Advances in Fire Convection Dynamics

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The convective column created by a fire has a strong impact on the behavior of the fire. This paper examines three aspects of fire-atmosphere interaction that influence the development of the convective column. The stratification of temperature, humidity and wind near the ground influences the early formation of the fire and its convective column, and can lead to unexpected variability in the fire's behavior. Moisture produced by combustion of woody fuels has the potential to enhance the convective column's vigor, but research is needed to determine whether this happens in actual fires. The structure of the atmosphere over large regions (the synoptic structure) can bring dry, high-momentum air down from heights of 10 or more km, affecting the convective column and fire behavior. Each of these topics represents an aspect of convective behavior around fires that is the subject of current research and has implications for fire behavior and firefighter safety.

Keywords: *fire, weather*

Introduction

For almost 100 years, the paradigm of fire behavior taught and employed in the United States has held that three main factors dictate fire behavior (Graves 1910). These factors are fuels, weather, and terrain. Historically, research and management have ranked the importance of the three factors for funding, time, and manpower in the aforementioned order. The fastest changing component of the behavior triad is the weather, and while it is not directly manageable or predictable over the long term, it is also one of the major causes of fire-fighter fatalities and fire escapes. (Whether human error or weather is the greater cause is not clear, especially in cases where human actions compromise the quality of the weather information available during fire management.)

A further common division of fire behavior is separation into "plume dominated" and "wind-driven" (sometimes called "wind dominated") fires. These categories seem reasonable and somewhat intuitive, but in reality it is quite difficult to decide whether a fire belongs in one or the other class. A particular fire may alternate between plume and wind dominated repeatedly during its existence. All fires are dangerous, but because a wind dominated fire spreads primarily in the direction of the prevailing winds, the danger is more predictable than for a plume dominated fire. Conditions above the ground play a major role in determining the behavior of plume dominated fires, and can lead to abrupt changes in direction or rate of spread. A strong updraft, whether tilted over due to strong winds or vertical in their absence, generates a stronger inflow of air at the ground and more vigorous fire development in general, so that updraft strength is directly related to many aspects of fire behavior that are important for firefighter safety.

Researchers and analysts have used two parameters, Byram's convection number (Nelson 1993) and the convective Froude number (Clark et al. 1996) to classify fires in the past. In practice, it is rare to have the data necessary to make such a classification. Even when data are available, these numbers change values over time and space, so that one part of a column may qualify as "plume dominated" for a time, while the remainder of the column at times is "wind driven." Because of this, the most common criterion used to determine a plume or wind dominated fire is purely subjective observation.

It is possible there is some discrete, definite boundary between plume and wind dominated fire behavior. It is more likely that while some fires are quite visibly in one class or the other at a particular time, most fires at most times fall in a grey area where it is unclear which process dominates. Because of this it is important to understand

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the physics of how fires interact with the atmosphere. Decades, if not centuries, of observations and anecdotes provide some understanding. In the last fifty years, that understanding has gone from statistical or qualitative in nature to more analytical and quantitative. The complexity of the situation has limited the utility of all of these types of understanding, however. To develop an analytical understanding of a complex system starting with a simplified model often allows progress that would otherwise be impossible. In the case of fire, starting with the "no wind" case, unrealistic though it is, does just that.

In this paper, we describe three aspects of fire convection and the interaction of fire with the atmosphere: layering of air near the ground, potential impacts of moisture, and synoptic influences on convection. We ignore wind in our discussions in order first to better understand the nature of the convection. Eventually, a complete theory of fire convection must include the influence of wind profiles. For now, however, the "simple" case of no wind presents enough unanswered questions.

Describing the Environment

The basic properties of the atmosphere that influence convective development during fires are the temperature and wind profiles. Generally speaking, fires of significant size develop under conditions of high atmospheric pressure. High pressure usually means clear skies and dry conditions, while low pressure indicates clouds and often rain. For this reason, the following discussion emphasizes high pressure situations.

The daytime temperature profile for an idealized atmosphere has four basic parts, depicted in Figure 1. At the bottom is the surface layer. Strong solar heating, especially when there is little available moisture, creates a region where the ground is very hot and the air temperature drops rapidly with height. This is generally an unstable layer, where vertical movement of air releases stored energy and adds to the turbulent energy. Above this, where air flow is unobstructed by the ground and surface structures, is the mixed layer. In this region, turbulence and heating from below churn the air so that moisture, momentum, and thermal energy are fairly uniform. This layer has neutral stability, meaning that when a bubble of air rises or falls it neither releases nor requires any energy. Above the mixed layer is, by definition, a relatively unmixed region. This layer is generally stable, often a thermal inversion, where vertical motion requires some energy input. Finally, in the situation typical for many large fires, a region of neutrally stable subsiding air tops the stable layer.

Generally, the mixed layer deepens from sunrise through midafternoon. As the sun heats the ground, which in turn heats the air near it, the increasingly buoyant air can rise and mix upward to greater heights. At night, the surface and mixed layers are often absent. Under high pressure, the clear skies lead to enhanced cooling at the ground so that a surface inversion forms. Above this, there may be a remnant mixed layer from the daytime, and another inversion above this. The lowest inversion has the greatest influence on fire behavior.

Moisture plays an important role in the short-term processes of fire convection and fire behavior, but less so than stability. Moisture in the surface layer can be low or high, compared to the mixed layer. For example, air from the Gulf of Mexico blowing northward into Missouri would be relatively moist. Air moving into the same area from the northwest, perhaps behind a cold front, would be relatively dry. For this reason, one cannot generally describe surface layer moisture in the same way as stability, even when focusing on conditions typical of large fires.

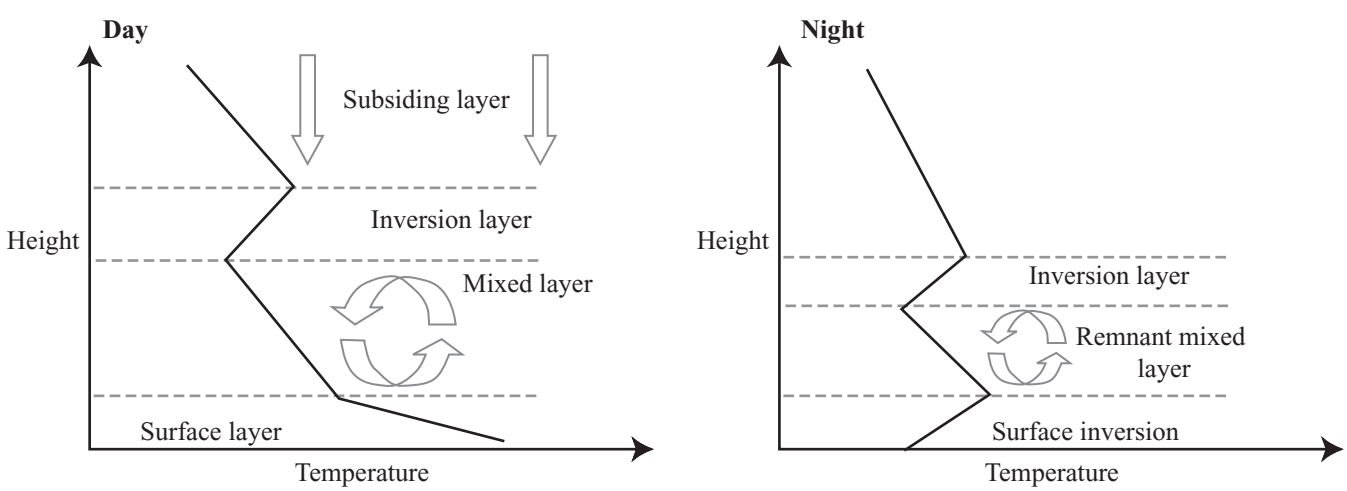

Figure 1. Idealized model of the vertical structure of the troposphere.

Table 1. Stages of fire-atmosphere interaction, based on the three-layer model. Air Layer is the layer of the atmosphere interacting with the fire during the given stage, while Stability, Plume Growth, Winds, and Moisture describe the qualities of the air properties typical of the layer involved in that stage.

Stage	Air Layer	Stability	Plume Growth	Winds	Moisture
Surface	Surface	Unstable	Rapid, energy added	Light and variable	Moist
Deepening	Mixed layer	Neutral	Moderate, no change	Stronger, variable	Dry
Penetration	Inversion and Subsiding	Stable	Slow, requires energy	Strongest, more steady	Drier

Above the mixed layer, the atmosphere is typically dryer than it is in the mixed layer. Subsidence above the inversion generally represents the driest part of the atmospheric profile.

Three Layer Model for Fire-Atmosphere Interaction

There are several ways to describe the stages, phases, or regions of fire. These include simple frameworks such as ground/surface/canopy or smoldering/creeping/running, and more complex concepts like Countryman's (1969) six zone framework describing stationary mass fires. These all have legitimate, valuable uses. The ground/surface/canopy distinction is useful for understanding behavior and fuel consumption patterns. The smoldering/creeping/running distinction tells a fire manager how quickly the fire is moving and what sorts of management actions are most appropriate. Countryman's (1969) zones divide a mass fire into six zones, based on a combination of visual properties and the apportionment of energy. None of these models, however, provides insight into the relationship between the fire and the atmosphere in a way that clarifies the influence of the atmosphere.

Potter (2002) proposed a three stage model for describing fire that emphasizes the relationship between the fire and the layers of the atmosphere described above. The stages of the model are the surface stage, the deepening stage, and the penetration stage. These stages are tied to fire's interactions with, and influence on, air in the surface layer, the mixed layer, and the inversion and subsidence layers, respectively. (In the penetration stage, the fire may interact with the inversion and then the subsidence layers, depending on the strength of the fire and the inversion.) Table 1 summarizes atmospheric properties during these three stages. In addition to the wind and stability aspects shown in the table, the moisture of the layers influences both fuel moisture (and therefore fire rate of spread and energy release) and plume development.

In this model, a fire does not necessarily go through all stages, and it can exist in a given stage more than once. All natural and prescribed fires begin in the surface stage. If there is a surface inversion, this is also a penetration stage – the surface air is stable, and any plume development requires the fire to do work. If a fire burns through a day and into a night, it may go from the deepening stage during the day back to a surface or penetration stage at night. In general, fires in the eastern U.S. tend to burn for one day, and would go through the stages in the listed order, before they return to the surface stage and die out. In the western U.S., fires are more likely to shift back and forth among the stages over multiple days. Because smoke can block sunlight and outgoing longwave radiation, it can affect stability so that yesterday's smoke influences the stages of today's fire.

The atmospheric three stage model has proven useful for some applications beyond research. In case studies of prescribed burns in Missouri and Michigan, we found that looking at the temperature, humidity, and wind of the layers involved in the stages and their contribution to BEHAVEPlus (Andrews et al. 2003) estimates of rate of spread and flame length, could explain some otherwise unexpected variations in these fire properties during prescribed burns. As a result, the Eastern Area Modeling Consortium (Heilman et al. 2003; USDA Forest Service 2004) now provides estimated values for temperature, humidity, and wind for the surface, mixed, and above-mixed layer air up to 48 hours in the future for use in BEHAVEPlus calculations. If the three sets of weather values yield widely varying fire property estimates, this suggests the potential for real-world variations in fire behavior.

Released Moisture

The main difference between small, scattered fair weather cumulus clouds and a towering, destructive cumulonimbus

cloud is the amount of water available in the atmosphere. Water and the energy released when it changes from vapor to liquid and from liquid to solid drive large storms, including tornadoes, downbursts, and strong straight-line winds.

Byram (1959) and Johnson and Miyanishi (2001) present a chemical equation for the combustion of woody material. The latter authors state that complete combustion of 1 kg of woody material yields 0.56 kg of water substance and 20 MJ[1] of energy. Potter (2003) proposes that during the combustion process, and after turbulent mixing of air near the ground, this moisture adds from 1 g to 5 g of water to each 1 kg of air rising in the fire's convective plume. (Moisture in air is often stated in terms of grams per kilogram (g/kg), with the understanding that this means "grams of water per kilogram of air". We follow this convention here.) The following discussion assumes that the air in the updraft from a large fire has been moistened by 2 g/kg. Potter (2003) presents a detailed discussion of the implications of this moisture, so we present a much abbreviated discussion here.

When air remains at a constant pressure and temperature, and water is added, one of the effects is a decrease in the average density. This is simply a result of the fact that the molecular weight of water is 16, while the average molecular weight of air is slightly less than 29 (Wallace and Hobbs 1977). The change is very small, but it can be important in calculations involving similarly small differences in density as air rises or descends. For example, at Mack Lake, MI on 5 May 1980 – the date of the Mack Lake fire (Simard et al. 1983) – calculations of the density of air without and with background moisture differ by only 0.004 kg/m^3. Using density without accounting for moisture, calculations indicate this air will freely rise to a height of 3000 m, and will not reach a height where the moisture in it condenses. When moisture is considered, the slight decrease in density is sufficient to allow the air to rise to the condensation level. The subsequent release of latent heat as the water condenses keeps the air warm enough that it can freely rise to 8800 m. If the fire had added 2 g/kg to the air, this height would increase to 9600 m.

The basic force behind thunderstorms is buoyancy, driven by the density differences between a parcel of air and the air around it. Consider, as an analogy, an ice cube in a glass of water. If the cube were pushed to the bottom of the glass, it would bob to the surface when released. If the ice cube were in peanut oil instead of water, the density of the cube would be greater than that of the oil, and the ice cube would sink. In the atmosphere, density differences are primarily due to temperature and moisture differences. Relatively hot or moist air is less dense than its environment, and will rise more energetically. If the moisture in the air condenses as the air rises, the condensation process releases energy that heats the air, further increasing its buoyancy and allowing higher, more vigorous ascent. One can calculate the energy released during this ascent and estimate the effect of increased temperature or moisture on that energy. For the Mack Lake Fire, warming the surface air by 2 K would have doubled the buoyant energy. Adding 2 g/kg of moisture to the surface air, instead, would have increased the buoyant

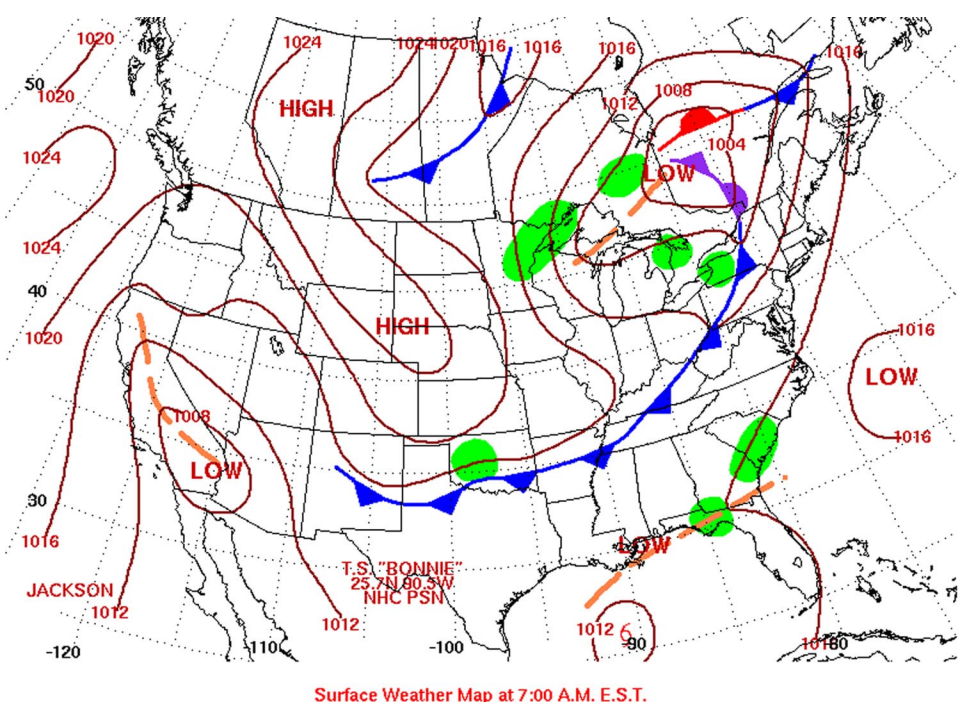

Figure 2. An example of a synoptic-scale low pressure system, with associated cold (blue) and warm (red) fronts. This map shows the pressure pattern for 1200 UTC (0800 EDT) on 11 August 2004.

[1]MJ = Megajoules

energy by a factor of 2.9, almost tripling it. Raising temperature by 2 K and moisture by 2 g/kg at the same time would have increased the buoyant energy of the surface air four-fold. Any of these increases in buoyant energy would have been sufficient to produce a vigorous updraft with strong inflow near the ground and strong near-fire horizontal winds.

Moisture in a fire plume has potential implications for downdrafts, as well. Downbursts, macrobursts, and microbursts are all types of downdrafts, varying in their spatial extent, duration and intensity - we will refer to them all simply as "downdrafts" here. Downdrafts develop through a combination of evaporative cooling and frictional drag from falling raindrops, snow, and hail. Without moisture to form rain, snow and/or hail, strong downdrafts would not form. More moisture means a greater potential for downdraft formation, though the manifestation of that potential depends on a variety of other factors. The connection between moisture and downdraft development is generally accepted and understood by meteorologists, and at least one fire study cited a downdraft as a cause of firefighter fatalities (Goens and Andrews 1998). Presently, however, the role released moisture could play in the formation of downdrafts is not known.

Synoptic Influence

In meteorology, "synoptic structure" refers to patterns that cover an area roughly one-half to two-thirds the size of the United States. The most common example of a synoptic structure is a low pressure system with cold and warm fronts (Figure 2). Synoptic weather systems can be thought of as the broad-scale organizing mechanism behind local weather. For instance, when a front passes over a given location, an observer on the ground might note a shift in wind speed and direction, a temperature drop or rise, rapid variations in humidity, or some combination of these changes. But observations at a single point seldom reveal the overlying synoptic system ultimately responsible for the formation of the front, the timing of its passage, the environmental changes that occur as it passes, and its lifespan.

Synoptic weather systems change throughout their lifetime. The fronts associated with low pressure systems can have varying intensities, which lead to different horizontal and vertical temperature and wind structures, so that one should not expect all fronts or other types of weather systems to affect fires equally. Furthermore, synoptic structures have varying effects on fires developing in different locations within them (Schroeder et al. 1964). As discussed above, information about atmospheric conditions in near-ground atmospheric layers can offer insight into the potential for unusual fire behavior. Synoptic weather patterns can, in turn, offer weather forecasters insight into how the near-ground atmospheric layers might vary. For this discussion we focus on how synoptic-scale weather systems can enhance or inhibit dry, windy conditions at the surface.

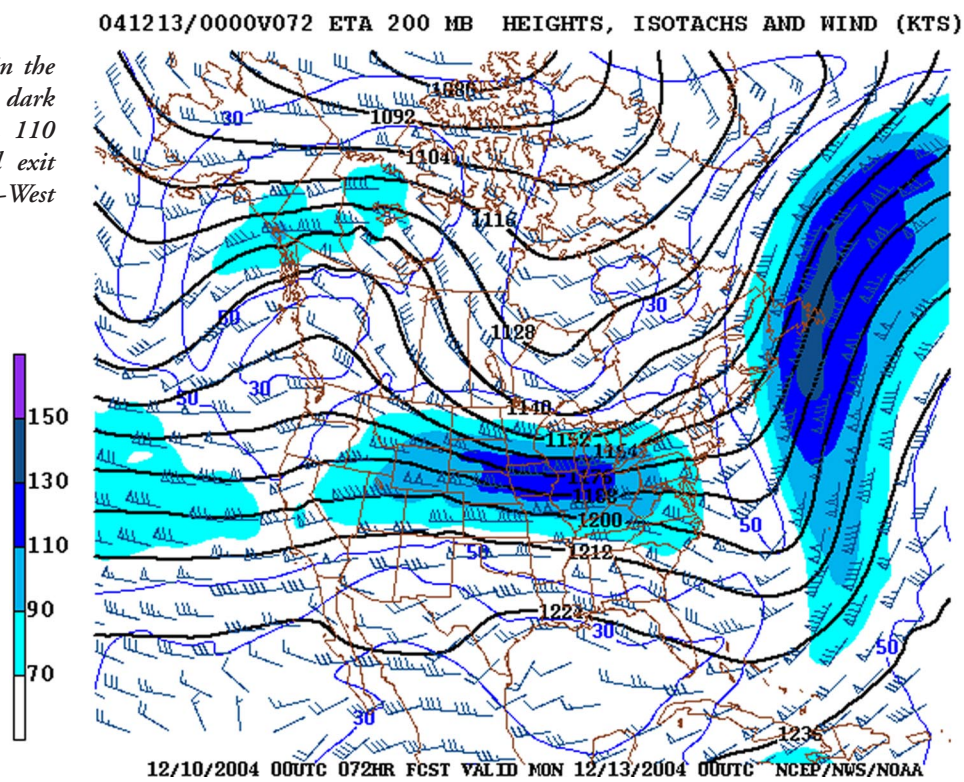

Figure 3. Example of a jet streak in the upper troposphere (250 mb). The dark blue area indicates winds between 110 and 130 knots. The equatorward exit region would be over the Kentucky-West Virginia area.

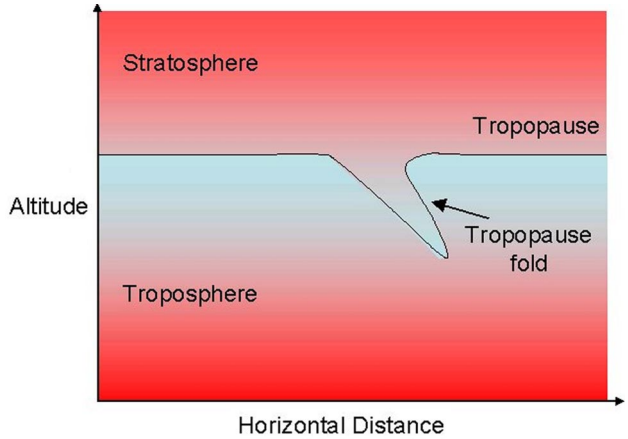

Figure 4. Illustration of a tropopause fold (not to scale).

Earlier, we described how the mixed layer deepens throughout the day. If the top of the mixed layer rises upward at a time and place where dry, windy air sits above but close to the top of the mixed layer, that dry and windy air may be drawn into the mixed layer. It may then descend to the surface, where it may influence fire behavior. Since the mixed layer can reach depths of 3 to 4 km, this type of interaction can draw down air that is substantially different from surface air.

Presently, two mechanisms have been identified as potential sources of descending, dry, windy air. One involves descent associated with regions 3 to 5 km above the ground where bands of high speed winds, known as "jet streaks", decelerate (Figure 3) These regions, known as jet exit regions, can span thousands of square kilometers. They typically have dry, fast moving air descending on the equator-ward side. Kaplan et al. (personal communication, manuscripts in preparation[2]) have found jet exit regions over several historically notable wildland fires.

The second potential source of descending, dry and windy air is known as a tropopause fold (Charney et al. 2003). The tropopause is the boundary, roughly 7 to 12 km above the ground, between the part of the atmosphere known as the troposphere (where temperature generally decreases with height) and the stratosphere above it (where temperature is constant or increases with height). Air in the stratosphere is much drier than air in the troposphere, so the tropopause marks a transition not only in temperature gradient, but also in moisture. Tropopause folds (Figure 4) are long, narrow intrusions of dry air that form in association with cold fronts, bringing air from the stratosphere down towards the ground. They do not typically reach the ground, except at high elevation locations, but it is possible for the mixing layer to rise upward to meet them, or for the energy from a fire to allow local mixing to reach a tropopause fold.

Conclusions

While thinking of fires in terms of the character of their convective columns is not new, recent work is connecting on-the-ground fire behavior more directly with the atmospheric processes within the convective column. These connections tie together the vertical temperature, moisture, and wind structures of the atmosphere, from the ground up to ten or more kilometers in altitude, with fuels, combustion, and subsequent fire behavior. This recent work brings many years of research in meteorology that was not originally associated with fire into the conversations and mental models now being used to understand fire behavior, especially extreme or erratic fire behavior.

The three topics (the three-layer model of fire-atmosphere interactions, the question of moisture's importance, and synoptic influences on fire behavior) discussed here provide examples of these new developments in the study of fire-atmosphere interaction and fire-driven convection. The three-layer paradigm is a simplistic framework that illustrates the potential for even small fires to behave in unexpected ways, and has potential as a planning tool. Questions about fire-released moisture indicate that there are potential ties between fuel load and fuel moisture, and the intensity and development of the fire's convective column, that go beyond simple heating of the air. The synoptic studies in progress now can provide insight into regional weather conditions that could influence fire behavior in previously unexpected ways. Each of these – and many topics that are sure to come to light as research proceeds over the next decade – has implications for fire fighter safety and resource management.

[2]Kaplan, ML, C Huang, YL Lin, and JJ Charney. [N.d.] A Multi-Scale Paradigm for Rapid Vertical Airmass Coupling Resulting in High Fire Weather Potential. Part I: Observations of the Double-Trouble Case Study. and Part II: Numerical simulations of the Double-Trouble Case Study. Manuscripts in preparation. On file with J. Charney, USDA Forest Service, 1407 S. Harrison Road, Suite 220, East Lansing, MI 48823.

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