Combining Turbulent Kinetic Energy and Haines Index Predictions for Fire-Weather Assessments

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***Abstract**—The 24- to 72-hour fire-weather predictions for different regions of the United States are now readily available from the regional Fire Consortia for Advanced Modeling of Meteorology and Smoke (FCAMMS) that were established as part of the U.S. National Fire Plan. These predictions are based on daily real-time MM5 model simulations of atmospheric conditions and fire-weather indices over specific modeling domains. Included in the suite of fire-weather indices provided by the FCAMMS is the well-known Haines Index (HI), an operational "mesoscale-type" index that characterizes the atmospheric risk of extreme fire behavior based solely on stability and moisture conditions in the lower to middle troposphere. 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. One of those variables is atmospheric turbulence (that is, wind gustiness), as measured by turbulent kinetic energy (TKE). TKE can be classified as a "boundary-layer-type" index, with its generation and dissipation dependent on wind shear and buoyancy conditions near the surface. Like the HI, predictions of TKE are available from the daily FCAMMS MM5 model simulations. This study examines the utility of combining the HI with TKE to assess potential atmospheric risk of extreme fire behavior. Output from the FCAMMS - Eastern Area Modeling Consortium (EAMC) MM5 simulations of fire-weather conditions over the western Great Lakes region is used to identify regional patterns of HI and TKE on a daily basis. A comparison of the patterns of the two indices allows for an assessment of whether large HI values typically occur with large near-surface TKE values, a potentially dangerous fire-weather condition.*

Introduction

The regional Fire Consortia for Advanced Modeling of Meteorology and Smoke (FCAMMS) (http://www.fs.fed.us/fcamms), established by the U.S. National Fire Plan (USDA Forest Service 2002), are providing daily 24- to 72-hour real-time fire-weather predictions for different regions of the United States as part of their research programs focused on developing new and improved tools for predicting fire-fuel-atmosphere interactions. These predictions are based on simulations performed with the Fifth Generation Penn State University (PSU)/National Center for Atmospheric Research (NCAR) Mesoscale Model (MM5) over specific modeling domains set up to cover the conterminous United States. The well-known Haines Index (HI) (Haines 1988) is one of many fire-weather indices routinely provided by the FCAMMS as part of their fire-weather predictions. As an operational index for fire-weather forecasting, the HI can be considered a mesoscale-type index that characterizes the stability and moisture conditions in the lower to middle troposphere. Its value is meant to provide an indication of the atmospheric risk of extreme fire behavior due solely to these atmospheric conditions.

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While the HI has proven to be a valuable tool for fire-weather forecasters in some regions of the United States, there are other atmospheric properties and processes that can affect the severity of fires, especially those properties and processes that characterize the atmospheric boundary layer where small-scale fire-atmosphere interactions are so important. Atmospheric turbulence, or wind gustiness, is one of those properties. Wind gusts are a reflection of turbulent eddies imbedded within the general circulation of air flow, with the energy associated with these eddies defined as turbulent kinetic energy (TKE). The generation and dissipation of turbulent eddies and TKE in the atmosphere are dependent on wind shear and buoyancy conditions. Strong vertical wind shears and unstable temperature lapse rates tend to increase atmospheric turbulence, while stable temperature lapse rates tend to dissipate turbulence. Predictions of TKE in the atmospheric boundary layer using the higher order level 2.5 closure from the Mellor-Yamada turbulence hierarchy (Mellor and Yamada 1974, 1982; Gerrity and others 1994) are available from the daily FCAMMS MM5 model simulations. However, unlike the HI predictions from the FCAMMS, TKE predictions have not been used in the past for characterizing atmospheric risk of extreme fire behavior.

The FCAMMS—Eastern Area Modeling Consortium (EAMC) has been investigating the utility of combining the mesoscale-type HI with TKE, a boundary-layer type index, for assessing the atmospheric potential for extreme fire behavior. For example, Heilman and others (2003) reported some initial results from an analysis of regional patterns of HI and TKE over the Northeastern United States based on daily EAMC MM5 fire-weather simulations covering the period 1 March 2003 to 18 July 2003. While the analyses were limited to the Northeast and covered a short period of time, they provided some important insight into where high HI and high TKE values typically occur in this region of the nation. The analyses also demonstrated that combining the HI and TKE via a simple product of the two indices may have some utility in predicting where both lower to middle tropospheric conditions and boundary layer conditions are especially conducive to extreme fire behavior, as shown by an application of this "combined" index to the Double Trouble State Park wildfire in New Jersey on 2 June 2002.

As a follow-up to the Heilman and others (2003) investigation, this paper describes a more comprehensive analysis of seasonal HI and TKE patterns over the western Great Lakes region of the United States derived from EAMC MM5 daily fire-weather simulations for year 2006. Comparisons of seasonal patterns of HI and TKE patterns along with analyses of the relative significance of wind shear and buoyancy effects in the atmospheric boundary layer in contributing to high TKE values when high HI values are also present provide new insight into the atmospheric dynamics that contribute to extreme fire behavior.

Haines Index Description

The well-known HI (Haines 1988) is a simple index that provides a measure of the lower to middle tropospheric instability and dryness. The index characterizes 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

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

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), respectively, at one of the pressure levels. The pressure levels, p1 and p2, are set at 950 mb and 850 mb, respectively, for low terrain elevations; 850 mb and 700 mb, respectively, for mid terrain elevations; and 700 mb and 500 mb, respectively, for high terrain elevations. The defined low, mid, and high terrain elevation regions for the United States can be found in Haines (1988). For the HI calculations performed in this study, both the low and mid terrain elevation designations are used.

Haines (1988) defined specific temperature lapse rate and dew-point depression thresholds for the low, mid, and high terrain elevation designations. Integer values of 1, 2, or 3 are assigned to the lapse rate (A) and dew-point depression (B) components of the HI, as shown in equation 1, depending on the actual values of the lapse rates and dew-point depressions in comparison to the defined thresholds. 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].

The lower to middle tropospheric temperature and dew-point temperature data required for calculating the HI typically come from radiosonde observations at 0000 UTC and 1200 UTC or from numerical weather prediction models that can provide output data specific to any time of the day. Haines Index observations or predictions are often presented in the form of maps that allow for a spatial analysis of regional patterns of the index. The HI can be classified as a mesoscale-type index because it attempts to capture the stability and moisture conditions of atmospheric layers that extend above the atmospheric boundary layer. As a mesoscale-type index, it can be useful for describing the atmospheric risk for extreme fire behavior over relatively large spatial areas. When fire plumes penetrate atmospheric layers characterized by high HI values, the potential exists for increased lofting of the plume and the downward transport of high-momentum, dry air from these layers to the surface, a potentially dangerous wildfire scenario.

Turbulent Kinetic Energy Description

While stability and moisture conditions in atmospheric layers above the boundary layer can influence fire behavior, turbulent atmospheric circulations (that is, wind gusts) within the boundary layer can also create an environment conducive to extreme fire behavior. Wind gusts are manifestations of turbulent eddies generated by wind shear and buoyancy effects, which can be large in the boundary layer. The amount of energy in these turbulent eddies is defined as turbulent kinetic energy, and is given by $0.5q^2$ where

$$q^2 = \overline{u'^2} + \overline{v'^2} + \overline{w'^2} \tag{2}$$

and $\overline{u'^2}$, $\overline{v'^2}$, and $\overline{w'^2}$ are the variances of the departure (turbulent) velocities in the horizontal x, horizontal y, and vertical z directions, respectively. Large vertical wind shears under thermally unstable (convective) conditions lead to a highly energetic turbulence regime (that is, large TKE values), whereas a thermally stable environment will tend to suppress any turbulence generated through mechanical wind shears and produce more laminar-type flows (low TKE values). Irrespective of the enhanced atmospheric turbulence generated by buoyancy and wind shears associated with a fire, an already highly turbulent atmospheric boundary layer can contribute to even more erratic fire behavior through interactions between the fire-induced and ambient boundary-layer turbulence regimes.

Simulations and predictions of TKE are possible in many of the current research and operational atmospheric mesoscale and boundary layer numerical models, including MM5. Turbulent kinetic energy can be simulated and predicted using the level 2.5 closure scheme from Mellor and Yamada (1974, 1982) given by

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

where the terms on the left side of the equation represent the local time rate of change of TKE, the advection of TKE by the three-dimensional mean wind V, and the vertical diffusion of TKE (parameterized in terms of diffusion coefficient K_q). The terms on the right side of the equation represent the production of TKE through vertical wind shear effects (P_s), the production or dissipation of TKE through buoyancy effects (P_b), and the nonbuoyant dissipation of TKE (ε) via the breakdown of turbulent eddies into smaller and smaller sizes. The production (P_s) of TKE through vertical wind shear effects is given by

$$P_s = -\overline{u'w'}\frac{\partial \overline{u}}{\partial z} - \overline{v'w'}\frac{\partial \overline{v}}{\partial z} \tag{4}$$

and the buoyant production or dissipation (P_b) of TKE is given by

$$P_b = \frac{g}{\theta_v}\overline{\theta_v'w'} \tag{5}$$

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 heat. The MM5 mesoscale model used in this study includes the Mellor and Yamada (1974, 1982) TKE formulation and is described in more detail by Gerrity and others (1994).

Unlike the HI, which can be easily computed from radiosonde observations or numerical model output, TKE as a potential fire-weather index has not been used extensively because it is fairly complex and is rarely, if ever, included in the suite of fire-weather variables made available to fire managers. However, the increasing availability and delivery of TKE predictions from research and development groups such as the FCAMMS have now made it possible to assess the feasibility of using TKE in some fashion as a potential fire-weather index.

Analyses of HI and TKE Patterns

The analyses presented here are built upon daily 48-hour real-time EAMC MM5 simulations (0000 UTC initialization) over a 4-km grid spacing domain covering the western Great Lakes region for the period of 1 January 2006 through 31 December 2006. Simulated patterns of the mid-afternoon frequency of occurrence of different HI and near-surface TKE values were analyzed as a first step in determining: (1) how frequently high HI values (5 or 6) occur concurrently with significant near-surface atmospheric turbulence in this region; (2) whether there are preferred locations where high HI and high near-surface turbulence tend to occur in this region; and (3) whether there is a seasonal dependence on those occurrence patterns.

Figure 1 shows the simulated frequency of occurrence of HI values equal to 5 or 6 (moderate or high atmospheric risk of large plume dominated fires) at 2000 UTC during the January-February-March (JFM), April-May-June (AMJ), July-August-September (JAS), and October-November-December (OND) periods in 2006. During the JFM period, mid-afternoon high HI values were most common over northern Iowa, southern Minnesota, western and southern Wisconsin, and central Michigan. The highest frequencies occurred over northeastern Iowa, with 25 to 30 percent of the days during this 3-month period characterized by HI values equal to 5 or 6 at 2000 UTC. During the spring and summer periods (AMJ and JAS), high HI values at 2000 UTC were more frequent and widespread in this region. HI values of 5 or 6 occurred more than 20 percent of the time at 2000 UTC over most of Minnesota, Iowa, southern Wisconsin, northern Illinois, and northern, western, and eastern Michigan. The autumn period (OND) was characterized

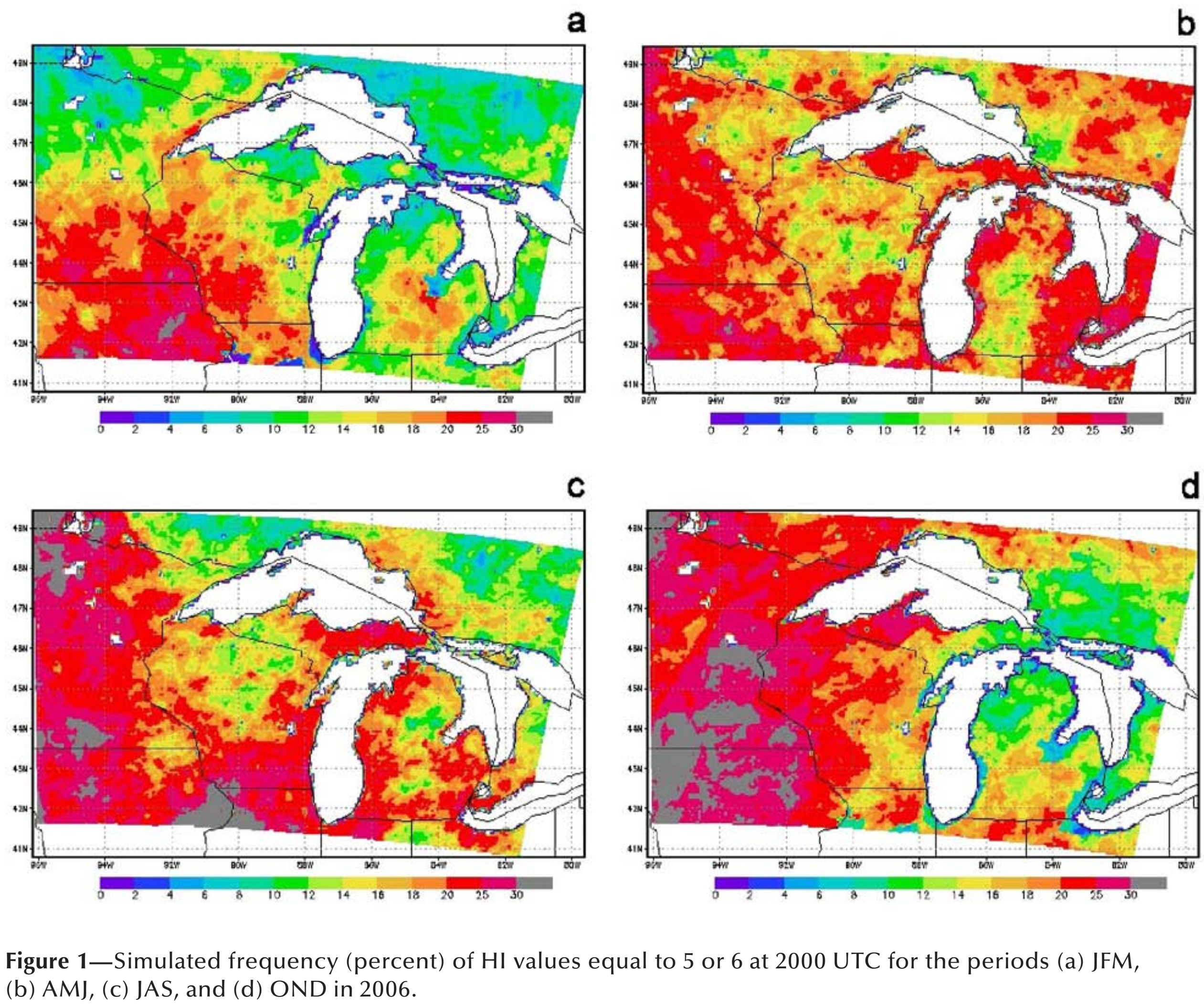

Figure 1—Simulated frequency (percent) of HI values equal to 5 or 6 at 2000 UTC for the periods (a) JFM, (b) AMJ, (c) JAS, and (d) OND in 2006.

by maximum frequencies of high HI occurrence at 2000 UTC exceeding 30 percent over large parts of Minnesota and Iowa, and minimum frequencies over much of northern Michigan. Overall, the simulated patterns of high HI occurrence over the western Great Lakes region in 2006 suggest that mid-afternoon lower to middle tropospheric stability and moisture conditions were more frequently conducive to extreme fire behavior over the western sections of the region than elsewhere during all seasons.

The simulated frequencies of occurrence of near-surface TKE values exceeding 3 m^2s^{-2} (significant turbulence) at 2000 UTC over the same four 3-month periods in 2006 are shown in figure 2. The percentage of days when near-surface turbulence was significant during the winter months (JFM) in 2006 was low over the western sections of the Great Lakes region. Only the upper peninsula and northern part of the lower peninsula of Michigan and along the shores of Lake Superior had relatively frequent occurrences of significant near-surface turbulence, generated primarily by mechanical wind shear effects. The increased stability of the atmospheric boundary layer during the winter months reduces the buoyancy contribution to TKE production. The spring months (AMJ) were characterized by increases in occurrence of high near-surface turbulence over the upper peninsula and northern sections of the lower peninsula of Michigan, northern Wisconsin, and large areas of Minnesota and Iowa. More than 30 percent of the days in some of these areas had near-surface TKE values exceeding 3 m^2s^{-2} at 2000 UTC. Overall frequencies of occurrence of high near-surface

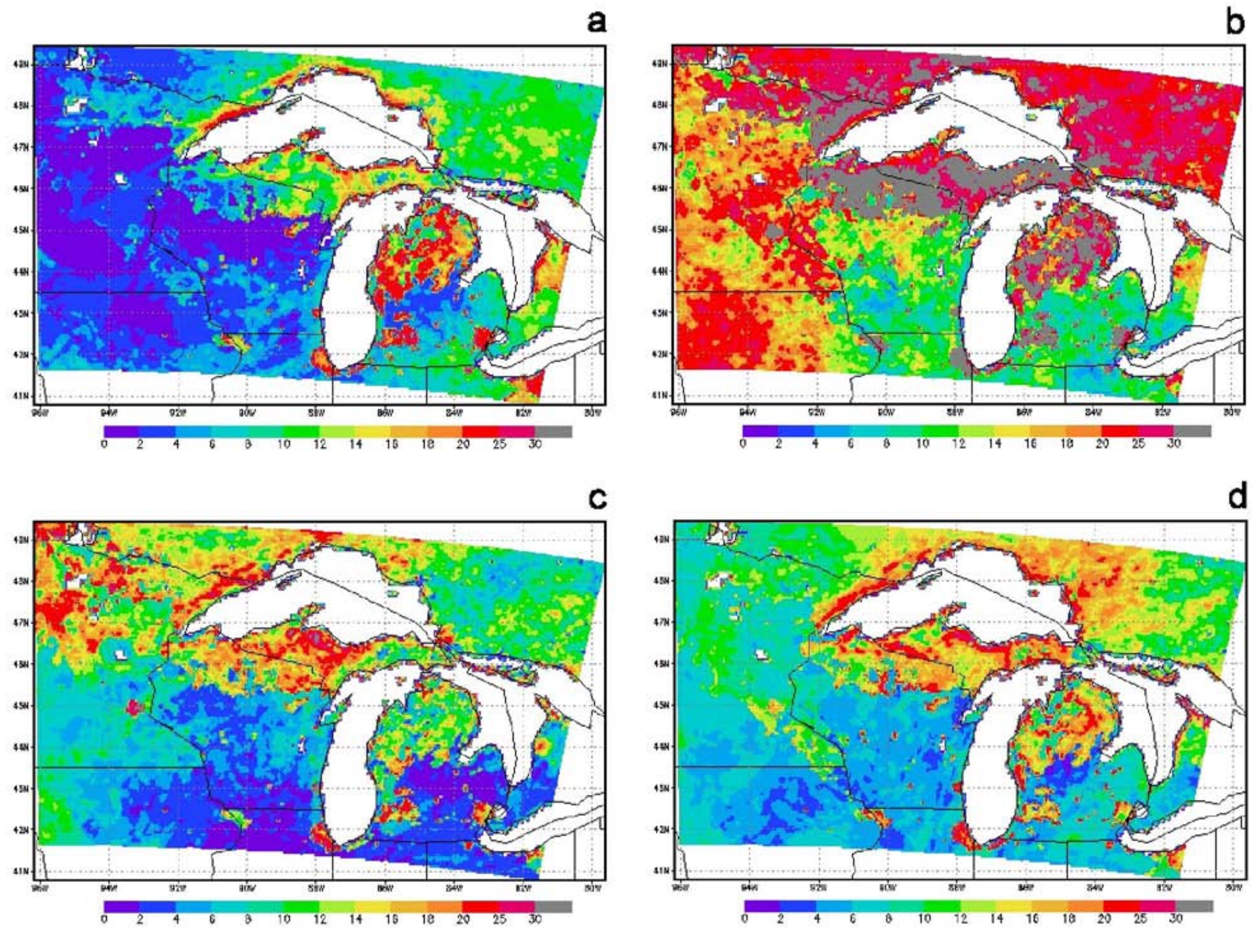

Figure 2—Same as figure 1 except for simulated frequency (percent) of near-surface TKE values greater than or equal to 3 m^2 s^{-2}.

turbulence were lower during the summer (JAS) and autumn (OND) periods over the western Great Lakes region in comparison to the maximum frequencies observed during the spring months.

A comparison of the HI and TKE frequency of occurrence maps in figures 1 and 2, respectively, reveals that large HI values in 2006 often did not occur in the same areas where large near-surface TKE values occurred. In fact, episodes of concurrent high HI and near-surface TKE values were infrequent. This suggests that combining the HI and near-surface TKE in some fashion could produce a highly discriminatory index that captures those relatively rare events when both the atmospheric mesoscale environment, as quantified by the HI, and the atmospheric boundary-layer environment, as quantified by near-surface TKE, are highly conducive to extreme fire behavior. One possible way of combining the indices is to simply take the product of the two indices. Figure 3 shows the simulated frequency of occurrence at 2000 UTC of episodes where HI x TKE > 15, a threshold meant to roughly capture those cases when the HI and TKE values are greater than or equal to 5 and 3 m^2s^{-2}, respectively. Over much of the western Great Lakes region, the occurrence of concurrent high values of HI and near-surface TKE in 2006 was relatively rare. It was only during the spring season (AMJ) that frequencies of occurrence above about 10 percent were common over large sections of Minnesota, Wisconsin, and Michigan. Frequencies above 20 percent also

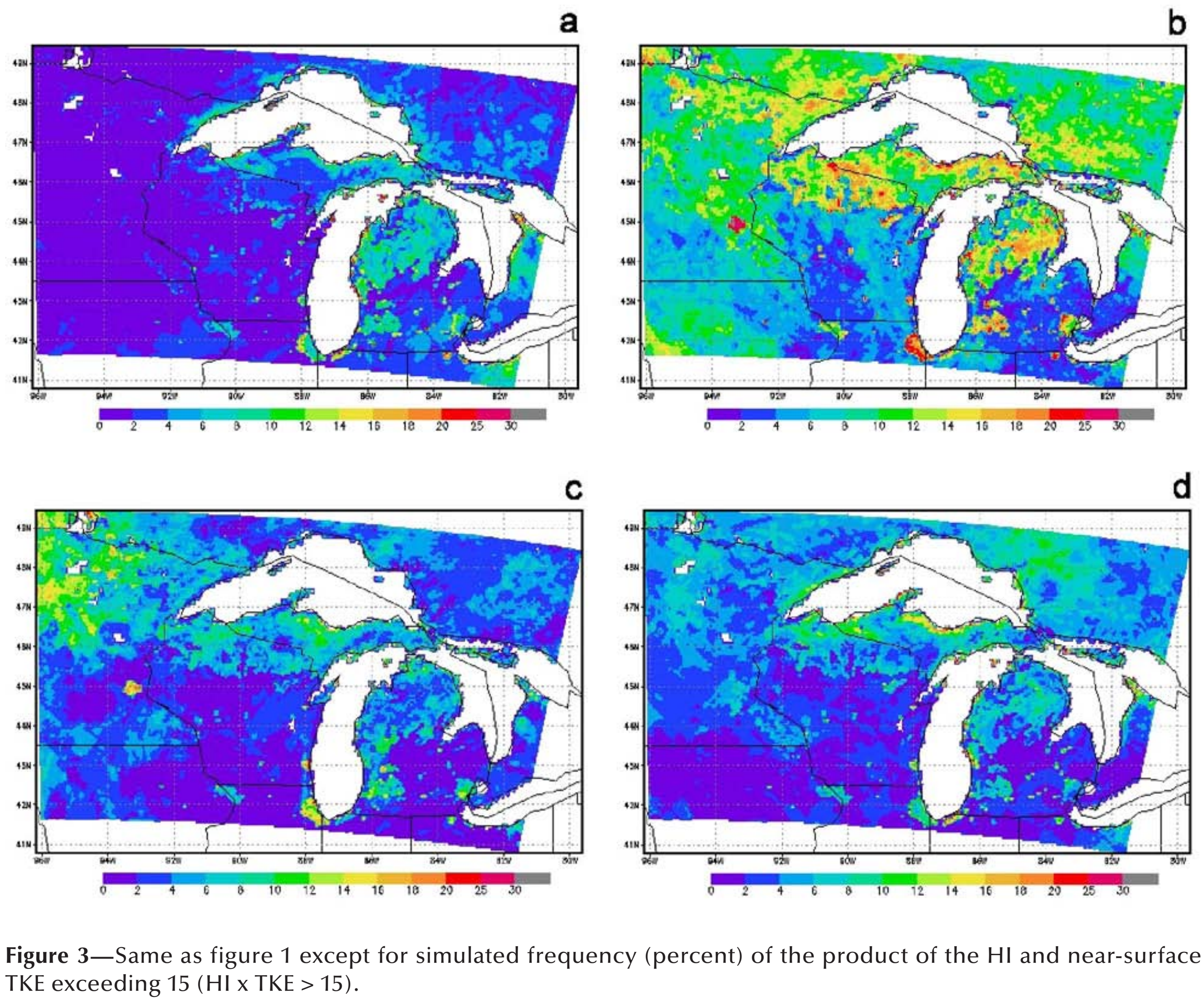

Figure 3—Same as figure 1 except for simulated frequency (percent) of the product of the HI and near-surface TKE exceeding 15 (HI x TKE > 15).

characterized the local urban areas of Minneapolis, Chicago, Milwaukee, and Detroit during the spring. During the summer months (JAS), the highest frequencies (~10 to 15 percent) occurred over northern Minnesota and these same urban areas. Frequencies in the fall were generally less than 10 percent everywhere except along the southern shore of Lake Superior.

Fire Case Studies

In order to test the feasibility of combining the Haines Index and TKE for assessing the atmospheric mesoscale and boundary layer risk of extreme fire behavior, preliminary analyses were carried out to determine the behavior of the product of HI and near-surface TKE values during actual wildland fire events in the western Great Lakes region in 2006. Twenty-one wildland fire cases in the western Great Lakes region were identified in 2006, ranging from 100 to nearly 32,000 acres in size. For each wildland fire case, the HI, near-surface TKE, and the product of the HI and TKE were computed each hour for the entire duration of the fire at locations corresponding to each wildland fire event (based on archived, real-time hourly output from the EAMC MM5 daily fire-weather simulations over the western Great Lakes region). Results from those simulations are shown in table 1. The five largest fires all had occurrences of maximum HI x TKE values greater than 15, with the largest value (32.196) observed during the Cavity Lake Fire in the Boundary Waters Canoe Area of northern Minnesota. Significant near-surface turbulence (TKE > 3 m^2s^{-2}) was simulated during these fires, with HI values ranging from 4 to 6 at the time

Table 1—Maximum values of the product of the Haines Index (HI) and near surface turbulent kinetic energy (TKE), and the dates, times, and Richardson number (Ri) values when the HI x TKE maximum values occurred during selected wildland fire episodes in the western Great Lakes region in 2006. Values of maximum HI x TKE exceeding the threshold of 15 are shown in bold.

Fire name	Start date	End date	HI	TKE	Max. HI*TKE	Date:time (UTC) of max HI x TKE	Ri	Acres burned
Cavity Lake	7/14	9/1	6	5.366	**32.196**	07/17: 0200	-0.314	31,830
Peatland	10/6	10/8	4	8.214	**32.856**	10/08: 1900	-0.018	6,625
East Zone Cmp.	9/8	10/1	5	6.282	**31.410**	09/22: 2300	-0.005	5,898
Red Lake 16	4/6	4/7	4	5.253	**21.012**	04/06: 2300	-0.028	3,650
Turtle Lake	7/13	8/3	4	4.651	**18.604**	07/16: 0300	-0.012	2,085
Grain Bin	4/26	4/27	5	2.519	12.595	04/26: 2000	-0.280	1,496
20 Mile	4/26	4/27	5	2.519	12.595	04/26: 2000	-0.280	1,456
Cederbend	11/21	11/22	5	1.232	6.160	11/23: 0600	0.036	727
Trail	4/10	4/11	6	3.068	**18.408**	04/11: 2300	-0.012	676
Richardville	4/22	4/23	5	2.214	11.070	04/24: 0000	-0.124	640
Red Lake 197	4/16	4/16	5	1.815	9.075	04/16: 1900	-0.281	550
Black River	4/16	4/17	5	0.620	3.100	04/17: 0300	-0.140	500
Easter Sunday	4/16	4/17	6	1.565	9.390	04/16: 2000	-0.026	348
Parkers Prairie	4/9	4/11	4	1.798	7.192	04/09: 2000	-0.028	326
Sharptail Burn	4/17	4/18	4	3.222	12.888	04/17: 2000	-0.280	317
219	7/19	7/24	5	5.735	**28.675**	07/19: 1900	-0.078	240
Shack	4/6	4/7	3	4.655	13.965	04/07: 0000	-0.012	200
Clementson	9/4	9/12	5	1.817	9.085	09/05: 1900	-6.807	149
Hammer	11/9	11/10	5	2.131	10.655	11/09: 0700	-0.002	115
Keystone	8/3	8/5	4	0.565	2.260	08/05: 0700	-0.184	106
Wobble Grade	7/12	7/13	6	1.418	8.508	07/12: 2000	-2.992	100

when maximum HI x TKE values were simulated. Fourteen of the 21 fire cases included in this study had simulated maximum HI x TKE values less than 15. Most of the maximum HI x TKE values during the analyzed fires occurred in the local afternoon or evening hours.

The application of a combined HI and near-surface TKE for spatially pinpointing where atmospheric mesoscale and boundary layer conditions are both highly conducive to extreme fire behavior was tested for the Cavity Lake Fire that burned nearly 32,000 acres from 14 July to 1 September 2006. Figure 4 shows the simulated patterns of HI, near-surface TKE, and HI x TKE values at 0200 UTC on 17 July 2006 (9:00 pm CDT on 16 July 2006). Most of the western Great Lakes region had HI values of 5 or 6 at this time, with large areas of HI = 6 covering parts of Minnesota, Wisconsin, and Michigan (fig. 4a), including the Boundary Waters Canoe Area of northern Minnesota. Significant near-surface turbulence (TKE > 3 m^2s^{-2}) also occurred in the region at this time, but was confined to much smaller areas located over northern Minnesota, southwestern Minnesota, northern Wisconsin, and parts of northern and western Michigan (fig. 4b). Figure 4c shows the spatial pattern of the product of the HI and near-surface TKE across the region, and clearly indicates that the mesoscale and boundary-layer conditions were highly conducive to extreme fire behavior in the BWCA of Minnesota where the Cavity Lake Fire was spreading rapidly at the time (McDaniel 2006). Values of HI x TKE exceeded 20 over much of the arrowhead region of northern Minnesota.

The product of the HI and near-surface TKE presented here represents a simple means of combining the two indices for capturing the concurrent atmospheric mesoscale and boundary layer risk of extreme fire behavior. The preliminary analyses of case studies carried out in this study suggest that computing the product may provide a useful tool for predicting when and where the stability/moisture conditions in the lower and middle troposphere and atmospheric boundary-layer turbulence could all contribute to extreme fire behavior at the same time, a relatively rare but dangerous situation.

Haines Index and Turbulence Dynamics

Beyond the spatial and temporal variability patterns of the HI and near-surface TKE in the western Great Lakes region, 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 examined how the mid-afternoon production of near-surface turbulence through wind shear and buoyancy processes (equations 3 through 6) varied with changing HI values during each season in 2006 across the western Great Lakes region. Figure 5 shows the frequency distribution of simulated near-surface TKE values at 2000 UTC for all HI classes for the JAM, AMJ, JAS, and OND periods in 2006. Considering all HI classes (2 through 5), mid-afternoon TKE values between 0 and 1 m^2s^{-2} were most common across the western Great Lakes region during the winter (2,530,087 occurrences – 53.9 percent; fig. 5a), summer (2,191,371 occurrences – 39.0 percent; fig. 5e), and fall (2,781,916 occurrences – 49.0 percent; fig. 5g) seasons. During the spring season, mid-afternoon TKE values between 1 and 2 m^2s^{-2} were most common in the region (1,887,489 occurrences – 34.4 percent; fig. 5c). The occurrence of mid-afternoon TKE values greater than 3 m^2s^{-2} for all HI classes was a relatively rare event. The percentages of all model grid points having TKE

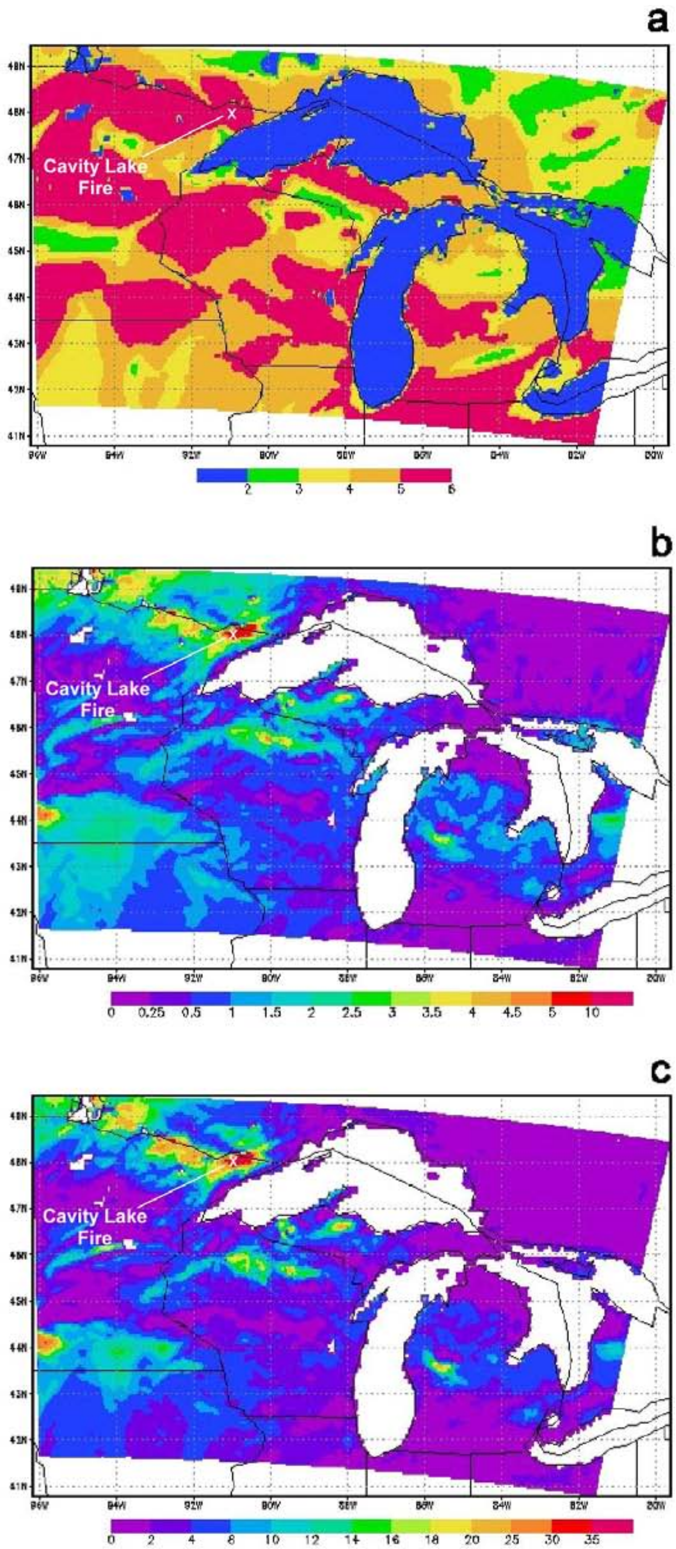

Figure 4—Simulated patterns of (a) HI, (b) near-surface TKE (m^2s^{-2}), and (c) HI x TKE at 0200 UTC on 17 July 2006. The location of the Cavity Lake Fire in northern Minnesota is highlighted with an "x" in each figure.

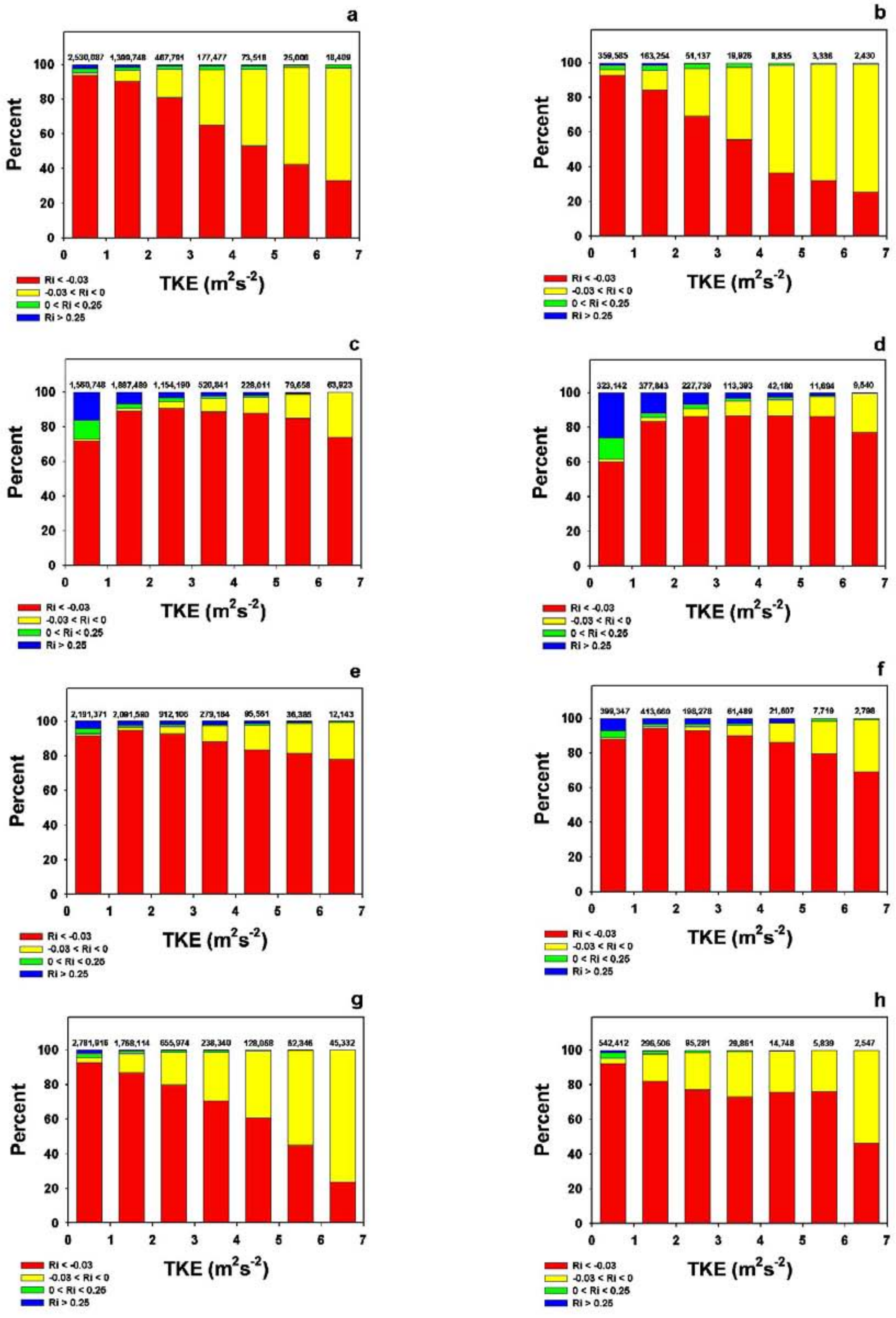

Figure 5—Frequency of occurrence (percent) of simulated near-surface TKE values in bins 0-1, 1-2, 2-3, 3-4, 4-5, 5-6, and > 6 m^2s^{-2} for all HI classes (2-6) (a, c, e, g) and for the high HI classes (5-6) (b, d, f, h) during the JFM (a and b), AMJ (c and d), JAS (e and f), and OND (g and h) periods in 2006 over the western Great Lakes region. 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.

values greater than 3 m^2s^{-2} at 2000 UTC in the winter, spring, summer, and fall seasons were 6.3, 16.2, 7.5, and 8.4 percent, respectively.

When only the high HI classes are considered (HI = 5 or 6), mid-afternoon TKE values between 0 and 1 m^2s^{-2} were most common during the winter (JFM) (359,585 occurrences – 59.1 percent; fig. 5b) and autumn (OND) (542,412 occurrences – 54.9 percent; fig. 5h) seasons in 2006. The spring (AMJ) (377,843 occurrences – 34.2 percent; fig. 5d) and summer (JAS) (413,660 occurrences – 37.4 percent; fig. 5f) seasons had more occurrences of mid-afternoon TKE values in the 1-2 m^2s^{-2} range than any other range. The occurrence of mid-afternoon TKE values greater than 3 m^2s^{-2} was still a relatively rare event even when HI values reached 5 or 6 in 2006. The percentages of all model grid points having TKE values at 2000 UTC greater than 3 m^2s^{-2} were 5.7, 16.1, 8.6, and 5.4 percent for the winter, spring, summer, and fall seasons, respectively.

Figure 5 also provides insight into the relative significance of vertical wind shear and buoyancy in the production and/or dissipation of near-surface turbulence under low or high HI conditions, as measured by the gradient Richardson number (Ri):

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

where g is the gravitational constant and θ is the potential temperature. As Ri becomes more negative, the production of turbulence through vertical wind shears 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. Positive values of Ri indicate that buoyancy is acting to suppress turbulence generated by vertical wind shears, with complete suppression of turbulence occurring when $Ri \geq 0.25$. As shown in figure 5, buoyancy effects dominated the production of TKE ($Ri \leq -0.03$) at 2000 UTC during the spring (fig. 5c,d) and summer (fig. 5e,f) periods regardless of the amount of turbulence (that is, TKE) present or the values of the mesoscale HI. However, for the winter (fig. 5a,b) and fall (fig. 5g,h) periods, there was a significant drop-off (increase) in the frequency of occurrence of buoyancy-dominated (shear-dominated) turbulence regimes as TKE increased. Unlike the other seasons in 2006, the spring months were characterized by numerous occurrences of $Ri \geq 0.25$ and $0 \leq Ri < 0.25$ when near surface turbulence was weak (TKE < 2 m^2s^{-2}) (fig. 5c,d).

Summary

We have followed up our initial study of HI and TKE behavior in the Northeastern United States region (Heilman and others 2003) with a new study that is 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 western Great Lakes region. Using the daily, MM5-based fire-weather predictions now readily available from the EAMC, we identified the 2006 seasonal patterns of occurrence of high HI, high near-surface TKE, and concurrently high HI and TKE, expressed as the product of the two indices. Broad areas of the western Great Lakes region experienced high mid-afternoon (2000 UTC) HI values (5 or 6) on more than 20 percent of the days during each season, with the highest frequencies of occurrence happening in the summer (JAS) and fall (OND) seasons over Iowa and Minnesota. The high HI occurrence patterns differ significantly from the frequency of occurrence patterns of high near-surface TKE (> 3 m^2s^{-2}). Episodes of significant, mid-afternoon near-surface turbulence were most common over the northern sections of Michigan, Wisconsin, and/or Minnesota, with the highest frequencies of occurrence (>30 percent of the days) associated with the spring (AMJ) period in these areas. The contrasting patterns of occurrence for these two indices during all seasons suggest that episodes of high HI and high near-surface turbulence at the same time, a potentially dangerous fire-weather condition, are relatively infrequent in this region of the United States. However, this infrequency does provide an opportunity for combining the Haines and TKE indices in some fashion so that the timing and location of these rare but important events can be anticipated.

In this study, the HI and near-surface TKE values were combined via a simple product of the two, and seasonal patterns of occurrence of HI x TKE exceeding 15 across the western Great Lakes region during 2006 were examined. Like the high near-surface TKE patterns of occurrence, mid-afternoon (2000 UTC) occurrences of HI x TKE exceeding 15 were most frequent in the spring over the northern sections of Michigan, Wisconsin, and Minnesota. The urban areas of Minneapolis, Milwaukee, Chicago, and Detroit also had occurrence maxima during the spring. Although the occurrence of high HI and high near-surface TKE at the same time may be relatively rare in this region, the simulation results from 2006 suggest that when it does happen, it tends to occur in those areas of the region that are most prone to wildfires (that is, northern Michigan, northern Wisconsin, and northern Minnesota) and during the springtime when wildfires in the region are most common.

The application of a new index based on the simple product of predicted HI and near-surface TKE values to actual western Great Lakes wildland fire episodes in 2006 suggests that this type of index may be a useful tool for pinpointing when and where atmospheric stability, moisture, and boundary-layer turbulence may collectively contribute to creating an ambient local atmospheric environment highly conducive to extreme fire behavior. The five largest wildlfires in the western Great Lakes region in 2006 occurred in locations where and during periods when the product of the HI and near-surface TKE exceeded a threshold (15) indicative of dry, unstable middle tropospheric layers above a highly turbulent boundary layer. Further testing of this type of combined index is planned for the western Great Lakes region and other regions of the United States via the regional modeling activities in the EAMC and other modeling consortia in the FCAMMS.

The primary mechanism responsible for mid-afternoon turbulence generation in atmospheric boundary layers over the western Great Lakes region during the spring and summer seasons in 2006 was buoyancy, regardless of the level of turbulence present or the value of the mesoscale HI. During the winter and fall seasons, large TKE values were more frequently associated with shear-dominated turbulence regimes than buoyancy-dominated regimes. This suggests that during the springtime wildfire season in the western Great Lakes region, atmospheric instability within the atmospheric boundary layer and above is more often than not the primary factor in generating near-surface turbulence that can interact with wildland fires. However, significant near-surface turbulence generated by ambient vertical wind shears can certainly create atmospheric environments conducive to erratic fire behavior, as shown by the Ri values ($-0.03 < Ri < 0$) for four of the five largest analyzed fires in this study and for five of the seven analyzed fires that had maximum HI x TKE values exceeding the 15 threshold (table 1).

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 different regions of the United States. Additional analyses of HI and TKE behavior for the Northeast and for years prior to 2006 will be carried out using the historical MM5 output data archive developed by the EAMC as part of its fire-weather prediction program. 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 and fire behavior.

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