9.5 USING MESOSCALE MODEL SIMULATIONS TO BETTER UNDERSTAND THE ROLE OF SURFACE MIXED-LAYER DYNAMICS IN FIRE-ATMOSPHERE INTERACTIONS

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1. INTRODUCTION

The indices and diagnostics use by fire-weather forecasters to predict fire-atmosphere interactions have traditionally been based on empirical relationships derived from observations of extreme fire behavior and the atmospheric conditions at the time of the fire. The Haines Index (Haines 1988), the Fosberg Index (Fosberg 1978), and the Canadian Fire Weather Index (Van Wagner 1987) are all examples of empirical indices that are used to predict or anticipate fire severity. Although these empirical indices have demonstrated utility, they are also prone to unpredictable and often undesirable behavior depending on the time of day, the season, the geographic location, and the prevailing weather regime of a given fire scenario (Potter 2002). It is therefore desirable to develop indices that are more directly tied to the atmospheric processes responsible for the observed fire-atmosphere interactions, and by doing so produce forecast products that are more generally able to predict or diagnose the potential for interactions for any location, time, or season.

Many of the currently used fire-atmosphere interaction indices were developed in the 1970s and early 1980s, before regular real-time access to mesoscale simulation data was commonplace. The indices were therefore derived from surface observations or, when atmospheric conditions aloft were required, from rawinsonde balloon data. When rawinsonde observations are employed, the index developers needed to choose whether 0000 UTC or 1200 UTC observations would be more appropriate. For most of the United States, the fire season extends from mid-spring to mid-autumn. In the eastern United States, 1200 UTC follows sunrise during the fire season, but is often too early in the day for the surface mixed layer to have fully matured. In the western United States, 0000 UTC is generally before sunset during the fire season, but the mixed layer is generally weakening by that time. Both of these factors make it difficult to develop effective fire-weather indices that depend on rawinsonde observations of mixed layer structures.

Some of the strongest and most dangerous fire-atmosphere interactions occur in the early afternoon, when the surface mixed layer tends to deepen rapidly and often approaches its maximum depth for the day (see e.g. Finklin 1973, Simard et al. 1983, Charney et al. 2003). In the continental United States, this time tends to fall between the two standard rawinsonde observation times, which complicates efforts to understand how atmospheric conditions aloft contribute to observed fire spread behavior. However, since the mid-1980s, mesoscale numerical weather prediction models have routinely been employed to simulate and predict the weather conditions in the United States. Since the depth and local characteristics of the mixed layer are known to impact fire behavior as well as smoke dispersion, it is reasonable to expect that mesoscale model simulations of mixed-layer processes could be used to produce indices with better resolving capabilities than rawinsonde data.

Using research funding from the congressionally established National Fire Plan, the US Forest Service created regional Fire Consortia for the Advanced Modeling of Meteorology and Smoke (FCAMMS) across the country. The Eastern Area Modeling Consortium (EAMC), located in East Lansing, MI, is responding to the need for new fire-atmosphere interaction indices by using mesoscale model simulations (MM5v3) to improve our understanding of the physical processes involved.

2. MIXED LAYER DYNAMICS

A simple idealized representation of the atmosphere under subsiding air in a high pressure system is shown in Fig. 1. The mixed layer in these situations usually exhibits a dry adiabatic lapse rate except for a superadiabatic layer very near the ground. Above the mixed layer, a shallow inversion layer separates the mixed layer from the subsiding layer, which is often referred to as the free atmosphere. Many fire-atmosphere interactions center upon the extent to which either the atmosphere alone or fire-induced atmospheric circulations can cause air from the free atmosphere to be transported or mixed down to the ground, where it can interact with and modify fire behavior and fire spread characteristics (Charney et al. 2003a).

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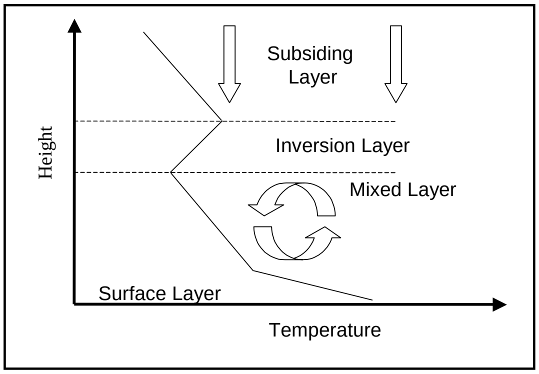

Figure 1: General structure of the atmosphere within a subsiding air mass aloft and mixed layer underneath. (The Inversion layer is exaggerated here for clarity.) (from Potter 2001)

There are two regularly-employed fire-weather indices, the Haines Index and the Ventilation Index (Hardy et al. 2001, and others), that are closely tied to mixed-layer depth (MLD). The Ventilation Index is defined as

$$VI = D_{ml}\left|\boldsymbol{u}\right|_{ml}$$

where D_{ml} is the depth of the mixed layer and V_{ml} is the average wind speed in the mixed layer. While the dependence of the Ventilation Index on MLD is clear from the equation above, MLD impacts on the Haines Index are somewhat more subtle. The Haines Index employs an atmospheric static stability calculation based on the temperature difference between two pressure levels, one of which is assumed to be near the top of the mixed layer, and the other in the free atmosphere above it (Fig. 2). Since the Haines Index uses fixed pressure levels that vary only depending upon the local elevation, the calculation can differ strongly depending on the local characteristics of the MLD (Potter 2002).

Many of the indices and concepts being developed by the EAMC take advantage of model-simulated mixed-layer evolution, both in real time and in case studies of past fire events. A mesoscale model accounts for planetary boundary layer (PBL) processes by employing a sub-grid scale parameterization to account for spatially varying interactions between the land surface and the overlying atmosphere, as well as the turbulence characteristics that would influence the grid-resolved variables. The grid-resolved components then evolve based on static stability and dynamic forcing, which can feed back on the PBL characteristics by altering surface conditions (e.g. through cloud-radiative forcing or soil moisture modification).

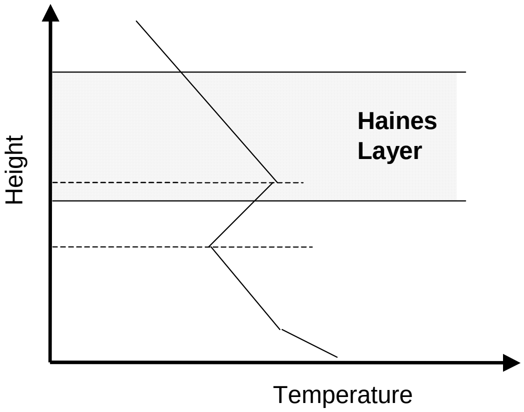

Figure 2: Preferred orientation of the Haines Layer and the mixed layer for optimum performance of the Haines Index. (from Potter 2001)

The depth of the PBL as identified by the PBL parameterization varies considerably depending on the scheme employed. For example, the Blackadar PBL parameterization calculates the depth of the PBL by determining the equilibrium height of a rising parcel in a convective situation (Blackadar 1979), while the Mellor-Yamada-Janjic PBL scheme determines the height of the PBL by calculating the vertical variation of Turbulence Kinetic Energy (TKE) (Janjic 1990). The depth of the PBL, in all of these cases, is used to identify the depth of the atmosphere that can potentially be modified by the sub-grid-scale parameterization. The implication of these modifications for calculating fire-weather indices or diagnostics can be profound, since the performance of existing indices and of new indices that depend on MLD could vary considerably based upon the influence of the various PBL schemes. In order to avoid circular arguments or to unfairly favor certain PBL parameterization schemes, it is desirable to develop fire-atmosphere interaction diagnostics that are independent of the parameterized PBL depth. A definition of the MLD that is based on the physical structures of the *resolved* model fields rather than that of an individual PBL parameterization is required.

There are several different methods of calculating the MLD, depending on whether the calculation is based on rawinsonde observations, wind profilers, laboratory experiments, or developed from theoretical arguments (see e.g., Doran and Zhong 1995). For the purposes of this investigation, the top of the mixed layer is defined as the atmospheric level where the surface-derived convective available potential energy (CAPE) is a maximum. CAPE is calculated using:

$$CAPE = \int_0^z \frac{\theta_0 - \theta(z)}{\theta(z)} dz$$

where θ_0 = the surface potential temperature, $\theta(z)$ is the potential temperature at a given level above the surface (Stull 1988). If the CAPE < 0 at the ground or if the CAPE = 0 at the ground and never increases, then the MLD is assumed to be 0. This method allows for the calculation of MLD using an arbitrary atmospheric profile, and is well-suited to mesoscale simulations where the lowest model layer is shallow (on the order of 10m) and the model vertical resolution is sufficient for capturing the relevant PBL structures associated with the mixed-layer dynamics.

CAPE arguments are also useful for fire-atmosphere interaction considerations because the first-order effect of the fire on the atmosphere is as a diabatic heat source. The CAPE calculation assumes that surface parcels are given an infinitesimal heat source that raises the parcel temperature above that of the environment and represents the potential buoyancy imparted on the parcel by the atmosphere. The effect of a fire on the atmospheric structure can be conceptualized in a CAPE framework as a much larger surface temperature modification, that can vary depending strength of the fire. This argument allows for the calculation of a new MLD based on the extent to which the fire could modify the atmosphere above it. This concept is particularly important for fires because the air directly above the mixed layer is often drier and exhibits higher momentum than the surface-based mixed-layer air. When the fire modifies the MLD, the updraft plume resulting from the diabatic heat input of the fire can tap into the free atmosphere air and, under certain conditions, entrain or transport the free atmosphere air into the mixed layer and down to the ground.

Temporal and spatial variations in the simulated MLD are potentially important considerations with fighting a fire. A mixed layer that grows at a steady and predictable rate through the afternoon presents a very different challenge from a mixed layer that grows and weakens sporadically through the day, either due to variations in surface radiative properties, static stability characteristics, or precipitation effects. Similarly, an environment exhibiting strong horizontal gradients in MLD presents more of a problem for firefighters than a horizontally homogeneous environment, in that sudden changes in fire behavior due to variations in the background mixed layer depth could lead to erratic fire behavior.

The presence of a diurnal low level jet (LLJ) can complicate the fire-atmosphere interaction problem considerably. As shown in Fig. 3, a mixed layer that grows quickly in the morning can mix the momentum in the LLJ is down to the ground through the afternoon. In these sorts of situations, fires can start to spread very rapidly (Charney et al. 2003b). A number of large and damaging historical fires appear to have resulted from this interaction, and in some cases, prescribed fires (fires started intentionally to reduce fuel levels or serve some other land management purpose) have escaped and become large wildfires due to this process (Simard et al. 1983). Predicting when surface mixing processes have the potential to tap into high momentum air within a LLJ and transport that air to the ground has the potential to save millions of dollars in firefighting and restoration costs if the prediction could help make lighting prescribed fires safer.

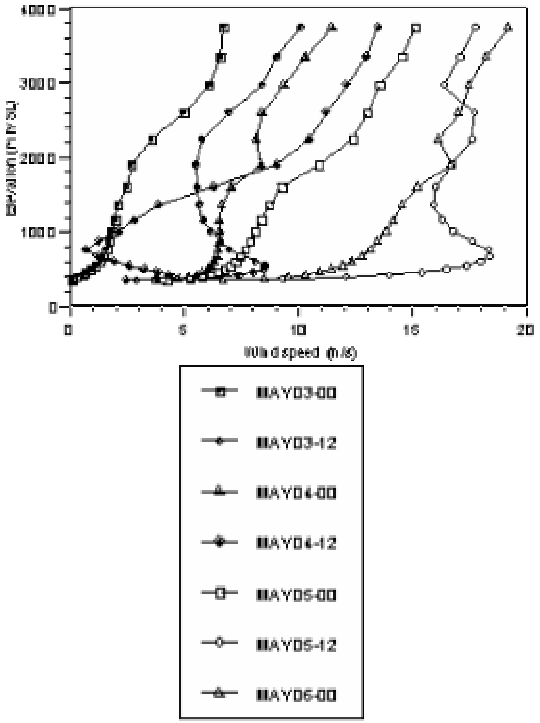

Figure 3: Simulations of wind profile variations over the three days leading up to the Mack Lake Fire. Note how the well-defined Low Level Jet at 1200 UTC on May 5th is mixed throughout the lowest levels by 0000 UTC on May 6th.

3. INDEX DEVELOPMENT

The EAMC and its cooperators are working on a wide variety of fire-weather index development and verification projects, ranging from very fine scale dynamics to climatological assessments of performance (Heilman et al., 2003). However, most of the EAMC index development efforts are designed to take advantage of real-time MM5 mesoscale simulations, with model grid spacing of either 12km or 4km. Parameterized mixed-layer dynamics therefore play a key role in many of the indices under development.

3.1 *MLD Variability*

Perhaps the simplest diagnostic that can be derived from MLD is to compute the horizontal gradient of the MLD at an instant in time (Fig. 4). A fire-weather forecaster could either examine the MLD gradient at the time of a fire, at the time of maximum MLD (usually in the early afternoon), or view a sequence of maps that would indicate the degree of variability in MLD gradient over the course of the day. This information could be used to anticipate the expected variability in fire behavior on any given day,

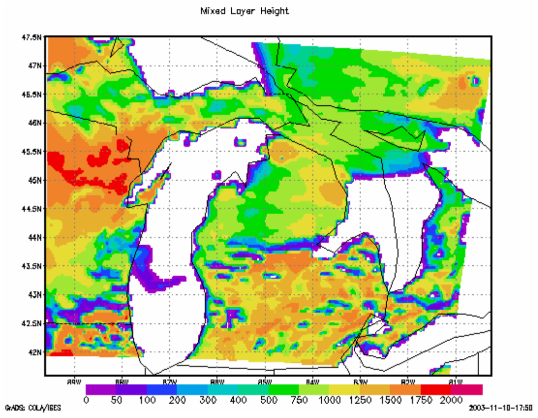

Figure 4: Simulated mixed layer depth (MLD) at the time corresponding to 1900 UTC on May 5th, 1980 (the Mack Lake Fire). Note the local variations in MLD evident in the simulated field, which would yield large values of the gradient of MLD at this time.

as well as providing advanced warning of particularly sudden changes in conditions.

The variation in MLD at a given point throughout the day is also an important consideration for fire-weather interactions. If the mixed layer is slowly varying throughout the day, the effect of the surface conditions on the air in the upper portions of the mixed layer will tend to be more pronounced. Conversely, if the MLD varies substantially though the day, the air in the upper portions of the mixed layer would be expected to share more characteristics with the free atmosphere above. Fig. 5 shows the variation over the afternoon of the MLD as well as the PBL parameterization of PBL height for the Mack Lake Fire. The MLD indicates a considerably higher degree of variability than the PBL Height. An index or metric that is sensitive to the degree of MLD variability at a point over the course of a day should correlate with overall variability in fire behavior due to fire-atmosphere interactions for that same time period. A temporal MLD variation index used in tandem with an index based on the horizontal gradient of MLD could exhibit even more predictive power.

3.2 *Environmental CAPE vs. Fire-modified CAPE*

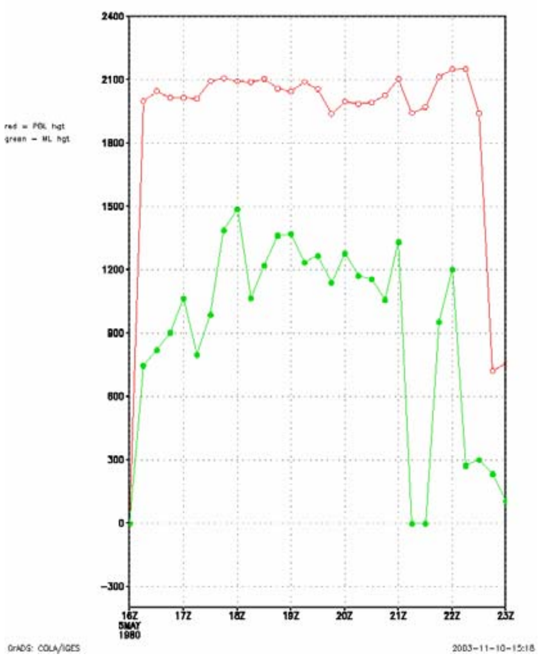

Figure 5: Simulated time series of PBL Height calculated by the MRF PBL scheme (red line) and the mixed layer depth using the CAPE method (green line) corresponding to 1600 UTC through 2300 UTC on May 5th, 1980.

As indicated in Section 2, CAPE has been identified as a potentially useful concept for assessing the overall potential for fire-atmosphere interactions in the background environment. CAPE can also be used to assess how the background environment might change under the influence of a fire. The impact of fire on surface parcels can be accounted for by treating the fire as an effective diabatic heat source at the surface. This will yield an effective MLD for the fire. This new MLD can, in some situations, vary considerably from the MLD indicated by the environment. By noting the magnitude of the difference between the environmental CAPE and the fire-modified CAPE, the potential for the fire to tap into air aloft that would not otherwise be accessible by the mixed-layer can be assessed. When this potential appears to be high, it can be inferred that the possibility of erratic or unexpected fire behavior would be greater.

Another potentially important CAPE-related product is the descent energy (Potter 2002), which identifies the downward force of the environment on a parcel in the lowest layers of the atmosphere. The descent energy represents how much energy input is required for a parcel of air to descend from a given level to the ground. In a fire situation, this calculation would indicate the level of origination of air that subsides in response to the rising fire plume. If the descent energy indicates that air with substantially different characteristics than the surface air would descend into the fire area, the fire-weather forecaster would expect rapidly changing conditions as a fire evolves, and would warn the fire managers and firefighters accordingly.

Potter (2001) presented the concept of Parcel Exchange Potential Energy (PEPE) and applied the conceptual framework to an idealized fire situation. PEPE is designed to assess the extent to which a fire is likely to force the exchange of surface air with air at any given level aloft. In essence, PEPE combines the effects of CAPE and descent energy into a single metric. In addition to determining parcel exchange potential, PEPE can also suggest the extent to which a fire is likely to alter the background environment such that stronger or weaker parcel exchange is expected.

3.3 *Average Mixed Layer TKE*

PBL schemes used within mesoscale models often predict or parameterize the TKE within the mixed layer. If the TKE is known, it is straightforward to calculate the potential for mixing within the PBL. By comparing TKE against other variables that concern the exchange of momentum and mass (potential temperature), and moisture at the top of the mixed layer, the extent to which the mixing process itself dominates the dynamical interactions can be determined.

In addition to assessing the vertical mixing potential across the top of the mixed layer, TKE could also be used to define the overall potential for turbulent flow to develop within the mixed layer, and the extent to which this turbulence might affect a fire. Turbulent flow leads directly to erratic fire behavior. Since many PBL parameterizations used in mesoscale models calculate TKE, this information is readily available and could be made available to fire-weather forecasters in the form of an index.

3.4 *Mixed Layer – LLJ Interactions*

The situation described in section 2 wherein the MLD increases suddenly in the late morning when there is an overlying LLJ is particularly dangerous to fire fighters. An index that can predict when LLJ momentum can suddenly mix down to the surface layers would be particularly valuable. The EAMC is developing an index that is sensitive to the strength of the elevated inversion that usually accompanies the formation of a diurnal PBL LLJ. This so-called mixed layer jet index (MLJI) has the following formulation:

$$MLJI = \frac{\left(\left. \frac{\partial |\mathbf{u}|}{\partial z} \right|_{ML} \right) \left(\left. \frac{\partial \theta}{\partial z} \right|_{ML} \right)}{H_{ML}}$$

where the vertical derivatives are taken across the top of the mixed layer, and H_{ML} is the MLD. The index is designed to indicate where the inversion will break down such that high momentum air in a LLJ can be mixed down to the surface. Additionally, the model can also indicate when, exactly, the developing mixed layer will lead to the erosion of a pre-existing inversion. By incorporating this information into the MLJI, it could be possible to provide fire-weather forecasters with both the inversion breakdown potential as well as when that breakdown is most likely to occur.

The concept of predicting when high momentum air associated with a LLJ might be mixed down to the surface can be generalized to account for all situations where mixing could alter surface weather conditions. By integrating the vertical fluxes of relevant mixing quantities from the surface up to a predetermined height above the MLD, the overall potential for the surface conditions to undergo changes due to vertical mixing can be assessed.

3.5 *Atmospheric Surface Boundaries*

It is well-known that surface fronts, land-sea breezes, and other types of atmospheric boundaries can strongly influence a fire situation (Shroeder et al. 1964, Simard et al. 1983, and others). The EAMC, in association with the second author, is working to develop a system that assesses the expected response of an active fire to the passage of a given type of atmospheric boundary. Since most atmospheric boundary passages are accompanied by a substantial change in MLD and/or characteristics, it is anticipated that mixed-layer calculations will play a major role in the fire-boundary interaction diagnostics that will be developed (see e.g. Uccellini et al. 1992, Young and Fritsch 1989, and Bosart 2003, for boundary analysis and identification techniques).

4. DISCUSSION AND CONCLUSION

A preliminary report on a research program that is designed to take advantage of mesoscale model PBL and mixed layer predictions for the development of new fire-atmosphere interaction tools has been outlined above. The Eastern Area Modeling Consortium is operating an MM5-based real-time prediction system for the north-central and northeastern United States. The model output is being employed to develop and test a variety of indices and diagnostics that can some day be incorporated into a fire-weather forecasting office and the information disseminated to fire managers and fire fighters in the field.

The concepts presented here represent an effort to update fire-weather indices that were developed in the 1970s and early 1980s, before mesoscale model data were regularly available to fire weather researchers or forecasters. The concepts employed in this study derive from, in many cases, well-established physical arguments and techniques employed in atmospheric science research and weather forecasting. However, most of these techniques have never before been applied to fire-weather forecasting.

As the concepts discussed here develop and evolve, it is anticipated that some “cross-pollination” will inevitably occur. The diagnostics and indices presented above are not intended to be mutually exclusive with respect to the dynamical processes to which they respond. Indeed, it is entirely possible that two or more of the concepts presented herein will lead to indices that “light up” at the same locations. However, it is important at this stage to try to account for as many different kinds of fire-atmosphere interactions as possible. After the initial development of the indices, the EAMC will pursue a rigorous testing and validation process to establish the robustness and utility of these calculations before they are passed on to fire-weather forecasters for public usage.

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6. ACKNOWLEDGEMENTS

This research was supported by Research Joint Venture Agreement 03-JV-11231300-101 between the University at Albany, SUNY and the USDA Forest Service North Central Research Station.