3.4 COMBINING THE HAINES INDEX AND TURBULENT KINETIC ENERGY FOR FIRE-WEATHER PREDICTIONS

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1. INTRODUCTION

Daily 24 to 48 hour fire-weather predictions for different regions of the U.S. are now readily available from the regional Fire Consortia for Advanced Modeling of Meteorology and Smoke (FCAMMS) (http://www.fs.fed.us/fcamms) established as part of the U.S. National Fire Plan. (USDA Forest Service 2002) These predictions are based on daily atmospheric mesoscale model simulations of atmospheric conditions and fire-weather indices over specific modeling domains, using the Penn Sate University (PSU)/National Center for Atmospheric Research (NCAR) Mesoscale Model Version 5 (MM5). One of the many fire-weather indices routinely provided in the FCAMMS fire-weather predictions is the well-known Haines Index (HI) (Haines 1988). The HI is an operational atmospheric mesoscale-type index that includes only stability and moisture conditions in the lower to middle troposphere to characterize the atmospheric risk of extreme fire behavior. However, there are other atmospheric variables that also influence the risk of extreme fire behavior, especially those that characterize conditions in the atmospheric boundary layer where small-scale fire-atmosphere interactions are so important. Atmospheric turbulence, as measured by turbulent kinetic energy (TKE), is one of those variables, and TKE can be classified as a boundary-layer-type index. The generation and dissipation of TKE in the atmosphere are dependent on wind shear and buoyancy conditions, which are two factors that affect the local environment surrounding wildland fires. Although predictions of TKE in the boundary layer using level-2.5 closure from the Mellor-Yamada turbulence hierarchy (Mellor and Yamada 1974, 1982; Gerrity et al. 1994) are available from the daily FCAMMS MM5 model simulations, they have not been used in the past for characterizing atmospheric risk of extreme fire behavior.

This study is a first step in examining the utility of combining a mesoscale-type fire-weather index (HI) with a boundary-layer turbulence index (TKE) for assessing the atmospheric potential for extreme fire behavior. Output from the FCAMMS - Eastern Area Modeling Consortium (EAMC) MM5 simulations of fire-weather conditions over two 4-km grid-spacing domains in the north central and northeastern U.S. is being used to identify regional patterns of HI and TKE on a daily basis (http://www.ncrs.fs.fed.us/eamc). A comparison of the patterns of the two indices allows an assessment of whether large HI values typically occur with large near-surface TKE values, a potentially dangerous fire-weather condition.

2. HAINES INDEX DESCRIPTION

The HI is a measure of the atmosphere's instability and dryness. Haines (1988) noted that dry and unstable air increases the probability that plume dominated wildland fires will become large and erratic. He devised an index that characterizes both the stability and moisture content of specific atmospheric layers, depending on the elevation above sea level of the underlying terrain. The index is defined as

$$HI = \overbrace{(T_{p1} - T_{p2})}^{A} + \overbrace{(T_p - T_{dp})}^{B} \quad (1)$$

where T_{p1} is the temperature (°C) at pressure level p1, T_{p2} is the temperature (°C) at pressure level p2, and T_p and T_{dp} are the temperature (°C) and dew-point temperature (°C) at one of the pressure levels. The pressure levels, p1 and p2, are set at 950 mb and 850 mb for low terrain elevations, 850 mb and 700 mb for mid terrain elevations, and 700 mb and 500 mb for high terrain elevations, respectively. The pressure levels at which the dew point depressions are calculated are 850 mb for low and mid terrain elevations, and 700 mb for high terrain elevations. The defined low, mid, and high terrain elevation regions for the U.S. can be found in Haines (1988). Over the north central and northeastern U.S., both the low and mid terrain elevation designations are used.

Specific temperature lapse rate and dew point depression thresholds are defined for the low, mid, and high terrain elevation designations (Haines 1988). Integer values of 1, 2, or 3 are assigned to the lapse rate (A) and dew point depression (B) components of Eq. (1) depending on the actual values of the lapse rates and dew point depressions. The two integers are added to create an index varying from 2 to 6, with the following adjective definitions for the potential for large plume dominated fires:

(A+B) = 2 or 3 [very low] (A+B) = 4 [low]
(A+B) = 5 [moderate] (A+B) = 6 [high].

Since its development, the HI has been used frequently by fire-weather forecasters across the U.S. to characterize the atmospheric contribution to the potential for severe fires. Both radiosonde observations at 0Z and 12Z and output from numerical weather prediction models have been used to calculate the HI and identify areas of high and low index values across the U.S. The index can be classified as a mesoscale-type index because (1) it attempts to capture the stability and moisture characteristics of atmospheric

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layers that extend above the atmospheric boundary layer, and (2) it can be very useful for describing the potential of the atmosphere for extreme fire behavior over relatively large spatial areas.

3. TURBULENT KINETIC ENERGY DESCRIPTION

Turbulent kinetic energy (q^2) is a measure of the kinetic energy of the turbulent component of atmospheric circulations and is given by

$$q^2 = \overline{u'^2} + \overline{v'^2} + \overline{w'^2} \qquad (2)$$

where $\overline{u'^2}$, $\overline{v'^2}$, and $\overline{w'^2}$ are the variances of the departure velocities in the horizontal x and y directions and in the vertical z direction, respectively. TKE is generated through mechanical shear effects and buoyancy effects. Atmospheric circulations characterized by large shears in a thermally unstable environment will tend to produce enhanced turbulence (i.e. large turbulent velocity components), whereas a thermally stable environment will tend to suppress turbulence and produce more laminar-type flows. Intuitively, one would expect a near-surface atmospheric environment characterized by significant turbulence to be more conducive to extreme fire behavior, irrespective of the enhanced turbulence caused by fire on its own.

Mellor and Yamada (1974, 1982) developed a four-level hierarchy of turbulence closure models for use in the planetary boundary layer. Level 2.5 of the hierarchy employs a prognostic equation for TKE given by

$$\frac{\partial}{\partial t}\left(\frac{q^2}{2}\right) + \mathbf{V} \bullet \nabla \frac{q^2}{2} - \frac{\partial}{\partial z}\left[K_q \frac{\partial}{\partial z}\left(\frac{q^2}{2}\right)\right] = P_s + P_b - \varepsilon \qquad (3)$$

where the terms on the left represent the local time rate of change, the advection by the three-dimensional mean wind **V**, and the vertical turbulent diffusion of TKE. The terms on the right represent the mechanical production of TKE through shear effects (P_s), the production or dissipation of TKE through buoyancy effects (P_b), and the dissipation of TKE as turbulent eddies are broken down into smaller and smaller sizes (ε). The mechanical production of TKE is given by

$$P_s = -\overline{u'w'}\frac{\partial \overline{u}}{\partial z} - \overline{v'w'}\frac{\partial \overline{v}}{\partial z} \quad , \qquad (4)$$

and the buoyant production or dissipation of TKE is given by

$$P_b = \frac{g}{\theta_v}\overline{\theta_v' w'}, \qquad (5)$$

where g is the acceleration due to gravity, $\overline{u}$ and $\overline{v}$ are the horizontal components of the mean wind, θ_v is the virtual potential temperature, and $\overline{u'w'}$, $\overline{v'w'}$, and $\overline{\theta_v' w'}$ are the vertical turbulent fluxes of momentum and sensible heat.

Turbulent kinetic energy can be classified as a boundary-layer-type index because it characterizes the energy of the turbulent component of atmospheric circulations, and this component can be significant in the atmospheric boundary layer where vertical wind shears and thermal instability tend to be large. Unlike the HI, TKE as a potential fire-weather index has not been used because of its complexity. However, the availability of TKE predictions in mesoscale models has now made the use of TKE as a potential fire-weather index possible. Calculations of TKE and the individual contributions of mechanical and buoyancy production of TKE within mesoscale models also provide an opportunity for examining how the spatial and temporal patterns of TKE and its production compare to HI patterns over different regions. It is through these analyses that we hope to determine whether there are preferred regions where high HI values (mesoscale conditions conducive to extreme fire behavior) tend to coincide with high surface TKE values (boundary-layer conditions conducive to extreme fire behavior.

4. EXAMPLE CASE STUDY

On 2 June 2002, a large wildland fire occurred in the Double Trouble State Park region of east-central New Jersey. The fire started around 17Z, burned 1300 acres, and resulted in the shutdown of the Garden State Parkway for over 12 hours due to dense smoke. An examination of the simulated atmospheric conditions before and during the fire suggested that the mesoscale environment over Maryland, southeastern Pennsylvania, Rhode Island, and New Jersey, as measured by the HI, was very conducive to extreme and erratic fire behavior, irrespective of the atmospheric boundary layer conditions present. Figure 1 shows the simulated HI values at 17Z on 2 June 2002, close to the onset time of the fire. Haines Index values of 6 were prevalent over this region, with much lower values over New York, Vermont, and New Hampshire.

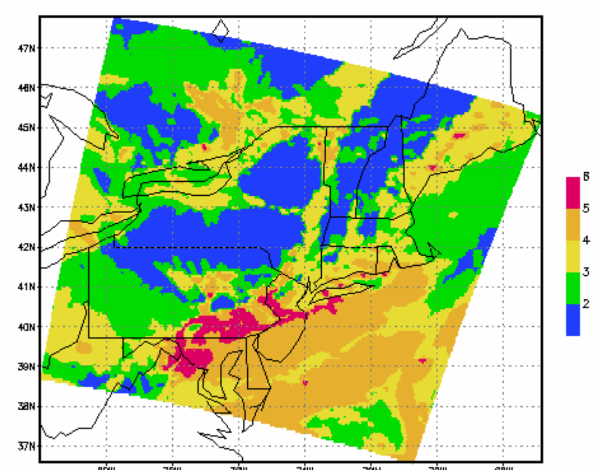

Figure 1. Simulated HI values at 17Z on 2 June 2002 over the EAMC 4-km grid spacing domain.

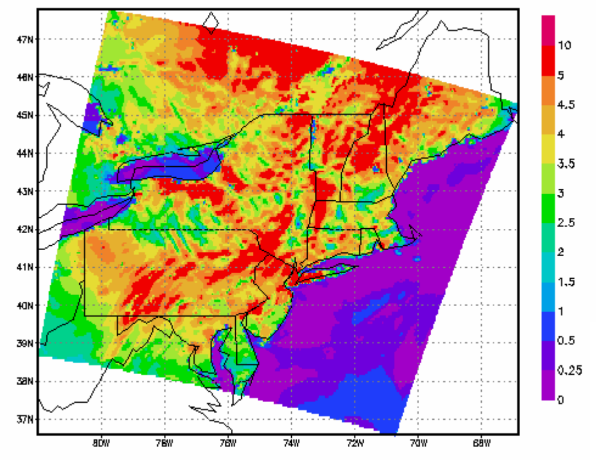

Figure 2. Same as Figure 1 except for simulated near-surface TKE (m^2s^{-2}). Note the irregular contour intervals.

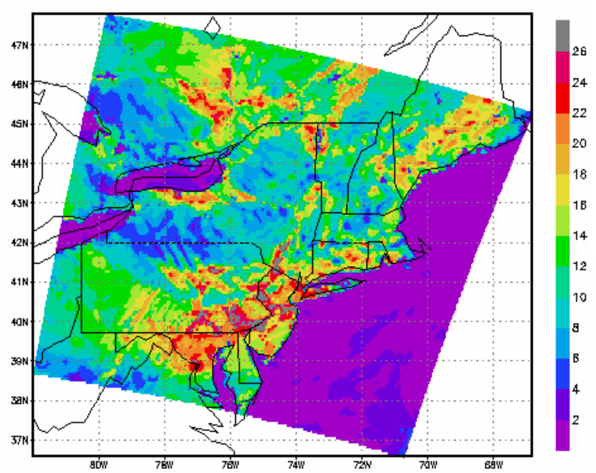

Figure 3. Simulated values (m^2s^{-2}) of the product of the HI and the 10 m TKE at 17Z on 2 June 2002 over the EAMC 4-km grid spacing domain using the PSU/NCAR MM5 modeling system.

The simulated near-surface (10 m) TKE values at 17Z on 2 June 2002 over the same domain are shown in Figure 2. Relatively high TKE values were prevalent over much of the domain. The high TKE values in this case were primarily the result of strong westerly to northwesterly winds and enhanced production of near-surface turbulence due to large vertical wind shears. A comparison of Figures 1 and 2 reveal that, in this fire-weather episode, large HI values did not necessarily occur in areas with large TKE values. However, there were specific well-defined areas where both the HI and the TKE values were large. This can be observed in Figure 3, which shows the spatial pattern of the product of the HI and TKE at 17Z on 2 June 2002. Within the region of large HI values over southeastern Pennsylvania, Maryland, and New Jersey, near-surface atmospheric turbulence was also significant. It is in this region where both mesoscale and boundary-layer conditions were particularly conducive to extreme and erratic fire behavior. The Double Trouble State Park fire occurred in this region. At the location of the fire, early-morning near-surface TKE values on 2 June were low but increased rapidly around 12Z with the growth of the mixed layer, the increase in near-surface wind speeds, and the shift in wind direction from southwesterly to northwesterly. This is in contrast to the "mesoscale" HI, which exhibited continuously high values (5 and 6) over the site beginning more than 18 hours before the start of the fire (Figure 4).

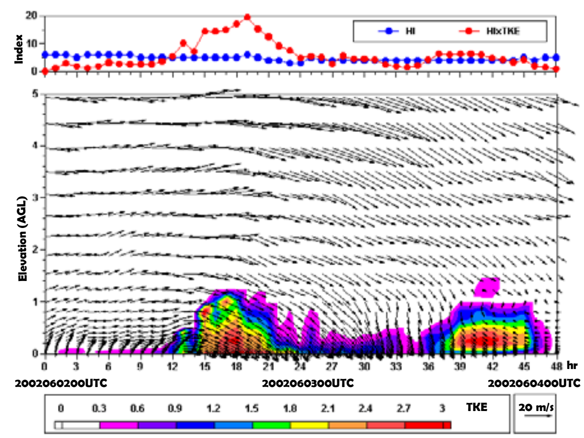

Figure 4. Time-height cross-section of the simulated winds ($m\ s^{-1}$) and TKE (m^2s^{-2}) at the location of the Double Trouble State Park fire on 2 June 2002. The wind vectors represent horizontal wind directions. The top time series plot shows the variation in HI (blue) and the product of the HI and TKE (red).

The spatial and temporal patterns of the simulated HI and TKE during the Double Trouble State Park fire suggest that under certain circumstances, the collective use of both indices for predicting the potential atmospheric contribution to extreme and erratic fire behavior may be useful. However, more research is needed to assess the spatial and temporal variability relationships between the HI and near-surface TKE in different regions of the U.S. The following section describes some of the preliminary analyses carried out to assess those relationships over the northeastern U.S.

5. PRELIMINARY ANALYSES OF HI AND TKE

The preliminary HI and TKE analyses reported here are built upon daily EAMC MM5 simulations (00Z initialization) over a 4-km grid spacing domain that covers the northeastern U.S. for the period of 1 March 2003 – 18 July 2003. However, the EAMC is developing a running archive of MM5 results for this domain as well as another 4-km grid spacing domain centered over the western Great Lakes region. The development of this archive will allow for seasonal and yearly analyses of HI and TKE values for most of the north central and northeastern U.S.

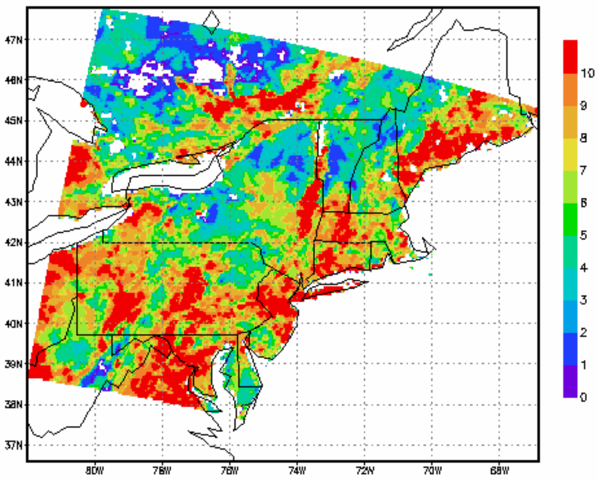

Figure 5. Simulated frequency (%) of HI values equal to 5 or 6 at 20Z for the period of 1 March 2003 – 18 July 2003 (only over land).

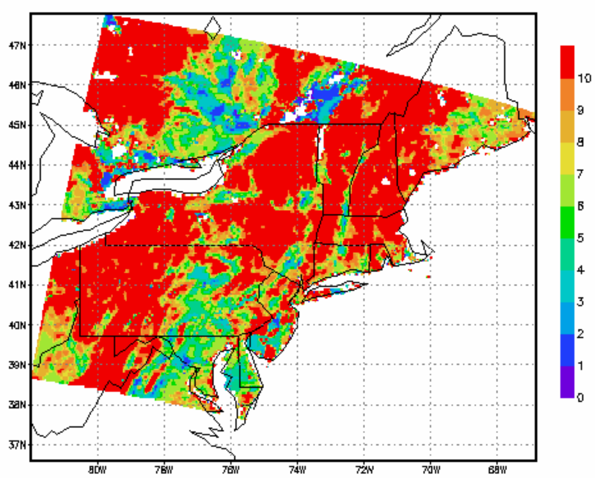

Figure 6. Same as Figure 5 except for simulated frequency (%) of near-surface TKE values greater than 4 m^2s^{-2}.

As shown in the HI and TKE patterns present during the Double Trouble State Park fire (Figures 1-4), large HI and near-surface TKE values can occur simultaneously in the same locations. We are currently examining the frequency of high HI and near-surface TKE values over this region, and whether those frequencies are seasonally dependent. Figure 5 shows the frequency of occurrence of simulated HI values equal to 5 or 6 for the period of 1 March 2003 – 18 July 2003 at 20Z. Although high HI values were relatively rare during this period, high values occurred more frequently (> 10%) over western and eastern New York, western and central Pennsylvania, northern Virginia, northern and central New Jersey, western Massachusetts, and southern Maine. Figure 6 shows the frequency of occurrence of simulated near-surface TKE values greater than 4 m^2s^{-2} (a very large value) for the same period at 20Z. Throughout the domain, there were large areas where TKE values at 20Z exceeded 4 m^2s^{-2} more than 10% of the days during this period. Comparing Figures 5 and 6 reveals that western Pennsylvania, western New York, and sections of southern Maine and northern New Jersey were areas where both high HI and high near-surface TKE values tended to occur during this period. The persistence of these patterns during the remaining months in 2003 and following years will be examined to create a short-period climatology of simulated HI and near-surface TKE variability in the region. This climatology will provide an indication of preferred locations where concurrent high HI and near-surface TKE values tend to occur, a potentially dangerous fire-weather condition.

The positive linear regression correlation coefficients of simulated 20Z HI and near-surface TKE values over the 1 March 2003 – 18 July 2003 period for the northeastern U.S. is shown in Figure 7. This figure suggests that the mesoscale HI has a higher positive correlation with the boundary-layer TKE index over the coastal areas of the simulation domain. Positive correlation coefficients are also relatively high over northern West Virginia and southern Pennsylvania. Extensive analyses of the atmospheric boundary-layer and mesoscale dynamics in these areas are needed to determine the causal factors that lead to high or low HI and TKE values at the same time.

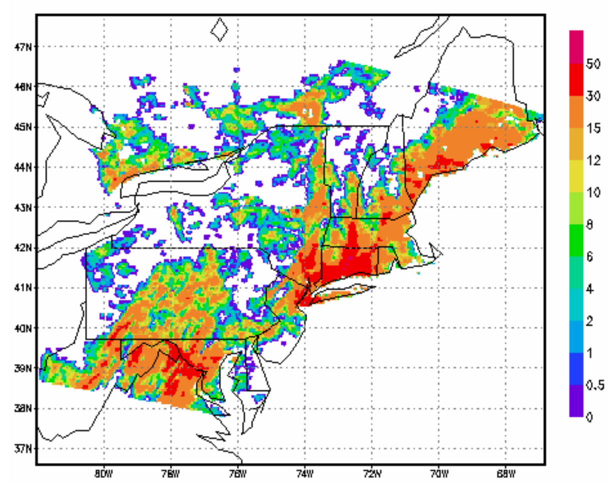

Figure 7. Positive linear regression correlation coefficients (x100) of simulated HI and near-surface TKE at 20Z for the period of 1 March 2003 – 18 July 2003 (only over land). Note the irregular contour intervals.

Beyond the spatial and temporal variability patterns of the HI and near-surface TKE in the northeastern U.S., the atmospheric dynamics associated with concurrent lower tropospheric instability and dryness (as measured by the HI) and near-surface turbulence (as measured by TKE) are also of interest. As part of our analyses, we are examining how the production of near-surface turbulence through wind shear and buoyancy processes (Eqs. 3-5) varies with changing HI values in areas where the HI and near-surface TKE tend to be positively correlated. Using those data points exhibiting positive HI and TKE correlations of $R \geq 0.4$ (Figure 7), we examined the distribution of TKE values under different HI conditions and the significance of turbulence production through wind shear and buoyancy effects under the different HI conditions. Figure 8 shows the frequency distribution of simulated near-surface TKE values for all HI classes for the 1 March 2003 – 18 July 2003 period. Considering all HI classes, TKE values between 0 and 2 m^2s^{-2} were the most frequent in this area of relatively high HI and TKE correlation. There were 5445 and 5971 occurrences of TKE values between 0-1 and 1-2 m^2s^{-2}, respectively, during this period. TKE values larger than 2 m^2s^{-2} were much less prevalent. Only 54 occurrences of TKE exceeding 6 m^2s^{-2} were noted.

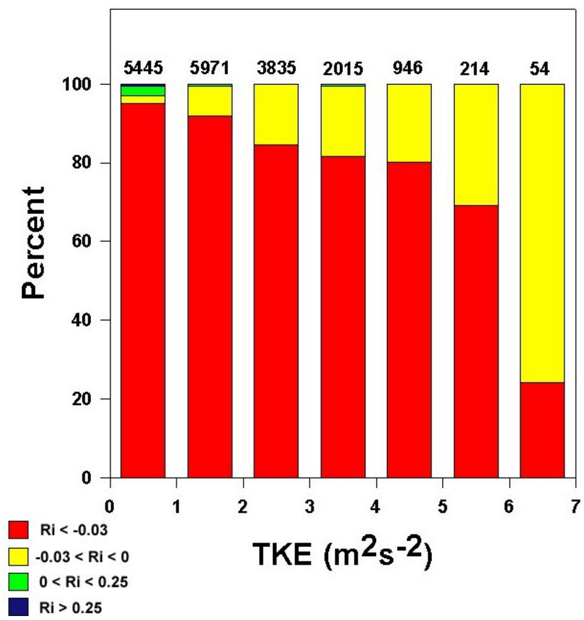

Figure 8. Frequency of occurrence (%) of simulated near-surface TKE values in bins 0-1, 1-2, 2-3, 3-4, 4-5, 5-6, and > 6 m^2s^{-2} for all HI classes (2-6) at model grid points exhibiting HI and near-surface TKE correlations of $R \geq 0.4$ for the period 1 March 2003 – 18 July 2003. The numbers at the top of each stacked bar indicate the total number of occurrences of TKE values within each bin while the different colors indicate relative TKE occurrence percentages under different Richardson number (Ri) categories.

Figure 8 also provides insight into the roles of wind shear and buoyancy production of TKE as measured by the gradient Richardson number (Ri):

$$\mathrm{Ri} = \frac{g}{\theta} \frac{\partial\theta / \partial z}{(\partial U / \partial z)^2 + (\partial V / \partial z)^2} \qquad (6)$$

where g is the gravitational constant and θ is the potential temperature. Under unstable conditions, Ri < 0. As Ri becomes more negative, the production of turbulence through wind shear becomes less and less important compared to the production of turbulence through buoyancy. When Ri is less than about –0.03, buoyancy completely dominates the production of turbulence. For –0.03 < Ri < 0, both shear and buoyancy effects play a role in the production of turbulence. As shown in Figure 8, buoyancy effects dominated the production of TKE when TKE values were less than 5-6 m^2s^{-2} (all HI classes). Only for instances when TKE exceeded 6 m^2s^{-2} did shear effects tend to dominate the production of TKE.

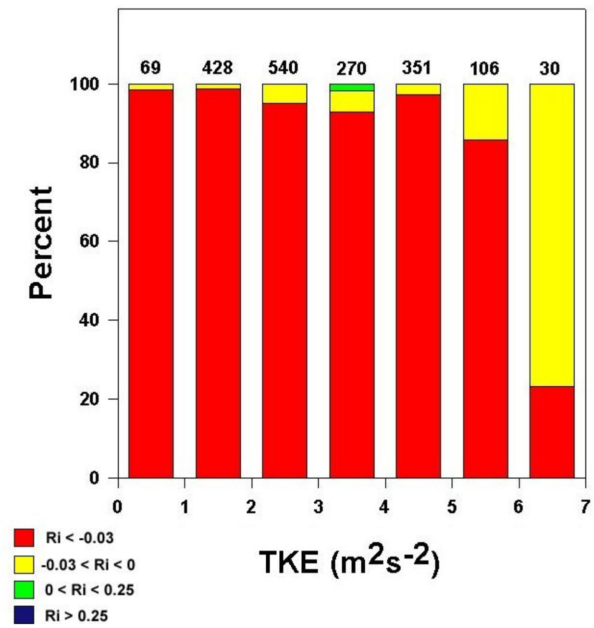

Figure 9. Same as Figure 8 except for just HI classes 5 and 6.

Figure 9 shows the frequency distribution of simulated near-surface TKE values for just HI classes 5 and 6 for the 1 March 2003 – 18 July 2003 period. The highest percentage of TKE values occurred between 2-3 m^2s^{-2} (540 occurrences). Comparing Figures 8 and 9 reveals that under high HI conditions, there are not only more frequent occurrences of higher near-surface TKE values but there is also a diminished drop-off in the frequency of occurrence of buoyancy-dominated turbulence regimes as TKE increases. For example, buoyancy dominated the turbulence regimes more than 93% of the time for TKE values up to 5 m^2s^{-2} under high HI conditions. Considering all HI classes, that percentage steadily dropped to about 80% for TKE values of 4-5 m^2s^{-2} (Figure 8). For very large TKE values (>6 m^2s^{-2}), shear production of turbulence dominated the turbulence regimes regardless of the HI conditions.

6. SUMMARY

Using the MM5-based fire-weather predictions now readily available from the EAMC, we have initiated a preliminary study examining the utility of combining the HI, a “mesoscale-type” fire weather index, with near-surface TKE, a “boundary-layer-type” index, for assessing the potential atmospheric risk of extreme fire behavior in the north central and northeastern U.S. Preliminary results have been presented for the northeastern U.S. in this paper.

A case study of the 2 June 2002 Double Trouble State Park fire in east-central New Jersey suggested that, under certain circumstances, the collective use of both the HI and near-surface TKE for predicting the potential atmospheric contribution to extreme and erratic fire behavior may be useful. This particular wildland fire was characterized by high HI and very high near-surface TKE values. The fact that both the mesoscale HI and boundary-layer TKE were high at the time and location of the fire indicates the atmosphere was very conducive to extreme or erratic fire behavior (i.e. lower tropospheric instability and dryness and near-surface instability and significant wind shears). Additional case studies of large wildland fires in the northeastern and north central U.S will be carried out to assess the prevalence of concurrent high HI and high near-surface TKE values during these events in these regions.

As demonstrated by the Double Trouble State Park fire case study, large HI and near-surface TKE values can occur simultaneously in the same locations. Our preliminary study is also examining the frequency of large HI and near-surface TKE values over this region, regardless of fire occurrence, and whether those frequencies are seasonally dependent. Using available archived output (1 March 2003 – 18 July 2003) from EAMC’s MM5-based fire-weather predictions for the northeastern U.S., we identified and compared the spatial patterns of high HI and near-surface TKE over this region. Although the spatial patterns of high HI and high near-surface TKE occurrence differed during this period, there were areas within this region where the HI and near-surface TKE were positively correlated. The most significant positive correlations generally occurred over the coastal areas and over northern West Virginia and southern Pennsylvania. This suggests that, at least in these areas, there was a tendency for larger HI values to occur simultaneously with enhanced near-surface turbulence.

In those same areas where the HI and TKE were positively correlated, we also examined the relative contribution of wind shear and buoyancy to near-surface TKE under different HI conditions during the 1 March 2003 – 18 July 2003 period. While buoyancy effects dominated the production of TKE, except when TKE values exceeded 6 m^2s^{-2}, the domination was even more significant under high HI conditions.

The analyses described here represent the first step in assessing the feasibility of combining the HI with near-surface TKE for fire-weather predictions in the north central and northeastern U.S. As the data archive of model output from the EAMC fire-weather prediction program expands, we will examine the seasonal and annual variability in simulated HI and near-surface TKE values over the north central and northeastern U.S. With these analyses and our further examinations of the dynamic behavior of the HI and near-surface TKE before and during actual wildland fire events, we hope to not only improve our understanding of atmospheric mesoscale and boundary-layer interactions during fire-weather events but also to determine the potential for combining these indices in some fashion for enhancing operational forecasts of extreme fire weather.

7. REFERENCES

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