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Climatic variability of a fire-weather index based on turbulent kinetic energy and the Haines Index

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Abstract
Combining the Haines Index (HI) with near-surface turbulent kinetic energy (TKE_s) through a product of the two values ($HITKE_s$) has shown promise as an indicator of the atmospheric potential for extreme and erratic fire behavior in the U.S. Numerical simulations of fire-weather evolution during past wildland fire episodes in the U.S. indicate that large wildfires and periods of rapid fire growth are often associated with and accompanied by periods of significant near-surface atmospheric turbulence. These findings provide new insight into the variability of ambient atmospheric turbulence during wildfire events over relatively short time periods. However, the ultimate application of a fire-weather index based on the product of the HI and TKE_s in fire-weather forecasts requires an understanding of where and when high values of the index typically occur. This study examines the spatial and temporal variability of TKE_s and $HITKE_s$ values over the U.S. using North American Regional Reanalysis (NARR) data. Study results indicate that there are preferred locations and periods for large TKE_s and $HITKE_s$ values, the temporal variability of TKE_s and $HITKE_s$ is regionally dependent, and there has been a general increase in TKE_s and $HITKE_s$ values over much of the U.S. over the last 30 years.

Additional keywords: turbulence, wildfire

Introduction

Recent modeling studies (Heilman and Bian 2007, 2010) have examined the feasibility of using atmospheric mesoscale model predictions of near-surface TKE (TKE_s) (Mellor and Yamada 1974, 1982; Janjić 1994) in combination with predictions of the well-known Haines Index (HI) (Haines 1988) as an atmospheric indicator of the potential for erratic wildfire behavior. The results from their studies suggest that periods of rapid wildfire growth are often associated with episodes when TKE_s exceeds 3 m^2s^{-2} at the same time the HI is equal to 5 or 6. These conditions are indicative of a highly turbulent boundary layer sitting beneath unstable and dry atmospheric layers aloft.

While these studies have provided a first step in determining the association of significant atmospheric boundary layer turbulence with extreme and erratic fire behavior, additional analyses are needed to determine how often high turbulence episodes occur and where they typically occur. Determining the climatic variability of TKE_s and the product of the HI and TKE_s ($HITKE_s$), including spatial and temporal patterns over the U.S., will provide critical baseline climatologies for comparisons with predicted and observed ambient TKE_s variability during actual wildfire events. It is through these comparisons that the efficacy of TKE_s as a potential operational fire-weather index can be assessed. This study provides a climatic assessment of the spatial variability of and temporal trends in TKE_s and $HITKE_s$ across the U.S. based on 30 years of 3-hourly TKE_s, temperature profile, and wind speed data obtained from the North American Regional Reanalysis (NARR) dataset (Mesinger *et al.* 2006).

Methods

The climatological analyses carried out in this study utilized data obtained from the National Centers for Environmental Prediction (NCEP) NARR dataset (Mesinger *et al.* 2006), a gridded and dynamically consistent atmospheric and land-surface hydrology dataset that covers the 1979-present period. Data are available every three hours on a 32-km horizontal grid spacing domain covering North America at 45 vertical levels.

For this study, TKE data at the NARR hybrid grid level 1 (12.0 m – 21.7 m above the surface) were used to quantify near-surface turbulent energy (i.e. TKE_s). Thirty years of TKE data at the hybrid grid level 1 were extracted from the NARR data set at each 3-hourly interval (0000, 0300, 0600, … 2100 UTC) from 0000 UTC on 1 January 1979 through 2100 UTC on 31 December 2008. These data provided the basis for developing a climatology of TKE_s and for examining its temporal variability over a sub-region of North America that includes the conterminous U.S. (25°N to 50°N, -65°W to -125°W). Three-hourly temperature, dew-point temperature, wind speed, sensible heat flux, and friction velocity data for the same 30-year period were also extracted from the NARR data set in order to compute values of $HITKE_s$ and the flux Richardson number (Ri). These additional data were analyzed to compare the spatial and temporal variability of TKE_s over the U.S. with the corresponding variability of $HITKE_s$, a potential fire-weather index (Heilman and Bian 2010), and to determine the relative contributions of wind shear and buoyancy in the production of near-surface turbulence over different regions of the U.S.

Key Results

Average daily maximum TKE_s and $HITKE_s$

There are regional differences in the average daily maximum TKE_s values that occur across the U.S. (Fig. 1) The highest average daily maximum TKE_s values occur over the high elevation areas in the Rocky Mountain and Appalachian Mountain regions, with the largest values (> 5 m^2s^{-2}) occurring during the months of April, May, and June. Values of TKE_s greater than 3 m^2s^{-2} indicate a highly turbulent environment. Over the Rocky Mountain and Great Plains regions, the highest daily maximum TKE_s values tend to occur from March through June. The Midwest and Southeast tend to have very low TKE_s values (< 1.5 m^2s^{-2}) during the months of June, July, and August. In the Northeast, the highest TKE_s values tend to occur during the months of October through April. The Autumn and Spring periods coincide with the primary wildfire periods in the Northeast.

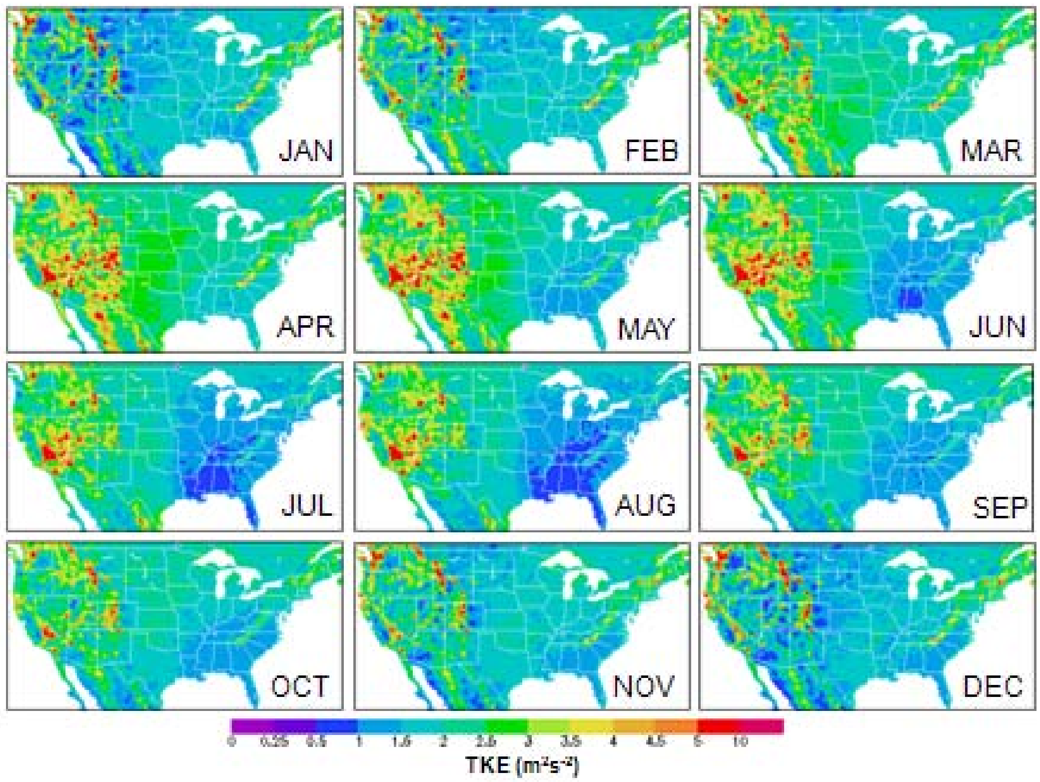

Fig. 1. Average daily maximum near-surface turbulent kinetic energy (TKE_s) over the U.S. for each month based on 3-hourly NARR data for the 1979-2008 period.

The average daily maximum $HITKE_s$ values across the U.S. also exhibit regional differences (Fig. 2). High daily maximum $HITKE_s$ values initially appear over northern Mexico and the Southwest in March and then spread northward through the Rocky Mountain region from April to August. Maximum values routinely exceed 15 m^2s^{-2} over many areas in the Rocky Mountain region. Over the eastern half of the U.S., average maximum $HITKE_s$ values are usually less than 10 m^2s^{-2} throughout the year, except for parts of the Appalachian and the northeastern U.S. regions where average maximum values reach 12-14 m^2s^{-2} from December through April. These results suggest that the use of the 15 m^2s^{-2} threshold value (Heilman and Bian 2010) as an indicator of the atmospheric potential for extreme or erratic fire behavior because of anomalous atmospheric turbulence conditions with high HI values is probably more applicable for the eastern half of the U.S., and that a higher threshold on the order of 20-25 m^2s^{-2} may be needed for the western U.S.

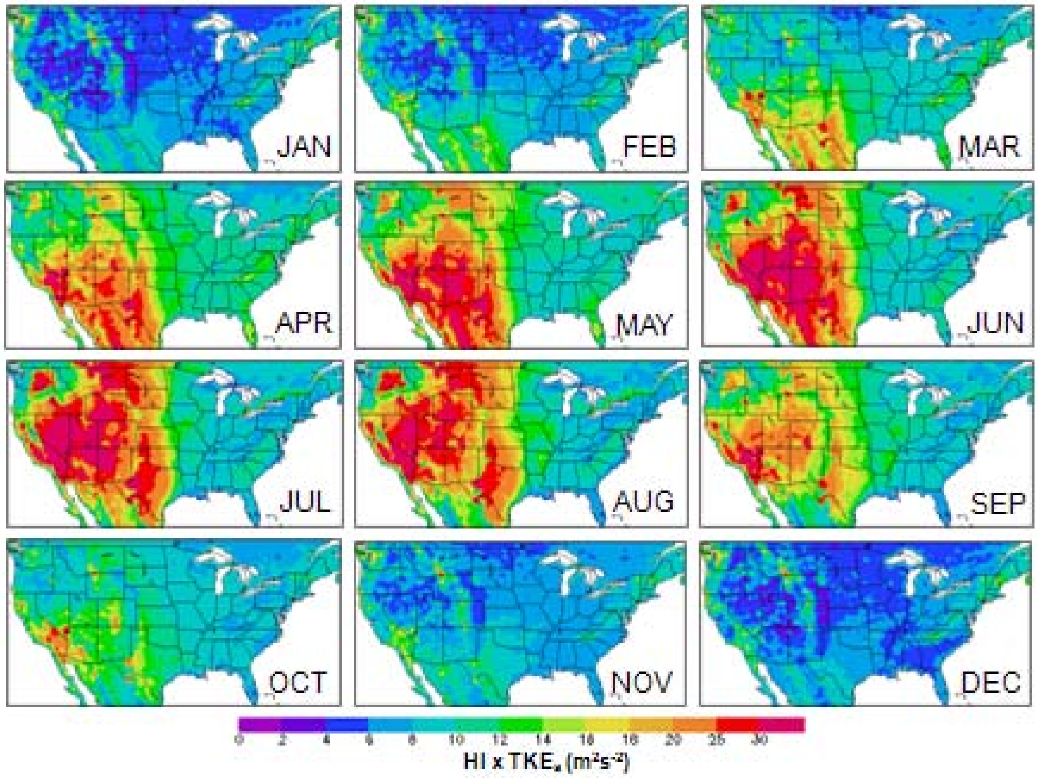

Fig. 2. Average daily maximum values of the product of the Haines Index and near-surface turbulent kinetic energy ($HITKE_s$) over the U.S. for each month based on 3-hourly NARR data for the 1979-2008 period.

Frequency of occurrence of high TKE_s and $HITKE_s$

The frequency of occurrence of daily maximum TKE_s values greater than 3 m^2s^{-2} and daily maximum $HITKE_s$ values greater than 15 m^2s^{-2} varies substantially from east to west across the U.S. For daily maximum TKE_s exceeding 3 m^2s^{-2}, the highest frequencies of occurrence are found over the western U.S.; many locations there typically have more than 60% of the days in any given month with maximum TKE_s exceeding the 3 m^2s^{-2} threshold. For most of the eastern U.S., the occurrence of daily maximum TKE_s values greater than 3 m^2s^{-2} is fairly rare (< 10% of the days each month). The exception is over the Appalachian Mountain and northeastern U.S. regions, where frequencies range from 30-60% during the November-May period. Over the Great Plains where grass fires are common, occurrences of maximum TKE_s values exceeding 3 m^2s^{-2} are most likely during the March–June period (30-50% of the days during those months).

The frequency of occurrence of daily maximum $HITKE_s$ values exceeding 15 m^2s^{-2}, a threshold indicative of a turbulent boundary layer sitting beneath dry and unstable atmospheric layers aloft, has a similar spatial pattern to the high TKE_s frequency pattern across the U.S. The highest frequencies of occurrence are found over the western half of the U.S., with frequencies in the 15-30% range (i.e. 15-30% of the days in a month have maximum $HITKE_s$ values that exceed the 15 m^2s^{-2} threshold). The eastern half of the U.S, with the exception of the Appalachian Mountain region, typically has frequencies of occurrence of 2% or less. Over the

Appalachian Mountains, high $HITKE_s$ values typically occur from November through April, with ~10-25% of the days in those months having $HITKE_s$ values that exceed 15 m^2s^{-2}.

Buoyancy and wind shear contributions

To assess the relative significance of wind shears and buoyancy in generating the observed TKE_s and $HITKE_s$ patterns across the U.S., a flux Richardson number (Ri) analysis was carried out. The frequencies of occurrence of $Ri < -0.03$, a threshold indicative of a buoyancy dominated turbulence regime, were mapped across the U.S. for each month. During the spring, summer, and early autumn seasons, buoyancy tends to be the dominant factor in generating high near-surface turbulence over the western half of the U.S. Wind shears are the dominant factor in generating high near-surface turbulence over the northern U.S. during the months of November through February. Over the Gulf Coast states of Mississippi and Alabama during the months of July and August, high turbulence events tend to be associated with wind shears under stable conditions. Both buoyancy and wind shear effects play a role in generating high turbulence events over many areas in the Midwest, Northeast, and Southeast during the spring and autumn wildfire seasons.

Temporal variability of TKE_s and $HITKE_s$

In order to identify possible differences in the prominent periods or frequencies of variability in the 3-hourly NARR TKE_s and computed $HITKE_s$ time series that may exist in different regions of the U.S., a continuous wavelet transform spectral analysis (Graps 1995, Torrence and Compo 1998) was performed on regionally averaged TKE_s and $HITKE_s$ time series for defined northwest (37.5°N-50°N, 95°W-125°W), southwest (25°N-37.5°N, 95°W-125°W), northeast (37.5°N-50°N, 65°W-95°W), and southeast (25°N-37.5°N, 65°W-95°W) domains covering the conterminous U.S. For both the northwest and northeast domains, the most prominent cycles or periods of variability in the 3-hourly TKE_s time series over the 1979-2008 period were annual, 6 months, and daily. Three-day to 4-month cycles were also common throughout the 1979-2008 period. This is in contrast to the southwest and southeast domains, where only daily and annual cycles in the TKE_s time series were prevalent.

The temporal variability in the $HITKE_s$ time series for the northwest, northeast, southwest, and southeast regions over the 1979-2008 period differs from the observed TKE_s variability. For the northwest and southwest regions, the most prominent cycles or periods of variability in the 3-hourly $HITKE_s$ were annual and daily, while the northeast and southeast regions were characterized by annual, 6-month, and daily cycles. Three-day to 4-month cycles in $HITKE_s$ variability were also prominent in the northeast and southeast regions. The east-west contrast in $HITKE_s$ temporal variability across the U.S. compared to the north-south contrast in TKE_s temporal variability is a key difference in the two turbulence-based indices.

In addition to the continuous wavelet transform spectral analysis of the 3-hourly NARR turbulence data, a 30-year trend analyses of the annual means of region-averaged TKE_s and $HITKE_s$ were performed to determine whether there have been any substantial long-term trends in these indices. The time series shown in Figs. 3 and 4 suggest there has been a general increase in TKE_s and $HITKE_s$ values over the 1979-2008 period for all regions of the U.S. For TKE_s, overall increases during the 1979-2008 period ranged from 4.12% in the northwest region to 12.92% in the southeast region. The largest increases in TKE_s occurred over the last 13 years (1995-2008) in all regions except the southwest, with the northeast and southeast regions showing 13.39% and 13.65% increases, respectively. Overall increases in $HITKE_s$ values over the 1979-2008 period ranged from 3.24% in the northwest region to 14.25% in the southeast region. Similar to the recent trends in TKE_s values, the largest increases in $HITKE_s$ values occurred over the 1995-2008 period in all regions except the southwest. Increases in the northeast and southeast regions were 15.46% and 16.54%, respectively.

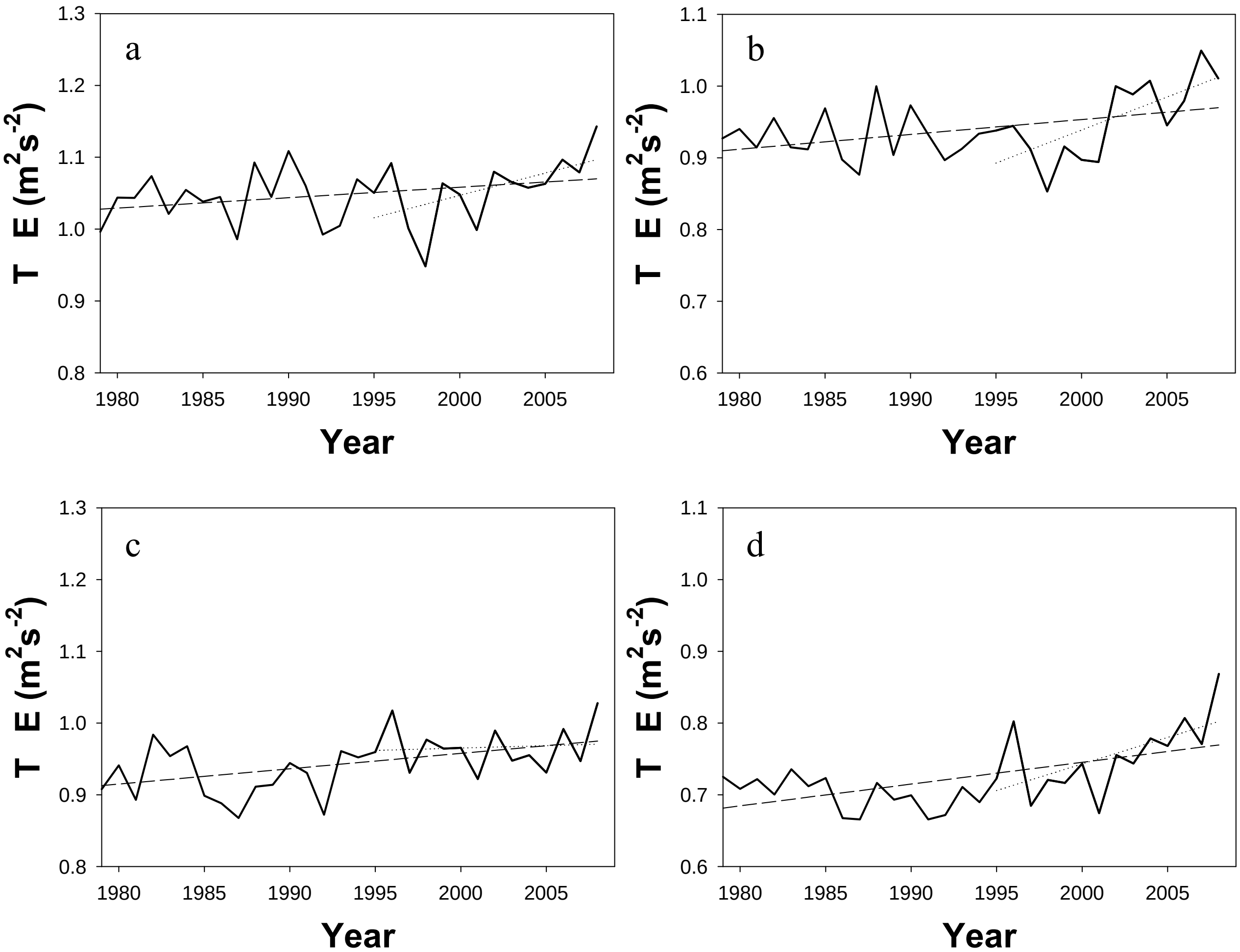

Fig. 3. Thirty-year (1979-2008) trends (solid) in the annual means of region-averaged near-surface turbulent kinetic energy (TKE_s) for the (a) northwest, (b) northeast, (c) southwest, and (d) southeast regions of the U.S. Linear regression lines represent the overall 1979-2008 (medium dashed) and 1995-2008 (dotted) recent trends.

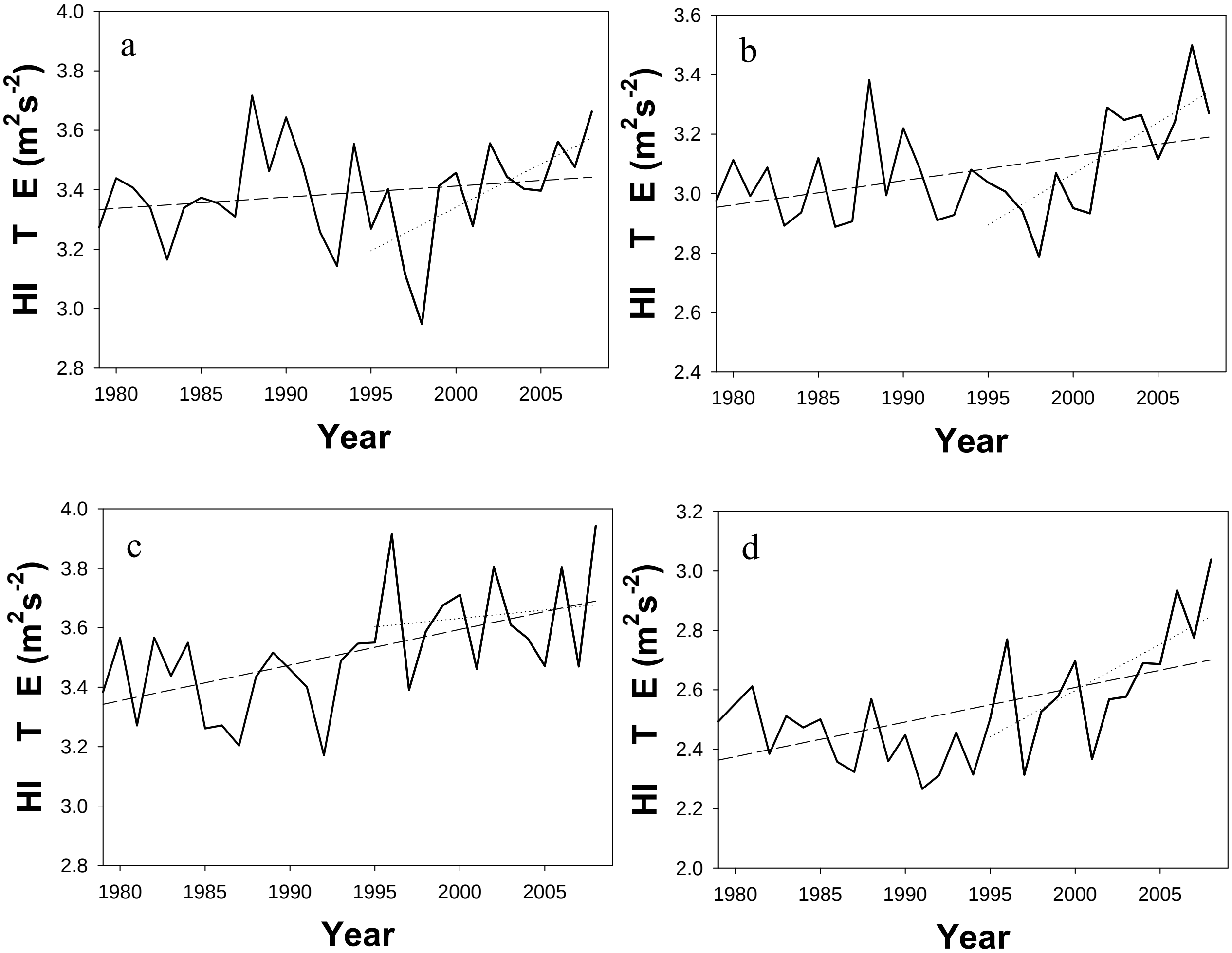

Fig. 4. Thirty-year (1979-2008) trends (solid) in the annual means of region-averaged $HITKE_s$ values for the (a) northwest, (b) northeast, (c) southwest, and (d) southeast regions of the U.S. Linear regression lines represent the overall 1979-2008 (medium dashed) and 1995-2008 (dotted) recent trends.

Conclusions

The analyses of the spatial and temporal patterns of TKE_s and $HITKE_s$ based on the 1979-2008 NARR data suggest that there are substantial regional differences in these indices across the U.S. Average daily maximum TKE_s and $HITKE_s$ values are highest over the high-elevation Rocky Mountain and Appalachian Mountain regions. Over the western half of the U.S., occurrences of daily maximum TKE_s and $HITKE_s$ values exceeding 3 m^2s^{-2} and 15 m^2s^{-2}, respectively, are relatively common from April through September. These thresholds are indicative of a highly turbulent atmospheric boundary layer sitting beneath dry and unstable atmospheric layers aloft, an atmospheric condition conducive to erratic or extreme fire behavior. Over the eastern half of the U.S., exceedances of these thresholds are less common. Because the 3 m^2s^{-2} and 15 m^2s^{-2} thresholds for TKE_s and $HITKE_s$ are frequently exceeded over the western U.S., adopting higher thresholds for these indices for operational fire-weather forecasts in the western half of the U.S. may be needed such that when threshold exceedances occur, it's truly an indication of an anomalous fire-weather event. More research is needed to identify appropriate region- or area-specific threshold values to enhance the efficacy of TKE_s and $HITKE_s$ as operational fire-weather indices.

The observed 30-year (1979-2008) trends in TKE_s and $HITKE_s$ indicate that, at least on a regional average basis, values of these indices have generally increased in every region of the U.S. The most significant increases in these indices have occurred during the 1995-2008 period in the northwest, northeast, and southeast regions of the U.S. An analysis of the long-term trends in near-surface wind shears and near-surface buoyancy, the primary mechanisms for generating atmospheric turbulence, is currently underway to determine their role in producing the observed long-term TKE_s and $HITKE_s$ trends.

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