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International *Journal* of Wildland Fire

Scientific Journal of IAWF

Volume 10, 2001

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International Journal of Wildland Fire, 2001, **10**, 103–111

A prescription for controlling the air pollution resulting from the use of prescribed biomass fire: clouds

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Abstract. Forestry, conservation, wildfire risk reduction, and agricultural uses of planned or prescribed fires as a tool for meeting the needs of wildland managers are increasingly in collision at the air pollution control and climate change cross-roads. The inevitable conflict resulting from the disparate goals of users has long been the subject of a combination of both systems and ecologically integrated analysis attempting to minimize the environmental impact and maximize the economic and societal benefits of this land management technique. We offer here experimental evidence for the viability of implementing a pollution control option that could substantially reduce the particulate emissions from prescribed fires in biomass and explore some of the logical implications of these concepts.

In nature, clouds and precipitation are the principal mechanisms by which the atmosphere is cleansed of particulate pollution, aerosols and smokes. We propose here, for consideration, using clouds as a part of the prescription for scheduling biomass fires.

Since in most areas biomass fire is already carried out within a detailed prescriptive plan which includes meteorological forecasts, the addition of additional meteorological scheduling constraints should be acceptable to most users providing that the benefits are correspondingly large. Reducing particulate smoke emissions in all size classes by at least 50% seems practicable.

Introduction

The rapid containment, control, and extinction of wildfires has been a major part of the fire management policy in the USA. During the past 20–30 years, a major vegetation change has occurred in ecosystems with a build-up of dead and dying vegetation on the forest floor. New prescriptions are needed to accelerate and to broaden the opportunities to use fire in treating these forests which some believe to be at a greatly increased risk of catastrophic fire. One of the very serious limitations of the use of prescribed fire is the smoke that is released and the impact this has on local and regional air quality. For many reasons, the atmosphere has an amazing capacity to cleanse itself of these particles. We discuss next some of the processes involved in atmospheric cleansing of biomass fire smokes. The USDA Forest Service has pioneered research on minimizing smoke emissions from fires by controlling a variety of fuels and meteorological conditions (Hobbs *et al.* 1979; Ward *et al.* 1982; Radke *et al.* 1983; Ward and Hardy 1984, 1986, 1989). This research resulted in a large improvement in our ability to quantitatively characterize emissions from fires. These new methods of quantifying emissions were utilized in this work (Ward and Radke 1993), as quantization of emission controlling factors is a necessary step toward control.

The smoke from biomass fires is usually viewed by the local public as merely a nuisance. In some regions (South America, Africa, and Asia, which encompasses most of the tropical zones worldwide) during part of the year, smoke is visible as a continuous smoke pall for days to weeks measurably decreasing visibility and insolation (i.e. sunshine!). Smoke from biomass fires is calculated by some scientists to have a globally measurable impact on the same size order as man's industrial and urban activities (Andreae 1991; Albini 1992). Indeed, a large fraction of this smoke is of deliberate anthropogenic origin. On a global

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scale, it has been suggested by some to have increased by 50% since 1850 (Levine 1991).

Since the impact of these smokes may be important in affecting global climate change (Crutzen and Goldammer 1992; Penner *et al.* 1994; Rosenfeld 1999), it clearly is important to review our options for their control and reduction. We do not conclude that the global impact of biomass fire smokes is malign, but rather note that this issue is still another facet of the vast geophysical experiment that mankind is carrying out on planet Earth with uncertain consequences. It is clearly one of the scientific and land management communities' responsibilities to continue to focus research on understanding processes and reducing the uncertainty associated with biomass burning.

We have evidence suggesting that an additional meteorological tool to use is a fire prescription which, when carried out, can predict the successful lofting of smoke into either deep convective cumulus clouds or overlying stratus clouds. We believe this approach offers substantial potential for the reduction of smoke's impact on both the atmosphere and our environment. Since water clouds are the principal means by which particulate pollution is removed from the atmosphere, we are presenting experimental evidence showing that, by selecting circumstances where the column of smoke from the prescribed fire is promptly ingested into clouds, a substantial degree of aerosol pollution control is achieved.

Smoke is meteorologically active

All airborne particles (AP) by virtue of their shape, size and chemical composition, have varying affinities and roles in clouds and precipitation. In the normal course of events, both liquid and frozen cloud elements require an airborne particle for their formation/nucleation, a nucleus. The nuclei for cloud water droplets are called cloud condensation nuclei (CCN). CCN distinguish themselves from the rest of the AP by being better or more efficient water droplet nuclei (Pruppacher and Klett 1978).

Typically, in locations remote from primary pollution sources, about 10% of the AP are active as CCN. Somewhat surprisingly, biomass smokes are exceptionally active meteorologically with nearly 100% of the smoke AP being classed as CCN (Eagan *et al.* 1974; Hudson *et al.* 1991). Also not surprisingly, CCN are the class of AP which are most easily removed from the atmosphere. As nearly 100% of biomass smokes are CCN, these facts are at the heart of this AP control concept.

Clouds, smokes and scavenging

In the 1980s it was postulated that the smoke from large and widespread fires following a nuclear war might result in additional catastrophes in global climate, Nuclear Winter (Turco *et al.* 1983; Crutzen *et al.* 1984). Concerns about this hypothesis prompted considerable research into the smokes from biomass and urban fuel fires. Of more interest here was work into the fate and lifetime of these smokes in the atmosphere. While it is conventional wisdom that clouds are the principal atmospheric cleansing system for the removal of airborne pollution particles, dusts and smokes (Hobbs 1993), many of the details of this important process known as cloud and precipitation scavenging remain both obscure and in numerical conflict (Radke *et al.* 1980; Jensen and Charlson 1984; Schwartz and Slinn 1992; Dutkiewicz and Husain 1998).

Somewhat dauntingly, previous efforts to address this multi-faceted problem whether theoretically or experimentally have met with only rather limited success and precision. The root problem seems to be a combination of the complexity of the issue and the range of spatial and temporal scales that must be addressed if the results are to be robust enough so that they can be extended to practical applications. The breakthrough in smoke scavenging by clouds, as is often the case, comes quite through chance. The recent studies of large biomass fires had been prompted primarily by a desire to improve our understanding of how much smoke large fires can reasonably produce under a variety of circumstances (Einfeld *et al.* 1989; Cofer *et al.* 1991; Penner *et al.* 1991; Radke *et al.* 1991; Susott *et al.* 1991; Ward and Hardy 1991; Nance *et al*. 1993). We studied a variety of fires including some rather large wildfires (Radke *et al.* 1991), but the most productive studies were from well planned and executed prescribed fires on scales which ranged from a few tens to thousands of hectares (Stocks 1991). These fires, which were multiply lit by helitorch, produced dramatic fires with heat releases briefly substantially larger than all the oil fires in Kuwait after the Gulf War.

Nearly half of these research fires were lit under meteorological circumstances such that the rapidly ascending volume of smoke was capped by convective water clouds. Four of these 10 cloud-capped test fires were crowned by very large cumulonimbus complexes whose precipitation intensity ranged from light to heavy with hail and frequent lightening. Figure 1 shows one of these cumulus-capped fires which quickly grew to over 30 000 ft and rained heavily.

This presented an unprecedentedly simple experimental scenario, illustrated in Figs 2 and 3, over a usefully broad set of circumstances. In this schematic figure, the heated air, gases and the smoke ascend from the fire and form a cloud in the classical manner which then ingests, processes, scavenges and transforms the fire's effluents.

The cloud evaporates on its downwind edges and the cloud-processed effluents are released minus those removed by precipitation and coagulation. The experimental design can be made complex but, at its simplest, it is basically a box process. Measure the fire emissions inputs to the cloud base. Characterize the cloud and observe what comes out. Delightfully simple conceptually and, while aircraft

Fig. 1. The Battersby Township fire (12 August 1988) where some 700 ha of Jack Pine and White and Black Spruce were ignited by helitorch in a prescribed mass fire which quickly produced a cumulonimbus perhaps better termed a 'fumulonimbus'.

experiments near the ground in poor visibility are never truly simple, the needed experimental protocols proved entirely 'do-able'.

Measuring the scavenging of smoke by clouds

There have been a number of experimental designs for quantitatively measuring cloud and/or precipitation scavenging which have been used in the past with somewhat variable results. We reviewed these methods primarily for compatibility with a single aircraft program within the abilities of the University of Washington's C-131A research aircraft and, more recently, to the very similar CV580 replacement. (Fig. 4). This robust heavy twin-engined research aircraft was ideal for this experiment. Its extensive meteorological and air pollution instrumentation, and nervy and skilled crew were a match for this difficult assignment. We identified several rather different experimental designs, which looked promising. Naturally, by choosing different designs, even if they are not completely independent, we add a great deal of confidence to our measurements in a field which has been historically fraught with poorly constrained experimental errors and barely quantitative results by consequence of achieving a degree of agreement between experimental methods. We describe these experimental methods in some detail below for at least two reasons. First, to the author's knowledge, these results represent the first reasonably systematic set of such measurements. Because these measures are 'firsts' and because we want the community to consider the implications of these results for additional practical fire prescriptions, we feel it necessary to present these results and methods at some length.

Second, we feel that these methods and results are worthy of replication and even more detailed confirmation. Further we would welcome advice from wildfire science professionals as to how we might improve these experimental protocols.

Method #1: The Box Method

Basically a box process model where the smoke concentrations and characteristics going into the fire-capping cumulus cloud (the box) and that which comes out. By using a conserved non-reactive gaseous tracer such as CO to correct for effects of sample dilution this becomes experimentally simple, requiring only two measurements (into the box and out) reasonably temporally linked so that the assumption of fire steady state is acceptably valid.

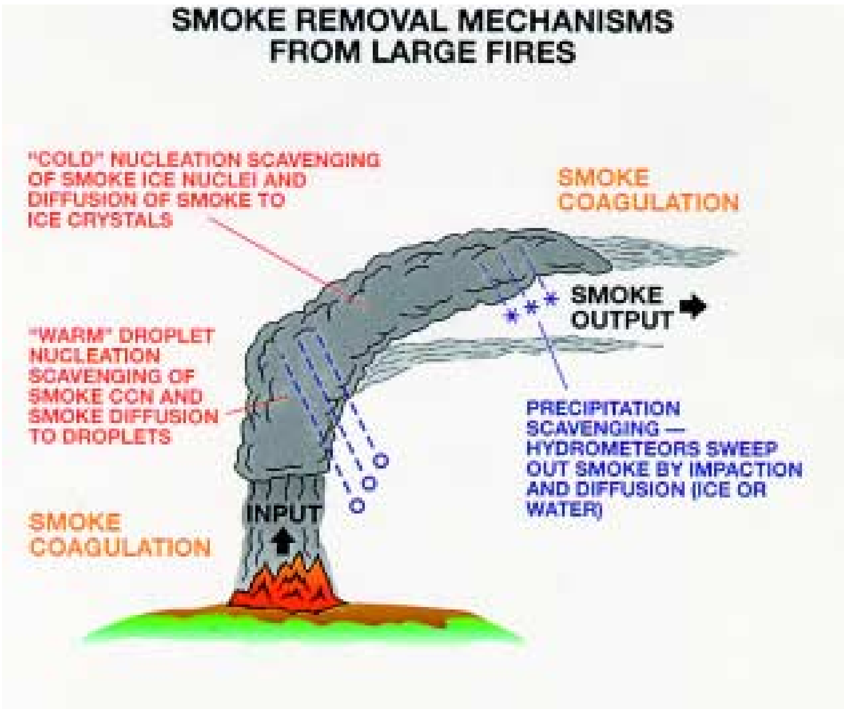

Fig. 2. An illustrative schematic of smoke removal by biomass fire-capping clouds.

Establishing the time scale over which these fires can be considered to be in a steady state condition and not flaring up or dying back, of course, introduces a significant operational uncertainty. None of these fires, even the largest, were steady sources over a period of hours, but most of these fires were reasonably stable for periods up to a few tens of minutes when we carried out our experiments.

Method #2: Smoke Combined in Cloud Water
Like Method 1, this is a two-step technique. The volumetric concentrations of particulate smoke going into the base of the capping cumulus is measured (similar to Method #1). Next the amount of smoke incorporated into the cloud's liquid water is measured using a cloud liquid water sampler (Hegg *et al.* 1984), which is then measured in post-flight

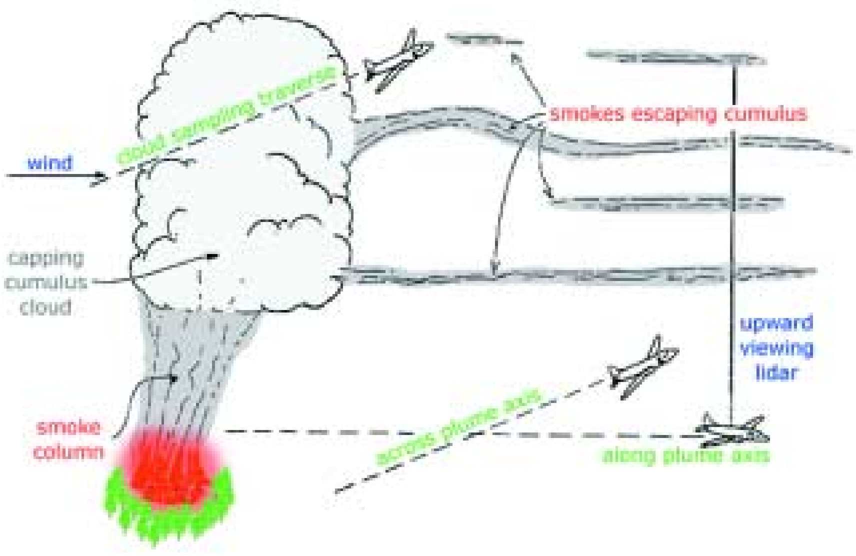

Fig. 3. An illustration of aircraft sampling protocol.

Fig. 4. The twin engined research CV580 aircraft.

laboratory analysis. The cloud liquid water content, and the mass of cloud water per volume of air measurements were each measured by independent technical means. By comparing the simultaneous mass of water collected with the cloud scoop, the equivalent air concentrations are determined, which yields the fraction of the smoke promptly scavenged through cloud nucleation and incorporated into the cloud water.

The principal uncontrolled error with this approach is that, if precipitation has begun, some smoke may have been removed in this parallel process unbeknownst/unobserved. Because of this constraint, the data are most valid if both the measurements are completed before the precipitation stage in the capping cumulus cloud's life cycle has begun.

Method #3: Smoke found between Cloud Drops

Measure the concentration of smoke particles which reside in the cloud interstitial to the cloud droplets and ratio that to the air equivalent concentration as found in Method #2 from collected cloud droplets. This method is a convenient way to directly measure the fraction of the smoke which has been nucleation scavenged. Both Methods #2 and #3 require some rather specialized sampling technology, but the tools for measuring the cloud interstitial aerosol (CIA) and collecting efficiently the cloud water are reasonably straightforward (Radke 1983; Hegg *et al.* 1984) and readily available on the C-131A research aircraft.

Method #4: The Box Model plus Emission Factors

This method requires the measurement of the Emission Factor characteristic of the fire; since this parameter's measurement is essential to this discussion we will elaborate on its measurement and derivation.

The emission factors are an expression of the effective yield of a particular product related to the mass of biomass material combusted. Particle (and other) emission factors for the fires were computed using the carbon-balance method of Ward *et al.* (1982) as adapted for aircraft sampling by Radke *et al.* (1988). This method requires in-plume measurements of all major carbon-containing products of combustion. These include CO_2 and CO, which are of primary importance, a less important subset of hydrocarbons (CH_4, C_2H_2, C_2H_6, C_3H_6, C_3H_8, and C_4 isomers), and the smoke particles (approximately 60% carbon). We assumed that all of the carbon in the fuel was released into the plume during the fire after being converted to the different carbonaceous products of combustion listed above. We further assumed that the concentration of particulate mass remained proportionally constant with reference to the concentrations of the gaseous products of combustion listed above for every Lagrangian parcel in the plume throughout the period of our measurements. This assumption is valid for particles with aerodynamic diameters less than 3.5 μm (a 3.5 μm cutpoint cyclone was used to remove larger particles before sampling on Teflon filters). The ratio of the mass concentration of carbon in the plume to the mass fraction of carbon in the fuel gives a measure of the mass of fuel required to produce the emissions contained in a unit volume of air in the plume after combustion. The reciprocal of this quantity, when multiplied by the corresponding concentration of particle mass, gives the particle emission factor (EF).

By measuring the fires particulate emission factors in the smoky air going into the cloud box and in the smoky air exiting the capping cumulus cloud, their ratio is a direct measure of the cloud's scavenging efficiency. Conveniently, no complicated and possibly error-laden calculations of dilution or equivalent air concentrations are needed to yield the smoke-scavenged fraction. Its only obvious flaw is through possible scavenging of carbonaceous gases (such as CO and CO_2), which would spoil the employment of the carbon-balancing method. Reviewing their water solubilities we find that we can neglect this potential error. Figures 2 and 3 show in rough schematic form both the smoke transitions and how an aircraft might be flown to make the needed observations.

Results and uncertainties

Each of these methods for determining the amount of smoke scavenged by their cloudy passage is fraught with a number of uncertainties that are resistant to formal error analysis. As they all involve differences between large numbers derived from difficult experimental procedures, we have reversed the normal presentation sequence by cautioning the reader before detailing the results. However, despite these quantitative uncertainties, considerable confidence in the surety of our results is gained from their remarkable consistency from this array of test fires, meteorological conditions, and analytical methods. This consistency strongly supports a belief that these results are robust and can be extended to an even larger array of meteorological circumstances.

While our discussion has focused on the fact that the smoke is ingested into the cloud and fractionally scavenged during its passage and release, we recognize that the fractions of AP scavenged by impaction and phorisis are time-dependent processes. However, our similar scavenging observations for rather different clouds suggests that the singular cloud nucleation step dominates the removed AP fraction, and thus we are justified in neglecting time dependence in this analysis.

Of roughly 10 cases for which we have some data on cloud smoke scavenging, four are of particular interest because we attempted to use more than one of the experimental methods on each and the smoke-capping clouds reached cumulonimbus proportions. These four fires took place in Ontario, Canada and were given these identifying names relating them to townships by Forestry Canada personnel.

Hardiman: 28 August 1987

The Hardiman fire took place under a cloudless sky which developed after early clearing of altocumulus and lower cumulus clouds. The fire produced a capping cumulus almost immediately with an initial cloud top 8200 ft and base 7200 ft. The cloud continued to grow both vertically and horizontally and, at a later stage (Ignition + 2 hours), cloud top was sampled (briefly) at 12 200 and observed to be much higher while bases remained 7200–7400 ft. Visible precipitation which was produced in the capping cumulus was not observed to reach the ground.

Battersby: 12 August 1988

Small cumulus and a broken upper altocumulus cloud deck were present when the Battersby fire was ignited. The fire produced a large capping cumulus with bases at 6000 ft and tops initially at 8300 ft and growing to above 12 500 ft. The capping cumulomnibus cloud was more substantial in the Battersby fire than in Hardiman. Both the capping cumulus clouds, and other natural cumulus cloud which developed in the area, produced showery precipitation which reached the ground.

Hill: August 10, 1989

The Hill fire appeared to be the most intense fire of the four being considered. The fire produced a capping cumulus cloud almost immediately with its base at 8000 ft and tops to 22 700 ft less than 1 h after ignition (ultimate cloud top height likely 10 000 ft higher than this). Precipitation, including hail, and lightning were present in the cloud. Remarkably heavy hail and precipitation were produced within minutes after fire ignition.

Wicksteed: 12 August 1989

A capping cumulus cloud formed in less than 10 min after ignition in an area with scattered small cumulus present. The capping cloud quickly reached 24 000 ft. Precipitation developed more slowly than Hill, but no heavy showers developed.

The Method 1 results for these four fires are shown in Fig. 5 (*a*–*d*). The smoke particle number and volume distributions are down in conventional format both before and after scavenging. The less familiar volume distribution becomes the AP mass distribution by rescaling by the factor of the mean AP density. The lower curves show the number and volume (mass) percentages removed (scavenged). The dashed curve represents a second sequential measurement during the fire (raw data not shown).

The results from experimental Methods 1, 2, and 3 are combined in Table 1.

Table 1. Smoke aerosol scavenging efficiency by cloud and precipitation processes for the submicron size fraction by three different measuring techniques

	Scavenging efficiency (%)		
	Method 1	Method 3	Method 2
Hardiman	~ 40		
Wicksteed	~ 60	75 ± 20	80 ± 50
Battersby	20–90		
Hill	10–50		40 ± 50

Writing the prescription

Deliberately choosing conditions where the fire's smoke will enter existing clouds, create new cumulus clouds (fumulus), or by fire's heat release greatly enhance cloud depth, will significantly reduce the smokes residence time in the atmosphere by promptly removing a useful fraction of the emitted smoke particles. Indeed, the cloud's residence time is found to be only minutes for the removal of at least half of the supermicron coarse particles (>20 μm diameter). These coarse particles are comparatively short-lived, but responsible for most of the soiling and locally evident ash fallout. These large ash-like particles normally have

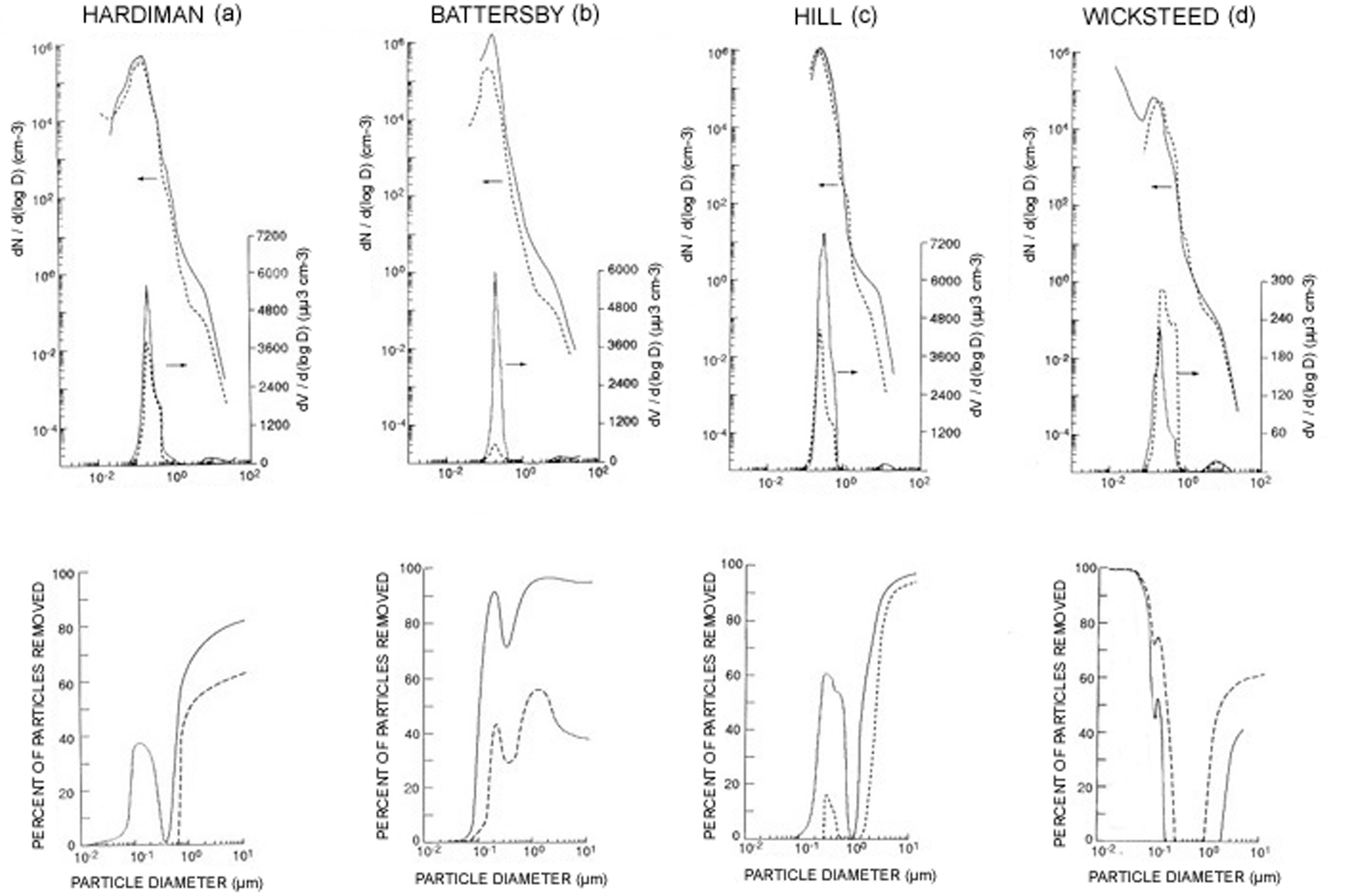

Fig. 5. Method #1 results from the Hardiman (*a*), Battersby (*b*), Hill (*c*) and Wicksteed (*d*) cases with smoke particle number and volume (mass) distributions before and after scavenging and the percentage of the smoke removed as a function of particle size.

atmospheric residence times of hours to days, and constitute only a few percent of the fire's total AP mass emissions, but can significantly impact the local attainment of EPA's PM 5.0 and PM 10 standards as well as that proposed for PM 2.5.

Since effective removal of this largest class of smoke particles by cloud cleansing doesn't seem to require precipitation formation, it is obviously the easiest case to incorporate in a burning prescription since low clouds, especially morning low cloudiness, are frequently observed over much of the forested regions of western North America. Indeed during the seasons of traditionally greatest burning frequency, a review of the relevant cloud statistics suggests that opportunities with low cloudiness or cumulus will occur on about 1/3 of possible days (Warren *et al.* 1986).

Our data strongly suggest that, to achieve a substantial reduction in smoke emissions in all AP size classes, a minimum capping cloud depth of ~2 km, accompanied by at least slight drizzle-like precipitation, needs to be achieved. Achieving these meteorological requirements imposes at least two different terms to the fire prescription:

(*a*) Stratocumulus with drizzle can pre-exist at the time of ignition. Since additional cloud vertical velocity and depth is likely to only enhance precipitation, these conditions will insure filling the prescription for effective cloud cleansing.

(*b*) Select a lifted stability index such that the heat and moisture from the fire is likely to result in deep moist convection. This criterion could be as simple as local evaluation of the Showalter stability index, or other similar standard meteorological products.

(*c*) The simple meteorological inputs described above could be replaced with a more robust coupled atmosphere fire model such as that of Clark *et al.* (1996). These sophisticated models or a subset of them could be used in a forecast mode to actually predict the depth of moist convection. Indeed the results presented in this paper could well be incorporated into such models to predict the actual net smoke cleansing effect on particular prescriptions.

The wildland fire manager and air pollution control authorities have the potential to prescribe fires in a manner that greatly reduces their impacts on air quality. This opportunity to work together could reduce particulate matter in the atmosphere by 30–50%. In addition, conditions thought to fall in the prescription window for maximum cloud smoke removal may be the same conditions when prescribed burning can most easily be done, from the standpoint of control of potential escapes. The prescription may work best for large prescribed fires producing deep convection or where multiple smaller fires are ignited with relatively stable overcast conditions. Less favorable days for cloud particle removal could be used for isolating large blocks of vegetation needing treatment. These large blocks could then be burned when near-unlimited burning conditions exist with a minimal adverse impact on air quality.

Acknowledgements

Portions of this work were carried out at the National Center for Atmospheric Research. The National Center for Atmospheric Research is operated by the University Corporation for Atmospheric Research under sponsorship of the National Science Foundation. Professor D.A. Hegg developed and carried out many of the cloud water analytical procedures that proved so useful in this work. The field measurements used herein were carried out by the Cloud and Aerosol Research Group at the University of Washington, Professor Peter V. Hobbs, Director. Critical to the success of this enterprise has been the long-term support of the U.S. Department of Agriculture, Forest Service, the National Science Foundation, and the Defense Nuclear Agency.

Ms Kay Dewar and Collette Stewart prepared the figures.

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