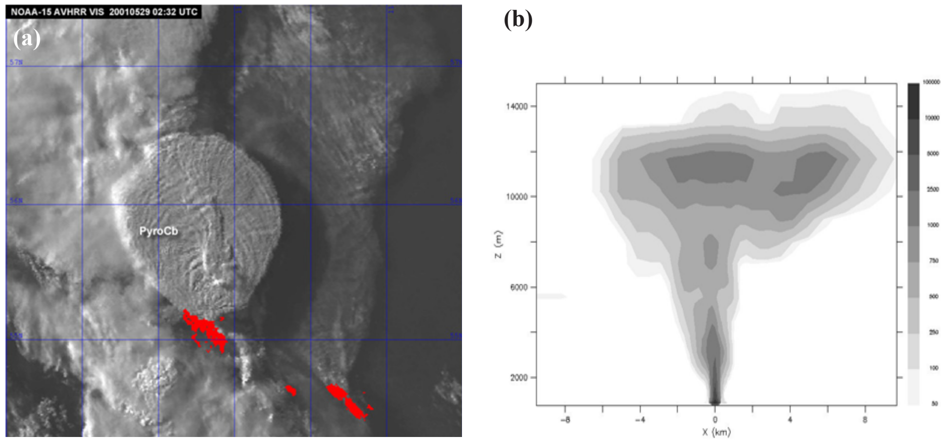

Figure 22: a) PyroCb over the Chisholm fire in Alberta in May 2001, observed from space (AVHRR image courtesy of NOAA; http://www.goes-r.gov/users/comet/npoess/multispectral_topics/fire_wx/, accessed 2 July 2014); b) Chisholm convective column simulated with ATHAM.

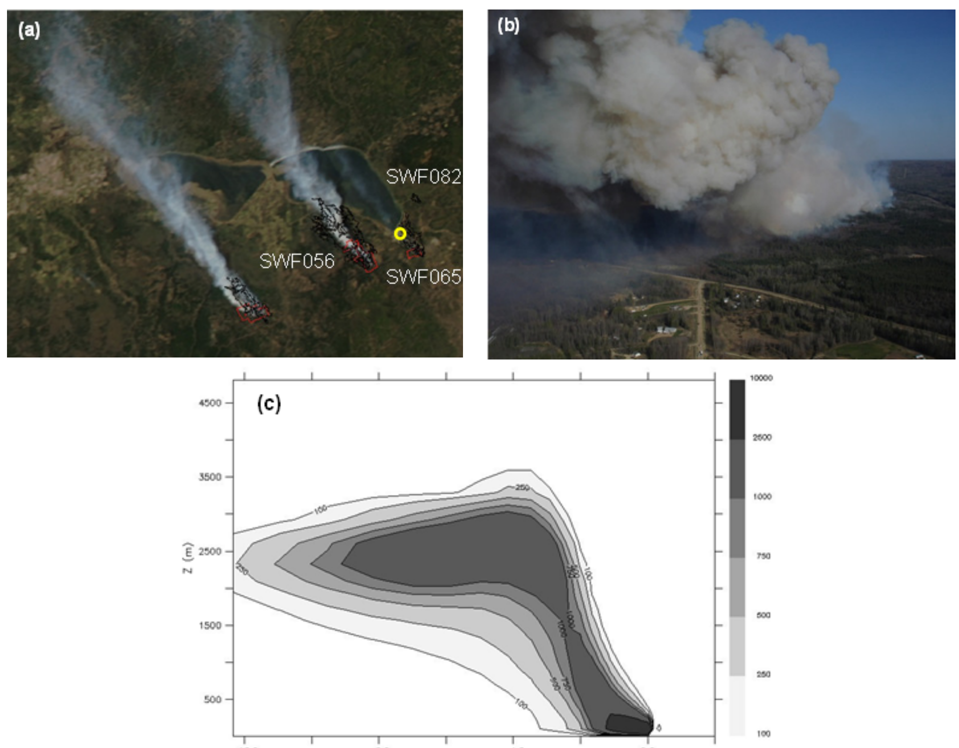

Figure 23. a) Smoke plumes from forest fires burning near the town of Slave Lake (yellow circle) in northern Alberta on May 15th, 2011 at 19:45 UTC (NASA image courtesy of MODIS Rapid Response Team); black polygons correspond to final fire perimeters; b) picture of the bent-over plume from fire SWF065 taken on May 14th (courtesy of Alberta Sustainable Resource Development); c) plume simulated with ATHAM for May 15th; horizontally integrated aerosol mass concentrations (in µg/m³) calculated after 30 minutes of simulation time.

components used in the ATHAM simulation were calculated with local meteorological records.

The story of a typical smoke plume is just beginning after the smoke has been launched into the atmosphere. Once aloft, various processes in the atmosphere, from turbulent diffusion to vertical motion, horizontal transport, removal by dry or wet deposition, coagulation or reaction with other species, affect the concentration of smoke. For most people, these processes only become relevant if and when they bring the smoke in contact with the ground where they live. This contact with the surface can happen in several ways:

- by large particles settling out in the immediate vicinity of a wildfire;
- by smoke particles being caught in descending air, such as that in a convectively unstable boundary layer or in the wake of a cold front; or
- by horizontal transport of smoke near and downwind of smouldering fires; essentially smoke that never loses contact with the ground as it moves.

Once in contact with the surface, portions of the smoke stick to various surfaces such as vegetation or buildings. Some aerosols remain suspended within the boundary layer thanks to turbulence, while others are breathed in by animals and people.

Short-term effects of Smoke

Visibility. One of the most noticeable effects of smoke is visibility reduction. As we learned in the discussion on smoke colour, one of the effects of the aerosols making up the smoke is to scatter light, making objects at a distance either barely visible or not visible at all. For activities such as transportation and tourism, reduced visibility is a significant issue. While it could be argued that a case or two of not being able to see a picturesque mountain is not the end of the world, the possibility of cars travelling at speed suddenly losing sight of what is occurring ahead of them makes dense smoke an immediate safety issue. Over the years, a number of multi-car collisions have occurred in situations where dense smoke has blanketed a highway, especially in the US southeast; e.g. Florida in 2012 (http://wildfiretoday.com/2012/01/29/fog-and-wildfire-smoke-cause-crashes-in-florida-9-dead/, accessed 11 March 2014). In a number of these cases, smoke particles have combined with conditions of high humidity to promote the formation of water droplets, leading to zero visibility, a phenomenon known as superfog.

In the US, problems with visibility reduction (and related health issues) due to regional haze have led the EPA to set out regulations for the states in order to improve visibility in national parks and wilderness areas.

Health. In order to be able to report on ambient air quality, government agencies have created various quantitative indices based on concentrations of different criteria air contaminants (CACs). In Canada, these indices include a provincial Air Quality Index (AQI) for some provinces, and the (mostly) national Air Quality Health Index (AQHI). An AQI category is determined by the concentration of the single worst pollutant, whereas AQHI indicates a level of health risk based on a mixture of pollutants including PM, ozone, and NO_2.

Jaffe et al., [2008] showed that in the western US, mean daytime ozone concentration increases by 2 ppb for every half a million hectares burned. The maximum ozone enhancement found was about 9 ppb. Smoke-impacted air masses can travel over long distances and do not stop at borders. In 2003, Siberian fires increased ozone background concentrations in the western US [Jaffe et al., 2004]. Also, a severe ozone episode characterized by surface concentrations over 125 ppbv (parts per billion by volume) in Houston, Texas in July 2004 was traced back to active wildfires in western Canada and Alaska a week earlier [Morris et al., 2006].

Smoke also affects:

- black carbon concentrations [Dutkiewicz et al. 2011];
- organic carbon concentrations in the western US [Spracklen et al. 2007].

During the summer of 2010, the extreme heat and heavy smog produced by hundreds of fires burning in western Russia were responsible for a death rate twice the normal value in Moscow (http://www.theguardian.com/world/2010/aug/09/moscow-death-rate-russia-wildfires, accessed 2 April 2014).

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According to the US EPA, the components of smoke can have significant adverse short-term effects on human health (Table 2). With respect to long-term health effects of exposure to short episodes of wildfire smoke, the EPA states that "People exposed to toxic air pollutants at sufficient concentrations and durations may have slightly increased risks of cancer or of experiencing other chronic health problems. However, in general, the long-term risk from short-term smoke exposure is quite low." [California Department of Public Health et al., 2008].

One study [Johnston et al., 2012], looked at global premature deaths due to fire smoke, and estimated that between 1997 to 2006, smoke killed approximately 339,000 people per year. Almost 80% of these fatalities occurred in Africa and southeast Asia where human use of fire to manage the land is common.

Particulate Matter	Eye irritation
	Respiratory tract irritation (persistent cough, phlegm, wheezing, difficulty breathing)
	Reduced lung function
	Bronchitis
	Aggravation of existing cardiovascular disease
	Pulmonary inflammation
	Reduced immune response
	Worsening of pre-existing asthma
CO (low levels)	Reduces oxygen delivered by the blood to the body
	Chest pain
	Cardiac arrhythmias
CO (high levels)	Headaches
	Dizziness
	Visual impairment
	Reduced manual dexterity
	Death
Formaldehyde, acrolein	Respiratory irritation

Table 2. Short-term effects of exposure to PM and gases according to the US EPA.

Categories	**Visibility in Miles**	**Particulate Matter Level (µg/m^3) (1-3 hr average)**
Good	13 miles and up	0 – 34
Moderate	9 to 13 miles	34 – 51
Unhealthy for Sensitive Groups	5 to 9 miles	51 – 89
Unhealthy	2 ¼ to 5 miles	89-201
Very Unhealthy	1 ¼ to 2 miles	201 – 339
Hazardous	1 ¼ mile or less	over 339

Table 3. Procedure for obtaining health information from visibility or three-hour particulate concentrations. Missoula County Environmental Health Division, Montana (http://www.co.missoula.mt.us/airquality/currentairquality/currentstatus-report.htm).

Given that visibility reduction increases with rising smoke concentrations, it is reasonable to make some general inferences about health issues that may arise from smoke under various visibility conditions. One procedure put together by the Missoula, Montana City-County Health Department provides a way of converting visibility reductions to statistical PM concentration and general health information for people who do not live close to an air quality particulate monitor: People are advised to:

1. "Face away from the sun"
2. "Determine the limit of your visibility range by looking for targets at known distances (miles). Visible range is that point at which even the high contrast objects totally disappear"
3. "After determining visibility in miles, use the chart (Table 3) to determine health effects and the appropriate cautionary statement."

Damage to infrastructure. In a previous section, it was mentioned that some smoke particles stick when they come in contact with various surfaces, both natural and man-made. Such deposits can cause discoloration and damage due to chemical reactions. An additional example of the damage that can be done is electrical arcing. Smoke particle buildup on the surface of insulators on transmission towers can lead to short circuiting, especially when combined with high humidity conditions, subsequent condensation of liquid water on the insulator and drying leading to uneven contamination and conductive pathways [Ramos Hernanz et al., 2006].

Deposits on insulators are in some cases not even necessary. Arcing from transmission lines to the ground or between wires can occur when fire and smoke are sufficiently close or dense, respectively, to create a conductive path. Arcing under these conditions is called a flashover [Powerlink Queensland, 2009].

Modelling smoke

Emission prediction from satellite retrieval. Fire emissions can be estimated using data retrieved by satellites. The Global Fire Emissions Database (GFED) [van der Werf et al., 2010], the Fire INventory from NCAR (FINN) [Wiedinmyer et al., 2011], and GBBEP-Geo [Zhang et al., 2012] are a few examples of biomass burning emission inventories derived from remote sensing data, such as fire pixel count, burn area, and fire radiative power. These methods partially follow the bottom-up approach and incorporate emission factors to calculate fire emissions. Inventories can be created for anywhere in the world where satellites can detect hotspots, and do not require on-site measurements. Some satellites also catch the diurnal variation of the burn rate, such as the one-hour increment implemented in the GOES biomass burning emission algorithm [Zhang et al., 2012].

Some studies have found that this bottom-up approach using satellite data results in severe underestimation for aerosol emissions [Ichoku and Ellison, 2013; Kaiser et al., 2012; Petrenko et al., 2012]. Burned area estimates derived from satellite data can vary drastically from those based on other methodologies and inventories. Satellites, depending on their sensors and mode of operation, can miss weak and/or short biomass burning events. For example, polar orbiters only catch hotspots once during daylight hours, but have high resolution, whereas geostationary satellites view the earth continuously, but at lower resolutions, especially at northern latitudes.

Smoke Plume Modeling. The two types of plume dispersion modeling approaches are Lagrangian and Eulerian. Lagrangian plume models follow parcels of smoke as they move and are classified into three types:

- simple Gaussian plume model (e.g., AERMOD)
- puff model (e.g., CALPUFF, HYSPLIT), and
- particle model (e.g., HYSPLIT, Daysmoke) [Goodrick et al., 2013].

Eulerian plume models can be thought of as simulating smoke as a series of snapshots of multiple parcels in a fixed grid domain. They can be as simple as a box model, where the studied domain is assumed to be in one well mixed grid box, or complex with full physics (e.g. ATHAM). Puff, particle, and full physics models all have fire specific physics such as plume buoyancy and entrainment, though they come with significant computational cost since they are more complex with fewer limiting assumptions. Finally, some plume dispersion models include chemical mechanisms capable of predicting concentrations of various chemical species downwind, including ozone chemistry and secondary organic aerosol (SOA) formation [Alvarado et al., 2013; Trentmann et al., 2003]. They usually do not include pollutant interactions with the environment.

Plume models, such as CALPUFF and DAYSMOKE, rely on outside weather models (e.g. WRF), for regional scale meteorology. They then adapt the various fields, most importantly wind, to more accurately reflect highly detailed terrain, and in some cases to conform to more detailed observations. These are termed diagnostic models [Odman et al., 2014].

Air quality Chemical Transport Models (CTMs) can represent the most significant chemical and physical processes that occur in the atmosphere, albeit with some error due to the need for simplifying approximations. CTMs can simulate multiple fire plumes over local, regional and global domains. However, CTMs cannot capture the detailed effects of a plume as explicitly as plume dispersion models. Often times, a fire may be smaller than the grid cell in a CTM, which results in the grid dilution effect and makes it difficult to track individual plumes. Many commonly used CTMs do not incorporate fire physics, which makes it impossible for the Eulerian models to predict smoke dispersion accurately. Plume-in-grid (PinG) is a mathematical approach used in CTMs to characterize point source plumes [Karamchandani et al., 2002]. PinG is, however, not appropriate for a wildland fire since wildland fires are area sources.

Other works have attempted to better resolve plumes in CTMs by increasing the grid resolution. For example, the grid near the plume is made finer by nesting or by introducing a grid that adapts to fire plume tracers [Garcia-Menendez et al., 2010]. Another approach is the coupling of a Lagrangian plume model in a chemical transport model, i.e., a plume inside a CTM is transported by a Lagrangian plume model until the plume is developed. When a portion of the plume moves a certain distance away from the fire, that portion of the plume is inserted in the CTM. Coupling and adaptive grid methods can be combined to enhance plume behavior and to minimize grid dilution in the CTM.

Smoke Forecasting. A few smoke forecast systems are already operational in North America. The BlueSky modeling framework was developed by the USDA Forest Service to predict daily impact of smoke from wildfires, prescribed burns, and agricultural fires for air quality regulations in the contiguous US [Larkin et al., 2009]. The Western Canada BlueSky Smoke Forecasting System has been operational since early 2010, as a collaborative effort between the British Columbia Ministry of Health, the University of British Columbia, the Canadian Forest Service, Alberta Environment and Environment Canada among others; the system was first used to qualitatively assess wildfire smoke transport in British Columbia and Alberta [Sakiyama, 2011]. Smoke emissions are based on fire behavior components calculated by Natural Resources Canada (http://cwfis.cfs.nrcan.gc.ca, accessed 27 June 2014). Another smoke forecasting system is run by NOAA and integrates the HYSPLIT dispersion model to produce daily 48-hour prediction of fine PM transport and concentration [Rolph et al., 2009]. An example of a global smoke forecasting model is FLAMBE, which bases predictions on satellite retrievals of fire hotspots [Reid et al., 2009]

Changing Climate and Implications for Fire and Smoke

Changing climate. A number of direct and indirect indicators from different research fields point toward a warming climate regime over North America. For example:

- annual area burned in Canada has doubled since the early 1970s to around 2 million hectares today
- wildfire season length in British Columbia has increased by 1-2 days per year since 1980 [British Columbia Ministry of Forests and Range 2010]
- nationally, Canada's mean temperature has increased by 1.4 degrees over the past 62 years (http://www.statcan.gc.ca/pub/16-002-x/2011001/part-partie2-eng.htm, accessed 18 May 2014)
- based on USFS records (http://www.ucsusa.org/global_warming/science_and_impacts/impacts/infographic-wildfires-climate-change.html, accessed 14 July 2014):
  - » the average length of the fire season in the western US has increased by 78 days since 1970. Fire seasons now last on average over 7 months
  - » the annual average number of wildfires larger than 1000 acres (405 hectares), has gone from approximately 140 in the 1980s to around 250 for the period from 2000-2012
  - » the start of snow melt now occurs from 1-4 weeks sooner than it did in the 1940s
- fire occurrence in Alaska has been on the rise for several decades [Turetsky et al., 2010]
- averaged over all ecoregions in the western US, the number of large wildfires has increased by seven fires per year since 1983; fire area has increased by 355 km^2 per year [Dennison et al., 2014]
- since 1970, the average annual temperature in the western US has increased by 1.9ºF (http://www.ucsusa.org/ global_warming/science_and_impacts/impacts/infographic-wildfires-climate-change.html, accessed 27 June 2014)

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

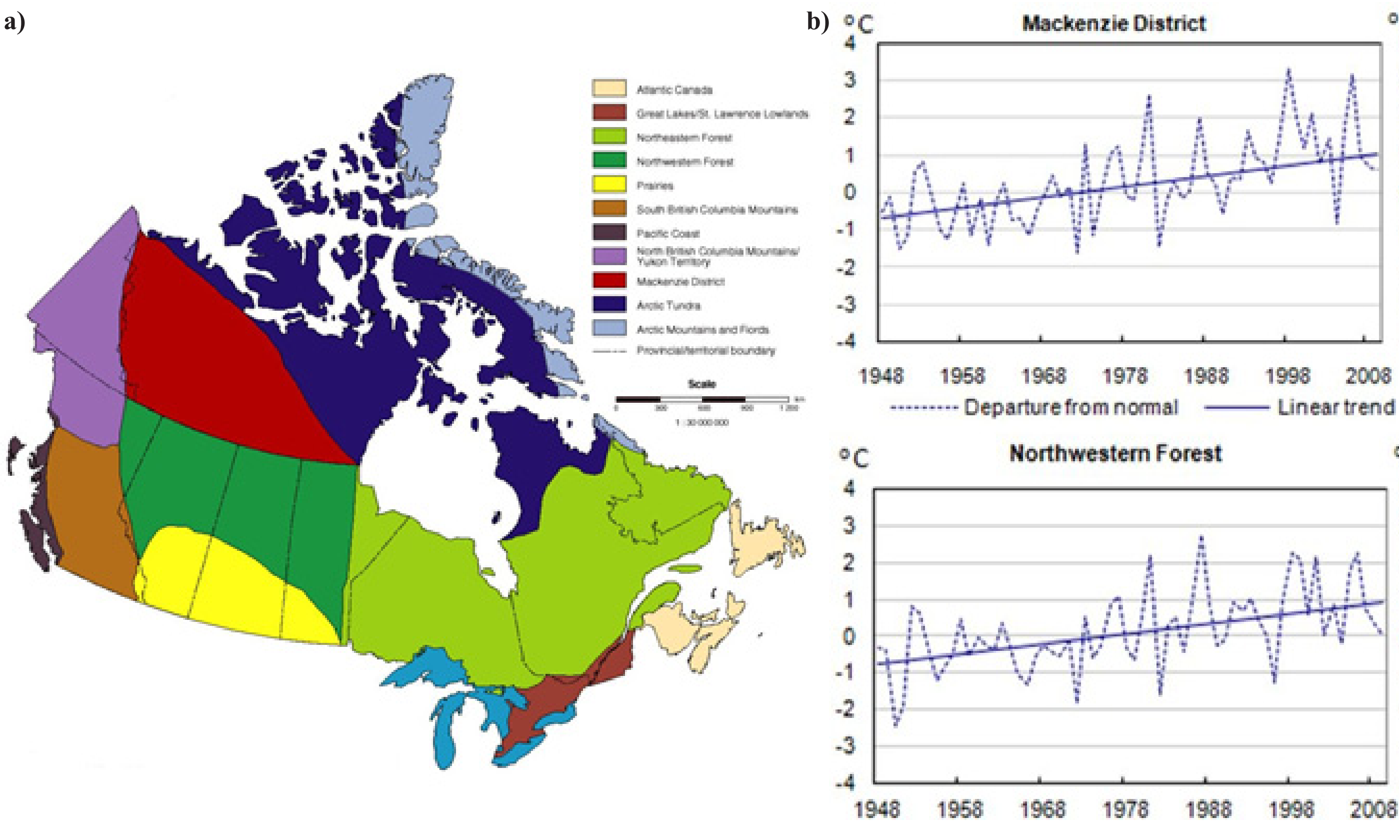

Figure 24. a) Canadian climate regions [Environment Canada, 1998]; b) Temperature departures from normal over the Mackenzie District and Northwestern Forest District, courtesy Environment Canada.

Most large fires in Canada are located in the Mackenzie District and Northwestern Forest climatic zones (Figure 24a). Meteorological records indicate that surface air temperature in both zones has increased since 1948 (Figure 24b).

A collaborative effort from various fire management agencies in Canada and Alaska has resulted in the creation of historical records of fire occurrences across the North American boreal zone. Figure 25 shows a map of the fire perimeters by decade for the period from 1960-2009. One-third of the area burned is located in a region stretching from northwestern Ontario to the

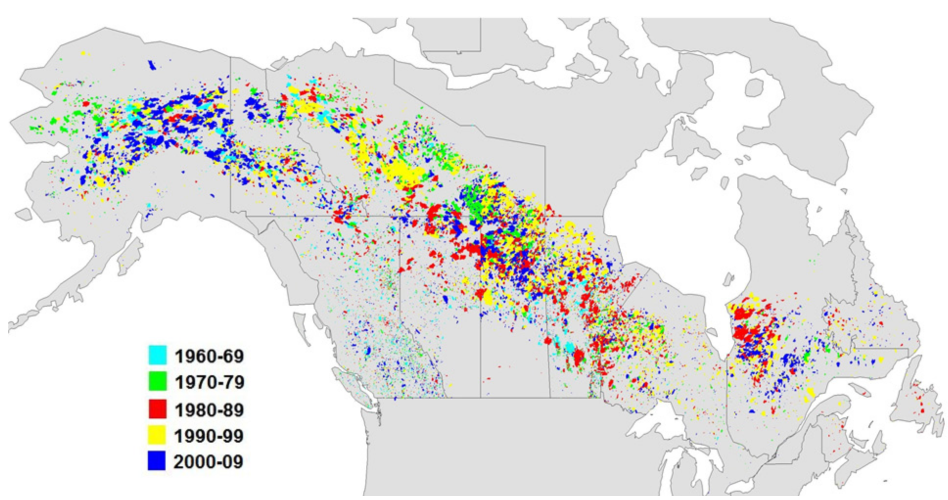

Figure 25: Decadal fire polygons in Canada and Alaska during 1960-2009. Plots based on data published by Canadian Forest Service, 2013, and the Alaska Interagency Coordination Center, 2014.

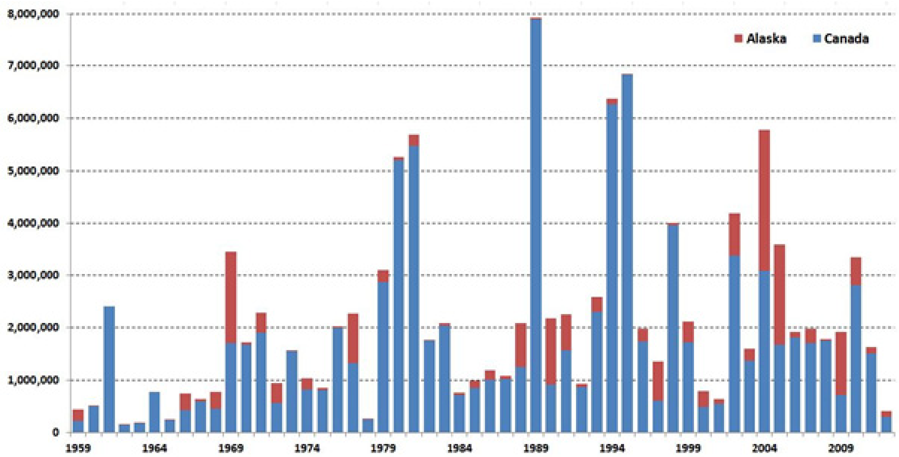

Figure 26. Annual areas burned (in hectares) in Alaska and Canada between 1949 and 2012. Chart based on data published by Canadian Forest Service, 2013, and the Alaska Interagency Coordination Center, 2014.

Northwest Territories [Krezek-Hanes et al., 2011]. A time-series of annual areas burned is presented in Figure 26. The Mann-Kendall statistical test indicates an upward trend in annual boreal area burned at the 99% significance level.

Impact of changing climate on fire weather and fire behaviour.
Observations as well as climate models applied to data from 1951 to 2011 have both found a statistically significant signal that indicates a poleward shift in the westerly jetstreams for both hemispheres. Projections indicate that this trend is likely to continue. Models also suggest that climate change could greatly impact boreal fire regimes [Flannigan et al., 2013]. For instance, projected climate deviation from historical values indicates that temperature and precipitation could increase by 2 to 2.5 C° and 5 to 10 mm, respectively in northwestern Ontario by mid-21st century (Figure 27). The historical values are based on weather records from Sioux Lookout (50º06’N, 91º55’W) between 1971 and 2000. Projected temperatures and precipitation amounts are obtained from an ensemble composed of over 60 Global Climate Model outputs for the 2041-2070 period (http://www.cccsn.ec.gc.ca/, accessed 18 May 2014). Stocks et al., [1998] calculated the change in the monthly severity rating (MSR) between $1xCO_2$ and $2xCO_2$ climate scenarios. MSR is a quantitative index to rate the difficulty of controlling fires. Their study suggested that MSR would increase by 50% during the fire season at Sioux Lookout.

A similar recent study by de Groot et al. [2013] looked at the boreal forest covered two Canadian climatic regions, the Mackenzie District and Northwestern Forest. Components of both Canadian FWI and FBP Systems were calculated with outputs from 3 global climate models and 3 scenarios for the end of the 21st century. Their results project an overall greater severity of fire weather conditions across western Canada’s boreal forest,

a) b)

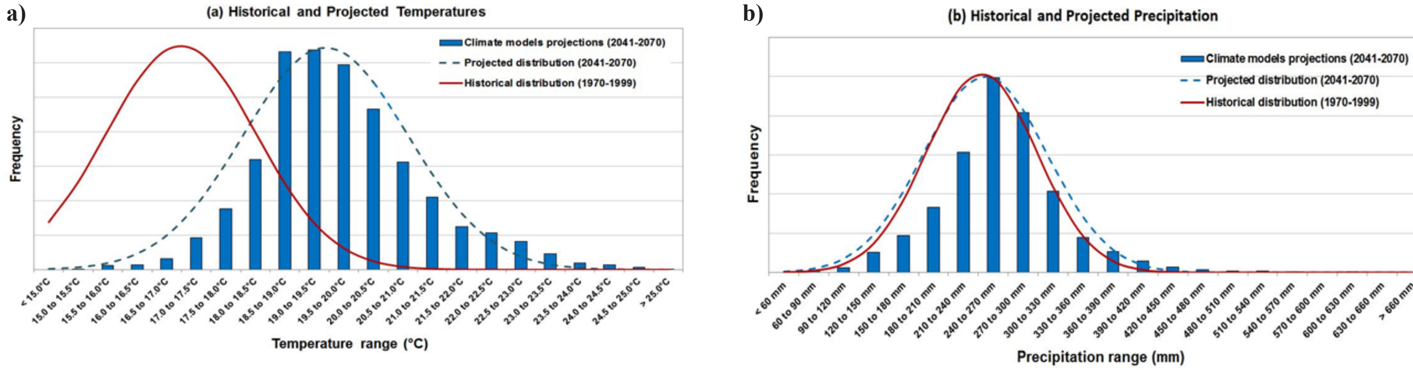

Figure 27: Historical and projected temperatures (a) and precipitation (b) during summertime at Sioux Lookout in northwestern Ontario. Histograms indicate how often projected the weather component falls into the ranges given on the x-axis. Solid and dashed lines represent normal probability curves fitted to the historical and projected datasets, respectively. Charts are based on historical weather data and Global Climate Model outputs both published by Environment Canada.

with higher fuel consumption, a slight increase in the amount of crown fire, and a bimodal distribution of fire intensity with peaks in spring and late summer.

A recent study by [Spracklen et al., 2009; Yue et al., 2013] using an ensemble modelling approach predicts an increase of background $PM_{2.5}$ and organic carbon for the second half of the 21st century. Additionally, as indicated in the emissions section, fires release black carbon (BC) particles in the atmosphere. BC is a light-absorbing and short-lived (from a few days to a few weeks) aerosol. It has a positive radiative feedback on the climate and contributes to warming by adding to the effect of greenhouse gases [Feichter and Stier, 2012] [Stone et al., 2008]. BC has been referred to as a short-lived climate forcer [Governing Council of the United Nations Environment Programme, 2011]. BC aerosol has an additional effect on climate through surface deposition. This effect is strongest when BC is deposited onto snow and ice surfaces, where it can reduce the snow albedo and thereby perturb the regional Arctic radiative balance [Flanner et al., 2007].

Climate researchers agree about an overall global warming trend, but determining which regions will warm and which will cool within the overall averaged warming process is more difficult to ascertain. We have already seen heavy and sustained smoke impacts on populations. Although due in large part to human neglect or direct ignition, these episodes (Russia in 2010, Indonesia/Singapore/Malaysia in 1997 and 2013) gave the world a taste of life under large areas of smoke for weeks and months at a time. The best available predictions at present indicate the world can expect more of the same. Tools currently being developed to predict smoke will assist us in both short-term and long-term decision making as we try to find the best way to cope. **§**

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Papers of Interest

Long-range transport of Siberian wildfire smoke to British Columbia: Lidar observations and air quality impacts

Paper published in Atmospheric Environment, 17 March 2014. Authored by P. Cottle, K. Strawbridge and I. McKendry.

In recent years, several poor air quality episodes on the west coast of North America have been traced, at least in part, to emissions of pollutants, dust and smoke from Asia. This paper provides preliminary results from a study of several episodes in which wildfire smoke crossed the Pacific from Siberia and caused significant reductions in air quality over southwestern British Columbia, Canada during the summer of 2012.

Tools. The lower Fraser valley of south-western British Columbia (BC) is home to over 70 surface air quality monitoring sites as well as two ground-based lidars, which form part of the Canadian Operational Research Aerosol Lidar Network (CORALNet). Each lidar is a nd:YAG Continuum Inlite III which is housed in a trailer, and which has three detection channels, one at 1064 nm, and one for each polarization at 532 nm. The system acquires a sounding every 10 seconds up to an altitude of 18 km at three meter resolution. Of the 70 surface air quality monitoring stations available, nine were chosen to be part of the study, due to their location as well as the fact that they were able to monitor both $PM_{2.5}$ and PM_{10} using tapered element oscillating microbalance (TEOM) instruments. This capability allows fine mode fraction (FMF, the ratio of $PM_{2.5}$ to PM_{10}) to be calculated.

In order to track smoke back to its point of origin, the team used the HYbrid Single-Particle Lagrangian Integrated Trajectory (HYSPLIT) model (version 4) on each day of interest. Back-trajectories were run at 6-hour intervals, and went back 150 hours from arrival time.

The US Navy Aerosol Analysis and Prediction System (NAAPS) was used to provide additional modelling of possible smoke particle origins and paths. Fire sources for the model were provided by the Fire Locating and Modelling of Burning Emissions (FLAMBE) and the GOES Wildfire Automated Biomass Burning Algorithm (WF_ABBA) projects.

The study. The months of July and August, 2012, saw an abnormally high number of wildfires (more than 17,000) take place in boreal Asia. Results from NAAPS showed large plumes periodically moving across the Pacific from Siberia to North America. The study focused on three such plumes which were identified by lidar on July 6-8, August 10th and August 13th. In the first episode, smoke particles were first seen between 2000-3600 meters above ground. They were gradually entrained into the boundary layer over the following week, causing several spikes in surface $PM_{2.5}$ and PM_{10} measurements. HYSPLIT back trajectories were run for July 8th from Vancouver, at termination altitudes between 1600-4000 meters. A large proportion of the resulting trajectories had passed over the Siberian wildfires six days earlier, confirming the paths indicated by NAAPS.

The two August episodes exhibited a similar pattern of smoke arriving aloft and descending to become entrained and mixed within the boundary layer. In these cases the initial smoke heights were higher than in July. Surface $PM_{2.5}$ spikes occurred again, but seemed to be less correlated to events aloft than in July. Again, NAAPS forecasts and HYSPLIT trajectories were consistent with Siberian fires as the main source of the aerosols detected by the lidars.

The volume depolarization ratio is the ratio of the perpendicularly polarized backscattered light to parallel polarized backscattered light, integrated over a layer. It is used when assessing atmospheric aerosols such as particles and droplets, and provides information on phase and shape. In this study, volume depolarization ratios for all three events for all altitudes were below 0.15, and the majority of the time below 0.1, with some variation in aerosol layer composition with altitude. However, from 500-3600 meters, volume polarization ratios exhibited a mean of 0.05 +/- 0.015. This low value as well as the lack of variation indicates that the aerosols were aged aerosols whose origin was biomass burning.

Interestingly, average $PM_{2.5}$ values for southwestern BC for July and August were significantly higher than average, suggesting that the smoke transport events occurred against the backdrop of an extended period of reduced average air quality in the lower Fraser valley.

Future plans. Several additional papers dealing with these events are planned, and will add significant new information from air chemistry instruments at Whistler BC and Mount Bachelor in Oregon, as well as information from a single particle soot photometer. §