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BUOYANT PLUME CALCULATIONS

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Abstract

Smoke from raging fires produced in the aftermath of a major nuclear exchange has been predicted to cause large decreases in surface temperatures. However, the extent of the decrease and even the sign of the temperature change, depend on how the smoke is distributed with altitude. We present a model capable of evaluating the initial distribution of lofted smoke above a massive fire. Calculations are shown for a two-dimensional slab version of the model and a full three-dimensional version. The model has been evaluated by simulating smoke heights for the Hamburg firestorm of 1943 and a smaller scale oil fire which occurred in Long Beach in 1958. Our plume heights for these fires are compared to those predicted by the classical Morton-Taylor-Turner theory for weakly buoyant plumes. We consider the effect of the added buoyancy caused by condensation of water-laden ground level air being carried to high altitude with the convection column as well as the effects of background wind on the calculated smoke plume heights for several fire intensities. We find that the rise height of the plume depends on the assumed background atmospheric conditions as well as the fire intensity.

Little smoke is injected into the stratosphere unless the fire is unusually intense, or atmospheric conditions are more unstable than we have assumed. For intense fires significant amounts of water vapor are condensed raising the possibility of early scavenging of smoke particles by precipitation.

Introduction

Many raging fires are expected to be produced in the aftermath of a major nuclear exchange. These fires could cause significant amounts of smoke to be lofted into the atmosphere with possible dramatic climatic consequences.¹⁻³ However, the magnitude of the climate effect depends on, among other things, the amount of smoke produced in the fires, its height of injection, and the extent to which it is scavenged by precipitation formed in the early rising smoke column.⁴⁻⁷

In this paper, we address the second of these three issues. The atmospheric dynamics associated with large fires have been studied before. For example, Brode et al.⁸ and Hassig and Rosenblatt⁹ have treated plume dynamics from large area fires using numerical simulations of the hydrodynamics associated with such fires. Carrier et al.¹⁰ and Manins¹¹ used a semi-analytic approach based on the plume rise theory developed by Morton et al.¹² All of these studies neglected the effects of the added buoyancy caused by the condensation of water vapor which is

produced in the fire or carried from ground level to altitude by fire-induced dynamics. Further, these models have been limited by assumptions of slab or axisymmetric geometries which may be unrealistic, particularly in the case of background winds.

More recently, Cotton⁶ has used a cloud-scale hydrodynamic model to study both plume rise and early scavenging of smoke. His model is three-dimensional and includes a relatively sophisticated treatment of condensation and precipitation. He has studied smoke injection heights for a single fire environment: a large area fire that takes place in highly unstable background atmospheric conditions and at high altitude above sea level.

In this work we extend the above studies by examining separately how the energy release rate of the fire and the background atmospheric conditions influence smoke injection heights. Our theoretical results without condensation or background winds will be compared to the more easily applied semi-analytic theory of Morton, Taylor, and Turner¹² as discussed by Carrier et al.¹⁰ and Manins,¹¹ in order to differentiate the effects of varying entrainment treatments. These results will also be compared to observations.

Description of Model

The model we have used was developed in both a two- and three-dimensional form for the purpose of modeling hydrodynamic flows within the internal combustion engine.¹³ It has been applied to the simulation of liquified natural gas (LNG) spills¹⁴ as well as to explosions of LNG. The model solves the equations of motion for a fully compressible, nonhydrostatic fluid. In addition to equations describing the conservation of energy, mass, and momentum, species equations for water vapor, condensed water (ice and/or liquid), and a mass-less tracer (smoke) are solved. Previous tests of the model, involving the applications referred to above, were restricted to spatial scales that are at least a factor of 10 smaller than the applications envisioned here.* For this work, we have expanded the vertical and horizontal extent of the model domain to 20 and 50 km, respectively. For most of our studies, mid-latitude spring/fall background temperatures from the U.S. Standard Atmosphere Supplements¹⁵ were adopted. This atmosphere has a lapse rate corresponding to 6.2°/km in the troposphere which extends to 11.5 km and is weakly stable under conditions of saturated adiabatic rise.

*The formulation of the finite difference scheme is indifferent to the overall extent of the physical simulation provided enough zonal resolution is available.

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Our initial simulations, reported earlier by Penner¹⁶ and Penner, Haselman, and Porch,¹⁷ were carried out with a turbulence prescription based on the model developed for small scale applications. In particular, the turbulent viscosity was set equal to

$$\mu_t = (\Delta)^2 k_d^2 \left\{ \left(\frac{\partial u}{\partial y} + \frac{\partial v}{\partial x} \right)^2 + \left(\frac{\partial w}{\partial x} + \frac{\partial u}{\partial z} \right)^2 + \left(\frac{\partial w}{\partial y} + \frac{\partial v}{\partial z} \right)^2 + 2 \left(\left(\frac{\partial u}{\partial x} \right)^2 + \left(\frac{\partial v}{\partial y} \right)^2 + \left(\frac{\partial w}{\partial z} \right)^2 \right) \right\}^{1/2} \quad (1)$$

This formulation, of course, neglects the effect of buoyancy-produced turbulence.¹⁸ In this work, we have included this effect by writing the turbulent viscosity as

$$\mu_t = (\Delta)^2 \left\{ k_d^2 \left[\left(\frac{\partial u}{\partial y} + \frac{\partial v}{\partial x} \right)^2 + \left(\frac{\partial w}{\partial x} + \frac{\partial u}{\partial z} \right)^2 + \left(\frac{\partial w}{\partial y} + \frac{\partial v}{\partial z} \right)^2 + 2 \left(\left(\frac{\partial u}{\partial x} \right)^2 + \left(\frac{\partial v}{\partial y} \right)^2 + \left(\frac{\partial w}{\partial z} \right)^2 \right) \right]^{1/2} + k_b^2 \left| \frac{g}{\theta} \frac{\partial \theta}{\partial z} \right| \right\} \quad (2)$$

where

$\Delta = (\Delta x \Delta y \Delta z)^{1/3}$, is a length scale,

$k_d = 0.2$, is a dimensionless constant,

$k_b = 0.2$ if $\partial \theta / \partial z < 0$,

$k_b = 0.0$, if $\partial \theta / \partial z > 0$, is a dimensionless constant,

$\theta = T_0(1000/P_0)^{R/C_p}$, is the potential temperature, and

$g = 980 \text{ cm/s}^2$, is the acceleration of gravity.

We have found that this added source of turbulence does not significantly affect smoke deposition heights in our model.

Model Testing

Data with which to test our model for conditions corresponding to a very intense fire are rare. Manins¹¹ lists several fires ranging in estimated magnitude from 2×10^4 MW to 1.7×10^6 MW. As shown below, smoke injection heights are sensitive to the amount of condensation that occurs in the rising smoke column. Thus, model results are sensitive to details of the assumed background atmospheric conditions. For the intense fires of WWII that developed into firestorms (e.g., Hamburg, Dresden, and Hiroshima), detailed information on background atmospheric conditions is not available. In addition, the reported smoke heights are typically from the incidental reports of WWII pilots and thus poorly known. Nevertheless, these WWII fires represent conditions closest to those we wish to consider here. Therefore, we will explore a simulation for the Hamburg firestorm as a test of our model for large, intense fires.

The Hamburg Firestorm: An Intense Energy Source

In the Hamburg fire, a total area of about 12 km^2 with a fuel loading of 157 kg/m^2 burned in about 6 hours.¹⁰ The estimated total power output was 1.7×10^6 MW.^{10,11,19} The observed ambient winds were light, less than 4 m/s at ground level. The atmospheric lapse rate was reported as $8.8^\circ/\text{km}$ up to 3 km and $1.67^\circ/\text{km}$ above that level (Brunswick²⁰ as quoted by Carrier et al.¹⁰). This ground level lapse rate is close to a dry adiabatic atmospheric lapse rate, but the lapse rate above 3 km seems unrealistically small. Therefore, for test purposes, we adopted the standard atmospheric profile for midlatitude spring, full conditions with a lapse rate of $6.2^\circ/\text{km}$ and no background wind. The atmosphere was assumed to be dry so that no condensation of water vapor took place. An energy release rate of 1.7×10^6 MW was assumed over a circle of radius 2 km .

Our results for smoke injection heights for the simulated Hamburg firestorm are shown in Figures 1a and 1b. As shown in Figure 1a, for a fully three-dimensional simulation after 1800 s of simulated fire, the smoke plume has risen to 12 km directly above the fire, but drops to about 8 km as it spreads away from the source. Thus, the smoke from this fire appears to "overshoot" its equilibrium height directly above the fire and return to lower altitudes downwind. This is a commonly observed feature for many of the smaller fires that have been studied in more detail.⁴¹

The velocity field for this simulation is shown in Figure 1b. The velocity field confirms that the smoke which is carried to the highest altitudes will be advected downward as it spreads away from the center of the fire. Thus most of the smoke after 6 hours of burning, will be injected near $8\text{--}9 \text{ km}$. These calculated smoke plume heights agree well with the observed values of $9\text{--}12 \text{ km}$ as quoted by Manins.¹¹ Thus, our model procedures seem to be verified, to some extent, for large-scale, intense fire conditions.

The Long Beach Fire: A Less Intense Energy Source

In contrast to the data available for large fires, examples of smaller fires are easily found. Here we choose to study one fire which took place in Long Beach in 1958,²² primarily because it represents the largest fire used to verify the Morton, Taylor, Turner¹² theory (hereafter referred to as MTT, see discussion below).

For this fire, the sky was clear indicating a dry, non-convective or stable atmosphere, and satisfying the conditions necessary to properly apply MTT. The smoke plume is described by Davies²² as being cone-shaped and 1000 m thick with a top at over 1800 m as observed 1.6 km downwind of the fire center. At 48 km downstream, the smoke plume was observed to be 1800 m thick with a top near $3,300 \text{ m}$. Atmospheric conditions were such that there was no wind to 1.2 km , and the temperature lapse rate was $6.5^\circ/\text{km}$. The heat release rate for this fire was $10,000 \text{ MW}$.²³ The radial extent of the fire was not given.

We simulated this fire using a calm background atmosphere which was assumed to be dry so that no condensation of water vapor occurred. The radius of the circular fire area was assumed to be 500 m . While this area might be somewhat large, model experiments with a slab con-

FIGURE 1a. Smoke mass mixing ratio contours in the x - z plane after 1800 s for the Hamburg firestorm simulation. The geometry of the model simulation assumed a reflection plane at $x = 0$ and $y = 0$, with a constant heat release rate of 1.7×10^6 MW extending over a circular radius of 2 km. Contour intervals are $1/10$ of the maximum predicted smoke mass mixing ratio, which was 7.24×10^{-5} gm/gm. The observed range of plume tops are shown, as well as the predicted top from Manins¹¹ and Carrier et al.¹⁰ The plume width parameter, b , calculated by Carrier et al.¹⁰ extends to infinity at the top of the plume.

FIGURE 1b. Velocity field in the x - z plane after 1800 s for the Hamburg firestorm simulation. The maximum predicted velocity was 67.8 m/s. (See caption for Figure 1a.)

figuration showed that the predicted smoke heights downwind of the fire were relatively insensitive to the areal extent of the fire, provided the total energy release rate was fixed. With smaller areal extent however, the overshoot near the center of the plume becomes more pronounced.

Smoke mass mixing ratio contours in the x - z plane for this fire are shown in Figure 2a. The velocity field is shown in Figure 2b. Our simulation appears to overestimate smoke heights close to the fire. However, the smoke appears to be spreading out in a band that is consistent with the smoke column as observed from 48 km away. The top of the smoke plume is quite consistent with that predicted by Briggs²² using MTT (see below).

FIGURE 2a. Smoke mass mixing ratio contours in the x - z plane after 3600 s for the Long Beach fire simulation. The geometry of the model simulation assumed a reflection plane at $x = 0$ and $y = 0$, with a constant heat release rate of 10^4 MW extending over a circular region with a radius of 500 m. Contour intervals are $1/10$ of the maximum predicted smoke mass mixing ratio, which was 2.18×10^{-5} gm/gm. The observed width and altitude of the smoke plume as well as the plume top predicted by Briggs²² are also shown.

FIGURE 2b. Velocity field in the x - y plane after 3600 s for the Long Beach fire simulation. The maximum predicted velocity was 16.6 m/s. (See Figure 2a caption.)

We conclude that our model provides a good description of smoke injection heights for a range of fire intensities, at least under dry, calm conditions where little condensation takes place. We describe below how water condensation affects smoke heights.

Comparison of Model Results to the Morton-Taylor-Turner Semi-Analytic Solution

Both of the fires described above have been studied using the Morton-Taylor-Turner¹² plume rise theory (MTT). This is a semi-analytic approach that is applicable in stably stratified atmospheric conditions. Morton et al. develop equations for an axisymmetric system assuming a radial form for the smoke plume that is similar for

all heights. This reduces the system of equations to three (species equations for water are not considered):

$$\frac{d}{dz} (b^2 \bar{w}) = 2\alpha b \bar{w}$$

$$\frac{d}{dz} (b^2 w^2) = b^2 g'$$

$$\frac{d}{dz} (b^2 w g') = -b^2 w N^2(z)$$

where

b = the effective radius of the plume

$\bar{w}$ = the average vertical velocity in the plume

$g' = g(\rho_0 - \rho)/\rho_1$

$N^2 = (-g/\rho_1)(d\rho_0/dz)$

ρ = density in plume

ρ_0 = ambient density

ρ_1 = reference density at the surface.

The first equation describes conservation of volume (or mass), the second, conservation of momentum, and the third, conservation of buoyancy. Further assumptions include the Boussinesq approximation (i.e., perturbations to density are small except as they affect buoyancy), and the assumption that the rate of entrainment of ambient air at height z is proportional to a characteristic velocity at that height, with proportionality factor α . These equations were transformed to a nondimensional form and then solved assuming a virtual point source at the nondimensional height $z_1 = 0.0$.

The MTT theory has been applied with few changes to large area fires by Manins.¹¹ He calculates, for example, the plume height for Hamburg as 9.2 km assuming an entrainment coefficient of 0.132. However, Manins treats the approximate 12 km² fire source area as a point at the surface, thereby neglecting the requirement of Morton et al. to determine a virtual source below the surface to account for fire area. Manins compares his model to a variety of large fires with rather good agreement. However, given the poor data usually available for large fires, and Manins' apparent disregard for the horizontal extent of the fire, this agreement may be fortuitous.

Carrier et al.¹⁰ also applied the Morton-Taylor-Turner theory to large area fires. They do, in fact, take account of the need to locate a virtual source below the surface to allow for the areal extent of the fire. But they then find that the Hamburg fire plume reaches only 4 km using the ambient entrainment coefficient of 0.093, considered appropriate for smaller fires. Carrier et al. therefore argue that entrainment rates are reduced due to a fire convection column whirl. They include equations expressing the conservation of angular and radial momentum in order to quantify the reduced entrainment expected in a spinning fire whirl. Unfortunately even this treatment is unsatisfying because both the area of the surface region, used to locate the virtual point source, and the entrainment coefficient can be adjusted until observations are matched.

Our calculated smoke heights for the Hamburg fire are compared to observations and those predicted by Carrier et al. and Manins in Figure 1a. The smoke heights for the Long Beach fire as predicted by Briggs²³ are compared in Figure 2a.

Our results for Long Beach are similar to those of Briggs. For Hamburg, our results compare well to those predicted by Manins, using ambient entrainment rates ($\alpha = 0.132$) and neglecting the areal extent of the fire or to those of Carrier et al. using reduced entrainment rates.

As mentioned above, our slab model experiments for the Long Beach fire showed little sensitivity to the areal extent of the fire if the total energy source was fixed.* This observation tends to support Manins' application of the Morton-Taylor-Turner theory which neglects the fire area but requires no adjustment of the entrainment rate. However, more study is needed to confirm this.

Results of Simulations for Large Area Fires

Previous sections have discussed the application of our model to both large (Hamburg) and small (Long Beach) fires. For both of these simulations, condensation of water vapor and background wind speeds were negligible. In this section, we explore the sensitivity of our model to these effects. Most of the calculations which follow were performed with a two-dimensional slab configuration, but we show a few comparisons to full three-dimensional simulations.

Figures 3-5 examine how smoke deposition heights change as background wind speeds and condensation of water vapor is added. Figures a, b and c in each case correspond to results computed with a slab configuration, while d corresponds to a full three-dimensional simulation.

Three fire intensity sources are considered: 8.9×10^4 W/m², 1.4×10^4 W/m², and 2.3×10^3 W/m². Assuming a heat release rate characteristic of burning wood, namely 2×10^4 J/g, the first intensity corresponds to burning a total fuel load of 10 g/cm² in about 6 hours, the second corresponds to burning 3 g/cm² in about 12 hours, and the third corresponds to burning 0.5 g/cm² in about 12 hours. These three fuel loadings represent the three nominal cases considered by Turco et al.² for city centers, suburban regions, and forested areas, respectively.

Emission rates for smoke were assumed to be 3% of the fuel consumption rate. In each calculation the smoke source region extended from -5 km to +5 km about the center. For all cases the ambient temperature profile is that for the spring/fall midlatitude atmosphere.¹⁵

In Figures a and b of each set only half the domain is shown since the simulation is symmetric about the origin. In Figures c and d, a background wind was assumed present which carried the smoke to the downwind side of the source region. The scale on the abscissa of these figures has been shifted accordingly.

In Figure 3a dry, calm conditions were assumed so that no background wind was present and water vapor did not condense. In Figure 3b the global average relative humidity profile from Manabe and Wetherald²⁴ was allowed to be carried aloft in the convection column. As vapor condenses at high altitude latent heat is released and drives the smoke plume higher.

*We varied the areal extent of the Long Beach fire by factors of 1/4 and 4.

FIGURE 3. Smoke mass mixing ratio contours in the x - z plane after 3600 s from a 5 km radius fire with a heat release rate of 8.9×10^4 W/m². Figures a, b, and c were produced using a slab-geometry model. Figure d represents a calculation from a full three-dimensional simulation. Contour intervals for each figure are $1/10$ of the maximum predicted mass mixing ratios which were 2.94×10^{-5} , 2.88×10^{-5} , 3.52×10^{-5} , and 3.98×10^{-5} gm/gm for Figures a-d, respectively. (See text for explanation.)

In Figures 3c and 3d average background winds (see Figure 6) were assumed present before and during the fire simulation.²⁵ These background winds change the developing smoke convection field and carry away the smoke that reaches the highest altitudes. However, as shown by comparison of Figures 3c and 3d, in the slab configuration, horizontal velocities are stronger and upward momentum is more easily damped than in the full three-dimensional simulation (compare the velocity fields shown in Figures 7a and 7b). Thus, the smoke does not reach as high an altitude over the fire source area in the slab case as compared to the more realistic three-dimensional case.

For this high intensity source the amount of water vapor which condenses is similar in both the two- and three-dimensional cases (see Figures 8a and 8b as well as the discussion below).

For the smaller intensity sources the effect of the latent heat of condensation is larger when no wind is present (compare Figures 4a and 4b and Figures 5a and 5b). However, a background wind is able to more effectively reduce

FIGURE 4. Smoke mass mixing ratio contours in the x - z plane after 3600 s from a 5 km radius fire with a heat release rate of 1.4×10^4 W/m². Figures a, b, and c were produced using a slab geometry model. Figure d represents a calculation from a full three-dimensional simulation. Contour intervals for each figure are $1/10$ of the maximum predicted mass mixing ratios which were 1.30×10^{-5} , 1.38×10^{-5} , 1.61×10^{-5} , and 1.67×10^{-5} gm/gm for Figures a-d, respectively. (See text for explanation.)

the injection height of the smoke for low compared to high intensity sources.

In Figure 4c (compared to 4a) the smoke is apparently lofted to higher altitudes as significant amounts of water condenses downwind of the fire. This effect is not present in the three-dimensional simulation (Figure 4d), because much less water condenses (compare Figures 8c and 8d). This is consistent with the tendency of the slab model to overestimate horizontal momentum and underpredict the amount of "overshoot" associated with any given fire (see for example, Figure 7). Thus, for this fire, in the slab model, the water vapor which is lofted with the initial plume remains at higher altitude and is more easily condensed. This adds buoyancy downwind of the fire, which lofts the smoke even higher.

Figures 9, 10 and 11 show the horizontally integrated smoke density within the model domain corresponding to each configuration as a function of altitude for the four cases and three fire intensities considered above. Apparently only a small fraction of the total generated smoke

FIGURE 5. Smoke mass mixing ratio contours in the x - z plane after 7200 s from a 5 km radius fire with a heat release rate of $2.3 \times 10^3 \text{ W/m}^2$. Figures a, b, and c were produced using a slab geometry model. Figure d represents a calculation from a full three-dimensional simulation. Contour intervals for each figure are $1/10$ of the maximum predicted mass mixing ratios which were 8.97×10^{-6} , 7.84×10^{-6} , 6.04×10^{-6} , and 1.26×10^{-5} , for Figures a-d, respectively (see text).

FIGURE 6. Assumed average background wind speeds used in the calculations shown in parts c and d of Figures 3-5. These winds are the average of 10 years of radiosonde data of the longitudinal wind at 45°N as presented by Oort.²⁵

FIGURE 7. Velocity field from the slab model simulation (a) and the full three-dimensional simulation (b) of a 5 km radius fire with heat release rate of $8.9 \times 10^4 \text{ W/m}^2$. Figures a and b correspond to the smoke mass mixing ratio contours shown in Figures 3c and 3d, respectively.

FIGURE 8. Mass mixing ratio contours of condensed water. Figures a-b compare the patterns and amounts of condensed water from the slab model and three-dimensional model for a fire of source strength $8.9 \times 10^4 \text{ W/m}^2$. Figures c-d compare a similar calculation for a fire of source strength $1.4 \times 10^4 \text{ W/m}^2$. Contour intervals for each figure are $1/10$ of the maximum predicted mixing ratios which were 2.56×10^{-3} , 3.91×10^{-3} , 6.24×10^{-3} , and $1.79 \times 10^{-3} \text{ gm/gm}$ for Figures a-d, respectively.

FIGURE 9. Total integrated smoke in model domain as a function of altitude after 1 hour for a high intensity fire of source strength $8.9 \times 10^4 \text{ W/m}^2$. Results are shown for the four simulations described in Figures 3a-d, as well as for the average vertical profile of smoke assumed by Turco et al.² Turco et al.'s profile extends up to 19 km.

FIGURE 10. Total integrated smoke in model domain as a function of altitude after 1 hour for a medium intensity fire of source strength $1.4 \times 10^4 \text{ W/m}^2$. Results are shown for the four simulations described in Figures 4a-d, as well as for the average vertical profile of smoke assumed by Turco et al.² Turco et al.'s profile extends up to 19 km.

reaches and remains at the highest altitudes. Depending on the background atmospheric conditions, most of the smoke is lofted to between 6-10 km for the high intensity case, between 2-8 km for the medium intensity case and below 3 km for the low intensity case.

The smoke injection patterns assumed by Turco et al.² are also included in Figures 9-11. Their assumed low-altitude smoke deposition heights correspond to a reasonable combination of the low and mid-intensity fire sources. However, even our largest intensity fire lofted little smoke to the stratosphere. (The tropopause is at 11.5 km in our model.) Under calm conditions, for a high intensity fire, if water vapor condenses, it may cause penetration of the tropopause by some of the smoke. But, in this case, the

FIGURE 11. Total integrated smoke in model domain as a function of altitude after 2 hours for a low intensity fire of source strength $2.3 \times 10^3 \text{ W/m}^2$. Results are shown for the four simulations described in Figures 5a-d, as well as for the average vertical profile of smoke assumed by Turco et al.² Turco et al.'s profile extends up to 19 km.

large amount of condensed water could also act to rapidly remove smoke via precipitation scavenging.

Conclusion

We have used a two- and three-dimensional hydrodynamic model to examine smoke injection heights above large-area fires. The height of smoke injection depends critically on

1. the intensity of the heat release rate,
2. the stability of the background atmosphere,
3. the amount of water vapor present in the background atmosphere (and therefore its tendency to condense), and
4. the background wind speeds.

For average conditions in northern midlatitude regions we predict smoke lofting to heights that are consistent with the bulk of the smoke distribution assumed by Turco et al.² for nominal fire source intensities of 1.4×10^4 and $2.3 \times 10^3 \text{ W/m}^2$. However, in contrast to their assumptions, little smoke is injected into the stratosphere even for a very intense fire.

The smoke injection heights reported here are preliminary since precipitation scavenging processes have not been included. Furthermore, processes which may alter smoke injection heights on time scales between those appropriate to the plume scales considered here and those appropriate to the initiation of global scale climate simulations^{2,4,8} need to also be addressed. These processes include, for example, coagulation of smoke particles, swelling due to interaction with water vapor, and heating and dynamics associated with absorption of solar energy by the smoke.

For these simulations, we have not included the source of water vapor due to fuel burning ($\sim 1 \text{ gram of water/gram of fuel burned}$). We conjecture that this source could add as much as 25% more condensed water to the

system for the high intensity case. Of course, there would be enhanced buoyancy due to the added latent heat of condensation, but we estimate that the plume top would be changed by at most 0.5 km.

The total smoke and condensed water in our three-dimensional simulations are summarized in Table 1. Clearly for a high intensity source, enough water is condensed to remove most of the smoke before it spreads to global scales. However, the clouds formed may not precipitate if "overseeding" occurs. The clouds formed above our higher intensity fires for average conditions contain more than 1 gram of condensed water per cubic meter of air, i.e., more than the amount generally assumed necessary to initiate precipitation in the ambient atmosphere. Whether these clouds would actually rain and remove much of the smoke at early times depends on the hygroscopic character of the smoke particles, how effectively the particles act as cloud condensation nuclei, as well as other poorly understood and, consequently, poorly modeled processes.^{6,7,40} Detailed microphysical models of the interaction of smoke particles with themselves and with water (vapor, liquid, ice) are needed to examine these critical issues.

TABLE 1. Total smoke and condensed H₂O in three-dimensional model domain.

Source strength (W/m ²)	Time (hours)	Smoke (tons)	Condensed H ₂ O (tons)
8.9×10^4	1.0	3.55×10^4	4.56×10^6
1.4×10^4	1.0	5.08×10^3	6.30×10^4
2.3×10^3	2.0	1.81×10^3	1.98×10^2

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