J2.7 IMPACT OF RELEASED FUEL MOISTURE ON ATMOSPHERIC DYNAMICS

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1. INTRODUCTION

A common component of fire incident reports and prescribed burn preparations is an estimate of the energy that was or will be released by the fire. Typically, this is based on the energy released by combustion of the fuel load, reduced to account for the energy that is required to evaporate moisture in the fuel materials. (e.g., Byram 1959, Anderson 1968, Simard et al. 1983.) The result of this computation is then used to calculate the flame length, spread rate, and a host of other fire behavior factors.

This approach does indeed give some indication of the direct flame behavior as driven by the combustion. The energy of evaporation is not trivial, however, and can still influence the fire's behavior. As the fire plume, with moisture in it, rises above the ground, adiabatic cooling will cause condensation, and the subsequent latent heat release influences winds in ways that may lead to modified fire behavior. In a footnote, Byram (1959) alluded to this fact, stating "The significance to fire behavior of this returned [condensational] energy at high levels is not yet known."

A fire releases prodigious amounts of moisture as it burns. Not only is there the pre-fire moisture held in the fuel materials, but there is also the moisture that is produced by the combustion process. Under certain conditions, the heat from a fire may also evaporate moisture from foliage without consuming it. Overall, the moisture injected into the atmosphere by a fire can amount to tons of water for each hectare that burns. Such a quantity of moisture can, in theory, substantially alter the dynamics of the atmosphere around the fire. This influence has been implicitly acknowledged by several others (e.g., Goens and Andrews 1998, Simard et al. 1983) since Byram, but has never been given careful consideration. I propose to demonstrate that not only could this moisture be important in driving the winds in the convective column, but also that it may be an important contributor to the more erratic and dangerous winds that can occur during a large wildfire.

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2. OBSERVATIONAL EVIDENCE

Observations from several fires provide strong direct support for the presence of released moisture. Essentially, any time a smoke plume rises high enough to form a pyrocumulus, and there are no other clouds in the vicinity, the implication is that the moisture in the pyrocumulous must have come from fuel combustion. If there is precipitation reported from a fire plume, this is further evidence of moisture being added to the atmosphere by the fire for two reasons. The first reason is that there must be adequate moisture to form the rain and the second reason is because the rain amount must be sufficient to survive the fall through typically dry environmental air without completely evaporating

During the Mack Lake Fire (Simard, et al. 1983), the sky was otherwise cloudless, surface humidity was 21-37%, and yet rain fell from the smoke plume on Oscoda, Michigan. The surface humidity and temperature indicate a water vapor mixing ratio of about 5 g kg^{-1}. As a crude approximation, based on Kessler's (1969) autoconversion of cloud water to rain water, at least 2 g kg^{-1} must condense to cloud water before rain begins to form. In the case of the Mack Lake sounding, this means air would have to rise to approximately 550 mb before any rain formed. The drops would then have to survive the fall through very dry air between 700 mb and the surface without completely evaporating, and remain abundant enough to be noted on the ground.

Photographic evidence from a number of fires available in the National Interagency Fire Center's Wildland photo gallery (http://firepix.blm.gov) shows fire plumes in otherwise clear skies. The Burgdorf Junction fire, on 27 July 2000, produced a plume that rises into an otherwise cloudless sky. The 0000 UTC 28 July 2000 sounding from Boise, Idaho indicates surface relative humidity of 15%, with values of 16% or less from the surface up to 850 mb. Similarly, during the Hash Rock fire near Prinville, Oregon on August 1, 2000, surface conditions (at Burns, OR, the nearest surface airways site) indicated relative humidity of 32%. Skies were reported clear with no notable weather occurrence at Burns, yet the fire produced a substantial smoke and water plume.

3. PHYSICAL ARGUMENTS

Physical conservation laws also support the notion that water release from burning fuels is substantial.The combustion equation presented in Davis (1959) and Johnson and Miyanishi (2001) states that the moisture produced by combustion of woody fuels is approximately (0.55+*M*) kg of water per kg of fuel, where *M* is fractional moisture content of the fuel before combustion. With fuel consumption for fires generally measured in tons per hectare or acre, the moisture yield, even for incomplete combustion, must also be on the order of tons per hectare. This moisture must go somewhere, and it must leave the immediate vicinity of the fire. If it goes up or sideways, it must be in the air. If it goes downward, into the soil, some mechanism must force the water in, and it should be straightforward to observe very wet soil after a fire. Since the air involved in the combustion is carrying the other combustion products upward, it is reasonable to assume that the water also goes upward.

I will present two physical models. The first estimates the direct emission of moisture from fire fuels into the combustion air, and the second estimates the moisture content of the air after turbulent entrainment near the ground. With a situation as complex as that occurring in a combustion zone, precise calculations are impossible. These are necessarily simple models, intended only to see if the moisture flux and moisture content are anywhere near what is observed or reasonable. They are meant to be a first step only. If the physical models and reasonable estimates of the input variables yield results that suggest moisture influences convection dynamics, then I will consider the models to support the hypothesis that combustion-moisture should be considered further.

First, then, consider the effect of combustion water on the mixing ratio of air in the combustion region. For the sake of this model, I will consider the horizontal dimension of the combustion zone to be approximately the width of the fire head, from front to back, and the vertical dimension to be the flame height. Let R be the rate of spread of the fire (m s^{-1}), L_H be the length of the fire head (m), ρ_f be the fuel loading (kg m^{-2}), and C_w be the ratio of water mass produced to the mass of fuel consumed (kg kg^{-1}). Then the rate at which the fire releases/produces moisture is

$$F_w = R\, L_H\, \rho_f\, C_w \qquad (1)$$

in units of kg s^{-1} where kg means kg of water substance.

Now, let u be the average windspeed of air entering the combustion region, ρ_a be the air density, and D be the depth of the layer of air directly entering the combustion region. Assume, also, that u and R are in the same direction, so that the fire is moving with the wind. The mass of air into which F_w passes is then

$$M_{air} = L_H\, (u\text{-}R)\, \rho_a\, D \qquad (2)$$

and as for F_w, units are kg s^{-1}, though these are kg of air.

Dividing (1) by (2) yields an estimate of the direct, immediate change in mixing ratio as a result of fuel combustion:

$$\Delta q_v = \frac{R\, \rho_f\, C_w}{(u\text{-}R)\, \rho_a\, D} \qquad (3)$$

in units of kg water per kg of air.

Simard et al. (1983) provide most of these parameters for the Mack Lake fire, and for various periods during the fire's duration. Consider the period 1238-1310 LST, immediately prior to the fire's biggest run. For this period, R is 1.25 m s^{-1}, ρ_f is 2.2 kg m^{-2}, and ρ_a is approximately 1 kg m^{-3}. Observed wind speed at Mio, Michigan was 4.5 m s^{-1}, but winds being drawn into the fire, could have been anywhere from this up to about 10 m s^{-1}. The best value of D is probably the flame height, which was reported at 10-13 m. As an upper limit on D, I will use 20 m, approximately the height of the trees in the area of the Mack Lake fire. Finally, the amount of moisture released per unit mass combusting, C_w, must be at least *M*, the fuel moisture content, but may be as high as (0.55+M). Simard et al. estimated fractional fuel moisture between 0.05 and 0.10; a lower limit for C_w is then 0.05, while an upper limit is 0.65.

Based on these measured and estimated values, Δq_v can be anywhere from 0.8 g kg^{-1} to 55 g kg-1. Most of this variation is due to the choice of C_w. Since the estimate of ρ_f is based on reported fuel consumed, rather than pre-fire fuel loading, the upper limit is more appropriate.

The lower of these values is a 15% increase over ambient conditions, while the upper value would represent a 10-fold increase. Neither of these amounts is small, and even the lesser is sufficient to alter the energetics of the circulation produced by the fire. The next period cited in Simard et al., from 1310 to1325 LST, would yield even greater values for these estimates – roughly four times the above values.

Considering that combustion region air temperatures can be tens or even hundreds of Kelvins above ambient, and wind speeds are highly erratic in the region, substantial entrainment must occur close to the ground. This turbulence will not only dilute the sensible heat added to the air by the fire, but also any latent heat (i.e., moisture) from the fire. Anecdotal accounts and coupled fire-atmosphere numerical model simulations indicate that during a fire, the air as low as 15-20 m above the combustion region may have perturbation temperatures on the order of 1 K to 3 K. Similarly, the perturbation in mixing ratio observed at these heights is approximately 1 to 3 g kg^{-1} (Jenkins, personal communication).

By assuming a plume-air temperature before dilution, T_p, a post-entrainment difference (δT) between the plume and environment, T_e, and conservation of energy, one can estimate the volume of air that the plume must entrain to reduce the air temperature to ($T_e+\delta T$). Assuming also (1) a simplistic cylindrical shape for the initial plume air and the post-entrainment plume, (2) no mean kinetic energy is lost to turbulence, and (3) that the plume radiates energy from its lateral faces during entrainment according to the Stefan Boltzmann law, the entrained volume is approximately

$$V_e=\frac{\pi RH}{\delta T}\ [R(T_p-T_e-\delta T)+ \frac{2\sigma}{\rho c_p}\ t_e(T_e^4-T_p^4)] \qquad (4)$$

Here, R is the radius of the initial plume air; H is the thickness of the initial plume cylinder of air; σ is the Stefan-Boltzmann constant; ρ is air density; c_p is the specific heat of air at constant pressure; t_e is the time it took for the mass of plume air to rise from the ground to the height (z_e) at which the final airmass temperature is ($T_e+\delta T$). This time can be specified directly, or computed based on an assumed ascent speed and height. The scale for R is approximately that of the actively burning fire-head width. The thickness of the initial cylinder, H, is related to inflow wind speed, but not in any directly obvious and calculable way.

The entrained volume, V_e, can then be used to compute a final perturbation mixing ratio if the initial plume-air mixing ratio is specified. Let q_e be the environmental mixing ratio, Δq the increase over q_e caused by fuel combustion as used in eq. (3), and q' the post-entrainment perturbation mixing ratio of the combined combustion and entrainment air. Conservation of water mass then shows

$$q' = \frac{(q_e+\Delta q)V_p+q_eV_e}{V_p+V_e} - q_e \qquad (5)$$

These equations represent a very simple model, and the values for most of the parameters can only be estimated within wide ranges. The results are meant only to determine whether the model yields order-of-magnitude values that show consistency between the results of eq. (5) and the simulated perturbation mixing ratios at 15-20 m in the coupled fire-atmosphere models.

Bearing this in mind, consider R of approximately 5 m, H of 1 m (H should be a small portion of z_e or else the model does not make physical sense), and z_e of about 15 m. In terms of temperature, let T_e be 300 K, δT be 2 K, and T_p be 350 K. The latter is subject to great uncertainty, and could reasonably be anywhere between 330 K and 500 K, but a perturbation of 50 K is in line with the results shown in Clark et al. (1996). With z_e of 15 m and estimating a vertical velocity of roughly 20 m s^{-1}, t_e is 1 s. Finally, I will estimate q_e at 10 g kg^{-1} and Δq somewhere in the range of 5 to 50 g kg^{-1}, based on the results of the earlier calculations.

Using these values yields V_e of 2 036 m^3 (or, between 1 250 and 7 880 m^3 for the range of T_p between 330 K and 500 K, respectively). The perturbation in mixing ratio that results after this middle-estimate of entrainment would be 0.2 g kg^{-1} if Δq is 5 g kg^{-1}, or 1.9 g kg^{-1} if Δq is 50 g kg^{-1}. If one considers the range of Δq and of T_p, the range of possible values for q' lies between 0.05 g kg^{-1} and 3.0 g kg^{-1}.

At the lower end, these values are negligibly small. The low-end estimate accounts only for pre-fire fuel moisture and neglects any water produced by combustion of the fuel. It also represents the highest estimate of the plume-air temperature before entrainment. The high end estimate is, I believe, more accurate in terms of Δq, and the middle-estimate is probably the most plausible. The range of values demonstrates, in any case, that the moisture produced and released by the fire has the potential, in theory, to affect the plume's behavior and the ascent of the air in it.

4. IMPACT ON ENERGETICS

Thus far, I have shown that there is observational support for the presence of water in fire plumes above and beyond that present in the ambient environment, and that based on simple models, it is plausible that this water comes from the drying and combustion of the fuels in quantities sufficient to affect atmospheric dynamics. Even if the water comes from fuels and is apparent in the plumes, there remains a question of just how much of an impact it might have on the energetics of plume convection.

One of the most commonly cited measures of the ease or difficulty of ascent for convection is the Convectively Available Potential Energy, or CAPE. This is simply a measure of how much buoyant energy could be released by a parcel of air with prescribed conditions at the surface rising to a higher level where it is in thermodynamic equilibrium with the environment. The computation of CAPE takes into account the condensation of water vapor, so that moisture content can affect the final CAPE and the level to which the parcel rises freely.

CAPE is not the only factor that determines the height to which a parcel of air may rise, or comes to rest in a real situation. Wind shear and the exact shape of the buoyancy profile (that is, at what levels the buoyancy energy is released) can affect how the CAPE manifests (McCaul and Weisman, 2001; McCaul and Cohen, 2002). For the present situation, CAPE is easily computed for the ambient environment of a real fire. A modified CAPE can also be determined, assuming some increase in parcel temperature, moisture or both due to the fire. This allows some assessment of the potential changes in plume height and updraft speeds due to combustion moisture and/or sensible heating of the plume air. Wind shear may be important, but its effects on the equilibrium height and CAPE release are not understood well enough that their impact can be included in this assessment.

Consider the Mack Lake Fire, again. I used a simple C++ program to compute CAPE and equilibrium height, z_{eq}, for a surface air parcel under observed conditions. In this case, the observed conditions were the 0000 UTC sounding from Flint, MI with the surface temperature and moisture adjusted to reflect the conditions observed at Mio, MI at the time of the fire (28.3º C temperature, 4.6º C dewpoint.) I then re-computed these measures for surface air with some combination of increased moisture and/or increased temperature, to reflect the potential influence of the fire. Moisture was increased by 0, 1, 2, or 3 g kg^{-1}. Temperature was increased by 0, 1, 2, or 3 K.

Table 1 shows the results of these tests for CAPE (results for z_{eq} are not shown.) For unmodified surface air, the CAPE was 93 J kg^{-1} and z_{eq} was 3010 m. These values indicate a very low potential for any sort of deep convection. However, addition of 1 K or 1 g kg^{-1} increased CAPE to 618 or 762 J kg^{-1}, respectively, and a z_{eq} over 9000 m. Further increases in moisture or temperature do little to raise z_{eq}, but do affect the total CAPE significantly.

Table 1. Computed CAPE (J kg^{-1}) values for temperature and moisture-adjusted surface are during the Mack Lake Fire. Units for ΔT are K, and units for Δq_v are g kg^{-1}.

		ΔT 0	1	2	3
Δq_v	0	93	618	865	1120
	1	762	1020	1280	1550
	2	1200	1460	1740	2010
	3	1670	1940	2210	2480

I also looked at the Air Force Bomb Range Fire (North Carolina, 22 March 1971). This fire (described in Wade and Ward, 1973) made a 1434 ha run in one hour on the first day, and at the time had a 4600 m convective column. Because the run occurred in the afternoon, I used the 0000 UTC sounding from Cape Hatteras on 23 March 2003, but with the observed surface temperature for the time and location of the fire, 22º C, instead of the much cooler 0000 UTC surface temperature. I also used the observed relative humidity (25%) at the time of the fire to compute the dewpoint temperature (1.1º C) at the surface.

For the ambient conditions, this fire had a CAPE of just 157 J kg-1. Even with 3 K and 3 g kg-1 increases in surface conditions, CAPE only reached 859 J kg-1. This is largely due to a strong inversion in the sounding between 730 mb and 716 mb, with a weaker stable layer continuing upwards to 600 mb (4212 m ASL.) Ambient z_{eq} was only 2746 m, and due to the inversion, z_{eq} remained below 4000 m for most combinations of Δq_v and ΔT. Only when Δqv was 3 g kg^{-1} and ΔT was 2 or 3 K did z_{eq} show a significant increase, extending past 7600 m. Given that the observed convection column reached 4600 m, there must have been a significant amount of water produced by this fire. For such a column to develop without enhanced water content would have required a ΔT of almost 9 K sustained to the top of the column.

5. STORM DYNAMICS

There are many aspects of storm dynamics that are relevant to fire-plume dynamics, as well. The influence of wind shear, CAPE, precipitation, etc. on circulations are several examples. There are, however, at least two major differences that limit the applicability of storm dynamics to fire situations. First, storms derive their energy from atmospheric moisture, but fires derive their energy from combustion. Second, storms develop in environments where there is ample surface moisture to feed the convection, but fires develop in environments where there is little surface moisture, so that combustion is efficient and fuels dry readily.

For the present topic, the latter distinction means that there is not much literature on the dynamics of storms or convection in dry, fire-prone environments. One of the few storm properties that does relate to dry environments is the formation of downdrafts, downbursts, and microbursts. These phenomena depend on evaporation of precipitation as it falls through dry air and creates a moist, negatively buoyant body of air that descends to the ground. The sort of dry lower atmosphere that fosters a fire seems ideally suited to such downdrafts forming, as long as the fire generates enough moisture to produce precipitation above this layer.

For a storm, wind shear and speed of the gust front largely determine how a storm propagates and whether it survives or dissipates. For a fire, I suspect that the most important aspect of wind is simply whether or not there is enough wind to tilt the convective column and separate updraft from downdraft. If this is the case, then downdrafts and downbursts can develop and reach the surface on any side of the fire. The stronger the downdraft is, the more likely it is that it will produce erratic winds and endanger fire fighters at the ground. Stronger winds will tilt the convective column more, displacing the downdraft and precipitation fallout regions farther downwind from the active fire region. This means that any downburst activity is removed from the fire head, and less likely to endanger fire fighters or fan the flames. In these cases, wind shear and turbulence may also dilute the negatively buoyant air to the point where the downdraft is negligible.

4. CONCLUSIONS

I have shown that there is some observational evidence to support the idea that fires produce large amounts of water and introduce it into the atmosphere. I have presented physical arguments that I believe demonstrate that the quantities of water produced by fires, and the quantities observed in fire convective columns are roughly consistent with one another and with the observed plume heights. I have also demonstrated that in two reasonably well documented cases, the amount of energy added to the convective column by reasonable amounts of water vapor is significant and matches qualitatively with observed plume behavior. Finally, I have presented very basic and qualitative arguments that speculate as to how fire moisture, introduced into an otherwise dry environment, could produce erratic, downburst winds.

In truth, many of these points were made by previous authors. However, the research literature seems to lack a recognition of how the points go together to form a consistent picture of the role combustion water plays in fire-atmosphere interaction. Fire behavior has three main components; fuels, atmosphere and topography. I believe that too often, these are viewed as distinct pieces and only minimal overlap is acknowledged. If combustion water does play the role I have proposed here, then there is an extremely strong tie between the fuel and atmosphere components that cannot be ignored. Gaining any better understanding of fire behavior, then, will require the fuels researchers to appreciate the role of the atmosphere more, and fire atmosphere researchers to appreciate the importance of fuels more.

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