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3.3 USING A SIMPLE PARCEL MODEL TO INVESTIGATE THE HAINES INDEX

Mary Ann Jenkins[†1]
Steven K. Krueger[2] and Ruiyu Sun[2]
[1]York University, Toronto, Canada
[2]University of Utah, Salt Lake City, Utah

1. INTRODUCTION

The Haines Index (Haines 1988) is a fire–weather index based on stability and moisture conditions of the lower atmosphere that rates the potential for large fire growth or extreme fire behavior. The Haines Index is calculated by adding a temperature term a to a moisture term b. For fires at low elevation, values from 1 to 3 are assigned to a based on the temperature lapse between 95 and 85 kPa:

$$\begin{aligned} \text{If } T_{p_{95}} - T_{p_{85}} < 4°\text{C, then } a{=}1, \\ \text{if } 4°\text{C} \leq T_{p_{95}} - T_{p_{85}} < 8°\text{C, then } a{=}2, \text{ and} \\ \text{if } T_{p_{95}} - T_{p_{85}} \geq 8°\text{C, then } a{=}3. \end{aligned} \tag{1}$$

For fires at low elevation, values from 1 to 3 are assigned to b based on the difference between the dry bulb and dew point temperatures at 85 kPa:

$$\begin{aligned} \text{If } T_{p_{85}} - T\text{dew}_{p_{85}} < 6°\text{C, then } b{=}1, \\ \text{if } 6°\text{C} \leq T_{p_{85}} - T\text{dew}_{p_{85}} < 10°\text{C, then } b{=}2, \\ \text{and if } T_{p_{85}} - T\text{dew}_{p_{85}} \geq 10°\text{C, then } b{=}3. \end{aligned} \tag{2}$$

The higher the Haines Index, the higher the potential for severe fire behavior. When $a+b=$ 2 or 3, the atmosphere is moist and stable, and the potential for large fire growth or extreme fire behavior is very low. When $a+b$ = 4, the potential is low. When $a+b=5$, the potential is moderate. When $a+b=6$, the atmosphere is dry and unstable, and the potential for large fire growth or extreme fire behavior is high. Note that the 85 kPa level is approximately 1500 m and the 95 kPa level is approximately 500 m Above Ground Level (AGL). The temperature drops in Equation (1) are therefore over $\sim$ 1000 m depth.

Put into operational use almost immediately, the Haines Index has since been studied to determine its effectiveness. While observational studies (e.g., Werth and Ochoa 1990, etc) show that the Haines Index has some skill at predicting the risk of large fires, there are also observational studies that show situations where the Haines Index breaks down (e.g., Werth and Werth 1998). The observational studies attempt to correlate the Haines Index with fire severity, but do not demonstrate how near–surface humidity and atmospheric stability enchance surface fires and cause them to grow. Without a clearer understanding of how the Haines Index works, it is difficult to conclude what are the reasons for its successes and failures.

The difference between this study and previous studies is that we interpret and explore the Haines Index as a two–dimensional parameter space. Implicit in the Haines Index is that the spectrum of severe wildfire behavior is dependent on two observable meteorological parameters: lower–level atmospheric stability and humidity. Although the two–dimensional space formed by these parameters is continuous, $a+b$ imply atmospheric conditions that distinguish 2 to 6 distinct hierarchies of fire severity or possible fire regimes. When the Haines Index is interpretated as a parameter space in which the potential for severe wildfire development is characterized by near–surface atmospheric stability and humidity, then fire properties associated with wildfire severity can be begin to be quantified and measured, and linked directly to ambient weather conditions.

Currently there is no formal physical definition for fire severity. It is generally accepted that dry, unstable air helps determine whether a wildfire will become as big in vertical as in horizontal extent, where significant vertical column development increases the probability that the wildfire will become large and/or erratic. For the purposes of this study, fire severity is described by variables associated with significant vertical column development, and these are high levels of buoyancy, high levels of maximum rise, and large vertical veloc-

† *Corresponding author address:* Mary Ann Jenkins, York University, Dept. of Earth & Atmospheric & Engineering Science, 4700 Keele Street, Toronto, Ontario, Canada M3J 1P3; maj@yorku.ca

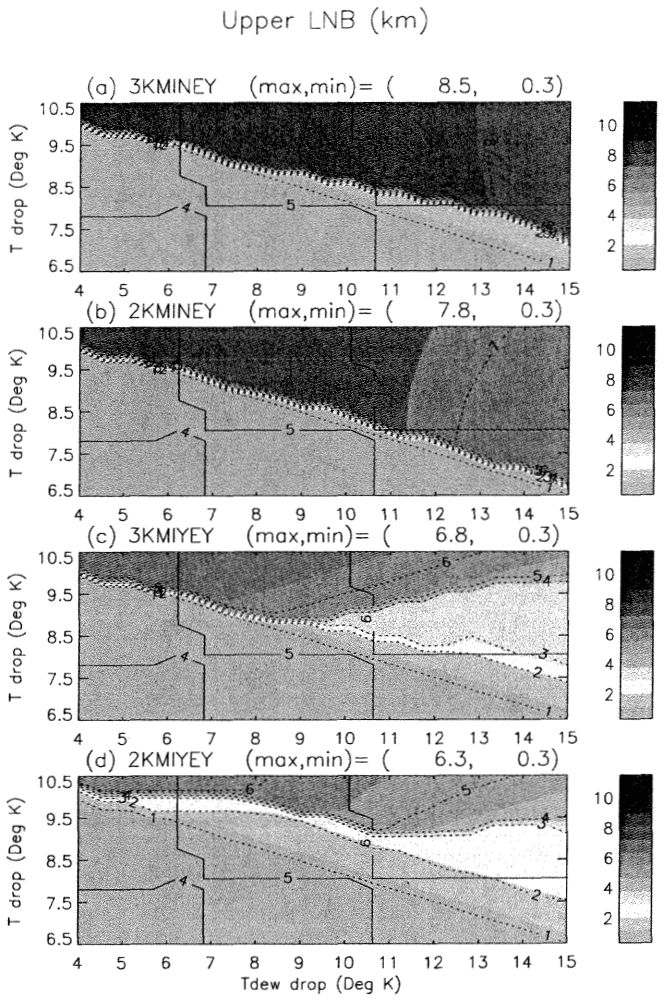

Fig. 1 Contoured display of the upper Level of Non–Buoyancy (upper LNB) from parcel model experiments 3KMINEY, 2KNINEY, 3KMIYEY, and 2KMIYEY as a function of drop in atmospheric temperature between pressure levels 95 and 85 kPa (vertical axis) and difference in atmospheric dry bulb and dew point temperatures (horizontal axis) at pressure level 85 kPa. The thin solid lines (labeled 4 to 6) indicate the Haines Index for each drop in atmospheric temperature between pressure levels 95 and 85 kPa, and difference in atmospheric dry bulb and dew point temperatures at pressure level 85 kPa. See text for details. Dashed lines indicate contour levels labeled in increments of 1 km. The maximum and minimum upper LNB values for experiments 3KMINEY, 2KNINEY, 3KMIYEY, and 2KMIYEY are indicated.

ities. The two–dimensional parameter space is therefore formed by determining these variables as functions of the low–level moisture and stability conditions that combined make up the Haines Index.

We use basic convective parcel model theory to construct the two–dimensional parameter space. The advantages of this approach

are that parcel model theory captures some important physics of convection, is simple to code, and model results are straightforward to interpret. This approach easily provides the large number of experiments that are required to complete the two–dimensional parameter space. Even though severe wildfire convection is considerably more complex and varied than convection represented by a simple parcel model, this study is a good start to understanding the influence of the background state on fire parcel convection and to examining the skill of the Haines Index at predicting wildfire severity, where wildfire severity is assumed to be directly connected to vertical column development and the result of significant fire parcel ascent.

2. THE PARCEL MODEL

A parcel model assumes that convection consists of discrete buoyant parcels, and goal of a parcel model is to predict the average properties of such parcels. The details of the simple parcel model used to describe the ascent of an entraining air parcel originating from a surface fire are given by Jenkins (2003). Vertically moving air parcels entrain or mix with environmental air, which modifies or dilutes their properties, where the usual, but not without exception, effect of entrainment is to lower parcel buoyancy. Suspended cloud droplets and rain water create a drag and contribute to negative buoyancy throughout the parcel's rise. In a parcel model pressure perturbations are assumed to be zero. This means that, in physical terms, a rising parcel immediately expands to adjust to the local environmental pressure, which is assumed to be hydrostatic. In reality the pressure perturbations that are excluded in the simple parcel model can cause vertical pressure gradients that can be important, even dominate, forces on air parcels. The simple parcel model also does not take into account aerodynamic drag or compensating downward motions of the surrounding air.

Air parcels in and just above a surface fire quickly absorb heat and moisture liberated by the burning fuel to reach temperatures and water vapor mixing ratios that are larger than environmental values. The fire parcel is therefore buoyant and accelerated ascent begins. As the fire parcel ascends, it expands and cools dry adiabatically, and can eventually reach saturation. Ascent above this level is saturated ascent, during which the parcel expands and cools moist adiabatically. Condensation and rain can occur, as the fire parcel maintains exact saturation. At some level, the fire parcel's temperature and humidity matches the surrounding temperature and humidity, and the parcel is, by definition, no longer naturally buoyant and it stops accelerating. The level at which this happens is called the Level of Non–Buoyancy or Neutral Buoyancy (LNB). Above the LNB, the fire parcel is no longer naturally buoyant. It begins deceleration, and eventually stops rising at the height of maximum ascent, when the parcel's Convective Available Potential Energy or CAPE is expended. CAPE is defined as

$$\mathrm{CAPE} \equiv \int_{z_{\mathrm{sfc}}}^{z_{\mathrm{LNB}}} g\left(\frac{\theta_v - \overline{\theta}_v}{\overline{\theta}_v}\right) dz \qquad (3)$$

for the purposes of this study. The z_{sfc} and z_{LNB} are the heights at the surface and Level of Neutral Buoyancy, respectively. Note that there is no barrier at the surface to convection for a fire parcel; the fire parcel begins its ascent at a temperature and humidity higher than surrounding values. Here CAPE is the maximum amount of kinetic energy per unit mass that a statically unstable air parcel acquires as it ascends from the surface to the highest LNB.

TABLE 1. The boundary layer depth and upper–level inversion (yes or no) for each experiment.

Experiment	Boundary Layer Depth (km)	Upper–level Inversion
3KMINEY	3	No
3KMIYEY	3	Yes
2KMINEY	2	No
2KMIYEY	2	Yes

An atmospheric profile can enable an ascending fire parcel to reach a LNB, continue rising and decelerating, to reach an level of free convection where it again becomes positively buoyant. The parcel continues accelerated ascent, rising to a higher LNB, then decelerating and finally reaching the maximum level of ascent. The results in Section 4 show how common these atmospheric profiles are.

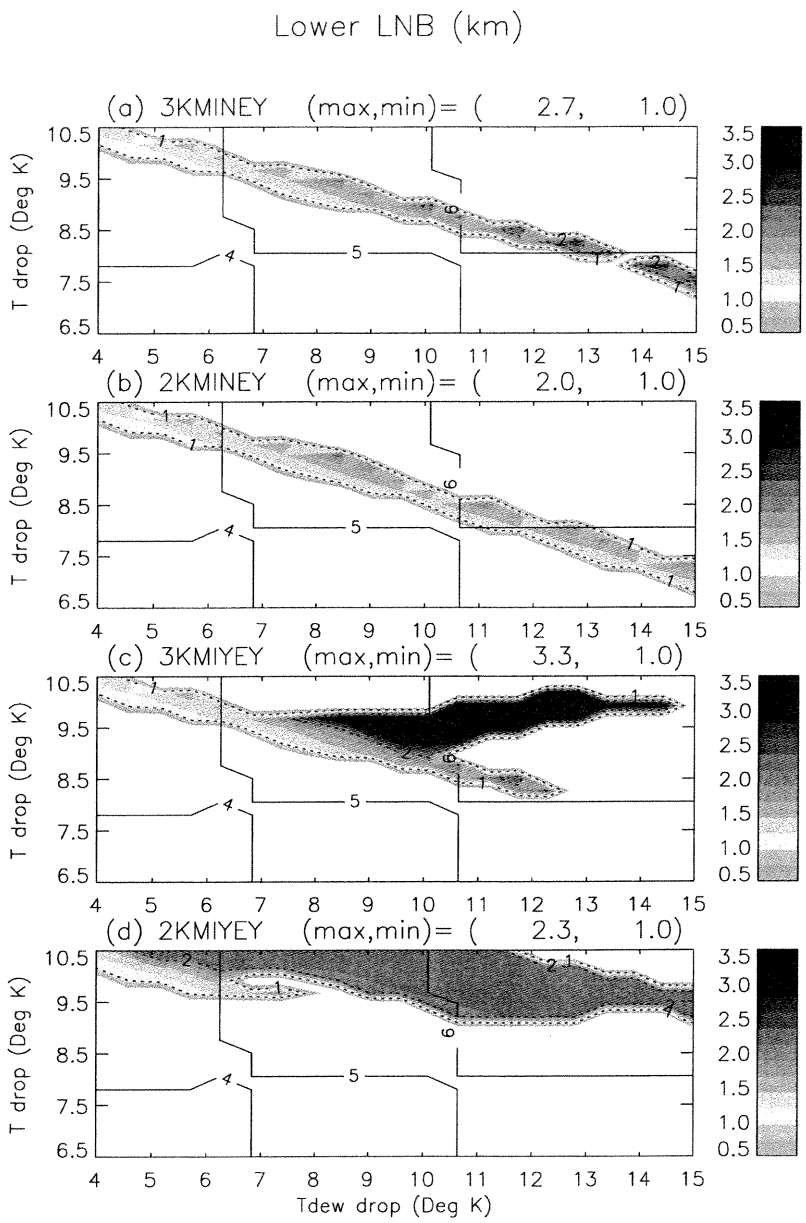

Fig. 2 As in Fig. 1 except for lower Level of Non–Buoyancy (lower LNB)

3. APPLYING THE PARCEL MODEL

The vertical profile of a summertime atmosphere often associated with extreme wildfire behavior is typically characterized by: a superadiabatic surface layer that can be less than a 1 m deep to sometimes 100 m deep;

above which is the boundary layer, a mixed, turbulent layer, 1 to 3 km deep, with a dry adiabatic lapse rate and constant humidity mixing ratio; above which is a relatively thin ($\sim$ 100 to 400 m) inversion layer caused by large–scale (high pressure system) subsidence; above which standard atmospheric conditions prevail until the tropopause at $\sim$ 11 km; and above that an isothermal (dry, stable) layer.

To create the environmental profiles needed to form the two–dimensional parameter space, this vertical profile of a summertime atmosphere was used as the basis for constructing 600 different profiles, where the low–level atmospheric stability and moisture conditions in the boundary layer cover the stability and moisture ranges specified by a and b in Equations (1) and (2).

The following differences in vertical structure were imposed on these profiles: a 3 km deep boundary layer, a 2 km deep boundary layer, a 3 km deep boundary layer with a 300 m deep inversion layer at the top of the boundary layer, and a 2 km deep boundary layer with a 300 m deep inversion layer at the top of the boundary layer. By introducing these four different vertical structures, four experiments were conducted and are listed in Table 1.

For this study, the surface temperature is 35°C (high surface temperature) and the surface mixing ratio is 9 g kg^{-1}(low surface humidity). The fire parcel is given a temperature excess of 2°C and a moisture excess of 1 g kg^{-1} water vapor mixing ratio. These values are based on the numerical simulations with a coupled wildfire–atmospheric model by Jenkins (2002). No surface superadiabatic layer was considered. Given these initial parcel properties, the parcel model was used to determine fire parcel rise to the height of maximum ascent. For each experiment predicted fire parcel properties were plotted as a function of near–surface atmospheric stability and moisture as defined by a and b in Equations (1) and (2). The average properties of the ascending fire parcel predicted by the parcel model are the Levels of Non–Buoyancy or Neutral Buoyancy or LNB, the level of maximum ascent, the maximum ascent velocity, the height of maximum ascent velocity, and CAPE.

4. RESULTS

The highest Levels of Non–Buoyancy reached by entraining fire parcels are plotted in Fig. 1. The most obvious feature of these plots, and those that follow, is that certain stability and humidity conditions result in a sharp cut–off in fire parcel ascent. Ascending fire parcels either lose their buoyancy abruptly at approximately 1 to 2 km or less, or continue to ascend above 2 km and possibly rise to 6 km AGL or higher before reaching the level of maximum ascent. The cross over for no or little appreciable ascent to significant ascent occurs for a fairly narrow combination of background stability and humidity conditions. As humidity in the atmosphere increases, the atmosphere has to be less and less stable for fire parcels to ascend to significant heights.

Fig. 1 shows that when entraining fire parcels do reach significant upper–level LNBs and there is no upper–level inversion, the LNB responds to environmental lower–level moisture (i.e., contour lines in Fig. 1a and Fig. 1b are nearly vertical and contour values decrease slightly with very low background humidity). In this case, the greatest LNBs reached by an entraining fire parcel ($>$ 7 or 8 km) occur when the boundary layer is not excessively dry and, as lower–level humidity increases, increasingly less stable. The 2 km instead of the 3 km deep boundary layer lowers the upper-level LNBs obtained by ascending fire parcels.

Fig. 1 shows that when an inversion layer is imposed above the 3 km (2 km) boundary layer, there are fewer stability and humidity profiles that allow fire parcels to ascend to appreciable upper LNBs. It is clear from Fig. 3c,d that an upper–level inversion greatly increases the influence of lower–level dryness. Unless lower–level atmospheric stability is near adiabatic or slightly superadiabatic, entraining fire parcels in environments with relatively low moisture are buoyant at heights greater than the inversion layer at 2 and 3 km, but only up to 4 km AGL. The 2 km instead of the 3 km inversion height inhibits parcel buoyancy even further when lower–level humidity is low. The most significant LNBs are confined to atmospheric profiles that are very moist and unstable. Fig. 1c,d suggests that the potential for explosive growth of a convection column in a fire can be limited by an upper–level inversion, and that this cap on convection can occur in atmospheres of lower–level stability and moisture that rate a Haines Index 6. In this situation the Haines Index falsely predicts

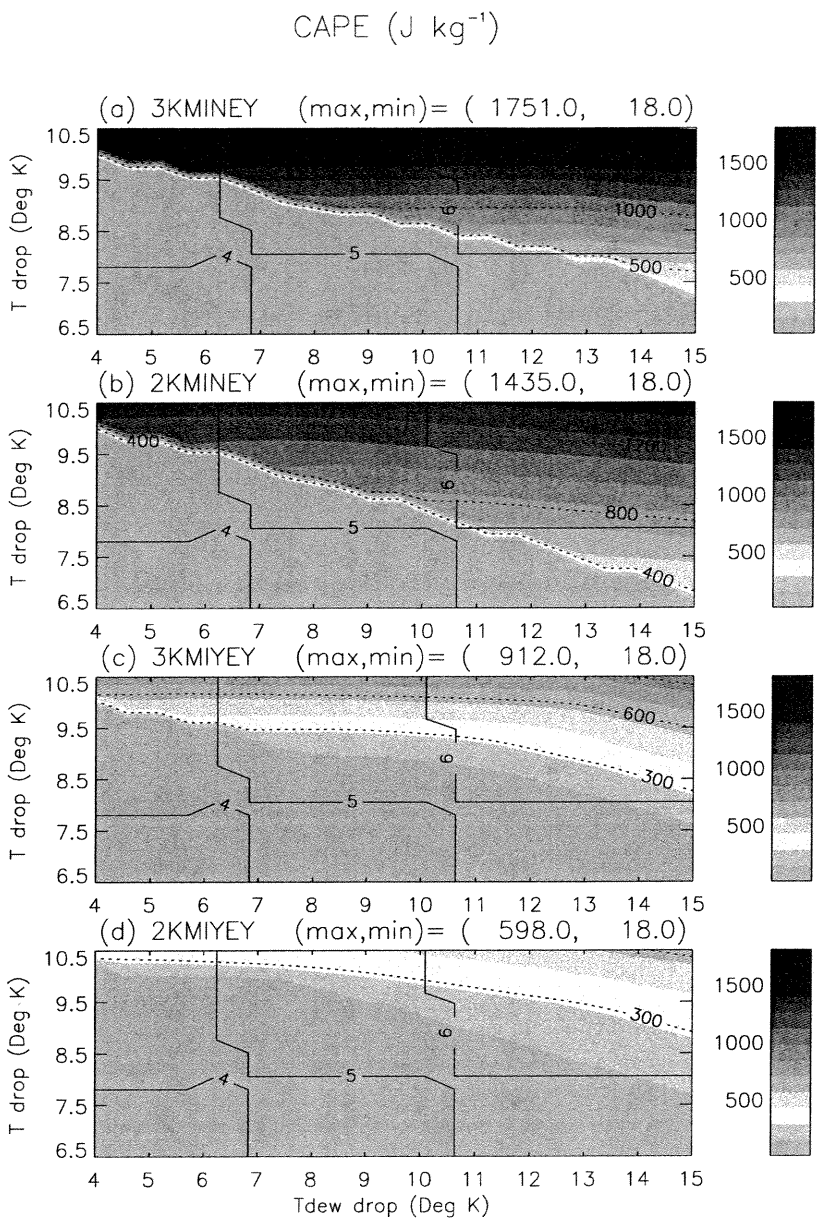

Fig. 3 As in Fig. 1 except for the Convective Available Potential Energy (CAPE). Dashed lines indicate contour levels of CAPE.

a high potential for large fire growth or extreme fire behavior.

The lowest Levels of Non–Buoyancy reached by entraining fire parcels are plotted in Fig. 2. It shows that parcels that did become negatively buoyant but managed to

reach a level of free convection and then an upper LNB are ascending in the environmental stability and humidity conditions of the cross over region from no or little appreciable ascent to significant ascent. Fig. 2a,b show that the 2 km instead of the 3 km deep boundary layer can lower these LNBs by almost 0.7 km when the lower–level atmosphere is relatively stable but dry. Fig. 2c,d show that an upper–level inversion increases the number of atmospheric profiles that hinder significant parcel ascent, and cause many more fire parcels to become negatively buoyant as they attempt to rise to the top of the inversion layer. The atmosphere below the inversion has to be less stable for fire parcels to rise, and the only atmospheric profiles that allow unhindered ascent are either unstable as in Fig. 2c (top), or unstable and very dry, as in Fig. 2d (top right corner). Fig. 1 and Fig. 2 (upper left corners) show that even when fire parcels are hindered in their ascent, they can reach peak LNBs.

Fig. 2b (lower right corner) shows that the 2 km instead of the 3 km deep boundary layer enables a parcel ascending in a very dry, very stable atmospheric profile to become negatively buoyant, but rise to reach a level of free convection and continue accelerated ascent. Why this slight difference in parcel behavior in Fig. 2b compared to Fig. 2a? This difference is specific to our design of background vertical temperature and humidity profiles. At the top of the boundary layer environmental moisture begins to decay, and to decay faster than temperature with height. When fire parcels pass the 2 km deep boundary layer where environmental humidity drops, the parcels can regain enough positive buoyancy to continue their ascent. Similar fire parcels at 2 km AGL in the 3 km deep boundary layer do not experience this background humidity drop and gain in positive buoyancy, and do not continue ascent. This is an example of how small differences in the vertical structure of humidity and temperature can have an appreciable (although not necessarily important) effect on fire parcel behavior.

The CAPE values predicted by the parcel model for entraining fire parcels are plotted in Fig. 3. For fire parcels that do reach significant LNBs, the CAPE is influenced primarily by the environmental temperature lapse rate (i.e., contour lines are relatively horizontal, and contour values increase with increasing temperature lapse), and the greatest CAPE is obtained when the boundary layer humidity is very low and temperature lapse rate is near adiabatic or slightly superadiabatic. The overall effect of the 2 km instead of the 3 km deep boundary layer is to lower the CAPE of ascending fire parcels, and the overall effect of an upper–level inversion is to lower CAPE further. Fig. 3c and Fig. 1c show that for entraining ascending fire parcels, smaller (larger) CAPE does not necessarily mean a low (high) LNB. Although the very largest CAPE values do occur when the atmosphere is very dry and unstable, and lower–level moisture and stability conditions rate a Haines Index 6, moisture conditions that do not rate a Haines Index 6 (i.e., $b = 1$ or 2) correspond to high CAPE values when the temperature lapse rate is large enough. In this situation, the Haines Index falsely predicts a moderate potential for large fire growth or extreme fire behavior.

Heights of maximum ascent predicted by the parcel model for entraining fire parcels are plotted Fig. 4, and the results are similar in pattern to the LNBs in Fig. 1. An upper–level inversion lowers heights of maximum ascent, especially when the atmosphere is dry and the boundary layer is 2 km deep instead of 3 km deep. Maximum ascent height is a direct measure of vertical column development, and significent vertical column development increases the probability that a wildfire will becomes large and/or erratic. Fig. 4 shows that entraining fire parcels reach the largest heights of maximum ascent when the atmosphere is moist and close to adiabatic or slightly superadiabatic. The moisture conditions do not rate a Haines Index 6 (i.e., $b = 1$ or 2), and in this situation the Haines Index falsely predicts a moderate potential for large fire growth.

Maximum ascent velocities predicted by the parcel model were calculated but not shown. The results are similar in pattern and trend to the CAPEs in Fig. 3. Note that this pattern to maximum ascent velocity and to CAPE is not sensitive to and does not change for each of the four background atmospheric profiles; An upper–level inversion or change in depth of the boundary layer only modifies the magnitudes of the CAPE and maximum ascent velocity. The most significant maximum ascent velocity and CAPE are usually obtained when the boundary layer humidity is very low and the temperature lapse rate is near adia-

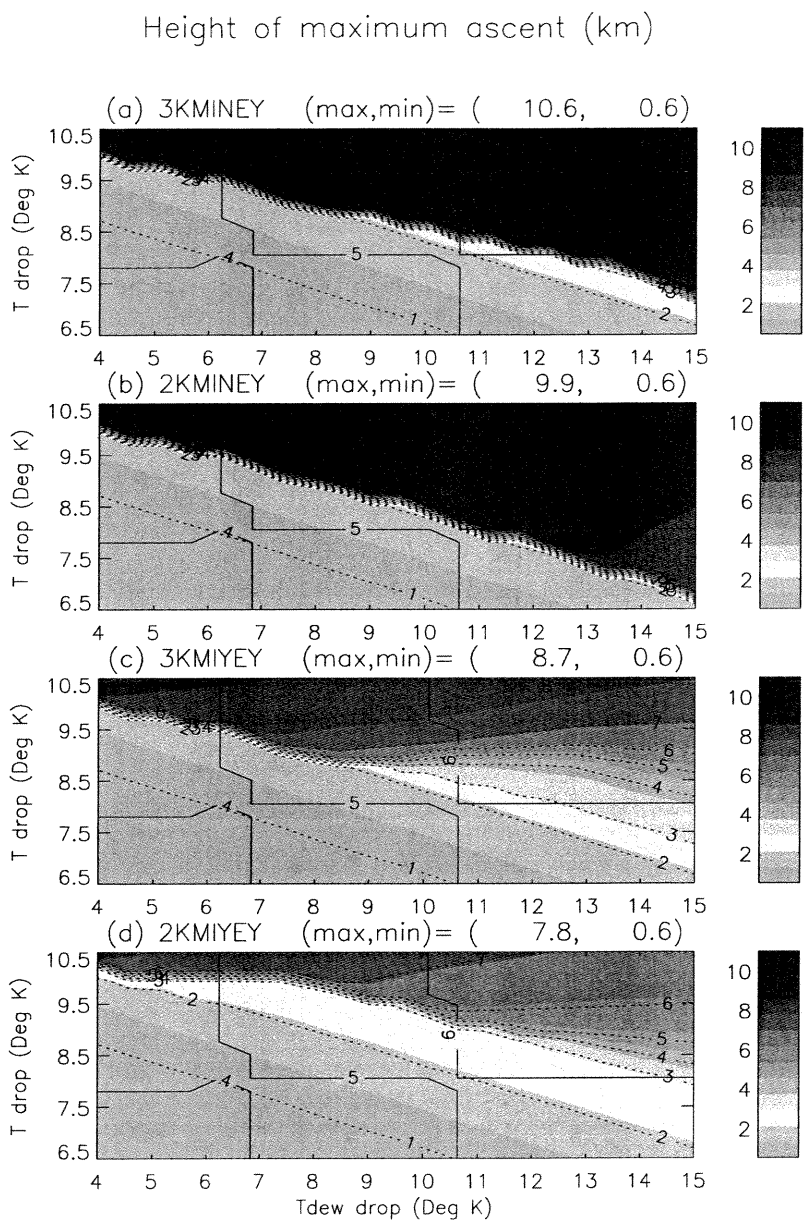

Fig. 4 As in Fig. 1 except for the height of maximum ascent.

batic, and lower–level moisture and stability conditions rate a Haines Index 6.

The heights at which entraining fire parcels reach maximum ascent velocity are plotted in Fig. 5. If parcel ascent was based on buoyancy alone, as presented by CAPE in Equation (3),

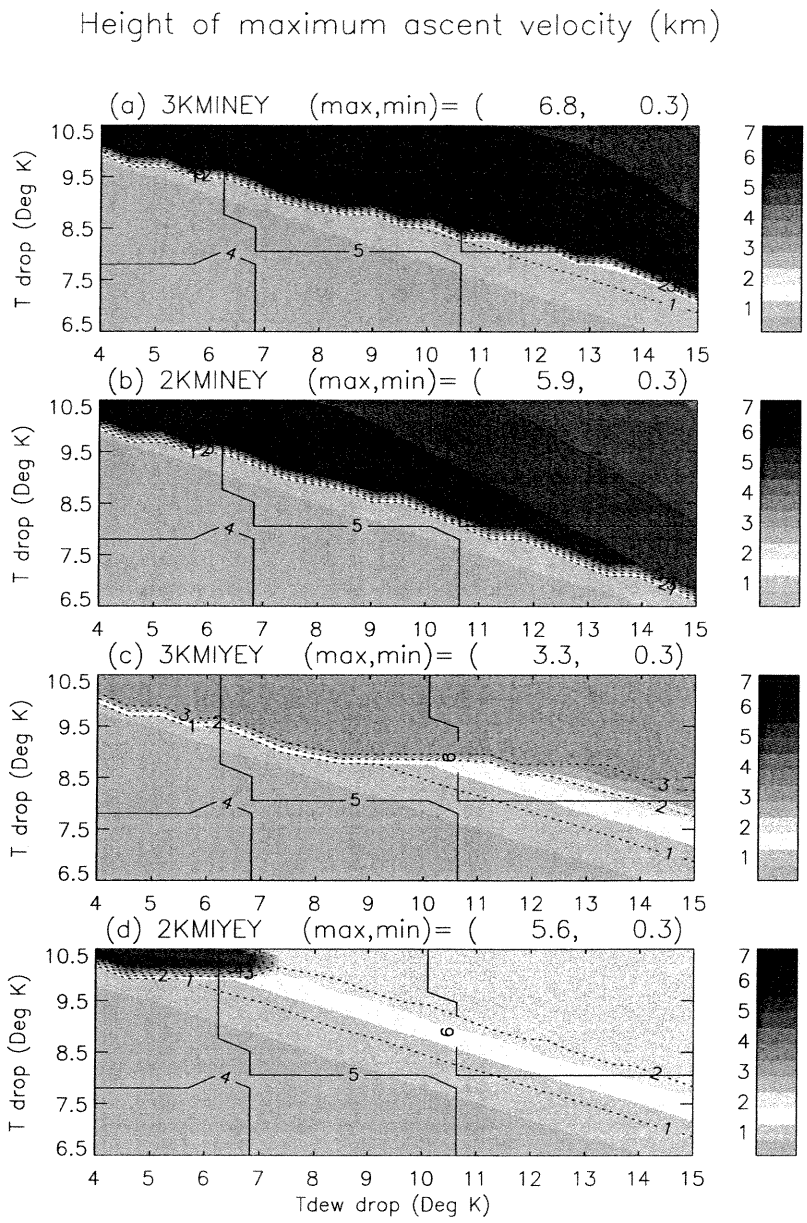

Fig. 5 As in Fig. 1 except for the maximum ascent velocity. Dashed lines indicate contour levels of maximum ascent velocity.

then the height at which a fire parcel reaches maximum ascent velocity would be identical the upper Level of Non Buoyancy. An upper–level inversion dramatically lowers the heights

at which fire parcels reach maximum ascent velocity. Fig. 5a,b, and d shows that there is low correlation between the largest ascent velocities and CAPE (Fig. 3a,b, and d) at great heights AGL. The heights that fire parcels reach maximum ascent velocity diminish as either the lower–level atmosphere becomes less stable or less humid. In Fig. 5c the height at which ascending entraining parcels reach maximum ascent velocity is restricted to $\sim$ 3 km, the height of the upper-level inversion. In Fig. 5d the height at which ascending entraining fire parcels reach maximum ascent velocity is restricted to $\sim$ 2 km, the height of the upper–level inversion, unless atmospheric stability is slightly superadiabatic and lower–level humidity is very, very high. In this situation, entraining fire parcels ascending in an unstable and very moist atmosphere first obtained updraft speeds of $\sim$ 11 to 13 m s^{-1} at approximately 2 km AGL, slowed, and then accelerated to reach maximum ascent velocities $\sim$ 15 m s^{-1} at approximately 5 km AGL.

5. DISCUSSION & CONCLUSIONS

The results given in Section 4 show that when parcel properties are plotted as functions of low–level atmospheric stability and humidity, there are two distinct regions of this two–dimensional parameter space. In the first region, the combination of environmental stability and humidity encourages significant ascent of fire parcels. In the second region, environmental conditions discourage parcel ascent. The primary role of low–level moisture appears to be to control the crossover from no or little ascent (the second region) to significant ascent (the first region). This study shows that for an atmosphere with a boundary layer and standard atmosphere above, as the lower–level atmosphere becomes dryer and dryer, entraining fire parcels can ascend to great heights even though atmospheric stability has increased, provided the combination of low–level stability and humidity is in the first region of the two–dimensional parameter space. The most important environmental characteristic as far as maximum vertical column development is concerned is a boundary layer temperature lapse rate close to, or slightly greater than, adiabatic. The results imply that as long as the lower–level atmosphere has a near–adiabatic lapse rate, a fire column will be characterized by significant ascent regardless of what the moisture conditions are.

This study shows that for an atmosphere with a deep boundary layer and standard atmosphere above, entraining fire parcel properties and magnitudes associated with significant ascent do not necessarily correspond to the potential for high fire severity predicted by a Haines Index 6. Most combinations of lower–level stability and moisture that rate a Haines Index 6 did result in significant vertical column development, as indicated by high levels of buoyancy (CAPE), high levels of maximum rise, and large ascent velocities. However, there were combinations of lower–level stability and moisture that rate a Haines Index 4 or 5 (i.e., for moisture conditions $b = 1$ or 2, and stability conditions $a = 3$) that also resulted in the same or even greater vertical column development (i.e, even greater heights of maximum ascent). This implies that these are atmospheric profiles for which a Haines Index of 4 or 5 would underpredict the potential for severe fire behavior. It appears that the stability term a in the Index should be given more weight than the moisture term b, especially when $T_{p95} - T_{p85} \geq 9.5°$C. The Haines Index does not discriminate between an atmosphere with a deep (2 km) boundary layer and a deeper (3 km) boundary layer. The results indicate that a 3 km deep boundary layer allows more significant parcel ascent and column development (higher LNB, CAPE, height of maximum ascent, etc.) than a 2 km deep boundary layer. These results suggest that the Haines Index may need to be refined or reformed depending on the vertical structure of the atmosphere.

The parcel model results imply that when an upper–level inversion is imposed at the top of the boundary layer, the Haines Index is not necessarily a good predictor of the potential for fire severity. An upper–level inversion significantly inhibits entraining parcel ascent, and the results of this study show that limited parcel ascent can occur in atmospheres of lower–level stability and moisture that rate a Haines Index 6. This implies that in these situations the Haines Index 6 would overpredict the potential for fire severity. Instead, the parcel model results indicate the most significant vertical column development in unstable and relatively humid atmospheric conditions. It appears that in this situation, the

moisture term in the Index should be given less weight than the stability term, i.e, when $T_{p_{85}} - T\mathrm{dew}_{p_{85}} \geq 10°\mathrm{C}$ and $T_{p_{95}} - T_{p_{85}} < 9.5°\mathrm{C}$. These results further suggest that the Haines Index may need to be refined or reformed depending on the vertical structure of the atmosphere.

Although the parcel model is an oversimplification of a fire thermal the study does provide a way to organize and group fire parcel properties to the maximum advantage. A study like this helps target the range of low–level moisture and stability conditions that are relevant to the phenomenon under investigation. It is possible to easily answer specific questions like what happens to convective column development if surface parcel properties or surface conditions are changed? Or if the height of the boundary layer or strength, depth, and height of the inversion are changed? The results give enough information, for example, so that the background humidity and temperature conditions for coupled wildfire–atmospheric numerical experiments be designed to focus on the problem being studied. The computational resources and personnel needed to simulate and analyze the simulated fires would be reduced. Application of this method to observations can help show how well the Haines Index correlates with severe fire behavior, and can help demonstrate how near–surface humidity and atmospheric stability affect wildfire behavior. In this situation, the vertical structures of the atmospheric chosen for study would truly represent the stability and humidity conditions found in nature that enhance surface fires and cause them to grow.

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