Biomass Burning Plume Injection Height Using CALIOP, MODIS and the NASA Langley Trajectory Model

Dr. Amber J. Soja
National Institute of Aerospace (NIA)
Resident at: NASA Langley Research Center
Climate Science and Chemistry and Dynamics Branches
21 Langley Boulevard MS 420 Hampton, VA 23681-2199
Phone: (757) 864-5603 Fax: (757) 864-7996
Email: amber.J.Soja@nasa.gov or amber.soja@nianet.org

Dr. T. Duncan Fairlie
NASA Langley Research Center
21 Langley Boulevard MS 401B
Hampton, VA 23681-2199
Phone: (757) 864-5818 Fax: (757) 864-7996
Email: t.d.fairlie@nasa.gov

Mr. David J. Westberg
Science Systems and Applications Incorporated
One Enterprise Parkway Suite 200
Hampton, VA 23666
Email: david.j.westberg@nasa.gov

Dr. George Pouliot
Physical Scientist Atmospheric Modeling Division/NERL/ORD
Research Triangle Park, North Carolina, 27711
Phone: (919) 541-5475
Email: Pouliot.George@epa.gov

ABSTRACT

Biomass burning emissions have the potential to alter numerous land and atmospheric processes, which has strong implications for air quality and feedbacks within the climate system. The heights to which biomass burning emissions are injected directly (i.e. black carbon on Arctic ice, pollution) and indirectly [above- under-clouds affects radiation balance (albedo - relative reflectance); modifies patterns of precipitation] impacts humankind and feedbacks to the climate system.

In this work, fire plume injection height is derived using satellite-based, high-resolution lidar in combination with other sensors and models. Two products are presented and initial statistics are discussed, all of which are derived from fires that burned in North America in August 2006. One of the products traces the vertical domain of a smoke plume back in time to the emitting fires. This river of smoke can be attributed to numerous fires that range in injection height from the surface to 6300 m above the surface. The second product combines numerous overpasses to produce the daily evolution of specific fire events.

We expect these data will be valuable to: local, state, national and international air quality communities; to public land, fire, and air quality management and regulations communities; to regional and global chemical transport modelers; to small-scale smoke plume dynamics modelers; for verification and validation purposes within the CALIPSO science and algorithm teams; and for general scientific communities (i.e. climate change, atmospheric processes, cloud and radiation balance, modeling patterns of precipitation).

1 INTRODUCTION

1.1 Objectives

This project takes advantage of multiple sensors on several platforms to generate detailed biomass burning plume injection height information that is produced using the Langley Trajectory Model (LaTM) and ESRI Geographic Information System (GIS) tools. Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observation (CALIPSO) data are used in combination with the LaTM, National Oceanic and Atmospheric Administration (NOAA) Hazard Mapping System (HMS) smoke product, and Moderate Resolution Imaging Spectroradiometer (MODIS) Thermal Anomaly (or Fire Detection) data to develop novel CALIOP-based smoke products for use in general scientific and Air Quality applications communities.

Specifically, we use the HMS smoke product and CALISPO track information to derive a daily database for North America that shows the spatial and temporal domains where smoke should exist in the CALIOP data. The coincident Cloud-Aerosol LIdar with Orthogonal Polarization (CALIOP onboard CALIPSO) aerosol products are extracted and used as input to the LaTM, which is run backwards in three-dimensional space and time until coincident with MODIS-based fires of interest. In this work, we present two distinct and innovative CALIOP-based biomass burning (BB) plume injection height (IH) products that will add further insight to enhancing the understanding of biomass burning plume dynamics, which should be valuable to numerous communities. In particular, CALIOP and other sensor and model data are being used to define: (1) daily fire plume dynamics; and (2) build a BB IH database that is associated with the variables that drive these dynamics, which includes both ground-based (i.e. fuels) and meteorological variables for North America.

1.2 Background and Motivation

Biomass burning is largely a natural process that is integral to ecosystem maintenance and resolving the beginning and end of successional processes. However, BB can adversely affect human health and serves as an interface between the biosphere, atmosphere and climate systems by affecting carbon balances, altering hydrologic regimes, modifying patterns of clouds and precipitation, modifying permafrost structure, altering direct and indirect emissions, and altering radiative forcings by changing albedo, both directly (i.e. vegetation change due to younger and more reflective species; black carbon deposition to the Arctic) and indirectly (i.e. precipitation, clouds) [1-9].

Biomass Burning (BB) Plume Injection Height (IH) directly influences the distance a smoke plume will travel, which impacts its destination (i.e. Arctic snow and ice; above- under-, within-cloud) and when a community might experience health risks and reduced visibility due to adjacent or remote BB events. BB emissions act as sources of pollution that are transported beyond localities and have the potential to affect global atmospheric chemistry [10-17].

Therefore, accurately estimating plume height has implications for the atmospheric and climate science research communities, regional and global chemical transport modeling (CTM) communities and for the Air Quality and regulations communities. BB burning not only directly releases greenhouse gas emissions, often from carbon pools that have been stored for centuries, but also these emissions can be transported long distances [18-22] and strongly feedback to the atmosphere and climate systems, the extent to which is currently being realized. Significant quantities of BB emissions were recently and unexpectedly discovered in the Arctic spring during a field campaign designed to investigate Arctic haze, and these BB emissions, specifically black carbon, have implications for the sensitive early-season ice, snow and cloud albedo feedbacks in Arctic [21, 23, 24] (websites located below citations ARCTAS; CATF). In the spring, Rossby waves are located farther south in comparison to the summer, allowing early-season BB emissions to be transported to the Arctic, which could lead to early melting of snow and ice, both of which feedback to the climate system, ultimately affecting albedo (relative reflectivity of land, atmosphere and clouds). Because black carbon is insoluble, this further enhances its affect as snow and ice melts, revealing black carbon from previous years.

Aerosols can influence the microphysical and macrophysical properties of clouds and hence impact the energy balance, precipitation and the hydrological cycle (indirect aerosol effects). Natarajan et al [21] focused on plumes that originated in Thailand and Russia and were transported to the Arctic during ARCTAS 2008 and found an overall positive radiative forcing, which resulted from radiative cooling at the surface and warming aloft, which highlights the dependence of radiative forcing on plume injection height and cloud interaction (smoke above-, in- or below-cloud). Additionally, researchers have suggested that plumes alter cloud patterns and droplet size, suppressing precipitation in the near field and invigorating precipitation downwind of fire events [10, 25, 26].

State, regional and federal air quality communities are interested in these data to improve plume injection height and dynamics within the Community Multiscale Air Quality (CMAQ), which is used for a number of critical environmental management and policy activities including regulation setting and regional strategy development for attainment of the National Ambient Air Quality Standards (NAAQS) [27-31]. Biomass burning is one of the primary causes of elevated airborne particulate matter ($PM_{2.5}$ particulate matter with a mean diameter of 2.5 microns or less), ozone precursors and regional haze. BB is an important source of primary $PM_{2.5}$ emissions and other pollutants that can form secondary $PM_{2.5}$, which have been linked to a series of significant health problems, including aggravated asthma, increases in respiratory symptoms like coughing and difficult or painful breathing, chronic bronchitis, decreased lung function, and premature death [32-36]. Ozone can irritate lung airways resulting in inflammation, wheezing, coughing, aggravated asthma, reduced lung capacity, and increased susceptibility to respiratory illnesses like pneumonia and bronchitis.

BB emissions are also a significant contributor to regional haze, which refers to air pollution that impairs visibility over widespread areas that may encompass several states [37]. The Regional Haze Rule requires that states work to protect and improve visibility in 156 national parks and wilderness areas, such as the Grand Canyon, Yosemite, the Great Smoky and Shenandoah. Recognizing exceptional events, which include BB, can unavoidably impact particulate matter and ozone level compliance, the EPA issued an Exceptional Events Rule that allows the exemption of certain monitored data. In essence, accurate comprehension of the height to which plumes are injected and transported has national legal significance and monetary ramifications, as well as implications to human, climate and ecosystem health. One can imagine future international air quality and carbon balance rules, as climate changes, through a Kyoto-like treaty.

Other potential uses of these data include processes that are often thought of as land-based but are intricately linked to the atmosphere [38, 39], such as enhancing the understanding of when and where potentially limiting nutrients (potassium) and harmful pollutants (mercury) are deposited. BB injects a host of gases and particulate emissions [40, 41], many of which are carbon-based, which has ramifications for the carbon-balance community. Additionally, air quality and land managers continually have to make burn/no-burn decisions (go/no-go decisions on prescribed fires) depending on weather conditions and smoke transport models in a balancing act with the objective of protecting property, ecosystems, and human health (safety and air quality) [42, 43]. Enhancements in understanding smoke plume dynamics and modeling would be helpful to state, federal and local forest agencies and state and local Departments of Environmental Quality.

Under current climate change scenarios, fire regimes are predicted to increase in terms of area burned, fire frequency, fire season severity, ignitions from lightning, and fire season length [3, 44-49]. Human population is increasing, while concurrently land clearing and interaction with the wildland-urban interface is increasing, both acting to exacerbate wildfires, even in tropical regions where natural fire regimes had been minimal. There is already evidence of increases in fire regimes, particularly in Northern Hemisphere upper latitudes, where the largest pools of terrestrial carbon are stored [3, 19, 20, 50-52]. For these reasons, understanding plume heights, which affects feedbacks to and from fires, becomes imperative.

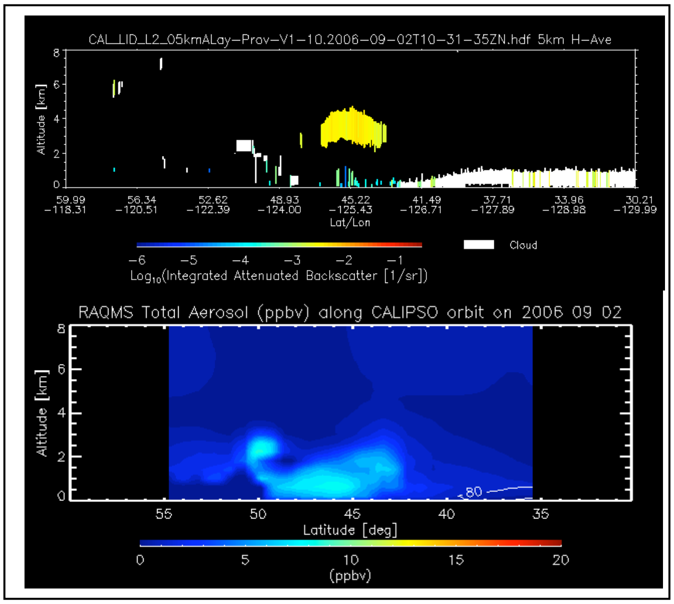
BB plume IH is a function of the fuels that are available to burn (ecosystem type, topography and fuel treatment/prescription), prevailing meteorology and the weather precipitating the fire event [53-59]. Historically, plume rise height was based on the pioneering work of G.A. Briggs [60, 61] and verified with limited field campaign data [62]. Anecdotal on-ground visual estimates, coincident aircraft pilot information and isolated lidar measurements have provided limited data to verify plume rise in models.

Efforts are underway to better parameterize and understand plume IH [59, 63]. In addition, researchers are exploiting satellite remote sensing observations to characterize BB IH and to assess parameterizations in regional and global models. Raffuse and colleagues [64] compared smoke plume height estimates using the BlueSky smoke modeling system with observations from Multi-angle Imaging SpectroRadiometer (MISR) and CALIOP satellite sensors over the United States. They found an ~50% low bias in simulated injection height for western states, and relatively low correlations overall for the United States compared with the observations [MISR $R^2 = 0.1$; CALIOP $R^2 = 0.22$]. Sessions et al. [65] found significant improvement in smoke injection estimates using a plume rise model [59] embedded in the WRF-Chem model, in combination with FLAMBE emissions calculations [66]. This argues for the importance of improved and expanded data sources from which models and parameterization can be advanced. Figure 1 shows an elevated smoke plume observed by CALIPSO and a Regional Air Quality Modeling System (RAQMS) simulation, demonstrating RAQMS could be improved by 33% using information gleaned from CALIOP data in this example.

MISR and CALIOP instruments are capable of distinguishing BB plume heights in the atmosphere [65, 67-73] and can provide the statistics necessary to understand and verify BB IH. Moreover, an increasing number of ground-based and aircraft lidar instruments are available for verification and validation of satellite data. MISR (360 km; pixel - 1.1 km horizontal x 500 m vertical) has a substantially larger swath width than CALIPSO (100 m diameter x 30 m vertical), which results in a greater opportunity to capture smoke plumes, in general, as well as a greater number of near source plumes.

Conversely, because MISR relies on multi-view angles to estimate the stereo height of distinct features, it requires abrupt well-defined columns and distinct boundaries, which limits views of large fires that generate extensive cumulous-like plumes. Hence, MISR cannot distinguish IH from large fires that lay down in the evening (typical cycle –fires dieback with increased humidity and decreased temperature), thus presenting a region that is extensively blanketed with smoke (no distinct plumes). In addition, MISR is a morning overpasses, so it does not capture the natural temporal variation of wildfires or the likely maximum IH, which generally peaks in late afternoon when the fuels are the driest.

Figure 1. CALIPSO data (upper panel) and model (lower panel) comparison. An elevated smoke plume is shown in yellow in the CALIPSO pictorial, while the aerosol concentration computed with an enhanced version of the RAQMS air quality model underestimates plume height by about 1/3 for this western U.S. fire, demonstrating the potential for improvement. Figure attribution: Chieko Kittaka and Brad Pierce.



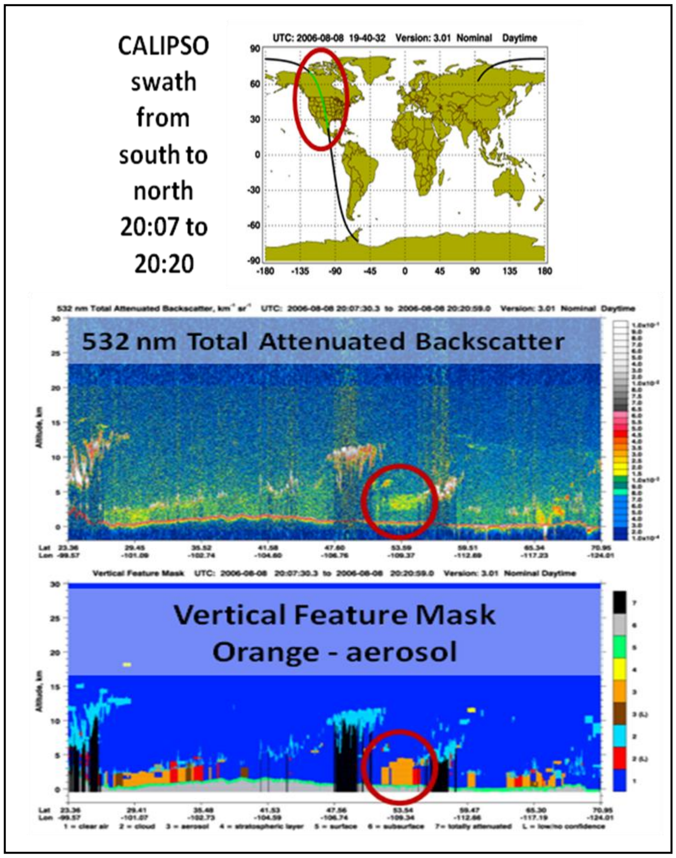
MISR data has been extensively interrogated, and the team has produced a data set that will continue to be useful for years to come [53]. The manuscript is based on the analysis of 5 years of satellite observations of smoke IH from North American fires (2002 and 2004–2007). They found plumes range from a few hundred meters to over 5000 m. The largest plumes were found over boreal regions (median values of 850 m), and the smallest plumes were found over cropland and grassland fires in the contiguous US (median values of 530 m), which argues for the dependence of IH on available fuel. A significant fraction (4–12%) of fire plumes were injected above the boundary layer (BL), and most of the plumes located above the BL (>83%) were trapped within stable atmospheric layers. MISR plume height data currently span many years and include most continents.

However, MISR data likely underestimate plume IH for two reasons: MISR is a morning overpass, so the peak of the fire day is missed; and MISR needs distinct boundaries, which are typically not produced by larger fires, which often generate irregular boundaries and smoky cloud-like features. For instance, the Tripod fire burned in Washington in 2006 and was one of the largest fires in the lower 48 in recent U.S. history. It burned vigorously in July (started ~ July 3rd) and August, and MISR IH was able to capture data for 4 days during that 2-month period [27 July (1 IH); 18 August (6 IH), 25 August (3 IH) and 27 August (5 IH)].

An underestimate in IH, either in models or by strictly relying on morning data to establish relationships, would overestimate local surface concentrations and underestimate long range transport and remote surface concentrations. In addition, a small number of large fires burn the majority of area, consequently producing a disproportionate amount of the total emissions. In Canada, 2-3% of the number of fires account for 97-98% of the total area burned; in Russia 1-2% of fires burn 50-70% of the area; in Alaska 96% of area burned is by large fires; and in Oregon, the largest 10% of fires account for 80% of the area burned [28, 74-77]. Consequently, if BB IH is misrepresented for larger fires, then a large portion of the emissions are misplaced in CTMs and climate models, with implications for air quality predictions and climate feedbacks.

The CALIOP instrument, onboard CALIPSO (first light on June 07, 2006) is an active lidar that can discriminate clouds and atmospheric aerosols, similar to those found in smoke plumes [68-70, 73]. CALIOP has a proven ability to discriminate aerosols and can distinguish the vertical structure of a smoke plume in the atmosphere (Figures 1 and 2).

Figure 2. CALIPSO granule with the orbit segment circled (upper panel) and the orbit segment curtains (version 3.01) are shown in the lower 2 panels. These data are from 08 August 2006 and show the segment of aerosols that will be analyzed later in this work.



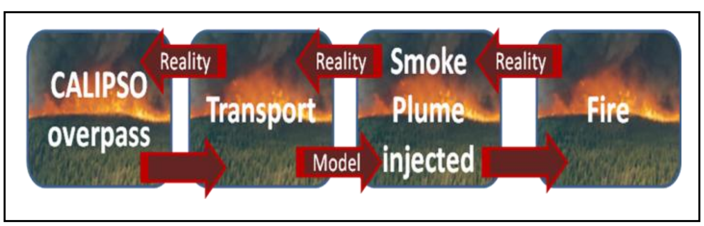
CALIOP-defined plume IH products are a necessary addition to the MISR-defined dataset, nonetheless CALIOP IH products are in their infancy [64, 78] in comparison to MISR. CALIPSO data are able to identify plume heights from extensive smoke fields and are able to capture the natural temporal variation of smoke plumes using multiple overpasses [79].

In concert, CALIOP and MISR data have the potential to add the statistical knowledge necessary to improve our understanding of the dynamics of fire plume injection height.

2. TECHNICAL PROCESS, DISCUSSION AND RESULTS

In using CALIOP data to distinguish fire plume IH or to build verification and validation (V&V) datasets, one must think in 3-dimential space and time (Figure 3). There are two basic products being generated using CALIPSO data: one that defines the fires that contribute to the portion of the CALIPSO segment that is smoke; and two, the diurnal evolution of a smoke plume from a particular fire event using multiple CALIPSO granules [80, 81].

Figure 3. Flowchart of the transport of smoke, representing the reality of smoke injection and transport through the atmosphere and the modeled simulation from the back trajectory perspective.



Also, a statistical database is being generated that links smoke plume IH to the variables that drive these dynamics (fuel, climate and weather), similar to the Val Martin et al. [53] manuscript. This is not a trivial task. For instance, in August 2006, there were a total of 294 smoke plume and CALIPSO Track segment pairs, and if overlapping plumes are only counted once, there were 163 pairs (2006 annual total 987). Although the process is time consuming, the data and product potential is much greater than originally conceived. The CALIOP-derived data are able to define the entire vertical plume domain captured, so mean data include a mean, minimum and maximum injection height (separate from product named in previous paragraph). For the limited number of plumes we have analyzed to date (all in North America, August 2006), the entire plume is injected in the boundary layer in 21% of cases (88- 96% for MISR), however the lower portion of the plume is injected in the boundary layer in 44% of cases (mean height 34% of cases). This example is based on a limited number of samples at a particular time of year, so a direct comparison to MISR data at this time would not be sensible. CALIOP data provide the opportunity to determine smoke plume IH, randomly, from all times of day, as well as from all ecosystems, fuel types and meteorological conditions, so these data, paired with MISR BB IH data, would be optimal.

2.1 Basic processing

Our initial focus was on North America to generate BB plume IH data, because this is a region where numerous datasets are easily available for V&V, such as the HMS smoke product, multiple geostationary satellites, and the USDA Forest Service readily shares fire information. Generating BB IH products is a multiple-step process:

- The HMS smoke product is overlaid with CALIPSO track information to determine the time and location of smoke aerosols (Figure 4). The HMS smoke product is derived using GEOS visible imagery, and the smoke plumes are hand drawn by humans throughout the day, as they evolve over time. Smoke plumes are drawn even when fire detections are not visible, often due to the size or timing of fire events, assuming that where there is smoke there is fire. Anthropogenic, industrial smoke plumes are semi-permanent features and are excluded. The temporal and spatial coincidence in smoke plumes and the CALIPSO track are extracted using Geographic Information Systems (GIS), a specialty software package that is well suited to geographic spatial and temporal assessments. These data are recorded and used to guide the extraction of CALIOP aerosol data.

- Aerosols are extracted from the Vertical Feature Mask product (latitude, longitude, time and altitude) and these data are used to initialize the Langley Trajectory Model (LaTM) (Figures 2, 4 and 5). We chose the aerosol vertical feature mask, as opposed to the aerosol smoke sub-type data, with the assumption that our information would be used to verify and inform the aerosol smoke sub-type algorithm, which has not been substantially V&V.

- The LaTM is initialized with the CALIOP observations and is driven by NASA Goddard Earth Observing System version 5 (GEOS-5) large-scale meteorological reanalysis data. Air parcel trajectories are computed backwards in 3-dimensional space and time until horizontally coincident with daily MODIS fire detections [82-84] (Figure 5). Trajectories are initialized at ~1 second intervals along the CALIPSO smoke segment track and at 100 m vertical intervals within the smoke plume. The LaTM uses a 15 minute time step. As the air parcel trajectories are traced back in time, each day there are unique coincidences with fires on the ground.

- An air parcel and a fire detection coincide when the following criteria are met: temporal and spatial coincidence; MODIS fire detection confidence must exceed 35%; horizontal range of the air parcel trajectory to fire must be under 20 km; and if the injection height is above the boundary layer (BL), coincidence must be with 6 or more active fire detections.

- CALIOP orbit segment information and the height at which air parcels and fire detections coincide are recorded. Coincident data are associated with the following list of data variables. Meteorological and fire weather variables are provided by or derived from GEOS-v5 data. MODIS provides land cover and the variables associated with thermal anomalies (fire detections). Geographic information is provided by GIS. The USDA Forest Service (FS) and the Canadian Forest Service provide information on specific fires, as required, and the FS provides fire weather variables for fires that burn in the United States. Canadian Fire Weather variables are calculated for the entire region analyzed [Build-Up Index (BUI); Fine Fuel Moisture Code (FFMC); Fire Weather Index (FWI)] [85].

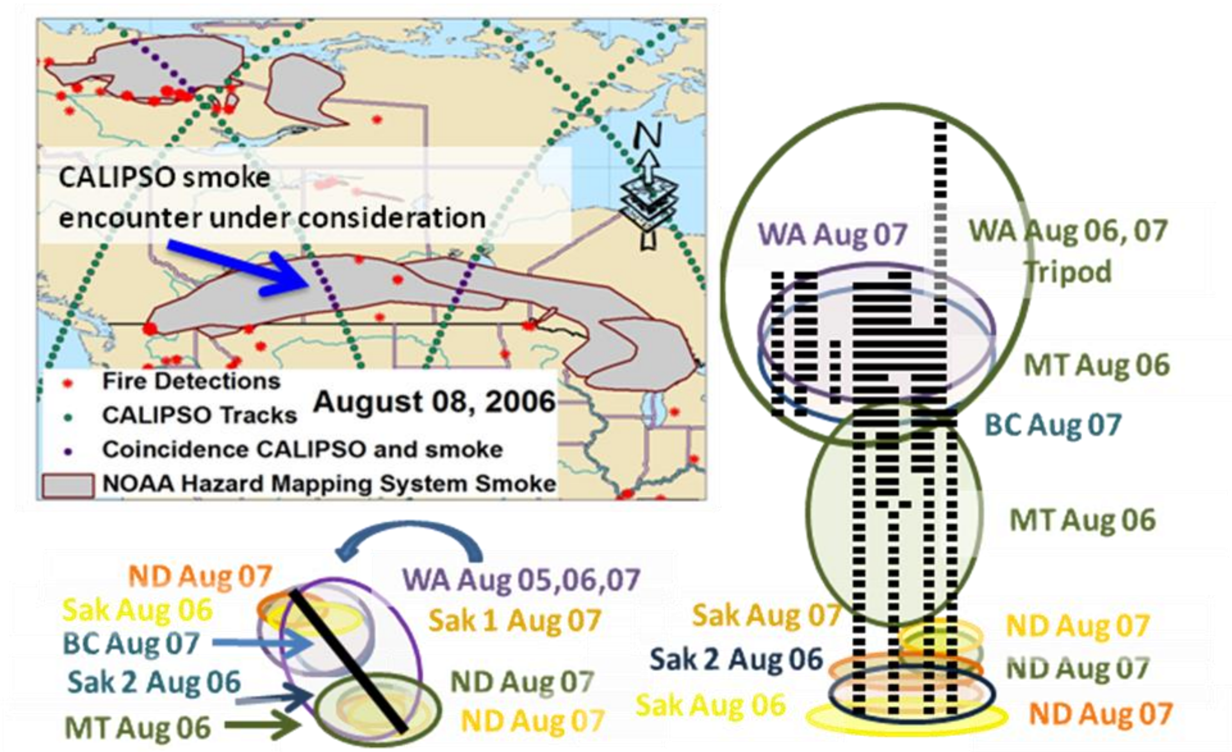
Location and state/territory; time of fire detection and coincidence; land cover (ecosystem type); MODIS Fire Radiative Power, brightness temperature, percent confidence and satellite; number of fire detections; number of air parcels; mean range; minimum, mean and maximum altitude; surface and mean sea level pressure; height of the planetary boundary layer and topography height; temperature and dew point at 2 and 10 m; wind speed at 2 and 10m; wind direction at 2 and 10m; relative humidity at 2 and 10m; temperature and relative humidity at noon, noon-noon precipitation, fire weather variables and bottom, peak and top of the stable layer.

- In previous steps, air parcels (AP) are extracted and run backwards in time until coincident with fire detections (AP-FD) and then each AP-FD pair are associated with fire, ecosystem and meteorological variables. Data are imported to GIS to conduct final analyses and establish mean 'statistics'. Mean statistics include the mean of all pertinent fire, weather and ecosystem variables and are calculated for each fire on each day. On August 9th, there were 18 CALIPSO orbit segments, which resulted in 261,580 AP run backwards in time to intercept with 2724 fire detections (multiple days), resulting in 38,494 total lines of data and 328 lines of mean statistics. Mean statistics are collected from only 3 days from the CALIPSO orbit, and any additional days may be used for specific fire event analysis.

- The attribution of particular smoke plumes are determined from multiple orbit segments in GIS. For instance, if we are interested in the Tripod fire, burning on August 4th, a minimum of 5 days processed AP-FD data (4th -8th) are required to ensure the injected plume is captured. For the 4th (Figure 6), there are 10 orbit segments that span 4 days that capture portions of the Tripod fire plume on the 4th at different times of the day.

One goal of this research is to use CALIOP data to develop understanding of daily fire plume dynamics in a variety of ecosystems by building a BB plume IH database and associating these data with the variables that drive these dynamics, which includes both ground-based (i.e. fuels, topography) and meteorological variables. However, at this model scale, topographic data are not analyzed, even though we recognize its importance. The intensity of a fire and fire behavior are dependent on the amount of fuel held within an ecosystem, the relative amount of moisture contained in the vegetation, duff and soil organic layer, wind and topography. These variables are largely under the control of weather and climate [3, 49, 51, 54, 86]. For this reason, it is essential to capture fire plume data from various ecosystems and under numerous weather conditions to gather the statistics necessary to fully assess and improve parameterization of BB plume injection heights. These statistics are crucial for moving forward in terms of understanding the aerosol quantities (amount fuel-weather-driven emissions), V&V of data and products, and to enhance model IH parameterization for CTMs, Air Quality and climate models.

Figure 4. In the top left, coincident NOAA Hazard Mapping System (HMS) smoke plumes, MODIS fire detections and CALIPSO orbit segments. The blue arrow points to the particular CALIOP segment under consideration. The horizontal (bottom left) and vertical (right) extent of the portion of the CALIPSO orbit segment that is classified as aerosols in the Vertical Feature Mask is represented by black lines (20:07:30.3-20:20:59.0v3.01daytime). The attribution of smoke aerosols in this example is from a number of fires, each represented by state acronym, dates injected and color coded in sync with the horizontal and vertical extent of their smoke distribution (circles).

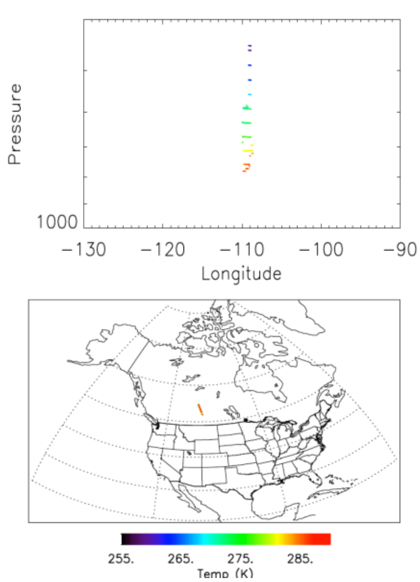


2.2 One CALIOP orbit segment

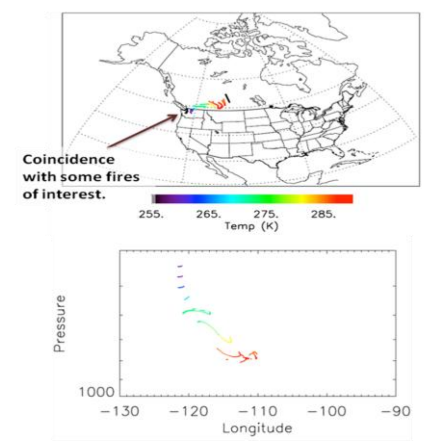
Using the methodology defined above in the '2.1 Basic processing' section, one seemingly-simple portion of a CALIOP orbit segment was examined (Figures 2, 4 and 5). It appeared this straight forward coincidence in the CALIPSO orbit segment and the smoke plume could be traced back to 1 or perhaps 2 responsible fires. However, in total, this smoke plume can be attributed to 9 separate fires, burning on different days (12 distinct daily events), as shown in the horizontal and vertical attribution of smoke in Figure 4.

Each fire contributes to unique portions of the segment. Back trajectories pass over initial "fires of interest" in North-Central Washington in the mid-troposphere (~500 mb, ~5200 m) at initialization minus 20 hours. At initialization minus 36 hours, back trajectories pass over "fires of interest" in North-West Montana, in the lower troposphere (~800 mb, ~2000 m) (Figure 5). In Washington (Tripod fire), coincidence is noted on August 6th, and the plume is injected to ~3400 m and on August 7th, to a mean of 3300 m, range 1900–6300 m; also in Washington (WA), a medium-sized fire is identified on August 7th (range 2200–4400 m); a plume is indentified in British Columbia (BC) on August 7th at about 3400 m; two fires are coincident in Montana (MT) burning on August 6th (mean 1980 m); three fires are identified in Saskatchewan (SK) on August 6th and 7th (~1000 m); and three fires are also identified in North Dakota (ND) burning on August 7th (~2000 m).

Figure 5. Initialization and transport of 'aerosol-filled' air parcels with the LaTM. This is the same orbit segment shown in Figures 2 and 4. Note the aerosols higher in altitude are transported more rapidly through the atmosphere than those at lower attitudes.



Trajectories are initialized along the CALIPSO path. Vertical initialization is shown on the top and the horizontal path is shown on the bottom.

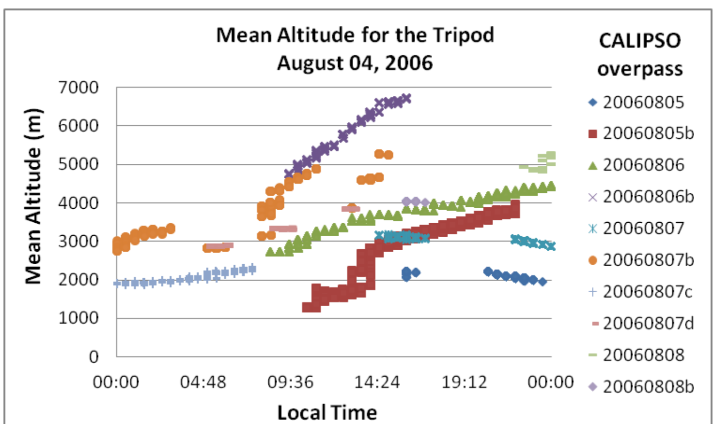


.
Initialization minus 24 hours (above) and there is coincidence with the fires burning in Washington.

As part of a verification process, we initialized forward trajectories from the individual fire sources identified, which showed the distinct horizontal and vertical contribution of smoke from each fire across the horizontal and vertical path of the CALIPSO segment (Figures 4 and 7). The fires that burned east of the granule (ND, SK) were transported at the surface westward towards the orbit path. Of the fires listed in the segment example described and shown in Figure 4, there is one coincident MISR overpass with one of the fires burning in MT, and the IHs are consistent, within 100s of meters.

Additionally, we analyzed GOES 15-minute data to piece together a movie (GOES East and West, each providing 30-minute data), which shows the smoke from several fires converging in a river of smoke and then being transported towards the CALIPSO path.

Figure 6. Mean altitude taken from multiple CALIPSO granules paired with MODIS data and the LaTM, depicting the daily evolution of a smoke plume.

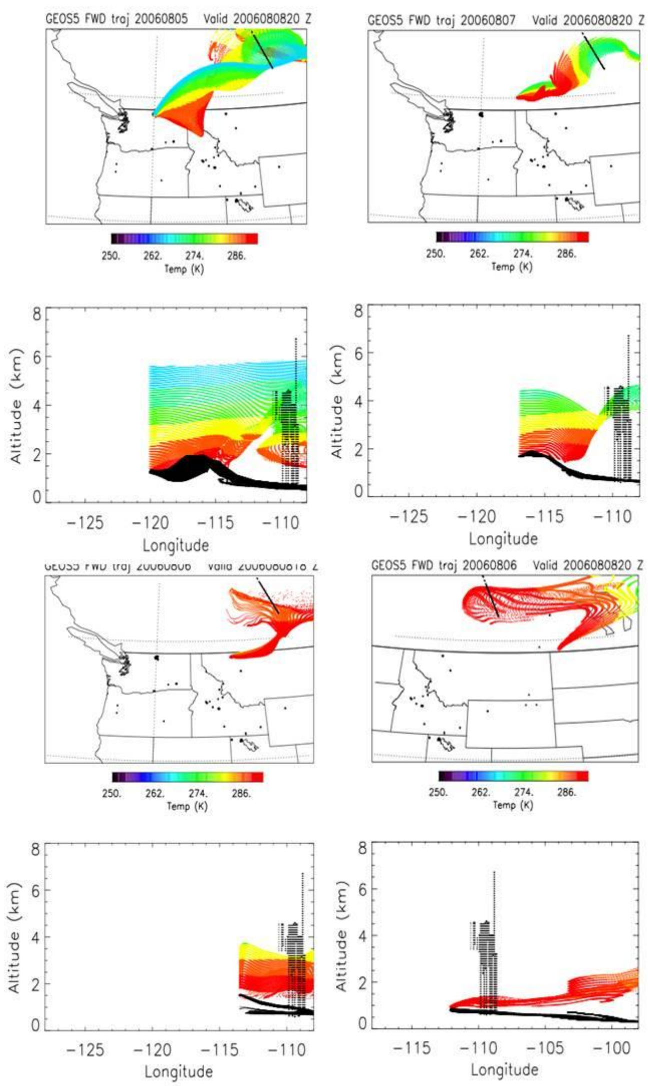


2.3 Plume evolution using multiple CALIPSO granules and orbit segments of one fire event

Because smoke travels faster when it is injected at higher altitudes in the atmosphere, this 'faster' portion of the smoke would be sensed first by the next downwind CALIPSO granule. At the same time, smoke that had been injected at lower altitudes on a previous day could be detected in the same CALIPSO segment at lower altitides. For this reason, using multiple CALIPSO granules, focused on one particular fire event, one can piece together the daily evolution of smoke IH and its detrainment (Figure 6). Even though smoke plume IH is variable during a day, peak IH are characteristically highest when fuels are the driest in late afternoon due to drying from sustained high temperatures and low relative humidity.

We have generated several daily evolution of fire graphics of the Tripod fire but none that are coincident with MISR data (2-month period only analyzed 4 days of Tripod) when the fire was burning most vigorously. However, on August 25th, there is spatial and temperal coincidence. There are 3 MISR assessments and 4 CALIOP-LaTM segments, 2 of which coincide with MISR overpass times (2 before MISR overpass, no value for comparison). One of the CALIOP-based segments show IH between 3800-4000 m above sea level (ASL) and the other between 1300-1400 m ASL; the mean MISR heights are 2040 m, 3060 m and 4260 m ASL. On August 27th, there is one CALIOP segment that is coincident with 5 MISR asessments. According to CALIOP-LaTM, at the MISR overpass time, smoke was injected at the suface, and this is consistent with MISR results, which show most of the smoke injected at the surface. The MISR and CALIOP-based methodologies produce strikingly simlar results, which argues for the accuracy of both the products.

Figure 7. Horizontal (top panel) and vertical (bottom panels) CALIPSO orbit segments with LaTM forward trajectories showing the portion of emissions transported from specific fires in WA, BC, ND and SK.



3.0 Conclusions

We have demonstrated the ability of CALIOP data paired with additional satellite sensors and models to: trace the attribution of particular smoke plumes to the emitting fires; and define the daily evolution of specific fires using multiple overpasses. When MISR data are available at the same space (fire event) and time, the two datasets compare exceptionally well. Processing CALIOP data is currently time consuming and tedious, but results are unique, in terms of the vast amount of plume data potential, the detail that can be extracted and the potential to view plumes statistically from all times of day. The interrogation of CALIOP data has the potential to greatly expand our understanding of fire plume injection heights at both detailed and larger scales, resulting in these data being valuable to numerous scientific and applications communities

Because biomass burning emissions and the height to which they are injected fundamentally influence numerous processes, we expect these data will aid understanding in: chemical transport and climate models; fundamental cloud, precipitation and aerosol processes; vertical transport; validation of aerosol and cloud parameterizations for regional, global, and climate models; lead to the development of three-dimensional smoke plume aerosol climatologies for use in the radiative environment and the effects of aerosols on precipitation; aerosol validation (and exclusion of biomass burning plumes) for a variety of instruments; and innovative land-based applications.

4.0 References

1 French, N.N.F., "The Impact of Fire Disturbance on Carbon and Energy Exchange in the Alaskan Boreal Region: A Geospatial Data Analysis", in *Natural Resources and Environment*. 2002, University of Michigan: Ann Arbor. p. 105.

2 Chapin, F.S., et al., "Changing feedbacks in the climate-biosphere system". Frontiers in Ecology and the Environment, 2008. **6**(6): 313-320.

3 Soja, A.J., et al., "Climate-induced boreal forest change: Predictions versus current observations". Global and Planetary Change, Special NEESPI Issue, 2007. **56**(3-4): 274–296, doi:10.1016/j.gloplacha.2006.07.028.

4 Bonan, G.B., F.S. Chapin, III, and S.L. Thompson, "Boreal Forest and Tundra Ecosystems as Components of the Climate System". Climatic change, 1995. **29**(2): 145.

5 Sokolik, I.N., "Dust", in *Encyclopedia of Atmospheric Sciences*, J. Holton, J. Pyle, and J. Curry, Editors Academic Press: London, 2003. pp 668-672.

6 Amiro, B.D., et al., "The effect of post-fire stand age on the boreal forest energy balance". Agricultural and Forest Meteorology, 2006. **140**(1-4): 41-50.

7 Sokolik, I.N., J.A. Curry, and V. Radionov, "Interactions of Arctic aerosols with land-cover and land-use changes in Northern Eurasia and their role in the Arctic climate system", in *Eurasian Arctic Land Cover and Land Use in a Changing Climate, 1st Edition., XXIV*, G. Gutman and A. Reissell, Editors Springer 2011. pp.

8 Liu, H.P., et al., "Changes in the surface energy budget after fire in boreal ecosystems of interior Alaska: An annual perspective". Journal of Geophysical Research-Atmospheres, 2005. **110**(D13): -.

9 Randerson, J.T., et al., "The impact of boreal forest fire on climate warming". Science, 2006. **314**(5802): 1130 -1132, DOI: 10.1126/science.1132075.

10 Andreae, M.O., et al., "Smoking rain clouds over the Amazon". Science, 2004. **303**: 1337-1341.

11 Crutzen, P.J., et al., "Biomass burning as a source of atmospheric gases CO, H_2, N_20, NO, CH_3Cl and COS". Nature, 1979. **282**: 253-356.

12 Fishman, J., "Identification of widespread pollution in the Southern Hemisphere deduced from satellite analysis". Science, 1991. **252**: 1693-1696.

13 Schultz, M.G., et al., "On the origin of tropospheric ozone and NO_x over the tropical South Pacific". Journal of Geophysical Research, 1999. **104**(5): 5829-5843.

14 Kaufman, Y.J. and I. Koren, "Smoke and Pollution Aerosol Effect on Cloud Cover". Science, 2006. **313**(5787): 655-658, 10.1126/science.1126232.

15 Koren, I., et al., "Measurement of the Effect of Amazon Smoke on Inhibition of Cloud Formation". Science, 2004. **303**(5662): 1342-1345, 10.1126/science.1089424.

16 Bonan, G.B., "Forests and Climate Change: Forcings, Feedbacks, and the Climate Benefits of Forests". Science, 2008. **320**(5882): 1444-1449, 10.1126/science.1155121.

17 Ramanathan, V., et al., "Aerosols, climate, and the hydrological cycle". Science, 2001. **294**(5549): 2119-2124, doi/10.1073/pnas.2237157100.

18 Wotawa, G., et al., "Inter-annual variability of summertime CO concentrations in the Northern Hemisphere explained by boreal forest fires in North America and Russia". Geophysical Research Letters, 2001. **28**(24): 4575-4578.

19 Zoltai, S.C. and P.J. Martikainen, "The role of forested peatlands in the global carbon cycle", in *Forest Ecosystems, Forest Management and the Global Carbon Cycle*, M.J. Apps and D.T. Price, Editors Springer-Verlag: Heidelberg, 1996. pp 47-58.

20 Apps, M.J., et al., "Boreal forests and tundra". Water Air and Soil Pollution, 1993. **70**(1-4): 39-53.

21 Natarajan, M., et al., "Radiative forcing due to enhancements in tropospheric ozone and carbonaceous aerosols caused by Asian fired during spring 2008". Journal of Geophysical Research, 2012. **117**: doi:10.1029/2011JD016584.

22 Damoah, R., et al., "Around the world in 17 days – hemispheric-scale transport of forest fire smoke from Russia in May 2003". Atmos. Chem. Phys., 2004. **4**: 1311–1321,1680-7324/acp/2004-4-1311.
23 Soja, A.J., et al., "ARCTAS: The Perfect Smoke". Canadian Smoke Newsletter, 2008. **Fall**: 2-7.
24 Warneke, C., et al., "Biomass burning in Siberia and Kazakhstan as an important source for haze over the Alaskan Arctic in April 2008". Geophys. Res. Lett., 2009. **36, L02813**: doi:10.1029/2008GL036194.
25 Lu, Z. and I.N. Sokolik, "Impact of wildfire smoke on clouds and precipitation in high latitudes". EOS Trans. AGU, 2009: Fall Meet. Suppl.
26 Lu, Z., I.N. Sokolik, and A.J. Soja. "Assessments of the Emission and Impact of Smoke from the 2002 Yakutsk Wildfires using the WRF-Chem-SMOKE Model and Satellite Data". In *AGU Fall*. San Francisco2011; pp
27 Pouliot, G., T. Pierce, and J. Vukovich. "Wildland Fire Emission Modeling for CMAQ: An Update". In *4th Annual CMAS Models-3 Users' Conference*. Chapel Hill, NC2005; pp
28 Soja, A.J., et al. "A methodology for estimating area burned using satellite-based data in Near-Real-Time in Oregon and Arizona." In *16th Annual International Emissions Inventory Conference - Emission Inventories: Integration, Analysis, Communication*. Raleigh, North Carolina: http://www.epa.gov/ttn/chief/conference/ei16/session10/a.soja.pdf2007; pp 21.
29 Soja, A., et al. "Comparing Fire Emissions Estimates for the Continental United States in Support of the National Emissions Inventory: Let's Take a Step Back to Move Forward". In *17th Annual International Emissions Inventory Conference - "Reinventing Inventories - New Ideas in New Orleans"*. Portland, Oregon: http://www.epa.gov/ttn/chief/conference/ei17/index.html#ses-122008; pp
30 Soja, A.J., et al., "Assessing satellite-based fire data for use in the National Emissions Inventory". Journal of Applied Remote Sensing, 2009. **3**(031504): 29.
31 Pouliot, G., et al., "Development of a biomass burning emissions inventory by combining satellite and ground-based information". Journal of Applied Remote Sensing, 2008. **2, 021501**.
32 Delfino, R., et al., "The relationship of respiratory and cardiovascular hospital admissions to the southern California wildfires of 2003." Occup Environ Med, 2009. **66**(3): 189-197.
33 Rappold, A.G., et al., "Peat Bog Wildfire Smoke Exposure in Rural North Carolina Is Associated with Cardiopulmonary Emergency Department Visits Assessed through Syndromic Surveillance". Environmental Health Perspectives, 2011. **119**(10): 1415-1420.
34 Moore, D., et al., "Population health effects of air quality changes due to forest fires in British Columbia in 2003: estimates from physician-visit billing data". Can J Public Health, 2006. **97**(2): 105-108.
35 Künzli, N., et al., "Health effects of the 2003 Southern California wildfires on children". Am J Respir Crit Care Med, 2006. **174**(11): 1221-1228.
36 Naeher, L., et al., "Woodsmoke health effects: A review". Inhalation Toxicology, 2007. **19**(1): 67-106.
37 Malm, W.C., et al., "Spatial and monthly trends in speciated fine particle concentration in the United States". Journal of Geophysical Research, 2004. **109**(d3): D03306, doi:10.1029/2003JD003739.
38 Swap, R., et al., "Saharan Dust in the Amazon Basin". Tellus, 1991. **44**((B)): 133-149.
39 Swap, R.J., et al., "Temporal and Spatial Characteristics of Saharan Dust Outbreaks". Journal of Geophysical Research, 1996. **101**: 4205-4220.
40 Andreae, M.O. and P. Merlet, "Emission of trace gases and aerosols from biomass burning". Global Biogeochemical Cycles, 2001. **15**(4): 955-966.
41 Akagi, S.K., et al., "Emission factors for open and domestic biomass burning for use in atmospheric models". Atmos. Chem. Phys., 2011. **11**: 4039–4072, doi:10.5194/acp-11-4039-2011.
42 Stephens, S.L. and L.W. Ruth, "Federal forest-fire policy in the United States". Ecol. Appl., 2005. **15**(2): 532–542. doi:10.1890/04-0545.

43 Riebau, A.R. and D. Fox, "The new smoke management". Int. J. Wildland Fire, 2001. **10**(4): 415–427. doi:10.1071/WF01039.
44 Flannigan, M.D. and C.E. Van Wagner, "Climate change and wildfire in Canada". Canadian Journal of Forest Research, 1991. **21**: 66-72.
45 Street, R.B. "Climate change and forest fires in Ontario". In *10th Conference on Fire and Forest Meteorology*. Ottawa, Canada1989; pp 177-182.
46 Price, C. and D. Rind, "Possible implications of global climate change on global lightning distributions and frequencies". Journal of Geophysical Research, 1994. **99**(D5): 10823-10831.
47 Overpeck, J.T., D. Rind, and R. Goldberg, "Climate-induced changes in forest disturbance and vegetation". Nature, 1990. **343**: 51-53.
48 Wotton, B.M. and M.D. Flannigan, "Length of the fire season in a changing climate". Forestry Chronicle, 1993. **69**(2): 187-192.
49 Stocks, B.J., et al., "Climate change and forest fire potential in Russian and Canadian boreal forests". Climatic Change, 1998. **38**(1): 1-13.
50 Gillett, N.P., et al., "Detecting the effect of climate change on Canadian forest fires". Geophysical Research Letters, 2004. **31**(18): DOI 10 1029/2004GLO20876.
51 Westerling, A.L., et al., "Warming and earlier spring increase western US forest wildfire activity". Science, 2006. **313**(5789): 940-943.
52 Alexeyev, V.A. and R.A. Birdsey, "Carbon storage in forests and peatlands of Russia". 1998, U.S.D.A. Forest Service Northeastern Research Station: Radnor. p. 137.
53 Val Martin, M., et al., "Smoke injection heights from fires in North America: Analysis of 5 years of satellite observations". Atmos. Chem. Phys., 2010. **10**: 1491-1510.
54 Stocks, B.J. and R.B. Street. "Forest fire weather and wildfire occurrence in the boreal forest of northwestern Ontario". In *Resources and Dynamics of the Boreal Zone*. Ottawa, Canada: Association of Universities of Canadian Universities for Northern Studies1982; pp 249-265.
55 Flannigan, M.D. and J.B. Harrington, "A study of the relation of meteorological variables to monthly provincial area burned by wildfire in Canada". Journal of Applied Meteorology, 1988. **27**: 441-452.
56 Prichard, S.J. and D.L. Peterson, "Landscape analysis of fuel treatment longevity and effectiveness in the 2006 Tripod Complex Fires". 2009, Joint Fire Science Program. p. 29.
57 Prichard, S.J., D.L. Peterson, and K. Jacobson, "Fuel treatments reduce the severity of wildfire effects in dry mixed conifer forest, Washington, USA". Can. J. For. Res., 2010. **40**: 1615–1626, doi:10.1139/X10-109.
58 Liu, Y., et al., "Important parameters for smoke plume rise simulation with Daysmoke". Atmospheric Pollution Research, 2010. **1**: 250-259.
59 Freitas, S.R., et al., "Including the sub-grid scale plume rise of vegetation fires in low resolution atmospheric transport models." Atmos. Chem. Phys. Discuss., 2007. **7**: 3385-3398.
60 Briggs, G.A., "Optimum formulas for buoyant plume rise". Philosophical Transactions of the Royal Society of London. Series A, Mathematical and Physical sciences, 1969. **265**(1161): 197.
61 Briggs, G.A., "Plume rise - recent critical review". Nuclear Safety, 1971. **12**(1): 15.
62 Clements, C.B., et al., "Observing the dynamics of wildland grass fires - FireFlux - A field validation experiment". Bulletin of the American Meteorological Society, 2007. **88**(9): 1369.
63 Freitas, S.R., et al., "The Coupled Aerosol and Tracer Transport model to the Brazilian developments on the Regional Atmospheric Modeling System (CATT- BRAMS) - Part 1: Model description and evaluation". Atmos. Chem. Phys., 2009. **9**: 2843-2861.
64 Raffuse, S.M., et al., "An Evaluation of Modeled Plume Injection Height with Satellite-Derived Observed Plume Height". Atmosphere, 2012. **3**: 103-123; doi:10.3390/atmos3010103.
65 Sessions, W.R., et al., "An investigation of methods for injecting emissions from boreal wildfires using WRF-Chem during ARCTAS". Atmospheric Chemistry and Physics, 2011. **11**(12): 5719-5744.

66 Reid, J.S., et al., "Global Monitoring and Forecasting of Biomass-Burning Smoke: Description of and Lessons From the Fire Locating and Modeling of Burning Emissions (FLAMBE) Program". Ieee Journal of Selected Topics in Applied Earth Observations and Remote Sensing, 2009. **2**(3): 144-162.
67 Kahn, R.A., et al., "Aerosol source plume physical characteristics from space-based multiangle imaging". J. Geophys. Res., 2007. **112**: doi:10.1029/2006JD007647.
68 Winker, D.M., et al., "Overview of the CALIPSO Mission and CALIOP Data Processing Algorithms". Journal of Atmospheric and Oceanic Technology, 2009. **26**(11): 2310-2323.
69 Omar, A.H., et al., "The CALIPSO Automated Aerosol Classification and Lidar Ratio Selection Algorithm". Journal of Atmospheric and Oceanic Technology, 2009. **26**(10): 1994-2014.
70 Liu, Z.Y., et al., "The CALIPSO Lidar Cloud and Aerosol Discrimination: Version 2 Algorithm and Initial Assessment of Performance". Journal of Atmospheric and Oceanic Technology, 2009. **26**(7): 1198-1213.
71 Kahn, R.A., et al., "Wildfire smoke injection heights: Two perspectives from space". Geophysical Research Letters, 2008. **35**(doi:10.1029/2007GL032165).
72 Mazzoni, D., et al., "A data-mining approach to associating MISR smoke plume heights with MODIS fire measurements". Remote Sensing of Environment, 2007. **107**(1-2): 138-148.
73 Vaughan, M., et al., "Fully automated analysis of space-based lidar data: an overview of the CALIPSO retrieval algorithms and data products". Proc. SPIE, Laser Radar Techniques for Atmospheric Sensing, 2004. **5575**: 16-30.
74 Stocks, B.J., "The extent and impact of forest fires in northern circumpolar countries", in *Global Biomass Burning: Atmospheric, Climatic, and Biospheric Implications*, J.S. Levine, Editor MIT Press: Cambridge, Mass., 1991. pp 197-202.
75 AFS, "Alaska Fire Service, Fire Statistics and Season Summary". 1992, Bureau of Land Management, US Department of Interior: Fairbanks, AK. p. 35.
76 Soja, A.J., et al., "AVHRR-derived fire frequency, distribution and area burned in Siberia". International Journal of Remote Sensing, 2004. **25**(10): doi:10.1080/01431160310001609725.
77 Valendik, E.N., "Temporal and spatial distribution of forest fires in Siberia", in *Fire in Ecosystems of Boreal Eurasia*, J.G. Goldammer and V.V. Furyaev, Editors Kluwer Academic Publishers: Dordrecht, 1996. pp 129-138.
78 Amiridis, V., et al., "Smoke injection heights from agricultural burning in Eastern Europe as seen by CALIPSO". Atmos. Chem. Phys. Discuss., 2010. **10**: 11567–11576, doi:10.5194/acp-10-11567-2010.
79 Soja, A., et al. "Biomass Burning Plume Injection Height Estimates using CALIOP, MODIS and the NASA Langley Trajectory Model." In *NASA Carbon Cycle & Ecosystem Joint Science Workshop*2011; pp
80 Soja, A.J., T.D. Fairlie, and D.J. Westberg, "Smoke plume injection height using CALIOP, MODIS, and the Langley Trajectory Model". Remote Sensing of Environment - target, in preparation.
81 Soja, A.J., T.D. Fairlie, and D.J. Westberg, "A CALIOP-based approach to assessing the daily evolution of smoke plumes". Can. J. Forest Research - target, in preparation.
82 Giglio, L., et al., "An Enhanced Contextual Fire Detection Algorithm for MODIS". Remote sensing of environment, 2003. **87**(2): doi:10.1016/S0034-4257(03)00184-6.
83 Pierce, R.B., et al., "Regional Air Quality Modeling System (RAQMS) predictions of the tropospheric ozone budget over east Asia". Journal of geophysical research, 2003. **108**(D 21): 8825, doi:10.1029/2002JD003176.
84 Pierce, R.B., et al., "Impacts of background ozone production on Houston and Dallas, Texas, air quality during the Second Texas Air Quality Study field mission". Journal of Geophysical Research-Atmospheres, 2009. **114**(D00F09): doi:10.1029/2008JD011337.
85 Van Wagner, C.E., "Development and Structure of the Canadian Forest Fire Weather Index System". 1987, Canadian Forest Service. p. 37.

86 Goodrick, S., "Modification of the Fosberg fire weather index to include drought". International Journal of Wildland fire, 2002. **11**(3-4): 205-211.

References to Websites

ARCTAS, Arctic Research of the Composition of the Troposphere from Aircraft and Satellites, 2008, http://www.espo.nasa.gov/arctas/
CALIPSO http://www-calipso.larc.nasa.gov/
CATF (Clean Air Task Force) International Meeting on Open Burning and the Arctic: Causes, Impacts, and Mitigation Approaches, 2010, Saint Petersburg, Russia, http://www.bellona.org/fires-and-the-arctic
HMS http://www.osdpd.noaa.gov/ml/land/hms.html
MODIS Fire Data http://maps.geog.umd.edu/firms/
MISR Multi-angle Imaging SpectroRadiometer plume heights http://misr.jpl.nasa.gov/getData/accessData/MisrMinxPlumes/
High Spectral Resolution Lidar (HSRL) http://science.larc.nasa.gov/hsrl/
Differential Absorption Lidar (DIAL)
Lidar Home Page at http://asd-www.larc.nasa.gov/lidar/lidar.html

Key Words
Fire, Biomass Burning, Satellite, Plume Injection Height, Emission Inventories, CALIPSO, CALIOP, MODIS, MISR.