

AIRBORNE MEASUREMENTS ON SMOKES FROM BIOMASS BURNING¹

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ABSTRACT

Airborne measurements have been made in the smokes from large fires of standing coniferous trees and logging debris, standing chaparral, fallen jack pine, and wheat stubble. Particle emission factors, particle size distributions, optical properties of the smokes, and trace gas concentrations in the emissions are derived from the airborne measurements. Major differences exist in these factors during any one fire, as well as from one fire to another. Measurements of optical scattering and extinction coefficients, with a time resolution of a few seconds, reveal significant spatial inhomogeneities in optical absorption within the smoke plumes.

1. INTRODUCTION

Wild forest fires, prescribed burning of forest logging debris, and silvacultural and agricultural burning combined constitute one of the largest sources of particles injected into the atmosphere and also a large source of trace gases (Wilson, 1970). However, despite the fact that 2 - 5% of the global land area is burned annually (National Academy of Sciences, 1984), there are still "...no satisfactory published estimates of amounts of biomass converted to gaseous and particulate matter..." (National Academy of Sciences, 1986). Uncertainties in the efficiencies with which biomass is converted into particles and trace gases in large fires is also a major uncertainty in quantifying the nuclear winter hypothesis (National Academy of Sciences, 1985).

In an effort to improve this situation we have made airborne measurements in the smokes from relatively large fires of standing coniferous trees, standing chaparral, fallen jack pine, coniferous logging debris, and wheat stubble. These fires, whether uncontrolled or prescribed for agricultural or forestry management, were intense, producing vigorous ascending columns of smoke often capped by a convective cloud. The sizes of the fires ranged from a few tens to many hundreds of hectares in area.

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Our measurements to date have emphasized determination of particle emission factors (mass of particles emitted into the air per unit mass of fuel burned), particle size distributions and trace gas concentrations in the smokes, and the optical properties of the smokes. A summary of our results on particle emissions from these fires is presented here. Results on trace gas emissions may be found in Hegg et al. (1987; 1988).

2. AIRBORNE INSTRUMENTATION AND PROCEDURES

The measurements were made aboard the University of Washington's C-131A research aircraft. This twin-engined, propeller-driven airplane carries instrumentation for measuring the size and nature of aerosol and cloud particles, trace gas concentrations, and meteorological parameters. Major portions of the aerosol system have been described by Radke (1983) and the trace gas instrumentation has been described by Hegg et al. (1987). The primary instruments used in the present study are listed in Table 1.

The aircraft made horizontal passes either through the ascending smoke column or perpendicular to the axis of a stabilized smoke plume from the fires. "Grab" samples of air for determination of aerosol size distributions were averaged over ~0.5 km of flight path, and those for carbonaceous trace gases and aerosol total mass over ~1 km of flight path. Plume structures were resolved with continuously measured variables (e.g., the light-scattering coefficient).

Particle emission factors were determined using the carbon-balance method (Ward et al., 1982). This requires measurements of the concentrations of carbonaceous gases and particles across a section of the plume and simultaneous measurements of the horizontal wind through this cross section. The emission factor (EF) for particles in a specified size range is given by:

$$EF = \frac{\text{mass flux of particles along the plume}}{\text{fuel consumption rate}} \quad (1)$$

Therefore,

$$EF = \frac{\bar{P} A V}{F} \quad (2)$$

where \bar{P} is the average mass concentration of the particles across a section perpendicular to the axis of the plume, A the cross-sectional area of the plume, V the horizontal wind speed through the section, and F the fuel consumption rate. Since the carbon burned per unit time (C_B) is given by:

$$C_B = F C_f \quad (3)$$

where C_f is the fractional mass of carbon in the fuel, we have from Eqs. (2) and (3):

$$EF = \frac{\bar{P} A V C_f}{C_B} \quad (4)$$

If deposition of the particles is negligible and the plume is in steady state:

TABLE 1. RELEVANT INSTRUMENTATION ABOARD THE UNIVERSITY OF WASHINGTON'S C-131A RESEARCH AIRCRAFT

(a) Particle Sizes and Concentrations

| Instrument | Equivalent Particle Diameter (μm) |
|--|--|
| Condensation nucleus counter* | > 0.005 |
| Diffusion battery with condensation nucleus counter† | ~ 0.01 - 0.1 |
| Electric aerosol analyzer† | ~ 0.01 - 1.0 |
| Active scattering aerosol spectrometer† | 0.09 - 3 |
| Laser aerosol spectrometer† | 0.5 - 11 |
| Optical particle counter† | 2.6 - 48 |
| Forward-scattering spectrometer probe* | 3 - 45 |

(b) Trace Gas Chemistry

| Gas | Technique | Detection Limit (ppbv) |
|-----------------------|--|------------------------|
| SO ₂ * | pulsed fluorescence | > 1 |
| O ₃ * | chemiluminescence (C ₂ H ₄) | > 5 |
| NO, NO ₂ * | chemiluminescence (O ₃) | > 1 |
| CO† | correlation IR spectrometer | > 100 |
| CO ₂ † | IR spectrometer | ± 2 ppm |
| NH ₃ † | impregnated filter | % variable |
| Whole air grab sample | GC/mass spectrometer (post flight) | variable |

(c) Aerosol Characteristics

| Parameter | Instrument | Range |
|--|---|---|
| Light-scattering coefficient | integrating nephelometer | $1 \times 10^{-6} - 2.5 \times 10^{-3} \text{ m}^{-1}$ |
| Light-extinction coefficient | optical extinction cell | $5 \times 10^{-5} - 10^{-2} \text{ m}^{-1}$ |
| Particle mass | quartz microbalance impactor | < 2 μm diameter |
| Bulk aerosol chemistry (soluble anions concentration) | Teflon filters, ion chromatography | $\left\{ \begin{array}{l} \text{Cl}^- \pm 14\% \\ \text{SO}_4^{2-} \pm 4\% \\ \text{NO}_3^- \pm 11\% \end{array} \right.$ |
| Particle morphology & chemistry | impaction, electron microscopy | > 0.2 μm diameter |
| Carbon soot§ | filtration, light absorption, pyrolysis | - |

* Continuous measurements.

† Grab sample measurements.

§ Analysis by Radiance Research and Sunset Laboratories.

$$C_B = [(\bar{P} C_p) + (\bar{CO}_2 C_{CO_2}) + (\bar{THC} C_{THC}) + (\bar{CO} C_{CO})]AV \quad (5)$$

where C_p , C_{CO_2} , C_{THC} , and C_{CO} are the fractional masses in the smoke plume of carbon in the particles, CO_2 , total hydrocarbons, and CO , respectively, and \bar{CO}_2 , \bar{THC} , and \bar{CO} are, respectively, the average mass concentrations of CO_2 , total hydrocarbons, and CO in the cross section of the plume. From Eqs. (4) and (5):

$$EF = \frac{\bar{P} C_f}{(\bar{P} C_p) + (\bar{CO}_2 C_{CO_2}) + (\bar{THC} C_{THC}) + (\bar{CO} C_{CO})} \quad (6)$$

If it is assumed that the particles move with the gases, so that they bear the same ratio to each other from one point in the plume to another, an expression similar to Eq. (6) will relate instantaneous measurements made at any point in the plume, where the average concentrations in Eq. (6) would then be replaced by point concentrations. It is this latter modification of Eq. (6) that we use to determine particle emission factors. Particle mass concentrations, over various size ranges, can be derived from the "grab" samples by measuring the particle size distribution, from weighing of filters through which the "grab" samples were passed, and from microbalance impactor measurements. The mass concentrations of the various carbon gases are obtained from GC-mass spectrometer analysis (Westberg et al., 1974; Rasmussen et al., 1974). C_p is measured through elemental carbon analysis of sequenced pyrolysis of quartz filters exposed to the smokes (Johnson et al., 1981). The value of C_f is taken as 0.5 (Bryam and Davis, 1959).

Measurement of the light-extinction, scattering, and absorption coefficients were obtained from a combination of continuous measurements and grab-bag sampling. Continuous measurements of the extinction and scattering coefficients were obtained with a highly stable 7 m long extinction cell and an integrating nephelometer (Weiss and Radke, 1987). This technique produces excellent agreement with filter samples analyzed by the integrating plate method (Weiss et al., 1979) and with the elemental carbon analysis of sequenced pyrolysis of the quartz filters.

The derived emission factor is strictly valid only at the point of measurement. Any process that adds or removes a pollutant between the source and the location of the measurement will change the derived emission factor for that pollutant. Such changes are often small if the measurements are made close to the fire, but cloud scavenging and gas and particle chemistry have the potential to significantly change the measured values of emission factors. The emission factors for particle mass given below were derived from measurements in smoke columns above the fire or at short distances downwind in stabilized smoke plumes. In some cases, however, the plume had been scavenged by capping cumulus clouds.

3. RESULTS

Using the techniques described in the previous section, we have examined emissions from nine major fires and one minor fire (of wheat stubble). Information on these fires is summarized in Table 2. Eight of the fires were prescribed burns, and two were portions of major wild fires on the Oregon-California border that burned largely uncontrolled for over a month in the late summer of 1987.

TABLE 2. FIRES EXAMINED IN PRESENT STUDY

| Fire | Date | Location | Size (hectare)* | Type of Fire | Fuel |
|--------------------|----------------------|-------------------------|-----------------|--------------|---|
| Abee† | 22 September 1986 | Montesano, Washington | 40 | Prescribed | Debris from Douglas Fir, & Hemlock |
| Eagle | 3 December 1986 | Ramona, California | 30 | Prescribed | Standing Black Sage, Sumac & Chamise |
| Lodi 1 | 12 December 1986 | Los Angeles, California | 40 | Prescribed | Standing Chaparral, Chamise |
| Lodi 2 | 22 June 1987 | Los Angeles, California | 150 | Prescribed | Standing Chaparral, Chamise |
| Hardiman† | 28 August 1987 | Chapleau, Ontario | 325 | Prescribed | Debris from Jack Pine, Standing Aspen & Paper Birch |
| Wheat | 31 August 1987 | Rosalia, Washington | ~10 | Prescribed | Wheat stubble |
| Myrtle/Fall Creek† | 2 September 1987 | Roseburg, Oregon | 2,000 | Wild Fire | Standing Pine, brush & Douglas Fir |
| Silver | 17-19 September 1987 | Grants Pass, Oregon | 20,000 | Wild Fire | Douglas Fir, True fir, Hemlock |
| Satsop† | 19 September 1987 | Satsop, Washington | 40 | Prescribed | Debris from Douglas Fir & Hemlock |
| Troy† | 8 October 1987 | Troy, Montana | 70 | Prescribed | Debris from Pine, Douglas Fir & True fir |

* Area estimates for the wild fires are very approximate; actual active flaming zones must have been much smaller.

† These fires produced a capping cumulus cloud at some time during the period of the measurements.

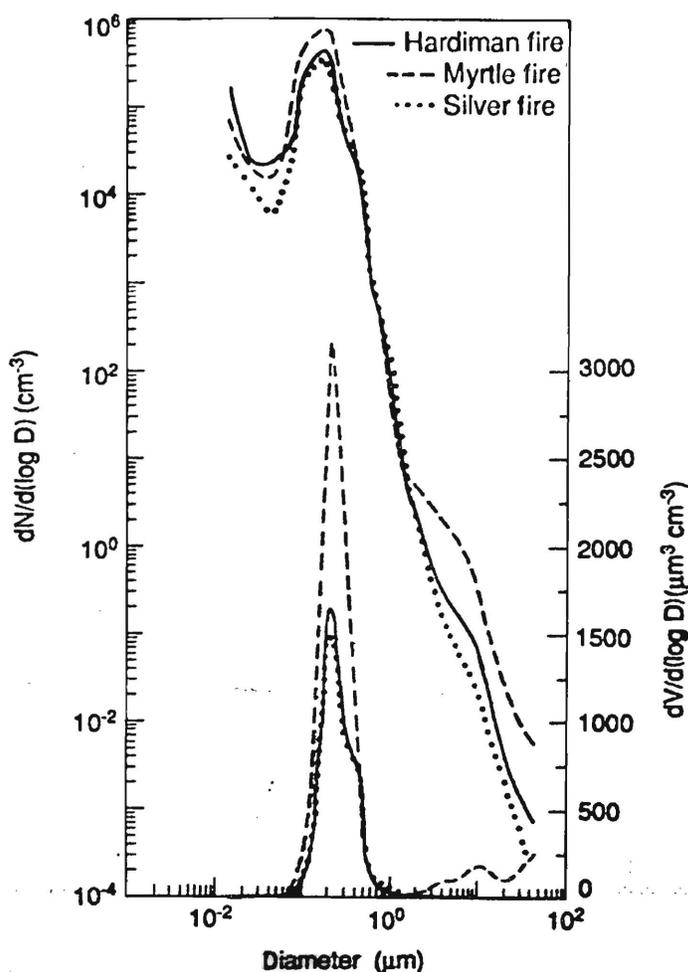


FIGURE 1. Average number and volume distributions of particles measured in the smoke plumes near the sources of three fires.

3.1 PARTICLE SIZE DISTRIBUTIONS

The particle size distributions, particularly the volume distributions, in the smokes showed comparatively little variation in shape from one fire to another or during any one fire while near the source, although particle concentrations varied widely. Shown in Fig. 1 are average particle size distributions for three of the fires. The nucleation mode ($<0.1 \mu\text{m}$ diameter) was the most variable: frequently it was nearly completely suppressed but occasionally it was prominent. The accumulation mode ($0.1 - 2.0 \mu\text{m}$) often dominated both the number and volume size distributions and it always contributed overwhelmingly to the light-scattering coefficient. The peak in the accumulation mode tended to move to slightly larger particle sizes as concentrations increased and as the age of the smoke increased. Particles in the accumulation mode consisted primarily of tarry, condensed hydrocarbons, typically spherical in shape, but they also contained some water-soluble inorganics (primarily SO_4^{2-} and NO_3^-) (Hegg et al., 1987); this accounts, in part, for their activity as very efficient cloud condensation nuclei (Radke et al., 1978).

The coarse particles ($>2 \mu\text{m}$) in the smokes showed considerable variations. In the Lodi 1 fire there was a mode near $10 \mu\text{m}$ that consisted largely of soil and condensed hydrocarbons (personal communication, 20 June 1987, W. R. Coffey, NASA Langley Research Center, Hampton, Virginia). Airborne measurements (not shown here) indicated that particles up to at least $4 \mu\text{m}$ in maximum dimensions, in concentrations of $\sim 10^{-6} \text{ cm}^{-3}$, were present in the smoke from the Lodi 1 fire. Such particles would produce another peak in the volume distribution at a size beyond that plotted in Fig. 1. A hint, at smaller sizes, of this ultra-giant mode can be seen on the right-hand side of the volume distribution plots shown in Fig. 1.

3.2 PARTICLE EMISSION FACTORS

The accumulation mode plays an important role in the particle emission factor, both because most of the mass resides in this mode and also because atmospheric residence times for larger and smaller particles are comparatively short.

Shown in Fig. 2 are the particle emission factors as a function of time for the Lodi 1 fire. Three independent measurements of particle mass are shown in this figure. The agreement between these measurements is excellent; the occasional discrepancies demonstrate both experimental errors and the danger of depending on a single technique for measuring particle emission factors. The large variations with time in the particle emission factors were probably caused by various attempts to reignite the fire. The peaks in the emission factor appeared to correspond to periods when the fire was spreading rapidly. This was contrary to expectation, since Patterson and McMahon (1984) and Hardy and Ward (1986) reported that increases in flaming combustion reduce the particle emission factor.

The time dependence of the emission factor for the Abee fire (Fig. 3) was quite different from the Lodi 1 fire. All of our measurements in the Abee fire were taken in

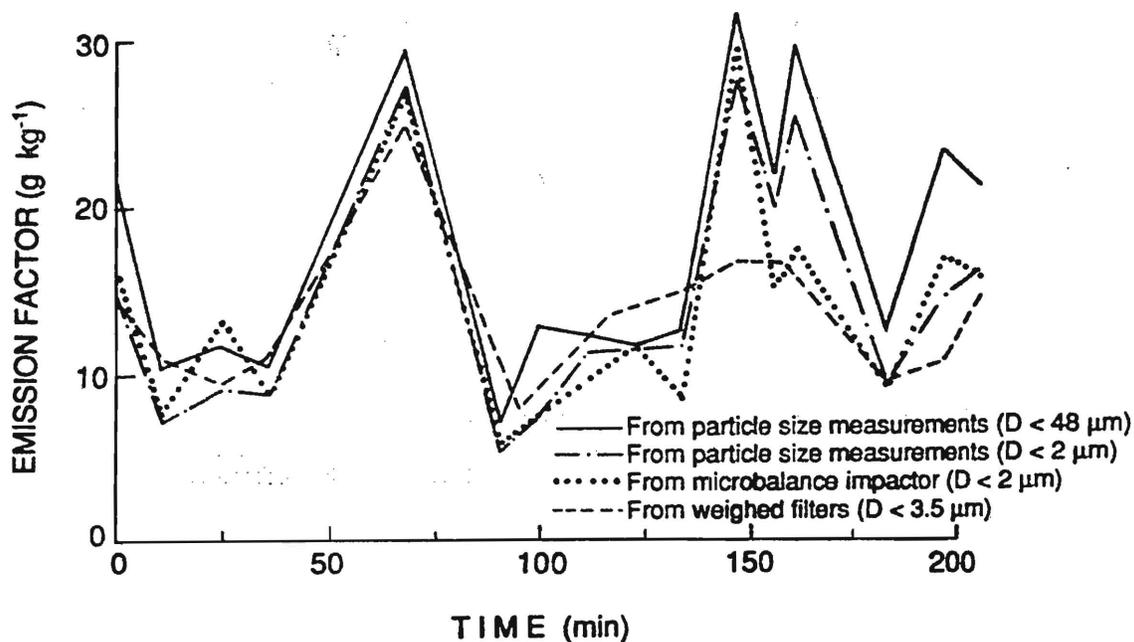


FIGURE 2. Emission factors for particle mass as a function of time after ignition for the Lodi 1 fire.

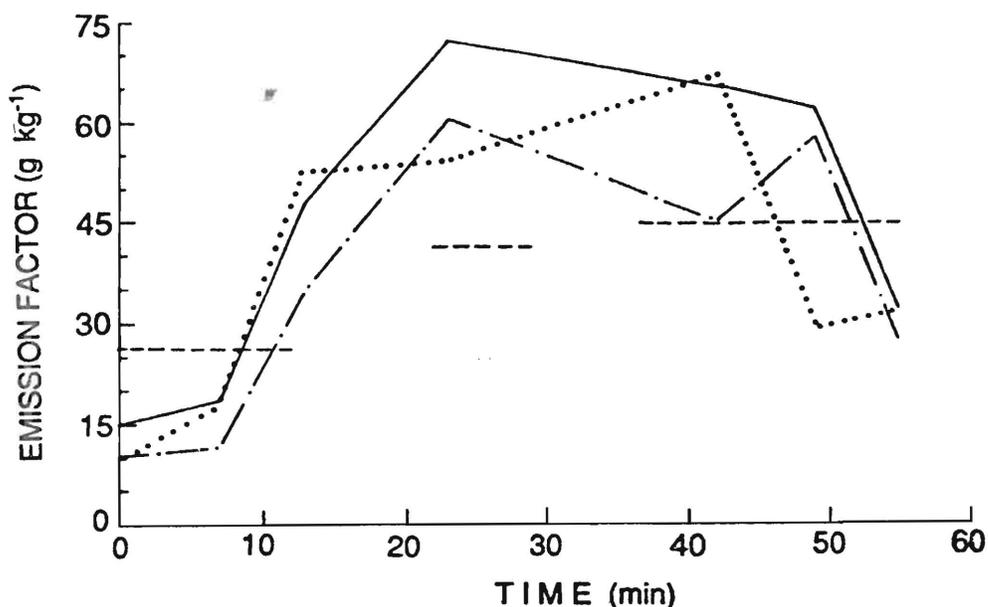


FIGURE 3. Particle emission factors as a function of time from the beginning of observations on the Abee fire. A vigorous cumulus cloud capped the smoke column for the first 10 - 15 min. The measurements were made downwind of this capping cumulus in the stabilized plume. (Data key as in Fig. 2.)

the stabilized (bent over) portion of the plume. During the first 10 - 15 min of observations, the particle emission factors were quite low. This could have been due to the scavenging of particles by a vigorous cumulus cloud that capped the smoke column during this period, or to more efficient combustion of fuel during this period. This fire yielded the highest sustained particle emission factor (37 g kg^{-1} for particles $< 3.5 \mu\text{m}$ diameter) measured in these studies. It should be noted that the Abee fire had a higher fuel loading and was smaller in area than the Lodi 1 fire.

Listed in Table 3 are the average particle emission factors for the ten fires. Note that the two wild fires (Myrtle/Fall Creek and Silver) produced some of the highest measured particle emission factors. The average particle emission factor (for particles $< 2 \mu\text{m}$ diameter) for all our measurements in all fires (71 data points) is $\sim 18 \text{ g kg}^{-1}$ with a standard deviation of 12.8 g kg^{-1} . For particles $< 48 \mu\text{m}$, the average particle emission factor is $24 \pm 16 \text{ g kg}^{-1}$.

3.3 OPTICAL PROPERTIES OF SMOKES

Our real-time measurements of the light-extinction coefficient (σ_E) and light-scattering coefficient (σ_S) allow us to examine the single-scattering albedo ($\bar{\omega} \equiv \sigma_S/\sigma_E$), the light-absorption coefficient ($\sigma_A = \sigma_E - \sigma_S$), and the specific absorption $BA = \sigma_A \times (\text{particle mass per unit volume of air})^{-1}$. Values of σ_E and σ_S measured across the smoke column from the Lodi 2 fire are shown in Fig. 4a. The center of the smoke column was markedly darker than its edges. Well downwind in the stabilized smoke plume not only was the center of the plume less dark but the entire plume was whiter (Fig. 4b). This may have been due to entrainment into the plume of cooler, whiter puffs from smoldering combustion and to "whiter" particle mass added to the plume by gas-to-particle conversion.

TABLE 3. PARTICLE EMISSION FACTORS (IN GRAMS OF SMOKE PER KILOGRAM OF FUEL BURNED) AND SINGLE-SCATTERING ALBEDO AND SPECIFIC ABSORPTION FOR ALL FIRES STUDIED

| | Emission factor (derived from size distribution of particles < 2 μm diameter) | | | Emission factor (derived from weighed filters for particles < 3.5 μm diameter) | | | Emission factor (derived from size distribution of particles < 48 μm diameter) | | | Mean value of single-scattering albedo $\tilde{\omega}$ ($= \sigma_s/\sigma_E$) | Mean values of specific absorption B_A ($\text{m}^2 \text{g}^{-1}$) |
|------------------------|--|-----------------------|--------------------------|---|-----------------------|--------------------------|---|-----------------------|--------------------------|---|---|
| | Mean | Standard Deviation | Number of samples (N) | Mean | Standard Deviation | Number of samples (N) | Mean | Standard Deviation | Number of samples (N) | | |
| Abee | 35.1 | 20.3 | 7 | 37.4 | 9.8 | 3 | 44.5 | 23.1 | 7 | ND [†] | ND |
| Eagle | 7.9 | 5.7 | 8 | 11.3 | 4.8 | 2 | 10.8 | 6.0 | 8 | 0.85 (N = 2) | 0.67 (N = 2) |
| Lodi 1 | 14.3 | 7.3 | 16 | 13.5 | 4.4 | 13 | 17.6 | 7.9 | 16 | 0.89 (N = 13) | 0.74 (N = 13) |
| Lodi 2 | 15.5 | 6.5 | 9 | 23.0 | 19.6 | 8 | 17.7 | 7.0 | 9 | 0.80 (N = 7) | 0.68 (N = 7) |
| Hardiman | 16.2 | 12.4 | 11 | 10.5 | 3.0 | 9 | 21.7 | 14.6 | 11 | 0.87 (N = 9) | 0.79 (N = 5) |
| Wheat | 43.8 | - | 1 | ND | - | - | 47.9 | - | 1 | NA [§] | ND |
| Myrtle/ Fall Creek* | 19.5 | 12.1 | 10 | NA | - | - | 29.3 | 16.5 | 10 | NA | 0.73 (N = 16) |
| Silver* | 26.4 | 13.6 | 2 | 20.2 | 12.7 | 3 | 32.5 | 17.1 | 2 | 0.88 (N = 3) | 0.36 (N = 3) |
| Satsop | 24.6 | 7.1 | 2 | 12.0 | - | 1 | 34.3 | 10.8 | 2 | NA | 0.37 (N = 1) |
| Troy | 17.1 | 12.4 | 5 | 9.7 | 3.0 | 5 | 30.2 | 19.5 | 5 | 0.82 (N = 3) | 0.82 (N = 3) |
| Averages | 18 \pm 13 (N = 71) | | | 16 \pm 12 (N = 44) | | | 24 \pm 16 (N = 71) | | | 0.86 \pm 0.07 (N = 37) | 0.72 \pm 0.18 (N = 44) |

* Wild fires.

† ND = No data.

§ NA = Not analyzed.

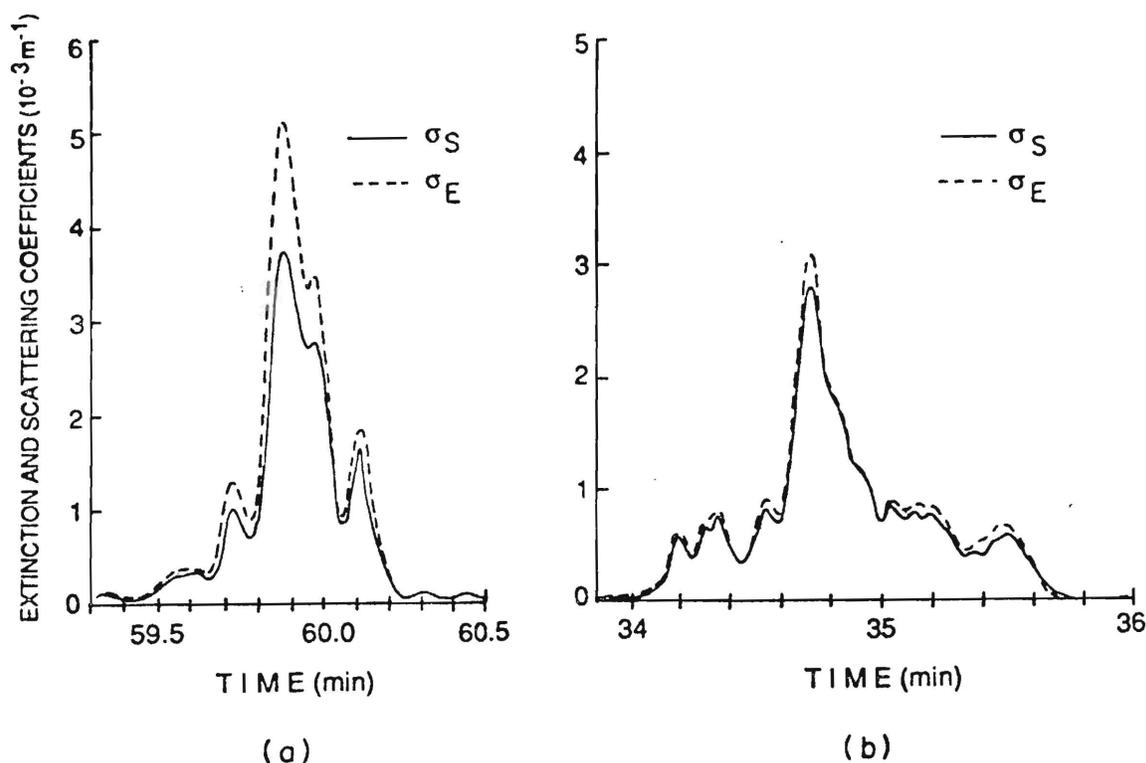


FIGURE 4. Light-extinction (σ_E) and light-scattering (σ_S) coefficients in the smoke from the Lodi 2 fire: (a) in the vertical column above the fire ($\tilde{\omega} = 0.78$), and (b) in the stabilized plume well downwind of the fire ($\tilde{\omega} = 0.93$).

Table 3 lists average values of $\tilde{\omega}$ and B_A for the fires studied. The average values of $\tilde{\omega}$ and B_A for all ten fires were 0.86 ± 0.07 and $0.72 \pm 0.18 \text{ m}^2 \text{ g}^{-1}$, respectively. Interestingly, the whitest smoke came from the Silver wild fire ($\tilde{\omega} = 0.88$) and the rather wet (late season) Lodi 1 fire ($\tilde{\omega} = 0.89$). Three of the prescribed fires (Lodi 2, Hardiman and Troy) had significant periods when $\tilde{\omega}$ was less than 0.75. During these periods the smokes were much darker (viewed from the aircraft) and, in the case of the Hardiman fire, these periods were clearly related to intense flaming combustion of the lighter fuels.

4. DISCUSSION

These results significantly increase the available data base on particle emission factors and the optical properties of smokes from forest fires. The average particle emission factor for the ten fires discussed here ($18 \pm 13 \text{ g kg}^{-1}$ for particles $< 2 \mu\text{m}$ diameter) is significantly larger than the average value ($4.1 \pm 1.5 \text{ g kg}^{-1}$ for particles $< 2 \mu\text{m}$ diameter) measured in a series of smaller, but rather intense, fires of logging debris by Radke et al. (1983). These results suggest some scaling of the particle emission factor with the intensity of the fire (lower EF with increased intensity) and/or the size of the fire (higher EF with larger fires). The particle emission factors for the two wild fires (19.5 and 26.4 g kg^{-1} for particles $< 2 \mu\text{m}$ diameter), while greater than the average for the smaller prescribed fires, were not the largest emission factors measured. The highest particle emission factor for particles $< 2 \mu\text{m}$ diameter for all of the fires (with the exception of the wheat fire) was for the Abee fire, which, if the period of apparent nucleation scavenging by cloud droplets is removed, averaged

45 g kg⁻¹. Our single observation of a very intense fire in wheat stubble gave a particle emission factor (for particles <2 μm diameter) of 44 g kg⁻¹; this suggests that further attention should be paid to this source of smoke. These were the only fires where the measured particle emission factors sustained values in excess of 30 g kg⁻¹, which is the value used in the National Academy of Sciences (1985) nuclear winter calculations for wild fires. Thus, our measurements suggest that the values for particle emission factors used in the National Academy Report are reasonable, but possibly on the high side.

In the National Academy of Sciences (1985) report it was concluded that, following a nuclear war, smokes from the burning of biomass would contribute about 20% to the smoke in the atmosphere. It was assumed that the smoke from biomass burning would have a significantly higher single-scattering albedo than the (blacker) smokes from urban fires. It was estimated that the globally-averaged, single-scattering albedo of the mixed smokes produced by urban and biomass burning would be ~0.6. In a recent modeling study of the nuclear winter hypothesis, Thompson et al. (1987) suggested that the globally-averaged, single-scattering albedo of the mixed smokes might be as high as 0.75.

If, as seems likely, smokes from urban fires are, on average, blacker than those from biomass burning, globally-averaged values of 0.6 and 0.75 for the single-scattering albedo are not inconsistent with the average value given in this paper of 0.86 ± 0.07 for the single-scattering albedo of smokes from biomass burning. However, our measurements also show that for significant periods of time the smokes from biomass fires can be quite dark. Thus, for three of the fires studied (Lodi 2, Hardiman, and Troy), single-scattering albedos ≤ 0.75 were measured for extended time periods, and the darkest smokes in the Lodi 2 and Troy fires had average single-scattering albedos of 0.65. The darkest smokes appeared to be associated with the most intense burning and long flame lengths (and, perhaps, associated lack of oxygen). Since these conditions are likely to be those that would occur in large fires produced by a nuclear war, and assuming smokes from urban fires are generally darker than those from biomass burning, our measurements suggest that the values for the globally-averaged, single-scattering albedo for the mixed smokes that have been used in modeling studies of the nuclear-winter hypothesis may be high (i.e., the mixed smoke could be darker than assumed in the modeling studies).

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KEY WORDS: Smokes from fires; nuclear winter hypothesis; forest fires; fires; particles from fires.