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A dynamics based view of atmosphere–fire interactions*

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Abstract. Current research on severe fire interactions with the atmosphere focuses largely on examination of correlations between fire growth and various atmospheric properties, and on the development of indices based on these correlations. The author proposes that progress requires understanding the physics and atmospheric dynamics behind the correlations. A conceptual 3-stage model of fire development, based on atmospheric structure, is presented. Using parcel theory and basic atmospheric dynamics equations, the author proposes possible causal explanations for some of the known correlations. The atmospheric dynamics are discussed in terms of the 3-stage model, but can also be viewed more generally. The overall goal is to reframe fire–atmosphere interactions in a way that will allow better understanding and progress in fire science, prediction, and safety.

Additional keywords: fire weather; behavior; plume-dominated fire; blowup fire.

Introduction

There is an extensive and growing body of literature on the subject of how the atmosphere influences wildfire behavior. Major works from that body include Byram (1954, 1959), KP Davis (1959), RT Davis (1969), Brotak (1976), Brotak and Reifsnyder (1977), Fosberg (1978), Chandler *et al.* (1983), Haines (1988), Rothermel (1991), Nelson (1993), García Diez *et al.*(1994), Clark *et al.* (1996*a*, 1996*b*) and Potter (1996). Generally, these studies have considered atmospheric stability, moisture, and/or wind profile and how they affect fire behavior.

These papers belong to three general categories. Those like Byram (1954), KP Davis (1959), RT Davis (1969), Brotak (1976), Brotak and Reifsnyder (1977), García Diez *et al.* (1994) and Potter (1996) look at correlations between a weather variable and fire behavior. The properties considered are usually of a regional nature (representing conditions over tens or hundreds of square kilometers), and are viewed in a predictive sense. Several studies in this group offer an explanation of why any correlation exists, but it is usually qualitative, brief, and not accompanied by an explicit physical derivation. Those like Byram (1959), Fosberg (1978), Haines (1988), and García Diez *et al.* (1994) attempt to produce an index or metric of severe fire risk based on some atmospheric property, usually one that a study from the first group showed correlated with fire behavior. Again, these indices reflect some regional conditions and are meant to be predictive. Finally, those like Clark *et al.* (1996*a*, 1996*b*) use coupled atmosphere–fire behavior computer models to simulate fire growth and behavior. These studies are useful for looking at fire behavior on small spatial and temporal scales, and the influence of one specific property on fire behavior. The models can show the influence of the sorts of regional properties examined in the earlier works, as well as clarify how the atmosphere changes a few tens or hundreds of meters from the fire and on very short time scales. They can also, because of their coupled nature, provide insight into the interactions between atmospheric and fuel processes.

While many of the indices show some skill at predicting the risk of a large fire, there are also areas or situations in which any given index breaks down (e.g. the Werth and Werth (1998) discussion of the Haines Index). Without a solid physical foundation for the index, or more generally, a

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physical explanation of how the atmosphere and fires interact, these breakdowns or failures cannot be addressed in a meaningful way. A sound physical model, even if it represents a considerable simplification of the situations involved, will help explain why a particular weather factor reflects fire risk or behavior.

This paper is an attempt to describe some of the physics behind relationships between mesoscale (horizontal scales of 1 to 100 km) atmospheric properties and fire behavior. It is intended to be a beginning only, and will be simple by design. The simplicity serves two purposes. It makes the initial attack on the problem more tractable, and it reduces the risk of boldly charging ahead and creating another index without first providing the necessary physical foundation for fire–atmosphere interactions.

The following discussion is about the atmosphere, ignoring fuels for the most part. One can view it as an attempt to address the question, 'for a given set of fuel conditions, how does the initial state of the atmosphere affect the subsequent fire-driven atmospheric circulation?'. The atmosphere does influence fuel conditions, primarily through moisture (e.g. Davis 1959). However the issues I will address are matters of the atmospheric potential to directly support or exacerbate a fire rather than the indirect influence of the atmosphere on fire behavior through fuel conditions. These questions must be confronted independent of questions regarding fuels or heat release, as atmospheric potential depends primarily on the atmosphere itself.

Atmospheric structure and fire stages

To begin, it helps to establish terms that will be used in the discussion. That includes a brief description of an idealized atmospheric structure and several atmosphere-based stages of fire development.

Works such as Schroeder *et al.* (1964) have shown that most large fires occur in regions of high atmospheric pressure. In these situations, the vertical structure of the atmosphere closely follows the description given by Stull (1988), consisting of four basic layers (Fig. 1). The lowest of these is the surface layer. This is the part of the atmosphere most subject to diurnal variations, and in it physical barriers such as the ground inhibit convective mixing. Above the surface layer during the day is the mixing layer, where free convection maintains an adiabatic lapse rate. Here, momentum and moisture are relatively well mixed. The mixed layer ends at some height above which the atmosphere is stable enough to suppress mixing layer convection. In extreme cases, this stable layer may be an inversion, and there is usually some degree of entrainment mixing between this layer and the mixing layer. Above the stable entrainment layer lies the free atmosphere. In a high-pressure system, this is also a region of subsidence and may be referred to as the subsidence layer.

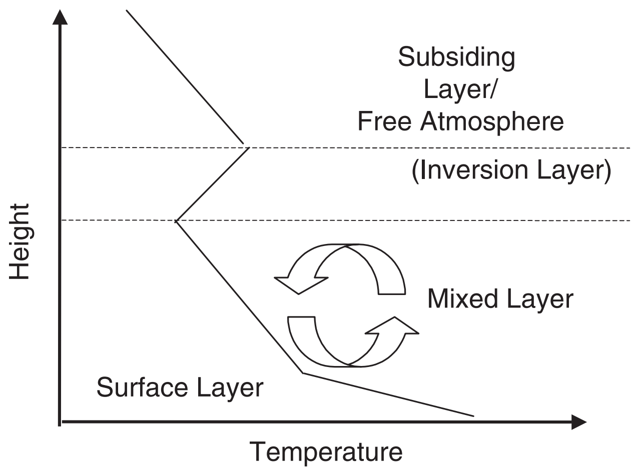

Fig. 1. Idealized vertical structure of the lower atmosphere.

At night, the base of the mixing layer often cools and becomes an inversion layer. In this case, the remainder of the mixing layer is referred to as the residual layer. I will focus here on the daytime structure, as this is the period when fires are most active, but the concepts I describe should work equally well at night.

Using this atmospheric structure as a framework, I propose that fire development can be described by a 3-stage model. The first stage is the surface stage, a period when the fire is low and it interacts only with air in the surface layer. As a result, surface layer winds drive fire spread and surface air dryness controls the drying of fuels.

The second stage is the deepening or mixing stage. The fire's energy release has enabled air to rise out of the surface layer, and as such the fire-induced circulation can tap into the entire mixing layer. The plume will rise freely as the fire-heated air ascends in the adiabatic environment. The top of the plume rises during this stage, faster than at any other time in the fire's life cycle.

During the deepening stage, mixed layer winds may cause the convective plume to tilt. To a first order approximation, assuming minimal entrainment into the plume, the plume will still rise to the same height in about the same amount of time as if there were no wind. In this respect, there is no substantial difference between a plume-dominated fire and a wind-driven fire.

As the fire passes through the deepening stage, air from various levels will descend to the surface at different times. As a first approximation, the average mixing layer dryness drives fuel drying. Vertical motions alter the near-fire surface winds, creating a vertical flux of horizontal momentum, and as a result the average mixing layer winds control fire spread. If one assumes that the durations of the surface and deepening stages are proportional to the depths of the surface and mixed layers, then the deepening stage will last roughly 9 times as long as the surface stage. [Stull (1988) specifically defines the surface layer as the lowest 10% of the boundary layer, whether that boundary layer is a mixed layer or a stable layer.] Based on this reasoning, the deepening stage and mixing layer air will have a stronger influence on the fire's behavior in the long run. The deeper the mixing layer, the longer and stronger this influence will be.

The third stage of development is the penetration stage, when convection has reached the top of the mixing layer and is pushing or digging into the stable layer/free atmosphere. The rate of vertical growth drops significantly, and there is lateral plume growth due to this vertical convergence. The strength of the stable layer is important in determining how much higher the plume rises, and the strength of the circulation caused by the fire below.

If horizontal winds are strong, the region of penetration will be carried downwind of the fire. This will reduce the dynamic feedback on the fire and decouple any downdraft or return flow from the fire. In this situation, mixing layer properties (dryness and winds), more than anything else, will still control fire spread and fuel drying. In a low wind environment, the effects of the stable layer and any air entrained into the mixing layer will feed back on the fire, with the potential to affect its behavior.

While entrainment of stable layer air into the mixing layer during the penetration stage may alter the mixed layer's average momentum and moisture, these effects will be relatively minor. The mixing layer is often over 1 km deep during the day, and the sheer volume of it is much greater than the volume of any entrained air. The influence of stability on circulation, while indirect, will be the primary channel by which the stable layer and free atmosphere affect fire growth.

In this framework, a given fire will likely experience each of the three stages multiple times. It may return to the surface stage at night, then go through the deepening and penetration stages again the next day, for example. Or, synoptic air movements may alter the environment in a way that forces the fire from one stage to another.

Countryman (1969) described a model of a stationary mass fire that included 6 zones, but differed from the present model in several important ways. It was based more on the observed structure of the fire's convective column than on atmospheric conditions or dynamics. It also focused on the structure of the column at a specific time, rather than considering any aspects of progression through time. The two models, therefore, may be complementary but are not directly comparable.

Dynamics

As noted above, all fires start in the surface stage. During this period, the only meteorological quantities able to influence the fire are surface winds and surface air dryness. Dryness can be expressed as relative humidity, dewpoint depression, mixing ratio deficit, or vapor pressure deficit. Relative humidity is the most commonly heard of these measures, but is inversely proportional to fuel drying rate

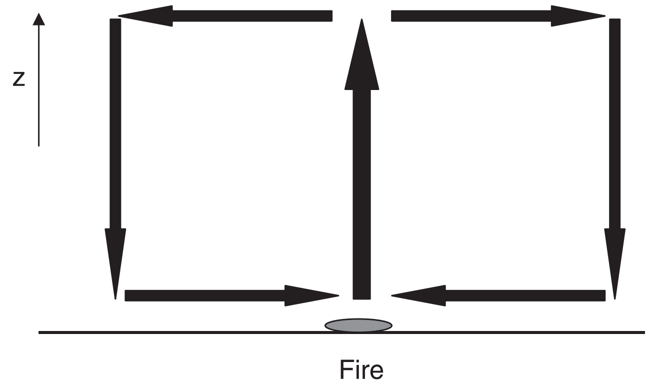

Fig. 2. Idealized, conceptual circulation of the atmosphere driven by fire with no environmental wind.

and of limited use in calculations. Mixing ratio and vapor pressure deficits are the most useful in computing vapor fluxes from fuels or drying rates, but are less commonly reported. Nonetheless, discussions of dryness in the remainder of this paper will focus on these deficits.

(In addition to surface winds and dryness, solar radiation can influence the drying of fuels as well as generate mesoscale air movements such as land–sea breezes or mountain–valley breezes. Because of the complexity it would add to this intentionally simplified discussion, I will not discuss radiation in this paper.)

In the deepening stage, free convection begins and the fire generates a circulation in the mixing layer. I will look at this circulation in its simplest form, where the fire creates an updraft that rises to some height where it spreads horizontally, causing a downward airflow and a return inflow at the surface (Fig. 2). I will work in two dimensions only, to start with, and begin without an ambient wind.

In this situation the first measure of the ease or difficulty with which air will rise is the convective available potential energy (CAPE): the energy released or absorbed when a parcel rises from the surface to a level z:

$$\mathrm{CAPE}(z) = g \int_0^z \frac{(\theta(0) - \theta(z'))}{\theta(z')} \, \mathrm{d}z' \qquad (1)$$

Here, g is the acceleration due to gravity, and θ is potential temperature. In the idealized atmosphere of Fig. 1, CAPE reaches its maximum value at the mixing height, and decreases with increasing height thereafter.

By mass continuity, assuming that density variations are small, air must descend from height z to the surface to replace the rising air. Assuming the circulation is somewhat like a storm-convective cell, the descent will take place over a broader region, be slower than the rising air, and may take place several kilometers from the updraft. This descending air will either release energy (if the atmosphere was unstable to begin with) or require energy to push it down (if the atmosphere was stable.) This energy is analogous to CAPE, but to avoid confusion I will call it descent energy, DE:

$$DE(z) = g\int_z^0 \frac{(\theta(z)-\theta(z'))}{\theta(z')}dz' \quad (2)$$

Note that dz < 0 here so that, when $\theta(z) < \theta(z')$ (i.e. the descending air is colder than its environment), DE > 0 as one would expect. When z is the mixing height, DE and CAPE are equal in magnitude and opposite in sign.

The direct dynamical effect of the fire on the atmosphere is the updraft it creates. The downdraft, inflow, etc. are secondary results of mass continuity. As such, CAPE is the most direct measure of how stability and the atmosphere's profile will influence a fire. Still, DE gauges how much of the CAPE will be consumed (or how much more energy will be added to it) in the necessary return flow. The difficulty of exchanging a parcel between the surface and height z is the sum of CAPE and DE, and I will call this the parcel exchange potential energy, PEPE:

$$PEPE(z) = CAPE(z) + DE(z) \quad (3)$$

With some algebra,

$$PEPE(z) = g\,[\theta(0)-\theta(z)]\int_0^z \frac{dz'}{\theta(z')} \quad (4)$$

PEPE(z) reflects the ease of forming a convective circulation of depth z. Note that PEPE is zero at the mixing height.

Figure 3 illustrates CAPE(z), DE(z), and PEPE(z)based on observed data from 0000Z on 30 July 1989 at Boise, Idaho. [This was a day during the Lowman fire, documented in Werth and Ochoa (1993), and is typical of many mid-afternoon soundings. For the present purposes, almost any afternoon sounding could be used.] As a fire progresses through the deepening stage, the height of the plume grows and so does the height from which a return downward flow originates. The net atmospheric energy released by the rising and sinking air increases until the plume reaches the height where PEPE is greatest, labeled z_{max} in Fig. 3. This will be the time when the atmosphere's contribution to the strength of the circulation has peaked, and thereafter any strengthening must be due to the fire's energy output.

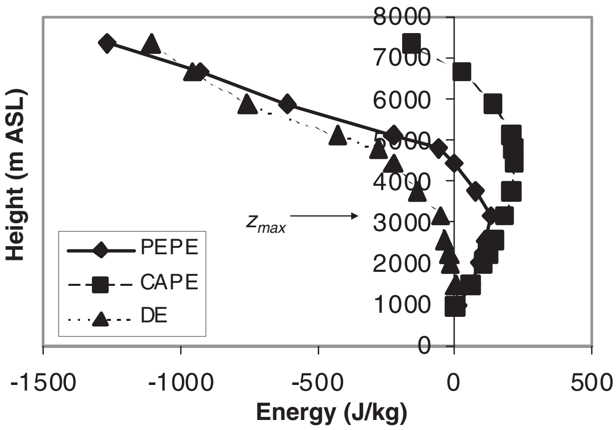

Fig. 3. Vertical profile of CAPE, DE, and PEPE computed from the 0000Z 30 July 1989 sounding at Boise, ID (surface elevation 871 m ASL).

Consider now the wind field just above the fire in the idealized case shown in Fig. 2. The fire-generated horizontal winds are equal and from opposite directions, while the vertical wind is zero right at the ground but has some non-zero (positive) value a short distance above the ground. I will assume that the fire and updraft are of the same horizontal dimensions, which I will designate δL. The incompressible version of the continuity equation in two dimensions is

$$\frac{\partial u}{\partial x} + \frac{\partial w}{\partial z} = 0. \quad (5)$$

If all of the potential energy released by a rising parcel manifests as kinetic energy, then the vertical velocity, w, is proportional to the square root of CAPE. (Because the focus here is on the updraft alone and just above the fire, I consider CAPE rather than PEPE.) Ignoring constants, the vertical derivative of w is then

$$\frac{\partial w}{\partial z} \propto \frac{1}{CAPE^{\frac{1}{2}}}\frac{\partial CAPE}{\partial z}. \quad (6)$$

Now let $\partial x = \delta L$ and designate the horizontal wind at a distance $\delta L/2$ from the center of the updraft to have magnitude u_{sfc}, directed inward towards the fire. The horizontal derivative in equation (5) is then simply ($-2u_{sfc}/\delta L$), which can be combined with equations (5) and (6) and rearranged to yield

$$u_{sfc} \propto \frac{\delta L}{CAPE^{\frac{1}{2}}}\frac{\partial CAPE}{\partial z} \quad (7)$$

The surface wind speed near the fire, then, will be proportional to the vertical CAPE gradient and the fire width, and inversely proportional to the magnitude of the CAPE. The steeper the near-surface vertical CAPE gradient is, the greater the speed of the surface wind that fans the flames and dries the fuels.

Consider next the significance of PEPE(z) near the mixing height. When convection reaches this level, all potential energy available to the circulation from instability has been released; any further deepening requires work for the ascending branch, the descending branch, or both. This is the point when the fire enters the penetration stage. The circulation is deepening, and the updraft air is still rising, but both begin to slow. If there is no entrainment, rising air will eventually stop and sink back towards the mixing height. The flatter the PEPE(z) curve is at the mixing height, the more stable the atmosphere is and the more kinetic energy a parcel loses (as work done) with a given increase in height.

If a fire adds energy δE to an air parcel, it effectively shifts the CAPE and PEPE curves in Fig. 3 to the right. This raises the mixing height for that parcel by an amount equal to

$$\delta z_{\mathrm{MH}} = -\,\delta E \left(\frac{\partial \mathrm{PEPE}}{\partial z} \right)^{-1} . \qquad (8)$$

For a given energy input then, $-(\partial \mathrm{PEPE}/\partial z)^{-1}$ indicates how easily a fire's circulation can penetrate above the mixing height. This will be reflected in the penetration stage, as the fire's convection pushes into the free atmosphere.

Wind complicates this basic model in several ways. It tilts the updraft, carries everything downstream, and creates an asymmetry that affects inflow and outflow strengths. Because the atmosphere's behavior is highly non-linear, the nature of the fire in the presence of strong winds is likely to be quite different from what has been described above. This discussion will emphasize situations with moderate winds, perhaps in the range between 1 and 8 m/s. If a left-to-right (positive x) wind is added to Fig. 2, the left side inflow is strengthened while the right side inflow diminishes. It is the left side, or upwind, circulation that drives the fire, while the downwind circulation primarily dries fuels. (The downwind circulation may also bear strongly on the safety of firefighters in the area. If it does, it is likely to be through small-scale turbulence, on a spatial and temporal scale below what I consider here.) I will focus on the upwind circulation hereafter.

The nature of the circulation over a fire under conditions with a non-zero environmental wind appears to be fundamentally different from that without wind. Banta *et al.* (1992) observed wind fields for a 700 ha prescribed burn using Doppler lidar. The environmental winds they cite during the fire were approximately 5 m s^{-1}. Their observations showed the downwind circulation forming a rotor-like structure, but limited observations of winds on the upwind side do not show a clear upper level outflow. Using a numerical model of the atmospheric boundary layer, Heilman and Fast (1992) obtained results that agree well with Banta *et al.* (1992), with a clear rotor-like downwind circulation and no clear upwind upper level outflow. These observations raise questions about the general form of the circulation created by a fire when there is a mean environmental wind. The following discussion will address some of these as they bear on the concepts presented in this study.

There are several ways one can quantify the character of the upwind circulation. Average parcel energy, an extension of the PEPE concept, looks at the support or suppression of a fire by the atmosphere in terms of energy. Vorticity arguments consider the wind field directly, but have a significant drawback. There are many other frameworks, some analogous to those used in storm dynamics, but I will focus on these two.

PEPE(z) reflects the support or suppression of vertical motion in the atmosphere. For a given height, z, PEPE(z) indicates the net energy released or absorbed by movement of air between the surface and z, the atmosphere's resistance to this vertical movement of air. When a mean horizontal wind is present, there is a dynamic resistance to horizontal movement against the wind and an enhancement of movement with the wind. If the wind field (again working in two dimensions) is given by $u(z)$, then the surface inflow is enhanced by $u(0)$ and the outflow aloft must push against $u(z)$. Assuming a closed circulation, where as much mass rises as sinks, moves left as moves right, the energy contributions of the environmental winds can then be added to PEPE to get an average parcel energy (APE) in the circulation:

$$\mathrm{APE}(z) = \tfrac{1}{2}\,[u^2(0) - u^2(z)] + \mathrm{PEPE}(z). \qquad (9)$$

It is very important to remember that this is not the energy of the fire's circulation. That would require knowledge of the fire-induced wind field, both in the vertical and horizontal dimensions. What APE reflects is, when positive, the energy the atmosphere already has to support a rotor-like circulation upwind of the fire; when APE is negative, it reflects the energy a fire must expend to produce a rotor-like upwind circulation.

Instead of looking at energies, one can consider the wind field directly. For the type of circulations under discussion, the y-component of vorticity is an appropriate measure of how strong the circulation is. Mathematically,

$$\eta = \left(\frac{\partial u}{\partial z} - \frac{\partial w}{\partial x} \right) \qquad (10)$$

The $(\partial u/\partial z)$ component can be computed for a given region from the mean environmental wind field. The $(\partial w/\partial x)$ component, however, is zero for an atmosphere in hydrostatic balance. Going back to CAPE and DE, and the conversion of these potential energies to kinetic energy, i.e. w, one can determine potential vertical velocities for updrafts and downdrafts, which can then be used for this gradient. All one needs is the horizontal scale for the circulation. Without an actual fire, the appropriate horizontal scale is unknown. This is a serious limitation on the use of η in any theoretical framework, or in any operational sense. Still, η is a reasonable measure to use for comparing numerical simulations of fires and the circulations they generate. And as more is learned from these, perhaps a method of determining an appropriate horizontal scale will emerge.

As I noted earlier, the nature of a fire's circulation when there is an ambient wind is probably not the rotor described by Fig. 2, a simply tilted or sheared version of it, or the same rotor superimposed on the ambient wind field. The question arises, then, of whether or not APE or η is at all useful for such a situation. In the figures presented by Banta *et al.* (1992) and Heilman and Fast (1992), three of the four segments of the rotor circulation are clearly visible; the only one missing is the upper level, upwind flow. Banta *et al.*'s figures show little data in this area, but Heilman and Fast's figures do show that, for moderate wind speeds, the mean flow is slower in the region where the upper level upwind flow would be. This suggests that, if the model results were viewed as perturbations from the background winds, there would be some sort of rotor-like circulation. While APE and η may not represent the atmospheric dynamics completely, they may still be useful tools for thinking about the role of the atmosphere in determining fire behavior. Furthermore, if they do prove useful, they may provide a theoretical dynamics basis for removing the distinction between plume dominated and wind driven fires.

Moisture

The role of atmospheric moisture in drying fuels was mentioned in the description of the 3-stage model. Davis (1959) provides a strong physics-based description of how atmospheric moisture influences fuel conditions, and how fuel moisture affects combustion. I will not dwell on these relationships here. Simply put, dry air matters because it dries fuels so that they burn more easily. Dry air's effect, then, is largely pre-combustion.

There is another important aspect of atmospheric moisture, where dryness *decreases* the risk of a blow-up fire. Moist air will rise higher than dry air due to latent heat release, adding strength to the overall circulation in a convective system. Banta *et al.* (1992) commented on the limited penetration of modeled smoke columns when there was no latent heat release in the model.

This latent heat release should be considered in computing CAPE or PEPE (it does not matter for DE, as that air is descending and moving away from saturation.) In equations (1) and (4), then, θ(0) should be adjusted when the rising air has reached saturation at the lifting condensation level, with ascent along a moist adiabat thereafter.

Quantifying the role of moisture in a physically meaningful way may be the biggest challenge in fire–atmosphere interaction dynamics. Air must be dry enough to desiccate surface fuels, but moist enough to boost convection with latent heat release. Yet it must be dry enough that it doesn't produce rain that will extinguish a fire. The latter concern raises questions of cloud microphysics, and what determines whether a cloud precipitates or not—updraft speed, temperature, and condensation nuclei concentrations all play a role. At this time, perhaps the most important point to make is that the situation is more complex than just 'dry air raises fire risk.'

Further Implications

In this section, I will discuss the general implications of this model on five aspects of the atmosphere or fire behavior.

When does blow-up really occur?

The 3-stage model of fire development does not address the question of when a fire will blow up. Since not all fires do blow up, it is clearly not the surface stage that influences blow-up. In terms of energetics, it would seem that blow-up would be a reflection of a large release of PEPE; this would place blow-up in the deepening stage. On the other hand, if there is a strong lid (i.e. a highly stable layer) on the mixing layer, this could cause a vigorous near-surface circulation as the energy released by the fire is trapped below the inversion. This would result in minimal penetration, but still a type of blow-up potential during the penetration stage.

In reality, both of these phenomena may occur. Some fires may blow up during deepening, others may do so during the penetration stage. This type of question may be best answered with coupled fire–atmosphere models, or through case studies of actual fires linked to mesoscale model simulations of the atmospheric conditions that accompanied the fires.

Smoke or fog inversions

Large, multi-day fires in mountainous terrain can produce a smoke layer that sits some height above the ground. On a clear, calm night the top of this layer (or any fog layer that forms, whether or not smoke is present) will cool radiatively and form the base of a temperature inversion. This stable layer may alter the circulation near the ground, trapping energy released from the fire beneath it. If or when the inversion weakens later in the day, the fire may rapidly gain access to the deeper mixed layer. In terms of PEPE(z), such an inversion would appear as a local sharp decrease (flat spot) in the profile at the height of the inversion (as in Fig. 4). As the inversion weakens, the flat spot would fill and it would become easier for the fire circulation to reach through it. Alternatively, the fire could escape the inversion if it burned up a slope to a height above the inversion, even while the inversion was still intact and strong. Careful observation of fire behavior and the temperature profile as the inversion weakens could yield insight into how CAPE and PEPE profiles affect fire behavior.

Diurnal atmosphere variations

The weakening inversion just mentioned is a specific case of more general diurnal variations in the lower atmosphere. As

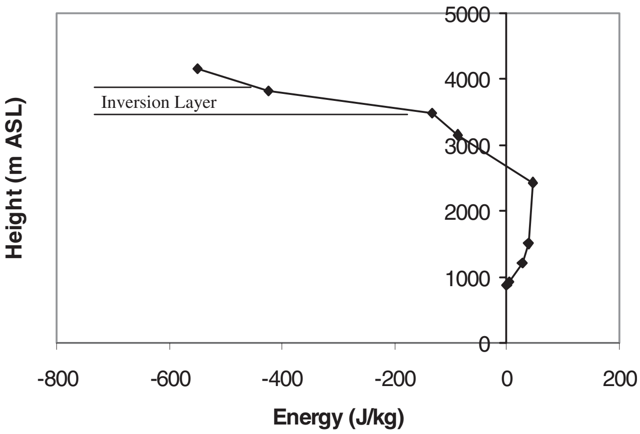

Fig. 4. Vertical profile of PEPE computed from the 0000Z 14 August 2000 sounding at Boise, ID (surface elevation 871 m ASL). At this time there was an inversion layer between 3480 m ASL and 3830 m ASL.

the day begins and the mixing layer deepens, PEPE(z) increases and the layer of freely accessible air grows. Places and times that experience rapid, extreme deepening of the mixing layer will be at greater risk of fire blow-up. This is not only due to the increase in PEPE, but to the availability of air with higher momentum at higher levels in the mixing layer.

Diurnal variations in local winds, such as mountain–valley or land–sea breezes, can also influence the energetics. Circulations that enhance the upwind *y*-vortex can be particularly dangerous as they push the fire forward faster and accelerate the whole circulation.

Bowen Ratio

The Bowen Ratio, β, is the ratio of sensible to latent heat flux at the earth's surface. In arid regions, daytime β can be quite large, while in humid regions it is usually low. In a general sense, an area or period that exhibits a high β will experience large diurnal variations in the mixing height, as sensible heat elevates surface air temperatures and causes that air to be buoyant.

This reasoning suggests a dual impact of drought on fire danger. Not only does drought yield more dry fuel, but it leads to a redistribution of surface energy flux from latent to sensible. This, in turn, deepens the mixing layer, increases PEPE, and raises the potential for a large atmospheric contribution to fire growth.

Spring green-up

Schwartz and Karl (1990), based on 20 years of daily data, noted that in primarily agricultural areas, spring daily maximum temperatures rise by approximately 0.3°C day^{-1} before green-up but less than 0.05°C day^{-1} in the weeks after green-up. Durre and Wallace (2001) used 30 years of surface and lower atmosphere data and showed that with spring green-up came an increase in lower atmosphere stability over the eastern United States. Both of these would lead to a decrease in average mixing height

Following the same reasoning as used in the Bowen Ratio discussion, these observations suggest that spring green-up, by decreasing mixing heights, may decrease the risk of blow-up fires. Testing this hypothesis would be quite difficult, since green-up also represents a change in fuel conditions.

Reflections on earlier studies

In the discussion regarding wind and how it influences fire dynamics, I made references to Banta *et al.* (1992) and Heilman and Fast (1992). I will now consider how the energetics and dynamics outlined above compare with other previous works. While there are a great many studies that examine fire–atmosphere interactions, the majority do not touch on the properties and concepts described here. For example, Chandler *et al.* (1983) include an entire chapter on fire weather, explaining the concepts of fire climate, air masses, stability, etc. But the subsequent discussion of how stability affects fire is tangential and qualitative, essentially saying that stability determines the height of the convective column. There are, then, many studies and reports that mention stability, energy, or moisture effects, but only a few do so in a way that is relevant to the present discussion. It is these few that I discuss here.

Byram (1954) is perhaps the most frequently cited paper on the subject of wind effects on blow-up fires. He describes the importance of high winds at or near the ground, with a low level jet in some cases. His method of compositing (simply cropping the lower levels of a sounding to match its base to the level of a fire under consideration) may be subject to criticism, as it assumes non-laminar flow without a stated justification, but no one to date has done a comparable analysis that remedies this error, so his work remains the only reference on this particular subject.

The general character of Byram's vertical wind profiles agrees with both the 3-stage model, and with the APE(*z*) or vorticity arguments I have outlined. In the 3-stage model, any of Byram's profiles would result in windy conditions during the surface or deepening stage, driving the fire at the start but allowing convective processes to dominate as higher levels of the mixing layer interact with the fire. The situation could be compared with a person blowing on a small fire to get it going, then letting the fire itself create the air circulation afterwards.

The wind component in APE(z) and the total *y*-vorticity, η, would be large for some of Byram's profiles, especially Type 1-a with the wind maximum right at the ground. Other profiles, with a jet within 1000 m of the surface but higher altitude speeds below the surface speed, would have decreasing η and wind component in APE(*z*) from the surface to the jet level, but increasing η and wind-APE(*z*) for heights above that.

Byram (1959) presented two quantities that he termed the power of the fire (P_f) and the power of the wind (P_w). Nelson (1993) provided the derivation of these quantities, yielding a slightly different form for each and merging them into one variable which he named convection number, N_c. The derivation of P_f depends heavily on buoyancy arguments, and is comparable to the derivation of either CAPE or PEPE. Inclusion or representation of the energy output from the fire in CAPE would make the two approaches even more similar, though it would make the new, modified CAPE dependent on the fire and not just the atmosphere.

The relationship between P_f and P_w could be compared with the relationship between the stability and wind components of APE, respectively. As just mentioned, PEPE and P_f are both functions of the atmospheric stability. Similarly, the wind component of APE and P_w are both measures of the strength of the wind, though the former measures energy and the latter measures energy flux. Rothermel (1991) used N_c to classify fires as wind-driven or plume-dominated, a terminology that is still used by many. Clark *et al.* (1996*a*, 1996*b*) employ the convective Froude number, F_c, in the same capacity others have used N_c. The two quantities differ in several ways, but both reflect the ratio of wind to buoyancy and use this to delineate whether a fire is likely to become a blow-up fire. The formulation of APE, and the theory that lies behind it, present the possibility of describing all fires by one dynamical model and eliminating what is in some ways an artificial separation.

Conclusions

The science of atmosphere–fire interactions has historically focused on correlations and empirical, parameterized relationships. While this has served reasonably well, and has represented the strongest science possible at any given time, it has not offered much in the way of explaining causal relationships. Furthermore, it has resulted in a range of indices, measures, graphical tools and conceptual paradigms that work in some places and times, but generally fail in others for unknown reasons. Avoiding these failures while developing and implementing improvements to the measures or indices can be accomplished only if we achieve an understanding of the actual cause and effect relationships between fire behavior and atmospheric properties.

I have presented what I consider an initial effort in that direction, by separating purely atmospheric fire behavior questions from fuel–atmosphere interactions (fuel drying), and presenting the former in a framework that depends on physical principles, equations, and laws. The framework uses tools and techniques, such as parcel theory, conservation of energy, and fluid dynamics equations, that have proven their worth and validity over many years in the atmospheric sciences. Many have strong parallels in the study of convective storm dynamics, and there are surely more areas of overlap between the two.

There are a great many ways this work could move forward, in ways that involve observation, simulation, operation, and theory. Detailed observations of the winds in fire convective systems, following Banta *et al.* (1992), are invaluable to refining theories. When cost or logistics prohibit field observation, we now have the ability to use computer simulations that allow us to change one property at a time and observe its impact on fire behavior. Operational testing—including validation—of the concepts described here, or developed in the future, is absolutely critical to the real-world, pragmatic significance of models and paradigms developed. In the area of theory, there are questions of the three-dimensional nature of fires, with all of the attendant complications of vorticity tubes, helicity, and multiple air streams interacting to influence fire behavior. It is entirely plausible that fire convection generates buoyancy waves in the atmosphere, and theory can address the possible impact of such waves on surface winds in the vicinity of fires. There is also the question of what balance of moisture, in both magnitude and spatial distribution, really primes the situation for a blow-up fire.

The concepts of PEPE, APE, and η are not presented here with the hope or intention that they become operational measures. They are theoretical tools, side effects of a way of thinking of fire–atmosphere interactions. If they are carried into operational application, they must be carefully evaluated for their ability to clarify or confuse the end user, and they must be validated against actual fire data to ensure that they work.

Finally, there is an opportunity to re-think many of the aspects of fire-weather behavior taken for granted in the operational (both fire forecasting and fire management) and research communities. The situation is extremely complex, and the state of scientific knowledge does not always coincide with the state of the operational community's needs. It is useful for all involved to take stock of what we really do and do not know, and to be certain that this is clearly communicated.

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