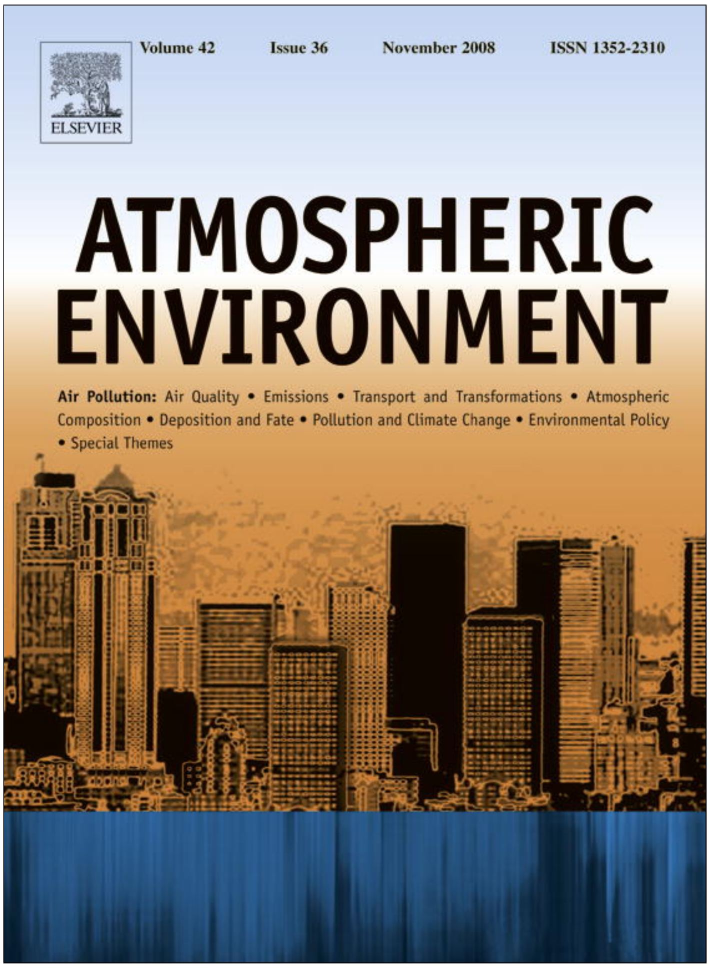
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Use of MODIS products to simplify and evaluate a forest fire plume dispersion model for PM_{10} exposure assessment

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ABSTRACT

Plume dispersion models may improve assessment of the health effects associated with forest fire smoke, but they require considerable expertise in atmospheric and fire sciences to initialize and evaluate. Products from MODIS (Moderate Resolution Imaging Spectroradiometer) sensors can simplify the process by providing (1) estimates of fire location, size and emission rates, and (2) data useful for assessing model output. By grouping individual MODIS fire pixels into discrete events we simulated the growth and decay of large fires and estimated their total burned area. Radiative power measurements for each fire pixel were multiplied against a fuel-specific coefficient to estimate particle emission rates. Using the CALMET/CALPUFF package we modeled the dispersion of these particles throughout a 325,000 km^2 area with complex terrain. Moderate agreement (mean $r = 0.61$) between estimated and measured PM_{10} concentrations was observed at five of six sites. Because surface measurements are only made at a limited number of locations, we used aerosol optical thickness (AOT) and color imagery product from MODIS for further evaluation. Strong trend association was observed between surface concentrations, model estimates and the AOT measurements. When CALPUFF plume contours were compared to smoke outlines traced from MODIS images we found an average overlap of 50% with better performance under high wind conditions. We conclude that this relatively simple and globally applicable approach can provide a strong foundation for enhanced smoke exposure modeling and public health risk assessment.

1. Introduction

Human exposure to potentially harmful forest fire smoke pollution is challenging to assess with data from air quality networks. Monitors tend to be sparsely distributed in remote areas, so measurements are rarely made in small, heavily impacted communities. Still, several studies have used air quality networks to measure ambient particulate matter concentrations during forest fire events. Here we focus on PM_{10} (particles less than 10 microns in aerodynamic diameter) as the most commonly measured pollutant, though most particles from biomass fires fall into the $PM_{2.5}$ fraction (Andreae and Merlet, 2001). Peak 24-h averages of 250, 270, 285, 375, 440, 700, and 930 $\mu g\,m^{-3}$ have been reported for British Columbia (Moore et al., 2006), Lithuania (Ovadnevaite et al., 2006), Singapore (Nichol, 1997), California (Phuleria et al., 2005), Brunei (Radojevic and Hassan, 1999), the Amazon Basin (Artaxo et al., 1994), and Malaysia (Brauer and Hisham-Hashim, 1998), respectively. Such high concentrations are likely to have measurable

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public health impacts, and simple tools are needed to improve epidemiological exposure estimation, to facilitate risk assessment, and to support public preparedness.

In recent years there has been interest in using quantitative and qualitative remote sensing products to supplement air quality network data (Hutchison, 2003; Wang and Christopher, 2003; Engel-Cox et al., 2004; Al-Saadi et al., 2005). Unlike surface monitors, satellite borne sensors can provide gridded arrays of measurements over vast geographic areas. Of particular interest are the aerosol products generated by Moderate Resolution Imaging Spectroradiometer (MODIS) sensors aboard US National Aeronautics and Space Administration's (NASA) Aqua and Terra Earth Observing Satellites (EOS). The MODIS aerosol optical thickness (AOT) is a measure of the light extinction in cloudless atmospheric columns with a horizontal resolution of 10 km (at nadir). By modeling the relationship between surface concentrations and columnar coefficients, statistical downscaling can be used to estimate surface conditions wherever MODIS measurements are made. While this approach shows promise with further refinement, preliminary studies report only moderate correlation ($r = 0.31$–0.70) between AOT and surface measurements (Wang and Christopher, 2003; Engel-Cox et al., 2004). Furthermore, the spatial resolution of estimates remains limited to 10 km which in forest fire applications, is wider than some plumes.

The true color images captured by MODIS instruments are available at much finer resolution (up to 250 m), but they provide no quantitative information about atmospheric aerosols. However, when not masked by cloud these images clearly show the spatial extent of smoke plumes. Color variation between smoke-affected pixels can be used to estimate whether the surface air quality is heavily or lightly impacted. In one novel use of these images Wu et al. (2006) were able to fill data missing (due to failure or intermittence) from 37 particulate matter samplers in Southern California during the 2003 fire season. Each pixel underlying the sampler locations was assigned a daily smoke density value of "no smoke", "light smoke" or "heavy smoke" in a geographic information system (GIS). Known surface concentrations were then regressed on smoke density and other potentially predictive variables. Once missing values were filled, exposure estimates were made for each zip code by spatial interpolation between the samplers. Although results were favorable, this use of MODIS data remains qualitative and the method is limited to areas with relatively dense monitoring networks.

Pollution dispersion models can provide concentration estimates at very high spatial resolution over large areas. Although commonly used for air quality forecasting, such models require complex inputs and parameterizations beyond the scope of most public health research. Furthermore, simulations of forest fire plume dispersion require output from equally complex sub-models of meteorological conditions, fire spread, and pollutant emission rates. If the domain spans political boundaries, modeling can be further complicated by inputs that are differentially measured by various authorities. Once a dispersion model is running its performance is challenging to evaluate when adequate data for validation are not available. Where few monitors exist, the relationship between model output and surface measurements may appear (1) weak due to lack of data; (2) weak due to poor model performance; or (3) deceptively strong due to specific attributes of the monitored locations. If exposure estimates based on dispersion model output cannot be assessed with data from other validated sources, they may be no more accurate than crude estimates derived only from surface measurements.

Here we describe an approach that makes plume dispersion models more accessible for pubic health applications by simplifying and evaluating them with MODIS fire detection, aerosol, and true color products. The study area is a mountainous 165,000 km^2 region of southeastern British Columbia, in Canada, which experienced the worst fire season in provincial records during summer of 2003 (Filmon, 2004). More than 640,000 residents were exposed to potentially harmful smoke pollution, but only six of the thirty-five communities (approximately 370,000 of the residents) were monitored by continuous Tapered Element Oscillating Microbalance (TEOM) PM_{10} samplers (see Fig. 1). The following methods were developed to estimate ambient daily PM_{10} concentrations for all communities so that the entire population can contribute information to subsequent epidemiological analyses. We use three simple approaches, each with strengths and weaknesses, to evaluate the overall quality of exposure estimates output by the model.

2. Methods

All MODIS products were processed with the HDF–EOS to GIS (HEG) conversion tool (Atmospheric Science Data Center, Langley, VA). Spatial analyses were conducted in ArcGIS 9.0 (ESRI, Redlands, CA), and statistical analyses were done with S-PLUS 7.0 (Insightful Corp, Seattle, WA). Dispersion of smoke-related PM_{10} was modeled in hourly time steps with CALPUFF for the period of July 1st through September 30th, 2003. Model parameters are summarized in Supplementary material. Strategies used to provide CALPUFF input and to evaluate CALPUFF output are described in the following sections.

2.1. The CALMET/CALPUFF modeling system

The CALMET/CALPUFF system (TRC Companies, Lowell, MA) is an advanced non-steady-state meteorological and air quality-modeling framework developed by atmospheric scientists. According to guidelines established by the US Environmental Protection Agency it is the preferred system for assessing long-range transport of air pollutants. The CALMET component is a meteorological interpolator that uses observed data and/or output from other models to calculate hourly temperature and wind fields for a three-dimensionally gridded domain (Scire et al., 2000b). The CALPUFF component uses CALMET fields to advect Lagrangian puffs of gases and/or aerosols emitted from modeled sources while simulating dispersion and transformation processes throughout the domain (Scire et al., 2000a).

2.2. Meteorological inputs

Mountainous terrain can produce localized winds that are not reflected in the output from coarse resolution

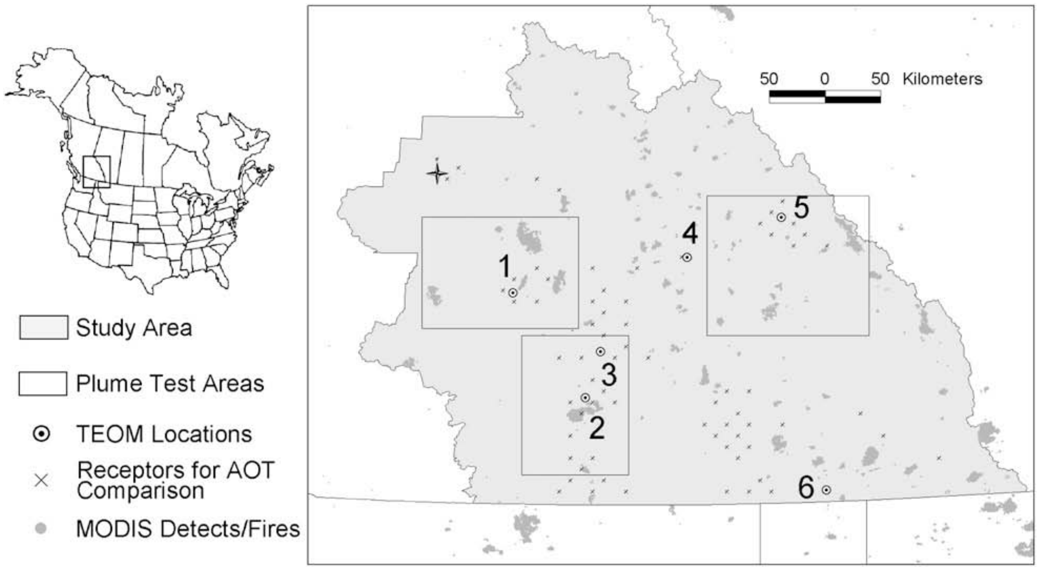

Fig. 1. Modeling domain including the study area in southeastern British Columbia, and parts of Alberta, Washington, Idaho and Montana. Towns with TEOM instruments are (1) Kamloops, (2) Kelowna, (3) Vernon, (4) Revelstoke, (5) Golden and (6) Creston.

numerical weather prediction models. To better account for the complex topography of the study area we ran CALMET at a 1 km horizontal resolution, with 12 vertical steps (20 to 5000 m). The CALMET initialization was tested with: (1) surface measurements; (2) 12 km output from US National Meteorological Center's ETA model (Black, 1994) run by SENES Consultants (Richmond Hill, Ontario); and (3) a combination of both inputs (Burkholder, 2005a). All three scenarios performed poorly under low wind conditions, but method (3) produced the best results based on our evaluation criteria (Burkholder, 2005b) and was used to produce the wind fields for this study.

2.3. Fire locations, sizes and emission rates

The 11,004 MODIS fire pixels detected in the study area during the study period (referred to herein as "MODIS detects") were grouped into 242 discrete fires (referred to herein as "MODIS events") based on their spatial and temporal proximity. Assuming that each MODIS detect represents 1 km^2 of burned area we drew circular buffers of radius 564 m (area = 0.99 km^2) around them and merged buffers within the same MODIS event to obtain polygons approximating the 242 burn scars. Polygon areas were divided by the number of MODIS detects they contained to estimate the average area burned per detect – a value used to adjust particle emission rates, as described latter in this section. By modeling the daily sequence of MODIS detects, the growth and decay of all events was simulated without the need for fire propagation and fuel consumption models.

Based on the 90 MODIS events matched to British Columbia fire size records we overestimate the total burned area by ~32,000 ha (about 20%). Of this, only ~7000 ha (about 4%) results from overestimation of the area burned by fires >1470 ha (the 75th percentile). Based on all 242 MODIS events, fires >1470 ha contain 91% of the 11,004 detects. Changes to model output are marginal when fires <1470 ha are excluded from the simulation (not shown), but we retain the smaller fires to ensure that their local effects on air quality are represented.

The particulate emission rate for each MODIS detect was estimated using its fire radiative power (FRP) measurement, which is the rate of release of the radiant component of the total heat energy generated by fire within a pixel (Roberts et al., 2005; Wooster et al., 2005). The same FRP value might represent an intense fire burning a small fraction of the pixel or a cool fire burning a large fraction of the pixel. Either way, Wooster et al. (2005) used a large set of measurements on small fires to show a linear relationship between time-integrated FRP and total biomass consumed. Roberts et al. (2005) used that result to show that satellite-measured FRP-based calculations of burned biomass agree with in situ measurements. Given that particles emitted are directly related to biomass consumed, and given that biomass consumed is directly related to FRP, it follows that particle emissions are directly related to FRP. Ichoku and Kaufman (2005) demonstrated this by using wind vectors from a global meteorological model to associate smoke-affected columns with specific fires. The total mass of aerosol in those columns (derived from their AOT) was then regressed on the summed FRP of all MODIS detects in the source fires. Application of the algorithm to multiple fire events worldwide yields emission coefficients for different fuel types and regions. Reported values ranged from 20 g MJ^{-1} for all Canadian forests to 107 g MJ^{-1} for Russian croplands (Ichoku and Kaufman, 2005). Based on this result we calculate an area-adjusted emission rate for each MODIS detect as follows.

$$\mathrm{Mass}(\mathrm{g\,s^{-1}}) = 20\left(\mathrm{g\,MJ^{-1}}\right) \times \mathrm{FRP_{MD}}(\mathrm{MJ\,s^{-1}}) \times \frac{A_{\mathrm{MD}}(\mathrm{ha})}{100(\mathrm{ha})} \quad (1)$$

where FRP_{MD} is the fire radiative power of the MODIS detect, A_{MD} is the average area burned per detect in the MODIS event, and 100 ha is the assumed pixel area of each detect. This approach yields emissions estimates that are consistent with output from the Emissions Production Model (EPM) version 1.0 (US Forest Service, Seattle, Washington) and the Fire Behavior Prediction system (FBP) version 4.3 (Canadian Forest Service, Edmonton, Alberta). The EPM was used to estimate heat release rates (to calculate plume rise) for this study.

2.4. CAPLUFF PM_{10} concentration vs. TEOM measurements

Output from dispersion models is traditionally evaluated by comparing concentration estimates to actual measurements, but the spatial coverage of these "gold standard" data may be limited. For example, surface concentrations of PM_{10} were measured at only six stations in the study area. We placed a CALPUFF receptor at each site and simulated PM_{10} dispersion from all 11,004 MODIS detects over the 92-day study period. Mean 24-h concentration estimates were compared to the daily averages measured at each station using time series plots and summary statistics. The Pearson correlation coefficient (r), mean error (ME), mean absolute error (MAE) and index of agreement (IOA) were calculated for each site as suggested by Willmott (1982). The IOA is defined in Eq. (2).

$$\mathrm{IOA} = 1 - \left[\sum_{i=1}^{N}(C_i - M_\mathrm{i})^2 \Big/ \sum_{i=1}^{N}(|C_i - \overline{M}| + |M_\mathrm{i} - \overline{M}|)^2 \right] \quad (2)$$

Where C_i is the CALPUFF estimate for day i, and M_i is the corresponding TEOM measurement.

2.5. CALPUFF PM_{10} concentration estimates vs. MODIS AOT

To better assess model performance around communities without TEOM instruments we use the MODIS AOT measurements. These values do not reflect surface PM_{10} concentrations, but they provide a spatially complete measure of the magnitude of atmospheric aerosol. We split the domain with a 10 km^2 grid (the resolution of the AOT product) and placed CALPUFF receptors in 70 of the 141 cells with a population density of more than 2 persons per km^2. One MODIS AOT raster (from the MYD04 and MOD04 products) showing the entire study area was identified for each day of the study period, and values at the 70 receptors were extracted. All MODIS events were modeled, and estimates for (1) the hours corresponding to MODIS AOT time stamps and (2) the 24-h means were recorded at each receptor. Correlations between AOT values and CALPUFF estimates were calculated with all available pairs (null AOT values due to cloud render the data temporally incomplete) over the 92-day study period. To put these results in context we also compared AOT values to 1-h and 24-h PM_{10} measurements and CALPUFF estimates at the six TEOM locations.

2.6. CALPUFF plume areas vs. MODIS true color images

While TEOM and AOT measurements can be used to assess the magnitude of PM_{10} concentrations output by CALPUFF, they cannot be used to evaluate the spatial accuracy of plume trajectories. To do this we established test areas around the towns of Kamloops (140 × 100 km), Kelowna (100 × 125 km) and Golden (145 × 125 km) in British Columbia. Only emissions from the MODIS detects within each test area were simulated, and surface concentrations of PM_{10} were estimated at 1 km resolution. Test durations were 21, 40 and 40-days, respectively. One MODIS true color image (from the MYD02 and MOD02 products, 500 m resolution) showing the entire study domain was identified for each test day (40 in total). Image colors were inverted to better distinguish smoke from cloud, and visible plumes originating from fires in the test areas were manually traced in GIS (referred to herein as "MODIS plumes").

Contours of test area CALPUFF estimates $>10\ \mathrm{mg\,m^{-3}}$ were plotted in Surfer 8.0 (Golden Software, Golden, Colorado) and exported to GIS for hours corresponding to the time stamps of MODIS plumes (referred to herein as "CALPUFF plumes"). Comparison between the CALPUFF and MODIS plume shapes was made by calculating the sensitivity and specificity of the horizontal overlap between them. Assuming MODIS plumes to be the "gold standard", areas covered by both MODIS and CALPUFF plumes were called "truly positive" (or TP), and those covered by neither were called "truly negative" (or TN). It follows that areas with CALPUFF but no MODIS plumes were "falsely positive" (or FP) and the opposite were "falsely negative" (or FN). Sensitivity and specificity are defined as TP/(TP + FN) and TN/(TN + FP), respectively (Fielding and Bell, 1997). Results close to 1.0 for both measures indicate a highly accurate plume, so we define the spread between measures as *discrepancy* = *sensitivity* + *specificity* − 1 to assess this. Values were calculated for all days on which MODIS plumes were not obscured by cloud.

3. Results and discussion

Fig. 1 shows the model domain, study area, three plume test areas, locations of six TEOM instruments, 70 CALPUFF receptors for the AOT comparison, and 242 MODIS events made up of 11,004 MODIS detects. Table 1 summarizes the attributes of the MODIS detects and MODIS events.

3.1. CALPUFF PM_{10} concentration estimates vs. TEOM measurements

Fig. 2 shows how CALPUFF estimates compare to the 24-h average PM_{10} concentrations in Kamloops, Kelowna, Vernon, Revelstoke, Golden and Creston over the 92-day study period. In the latter five cases, estimates track well with TEOM measurements, and peak concentrations are realistic. These results are further supported by the correlation, error and agreement measures summarized in Table 2. Given that small increases in ambient particulate matter can be associated with measurable public health effects (Dockery and Pope, 1994), the CALPUFF exposure estimates can be classified into discrete categories like "background", "low smoke", moderate smoke" and "high smoke" prior to use in epidemiological analyses or health risk assessment. As such, we place greater emphasis on the

Table 1
Attributes of fire events, MODIS detects and CALPUFF fires included in our model

Attribute	Mean	SD[a]	Min	Median	Max	IQR[b]
MODIS event duration (days)	10	13	1	3	68	1–19
MODIS event size (ha)	1831	4444	100	400	33178	136–1470
MODIS detects per fire event	62	141	1	8	973	2–64
MODIS detect FRP (MW)	69.8	152.4	5.4	29.8	1751.2	18.0–58.9
Area burned per detect (ha)	40.1	12.3	23.6	37.2	100.0	31.1–43.4
Particle emission rate (g/s)	540.4	1204.4	33.36	234.0	18567.4	141.3–459.8
Heat release rate (MBTU/s)	180	56	106	166	451	139–195

[a] SD = standard deviation.
[b] IQR = interquartile range.

measures of agreement (*r*, IOA) than on measures of error (ME, MAE).

In a similar study Langmann and Heil (2004) used the REMO dispersion model to simulate atmospheric transport of aerosols from the Indonesian and Australian fires in 1997/1998. They estimated weekly burned area from ATSR (Along Track Scanning Radiometer) fire count data, and emissions were calculated for each fire according to the Levine (1999) estimates of biomass density and combustion efficiency for three fuel categories. Six months of model output was compared to mean 24-h measurements of particulate matter at seven sites in Malaysia. Ambient concentrations were considerably higher than those reported here for British Columbia and the model consistently underestimated measured values. Time series plots show that estimates tracked well with measurements and

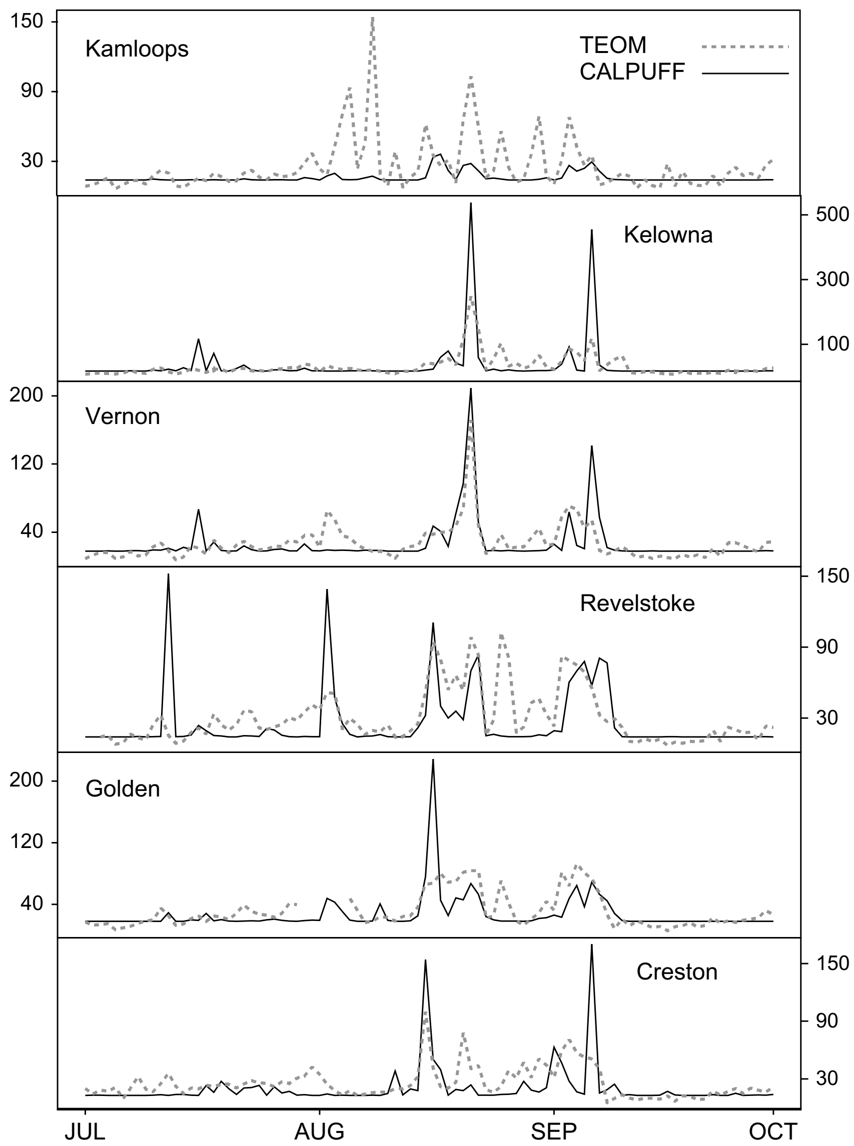

Fig. 2. Time series plots showing 24-h average PM_{10} concentrations as (1) measured by TEOM instruments and (2) estimated by the CALPUFF model in six locations.

Table 2
Agreement between 24-h average CALPUFF estimates and TEOM measurements at six sites over 92-days

Receptor	Measure[a]	Kamloops ($N=92$)	Kelowna ($N=92$)	Vernon ($N=92$)	Revelstoke ($N=90$)	Golden ($N=86$)	Creston ($N=92$)
Central	R	0.377	0.731	0.762	0.529	0.530	0.474
	ME	−9.43	3.21	−0.75	−4.75	−4.00	−5.03
	MAE	12.3	20.0	10.5	14.5	12.6	12.2
	IOA	0.382	0.730	0.859	0.676	0.699	0.683

[a] R = Pearson's correlation coefficient. ME = mean error. MAE = mean absolute error. IOA = index of agreement, as defined in Eq. (2).

reported correlations ranged from 0.44 to 0.73 (as compared to 0.37–0.76 in this study).

Among the five sites where CALPUFF performed well in British Columbia, systematic overestimation of surface concentrations is seen only in Kelowna, largely due to one powerful fire that contains 18% of MODIS detects in the 99th percentile of FRP values. Concentrations are underestimated at all sites between August 23rd and September 1st, 2003. During this period MODIS detected only 1140 fire pixels, compared to 3546 in the preceding ten days and 1882 in the following six days, after which it began to rain throughout the study area. Furthermore, the mean FRP during this period was only 54.0 MW while mean FRP during the other periods were 69.1 and 64.0 MW, respectively. This combination of fewer detects and less powerful fires resulted in reduced particle emissions within CALPUFF. True color images from these days reveal a period of moderate to heavy cloud, which can lead to detection suppression and reduced FRP measurements (Giglio et al., 2003; Kaufman et al., 2003). Researchers continue to develop new algorithms for detecting smaller and less powerful fires with MODIS data (Giglio et al., 2003; Li et al., 2005; Morisette et al., 2005), so this limitation may be improved or resolved as enhanced methods become operational.

Concentrations at the Kamloops station are consistently underestimated. According to administrative records, the Strawberry Hill fire near to Kamloops burned 5730 ha between August 1st and 10th, but our methodology (described in Section 2.3) estimated only 4073 ha. When MODIS data are spatially compared to the recorded fire perimeter, detection failure on the down slopes of this topographic feature is evident. Furthermore, the mean FRP for MODIS detects in this event is only 41.5 MW. Given its close proximity to a large population, this fire was aggressively managed, and we hypothesize that suppression activities resulted in reduced MODIS detection and power.

Using the instantaneous FRP to estimate an average rate of particulate emissions from each MODIS detect (Eq. (1)) is a simplification that may have contributed to the observed discrepancies. In reality fire intensity varies considerably throughout the diurnal cycle, with fuel consumption and emissions rates generally peaking in the mid-afternoon and slowing during the night (Beck et al., 2002). In preliminary tests we imposed such hourly variation on PM_{10} emissions, but found that peak CALPUFF estimates were vastly inflated while low concentrations remained unchanged. We therefore generalized daily emissions by (1) representing each MODIS event as a composite of detects from the four overpasses and (2) adjusting emissions to reflect the average area burned by each detect in that event. More recent work by Ichoku et al. (2008) explicitly characterizes diurnal variation in FRP flux (W m^{-2}). This is a product of the number of MODIS detects and the mean FRP measured during each overpass divided by the land area of the region where the fires were burning. Plots for most regions show maximum flux occurring at the afternoon (~13:30 local time) overpass, though the variability between passes was relatively low throughout Canada (Ichoku et al., 2008).

3.2. CALPUFF PM_{10} concentration estimates vs. MODIS AOT

Table 3 shows how 92-days of CALPUFF estimates compared to AOT values at 70 sites in the study area. Correlations were not sensitive to latitude, longitude, elevation, distance to the nearest large fire, or the number of AOT values available for comparison (N ranges from 38 to 65 out of 92-days). Although correlations are moderate, they are comparable to those reported elsewhere for the relationship

Table 3
Summary of the correlations between MODIS AOT values and (1) CALPUFF estimates at 70 receptors distributed over populated areas, (2) CALPUFF estimates at the locations of six TEOM instruments, and (3) TEOM measurements at those locations

	70 sites CALPUFF		Six sites CALPUFF		Six sites TEOM	
	1-h[a]	24-h[b]	1-h	24-h	1-h	24-h
N pairs	38 to 65 (out of 92-days)		48 to 60 (out of 92-days)		46 to 60 (out of 92-days)[c]	
Weakest	−0.090	−0.074	0.321	0.312	0.448	0.435
Mean	0.349	0.371	0.505	0.478	0.500	0.578
Standard deviation	0.211	0.187	0.132	0.153	0.042	0.088
Strongest	0.848	0.730	0.688	0.713	0.537	0.673

Values for AOT are only available for cloudless pixels, so the number of daily AOT/CALPUFF pairs used in correlation calculations (N pairs) was less than 92 in all cases.

[a] Hour nearest to the time of daily AOT capture.
[b] Average for the calendar day of AOT capture.
[c] Missing TEOM measurements reduced the number of pairs from 48 to 46 at one site.

Table 4
Summary of the spatial comparison between MODIS and CALPUFF plumes

Mean Measure[a](SD)	Kamloops ($N = 30/40$)	Kelowna ($N = 16/21$)	Golden ($N = 24/40$)
MODIS plume area (km^2)	1014 (834)	1605 (1149)	1169 (1127)
CALPUFF plume area (km^2)	1712 (1484)	1957 (1368)	1948 (1787)
Truly positive area (km^2)	615 (661)	821 (780)	534 (770)
Falsely negative area (km^2)	399 (328)	784 (541)	635 (616)
Falsely positive area (km^2)	1096 (1170)	1137 (1047)	1414 (1178)
Truly negative area (km^2)	11894 (1556)	9768 (1516)	14790 (3756)
Sensitivity	0.57 (0.29)	0.46 (0.23)	0.42 (0.24)
Specificity	0.91 (0.09)	0.90 (0.09)	0.91 (0.08)
Discrepancy	0.53 (0.25)	0.64 (0.20)	0.74 (0.16)

Numbers in parentheses are standard deviations with N samples.
[a] Sensitivity = TP/(TP + FN); Specificity = TN/(TN + FP); Discrepancy = Sensitivity + Specificity − 1.

between MODIS AOT and surface concentrations of particulate matter. For hundreds of sites across the United States, Engel-Cox et al. (2004) found mean 1-h and 24-h correlations of 0.40 and 0.43 (compared to 0.35 and 0.37 here), respectively, and showed increasing strengths of association from west to east. A single pocket of weak and negative values was observed in the Pacific Northwest along the British Columbia border.

Table 3 also shows how MODIS AOT values compare to CALPUFF estimates and PM_{10} measurements at the locations of six TEOM instruments (N ranges from 46 to 60 out of 92-days). Mean correlations are similar for the CALPUFF and TEOM data, and the ranking from weakest to strongest site is identical in both cases. Although the sample size is small, this trend association between AOT values, CALPUFF estimates and TEOM measurements suggests that correlation gradients may be useful for qualitative spatial evaluation of model performance. Furthermore, TEOM measurements are similarly correlated with CALPUFF estimates ($r = 0.57$) and AOT values ($r = 0.58$), which suggests that AOT might also be useful for exposure assessment. However, the incompleteness of the AOT data renders them less than ideal for applications where complete temporal information is required. Furthermore, the spatial resolution of the AOT product is 10 km^2 whereas the resolution of CALPUFF is established by the user (1 km^2 in this case). These issues highlight limitations of AOT for public health applications, though we do intend to investigate their utility as a measure of smoke exposure for epidemiological research.

3.3. *CALPUFF vs. MODIS plumes*

Table 4 summarizes the spatial comparison between CALPUFF and MODIS smoke plumes around Kamloops, Kelowna and Golden. Weak sensitivities suggest that our model has only a moderate probability of predicting smoke where smoke is actually observed. Performance is poorest on days with low winds and small plumes. Sensitivities become 0.70, 0.59 and 0.55 for Kamloops, Kelowna and Golden, respectively, when the calculation is weighted by the truly positive plume area. Strong specificities suggest that CALPUFF reliably does not predict smoke in unaffected areas, though false positives are large compared to true positives and false negatives. This is partially due to the 10 mg m^{-3} cutoff resulting in CALPUFF plumes that are systematically larger than their MODIS counterparts. We established this value by comparing 10 test MODIS plumes to CALPUFF plumes with 5, 10, 20 and 50 mg m^{-3} contours and assessing which concentration best approximated the manually traced plume sizes. Although the 10 mg m^{-3} cutoff resulted in minimal estimation error, the test cases were not randomly selected – MODIS plumes from cloudless days were preferentially chosen because we assumed they were more accurate. While color manipulation can help to differentiate smoke from cloud, areas with lower aerosol concentrations may not be clearly visible on partially cloudy days. Therefore the size of each MODIS plume may be inversely proportional to the degree of cloudiness at its time of capture, resulting in a systematically flawed “gold standard”.

Analysts at NOAA use imagery from GOES (geostationary operational environmental satellites) to manually identify smoke plumes for the North American fire hazard mapping system[1] (referred to herein as “HMS plumes”). When qualitatively compared to our MODIS plumes the HMS plumes were generally larger, confirming that our method underestimated plume size. To assess CALPUFF performance against these HMS plumes we dissolved the individual polygons into a single daily shape, and we output 24-h plumes from CALPUFF with a 5 mg m^{-3} cutoff. Limited availability of the HMS data reduced the number of comparable dates to 22 of 40, 12 of 21 and 16 of 40 for Kamloops, Kelowna and Golden, respectively. Specificities were marginally improved in all cases (Kamloops = 0.93, Kelowna = 0.93, Golden = 0.94) due to an overall decrease in falsely positive plume area. Sensitivity was increased to 0.61 and 0.49 in Kelowna and Golden, respectively, but remained virtually unchanged at 0.58 for Kamloops. It appears that daily averaging smoothed directionality errors for CALPUFF plumes in the complex terrain of the first two test areas, but had less impact in the lower elevations around Kamloops. Nevertheless the incidence of falsely negative plume area remained high in all test areas suggesting error between the observed and modeled plume trajectories.

Some error is attributable to the CALPUFF plumes being based on estimates of surface concentration while the MODIS and HMS plumes are traced from a birds-eye view that is impossible to replicate with model output. However, poor overlap between plume trajectories is most obvious during times of low and moderate wind, when CALMET

[1] http://www.firedetect.noaa.gov/viewer.htm.

performance is known to be poor (Burkholder, 2005b). Initializing CALMET with output from a numerical weather model running at higher resolution (2 or 4 km instead of 12 km) may produce better results in complex terrain, though surface measurements alone might be adequate in areas with simpler topography.

Results still compare well to those reported elsewhere. The Air Resources Laboratory at NOAA models wildfires detected by its hazard mapping system (from which the HMS plumes were extracted) with the HYSPLIT dispersion model to make daily estimates of smoke-related elevations in $PM_{2.5}$ across the United States. Emissions estimates are derived from the BlueSky framework for modeling smoke from prescribed burns. Output from the ISFT is evaluated daily using a statistical coefficient called the Figure of Merit in Space (FMS) as described by Klug et al. (1992), which is similar to the sensitivity and specificity calculations used here. At multiple concentration contours the overlapping area between two plumes is divided by the total area covered by both plumes, with values ranging from 0 (no agreement) to 1 (perfect agreement). Mean FMS values for July through September 2006 at the 1, 5, 20 and 100 $mg\,m^{-3}$ contours were 0.14, 0.11, 0.06 and 0.02, respectively.[2] In contrast, the mean FMS values for Kamloops, Kelowna and Golden are 0.27, 0.26 and 0.17, respectively.

4. Conclusions

Dispersion models of fire smoke can produce estimates at the spatial and temporal resolution necessary for public health applications, but this complex process is challenging to simulate and model output needs rigorous evaluation. The MODIS-CALPUFF approach presented here produces results comparable to those found in more sophisticated work, but all studies report considerable error between observed and output data under some conditions. Using the measurement, spatial and temporal strengths of different data sets allows for straightforward and holistic evaluation of model performance. Our methods can provide public health researchers with simpler, more accessible and globally applicable tools for enhancing smoke exposure assessment and, therefore, advancing understanding of health risks associated with forest fire smoke.

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Appendix. Supplementary data

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.atmosenv.2008.05.008.

[2] http://www.arl.noaa.gov/smoke/MonthlyFMS.pdf.

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