CSIRO PUBLISHING

www.publish.csiro.au/journals/ijwf International Journal of Wildland Fire, 2007, 16, 139–152

Climatological and statistical characteristics of the Haines Index for North America

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Abstract. The Haines Index is an operational tool for evaluating the potential contribution of dry, unstable air to the development of large or erratic plume-dominated wildfires. The index has three variants related to surface elevation, and is calculated from temperature and humidity measurements at atmospheric pressure levels. To effectively use the Haines Index, fire forecasters and managers must be aware of the climatological and statistical characteristics of the index for their location. However, a detailed, long-term, and spatially extensive analysis of the index does not currently exist. To meet this need, a 40-year (1961–2000) climatology of the Haines Index was developed for North America. The climatology is based on gridded (2.5° latitude × 2.5° longitude) temperature and humidity fields from the NCEP/NCAR reanalysis. The climatology illustrates the large spatial variability in the Haines Index both within and between regions using the different index variants. These spatial variations point to the limitations of the index and must be taken into account when using the Haines Index operationally.

Introduction

Originally introduced in 1988 as the 'Lower Atmospheric Severity Index,' the Haines Index characterises the potential impact of dry, unstable air ~1 to 3 km above the surface on wildfire behaviour and growth (Haines 1988). In particular, the Haines Index provides a measure of the likelihood of plume-dominated fires becoming large or displaying erratic behaviour (Werth and Ochoa 1993). The Haines Index is a widely used tool in wildfire forecasting and monitoring, and in the United States the index is regularly included in the National Weather Service daily fire weather forecasts and the USDA Forest Service's Wildland Fire Assessment System. Meteorological and land management agencies of other countries (for example, the Servicio Meteorológico Nacional of Argentina) also calculate and utilise the Haines Index for assessing wildfire behaviour and growth.

The Haines Index is the sum of a stability (A) component and a humidity (B) component calculated from the lower atmosphere environmental lapse rate (i.e. the change of temperature with height) and dewpoint depression, respectively. Depending on location, one of three Haines Index variants (referred to as 'low', 'mid', and 'high') is used in order to at least partially account for regional variations in surface elevation. For each variant, the temperature and humidity differences are assigned an ordinal value of 1, 2, or 3 to ensure equal weighting of the two components. The ordinal values of the components are then summed. The resulting Haines Index ranges from 2 (very low potential of large or erratic plume-dominated behaviour) to 6 (very high potential). See Appendix 1 for a more complete description of the Haines Index and its derivation.

Haines (1988) patterned the index after commonly used stability indices developed for forecasting thunderstorms and severe weather such as the K index (George 1960) and Total Totals index (Miller 1972). Like these indices, the Haines Index uses temperature and humidity observations at mandatory pressure levels or at pressure levels that, at the time the index was introduced, were usually included in radiosonde (i.e. balloon sounding) reports (Table 1). This approach constrains the index to a fixed pressure layer (for example the 950–850-hPa layer for the low variant), which can vary substantially in terms of its distance above the earth's surface, particularly in areas of steep and irregular topography. As a result, for some locations the lower portion of the layer used in the index calculation may regularly be located well above the typical mixing depth, whereas for other locations, the lower boundary is generally found within the mixed layer (Werth and Werth 1998; Potter 2001). The variation in elevation relative to the surface has large implications for the steepness of the environmental lapse rate and the magnitude of the A component, as well as for the moisture at the pressure level used to compute the B component. Previous researchers have identified a significant positive correlation between the elevation of a station and the frequency of large index values (Werth and Werth 1998). This elevation bias must be considered when using the Haines Index operationally.

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10.1071/WF06086 1049-8001/07/020139

Table 1. Calculating the Haines Index
From Haines 1988

Elevation	Stability (A) component		Humidity (B) component	
	Calculation	Categories	Calculation	Categories
Low	950-hPa temperature minus 850-hPa temperature	A = 1 if <4°C, A = 2 if 4 to 7°C, A = 3 if ≥8°C	850-hPa temperature minus 850-hPa dewpoint	B = 1 if <6°C, B = 2 if 6 to 9°C, B = 3 if ≥10°C
Mid	850-hPa temperature minus 700-hPa temperature	A = 1 if <6°C, A = 2 if 6 to 10°C, A = 3 if ≥11°C	850-hPa temperature minus 850-hPa dewpoint	B = 1 if <6°C, B = 2 if 6 to 12°C, B = 3 if ≥13°C
High	700-hPa temperature minus 500-hPa temperature	A = 1 if <18°C, A = 2 if 18 to 21°C, A = 3 if ≥22°C	700-hPa temperature minus 700-hPa dewpoint	B = 1 if <15°C, B = 2 if 15 to 20°C, B = 3 if ≥21°C

The use of fixed pressure layers can lead to considerable spatial variation in the value of the Haines Index as a function of changing elevations, local and complex physiography, and the pressure layers used in the calculation of the index. In order to employ Haines Index observations and forecasts in an effective and meaningful manner, fire forecasters and managers must be aware of the climatological characteristics of the index. A climatology provides information on the typical index values for a location or region and can be used to estimate the likelihood of high index values. In addition, climatological analyses of the temporal persistence of the Haines Index can be useful in decision making, providing an indication of the length of time that high index values might persist. For example, different fire management strategies are likely for areas where the atmospheric potential for wildfire is usually high for only one or two consecutive days compared to locations where the potential can remain elevated for an extended period. In addition, a climatology can help fire managers and forecasters to assess for their location whether the Haines Index is a useful discriminator of days with unusual instability and/or dryness, or if other measures of stability and humidity should be used instead. Furthermore, a long-term climatology is necessary to evaluate historical variations and potential future changes in the atmospheric component of wildfire hazard.

A comprehensive, long-term, and spatially extensive climatology of the Haines Index does not currently exist. The few previously published climatological analyses have generally been confined to short time periods and to either single radiosonde locations (Jones and Maxwell 1998; Croft *et al*. 2001) or limited geographical areas (e.g. Werth and Werth 1998). Consequently, fire managers and researchers either do not have a 'baseline', or have at best a limited baseline, to compare observed, forecasted, and potential future values of the Haines Index. To in part address this need, a 40-year (1961–2000) climatology of the Haines Index that covers most of North America was developed. The climatology focuses on annual, seasonal, and monthly variations in the frequency, statistical characteristics, and persistence of the Haines Index. The climatology is an outcome of a larger, ongoing research project that is investigating potential future changes in the atmospheric component of wildland fire risk for a perturbed (warmer) climate. Below, the data and methods used to develop the climatology are described. Several maps of representative statistical analyses are then presented along with a brief discussion of the patterns they reveal. Finally, the scientific and operational implications of the climatology are discussed.

Data and methods

The climatology is derived from reanalysis fields available from the National Centers for Environmental Prediction (NCEP) and the National Center for Atmospheric Research (NCAR). The NCEP/NCAR reanalysis is a global dataset with a spatial resolution of 2.5° latitude by 2.5° longitude (Kalnay *et al*. 1996). Reanalysis data are a 'hybrid' of observations and short-range forecasts. A short-range forecast serves as a first guess field, which is then modified by observations from radiosondes, satellites, ships, buoys, and aircraft. At the core of any reanalysis is a data assimilation system that includes a global operational forecasting model, complex algorithms for quality control of raw observations, and space and time interpolation schemes (Kalnay *et al*. 1996). The same data assimilation system is used for the entire period of the reanalysis in order to eliminate artificial climate trends introduced by changes to the components of the data assimilation system. The NCEP/NCAR reanalysis fields include temperature and humidity (along with several other variables) at the mandatory pressure levels. The reanalysis fields were chosen over radiosonde observations because of their greater and more uniform spatial coverage over the study area and because of concerns about the quality of the radiosonde data. The large number of discontinuities in radiosonde time series at individual stations as a result of station relocations and changes in sensors and observing practices can make the radiosonde record difficult to use for climatological analysis (e.g. Elliott and Gaffen 1991; Elliott *et al*. 1998; Gaffen *et al*. 2000; Winkler 2004). Although the reanalysis fields extend back to 1948, only the period from 1961 to 2000 was used because a considerably larger number of observations, particularly satellite and aircraft observations, were included in the later period assimilation runs (Kalnay *et al*. 1996).

The climatology is limited to 0000 UTC. This time period was originally chosen by Haines (1988) because upper-air observations were only available at 0000 UTC and 1200 UTC. For much of the North American continent, heating, and hence instability, are generally larger at 0000 UTC, and this is closer to the time of greater fire danger in most of North America. There is some debate in the literature regarding the best choice of observation

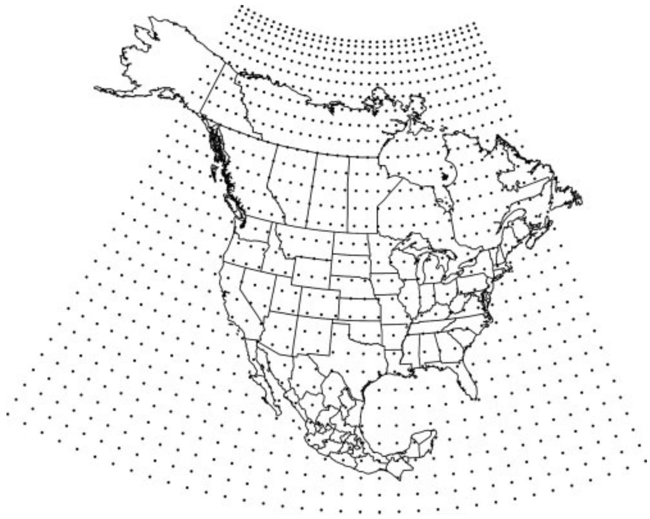

Fig. 1. Study area and location of NCEP/NCAR reanalysis grid points.

time for calculating the Haines Index. Several authors (e.g. Werth and Werth 1998) argue that index values calculated using 1200 UTC observations better capture synoptic-scale stability and humidity conditions, particularly at high elevation locations with deep mixing depths, and that the correlation of high (5 or 6) index values with wildfire extent is better for this observation time (Brotak 1992–1993). Other authors feel equally strongly that Haines Index values calculated at 1200 UTC may underestimate fire potential (Jones and Maxwell 1998), and that observations at 0000 UTC are more representative of the conditions when wildland fires are most active (Kochtubajda *et al.* 2001). Future plans include expanding the climatology presented here to include additional time periods.

As discussed in more detail in the appendix, Haines divided the United States along climatological divisions into three regions (low, mid, and high) according to the generalised surface elevation. Three different variants of the Haines Index were formulated so that the pressure layer used in the index calculation is 'high enough above the surface to avoid the major diurnal variability of surface temperature and surface-based inversions' (Haines 1988), but not so high that the index is measuring mid-tropospheric rather than lower-tropospheric stability and humidity. To extend the boundaries for the low, mid and high variants into Canada and Mexico, the Haines boundaries for the United States were first overlaid within a Geographic Information System (GIS) onto the generalised terrain field for the NCEP/NCAR reanalysis. The boundaries were compared visually to the elevation contours, and the 300 and 1000-m contours were found to best outline Haines' original boundaries between the low and mid regions and between the mid and high regions, respectively. These contours were then used to define the regional boundaries for Canada and Mexico.

The A component, B component, and Haines Index were calculated for the reanalysis grid points bounded by 10° and 85°N latitude and by 60° and 145°W longitude (Fig. 1). The study area covers most of North America with the exception of western Alaska and extreme eastern Canada. The domain was chosen to maximise the land area considered, while minimising computational complexity and empty ocean areas.

The climatology focuses on annual, seasonal, and monthly variations in the characteristics of the Haines Index. Several different parameters were included in the climatology including standard statistical measures such as mean, median, standard deviation, and percentiles. In addition, frequency and persistence measures are provided for Haines Index values ≥ 4 ('moderate' or greater potential of plume-dominated fires), ≥ 5 ('high' or 'very high' potential), and $=6$ ('very high' potential). The complete list of parameters included in the climatology is provided in Table 2. All analyses are in map format and are displayed on an Albers map projection. Only the analysis over the North America land area is shown; values for the neighbouring ocean surfaces have been masked.

Climatological characteristics of the Haines Index

To illustrate important spatial variations in the Haines Index, analyses are presented below for a subset of the parameters included in the climatology. For the purpose of this discussion, annual values of the low variant are shown, and summer (June, July, and August) values of the mid and high variants are shown. Analyses for the other time scales and statistical parameters included in the climatology can be viewed as part of an electronic atlas available at http://www.haines.geo.msu.edu (verified March 2007).

The parameters chosen are statistical measures that the authors judge to be of particular interest to the research and operational community and that are easily comparable to previous climatological analyses of the Haines Index. In addition to the Haines Index itself, climatological analyses for the individual A and B components are also shown below, as these analyses can provide fire forecasters and managers with insights as to why their location may have generally lower or higher Haines Index values.

'Low' variant of the Haines Index

Spatial variation in the magnitude of the vertical temperature gradient between the 950 and 850-hPa levels is small across eastern North America (Fig. 2). For most of the region, the temperature difference falls between 4 and 7°C. These values translate to an average A component value of 2 (Table 1). An exception is northern Canada where the average environmental lapse rate is smaller, between 1 and 4°C (equivalent to an A component of 1). In general, the average dewpoint depression increases from north to south across the low variant region. The highest average dewpoint depressions are found along the Gulf Coast and are on the order of 10 to 11°C, corresponding to a B component of 3. Dewpoint depressions are smallest in northern Canada south of Hudson Bay where average values of 7 to 8°C correspond to a B component of 2.

The average values of the Haines Index are smallest (~3.0 to 3.5) in extreme north-eastern North America, north-central Canada, and the northern Great Lakes region (Fig. 2). Larger average Haines Index values of 3.5 to 4.0 in the south-eastern United States reflect the generally larger dewpoint depressions in this area, whereas the average Haines Index values of 4.0 to

Table 2. List of parameters including in the Haines Index climatology
All parameters were calculated for annual, seasonal, and monthly temporal scales. Parameters for which maps are included in the text are shown in italics

Measures of central tendency	Measures of variability and range	Frequency parameters (expressed as a percentage)	Persistence measures (expressed in days)
Average value of the Haines Index, A component, and B component	Standard deviation of the Haines Index, A component, and B component	*Frequency of 0000 UTC observations with Haines Index values ≥4, ≥5, and =6*	*Average run length of Haines Index values ≥4, ≥5, =6*
Median value of the Haines Index, A component, and B component	75th, 90th, 95th, and 99th percentile of the Haines Index		*Maximum run length during the 40-year period of Haines Index values ≥4, ≥5, =6*
	75th, 90th, 95th, and 99th percentile of the A component		Average number of 1-day, 2-day . . . 14-day, and ≥30 day runs of Haines Index values ≥4, ≥5, =6
	75th, 90th, 95th, and 99th percentile of the B component		

4.5 in eastern Texas and Oklahoma are primarily a function of lapse rate.

Haines Index values of ≥4 occur on more than 50% of all days for a large area extending from the Great Lakes southward (Fig. 3). In central Texas over 80% of days per year have index values ≥4. These high frequencies indicate that in this region an index value of 4 has limited ability to discriminate between days with unusual stability and humidity conditions. This conclusion is reinforced by the plot of maximum run length, which shows that in at least one year during the 40-year study period portions of central Texas had index values ≥4 on close to 120 consecutive days. Only in north-central and north-eastern Canada do index values of 4 likely have some discriminatory power.

Index values ≥5 are considerably less frequent, especially in northern Canada where fewer than 10% of all days have a 'high' or 'very high' potential for large or erratic plume-dominated fires (Fig. 4). However, in eastern Oklahoma and Texas, index values ≥5 occur on 30 to 60% of all days, suggesting that in this region even index values of 5 are not particularly good discriminators of atypically favourable conditions for large or erratic plume-dominated fires. The spatial pattern of the maximum run length of index values ≥5 is very similar to the overall frequency. The longest duration was less than five days in the Canadian Maritimes, and less than 10 days elsewhere in north-eastern Canada. For most of the United States east of the Mississippi River, the maximum duration in 1961–2000 of index values ≥5 fell between 5 and 15 days. In contrast, observed maximum durations increase sharply west of the Mississippi River and approach 60 days in central Texas.

In general, the frequency of Haines Index values equal to 6 increases from east-to-west across eastern North America (Fig. 5). A Haines Index value of 6 at 0000 UTC occurs on less than 1% of the days per year in eastern and north-central Canada and the south-eastern United States. The frequency increases in the Ohio Valley and the Great Lakes regions to 1–2% of all days. A large gradient is observed farther west, and the frequency of days with very high fire potential, as indicated by the Haines Index, increases to around 20% in central Oklahoma and Texas. In north-eastern Canada and extreme southern Florida, there were no consecutive days during 1961–2000 of Haines Index values equal to 6, meaning that a day with very high fire potential was always followed by a decrease in fire potential the following day. Strings of days with very high fire potential were also rare along the Atlantic coast of the United States and in north-central Canada, where the maximum persistence was approximately two days. Maximum run lengths in the Great Lakes and Ohio Valley regions were somewhat larger at four to five days. Farther west, extended periods of very high fire potential occurred during the study period with the longest periods (more than 20 days) observed in central Texas and Oklahoma.

'Mid' variant of the Haines Index

During summer, strong east-to-west gradients in the climate parameters for the mid variant of the Haines Index are found across the Central Plains of North America (Fig. 6). The average environmental lapse rate between the 850 and 700 hPa levels ranges from 8 to 10°C (A component of 2) in north-eastern Minnesota to 11 to 14°C (A component of 3) from western Manitoba southward to north-central Texas. In north-western Canada, the average environmental lapse rates range from 8 to 10°C (A component of 2). Similar values are found in the elevated Appalachian region, although summer is not the primary fire season in this portion of the mid Haines region. Average dewpoint depressions generally increase westward in summer from ~6 to 7°C (equivalent to a B component of 2) in north-eastern Minnesota to over 13°C (B component of 3) in a narrow zone that extends from south-eastern Montana to north-west Texas. The smallest dewpoint depressions are found at high latitudes in north-western Canada. (Note that the low and mid variants of the Haines Index both use dewpoint depression at 850 hPa.)

An east-to-west gradient is also evident in the average summertime Haines Index values for the mid variant region (Fig. 7). Average values range from ~3.5 in northern Minnesota to 5.5 in north-western Texas. Elsewhere (north-western Canada and the Appalachians) the average index value is 3.0 to 3.5. The large average Haines Index values in the western portion of the Central Plains result from both large environmental lapse rates and large dewpoint depressions, and suggest that on average this area has a moderate to high potential of plume-dominated fires during summer, at least as measured by the Haines Index. On the other hand, the lower average index values in north-western Canada reflect generally higher relative humidity and suggest a low potential for plume-dominated fires.

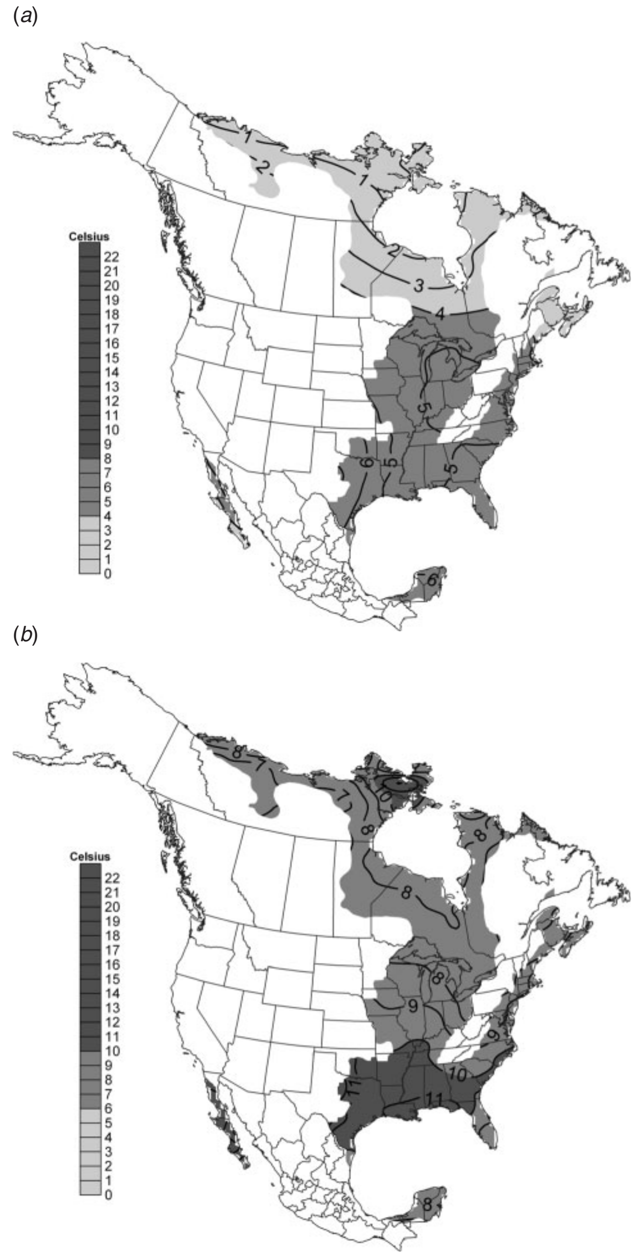

Fig. 2. Annual mean (*a*) environmental lapse rate (950-hPa temperature minus 850-hPa temperature) in °C, and (*b*) 850-hPa dewpoint depression (°C) during 1961–2000 for the low variant of the Haines Index. Shading refers to the categorical values for the stability (A) and humidity (B) components, with light shading, medium shading, and dark shading representing categorical values of 1, 2, and 3, respectively. Locations outside the low variant region are shown in white.

In much of the Central Plains and Canadian Prairies, over 70% of summer days have Haines Index values ≥4 (Fig. 8), and in some areas the frequency is over 90%. Even in the northern portions of the Yukon and North-west Territories, and in Nunavut, more than 30% of summer days have index values associated with a moderate or greater potential of plume-dominated fires. Not surprisingly given these high frequencies, index values ≥4 are very persistent. The maximum run length for the 40-year period ranged from 30 days to over 120 days for much of the mid variant region. Only in north-western Canada, northern Minnesota, south-western Ontario and in the Appalachians were the maximum run lengths shorter than 30 days.

In the Central Plains, at least 30%, and for some locations over 80%, of summer days have index values that fall within the high or very high fire potential categories (i.e. index values ≥5) (Fig. 9). Elsewhere in the mid variant region, the frequency of index values ≥5 is ~10–20%. Index values ≥5 can be remarkably persistent. For much of the Central Plains and Prairie Provinces maximum run lengths in 1961–2000 ranged from 10 to 60 days, and in north-west Texas the maximum run lengths exceeded 90 days, which encapsulates the entire summer season.

Haines Index values of 6 (very high fire potential) are observed at 0000 UTC on less than 3% of all summer days in the Appalachians and northern portion of the mid variant region (Fig. 10). Elsewhere, however, the frequency of days with a very high potential for plume-dominated fires increases from approximately 5% of all summer days from central Alberta and Saskatchewan to central Texas, to over 40% of all summer days in a narrow zone that extends from north-eastern Montana to north-western Texas. Maximum run lengths during the study period were three or fewer days in the northern and eastern portions of the mid variant region compared to over 20 days, and in some locations over 60 days, in the western Central Plains.

'High' variant of the Haines Index

Summertime average environmental lapse rates for the high version of the Haines Index exceed 15°C across western North America (Fig. 11). These larger values, compared to the temperature differences for the low and mid variants, reflect the thicker layer (700–500 hPa) over which the high variant of the Haines Index is calculated. The largest values are located in the Great

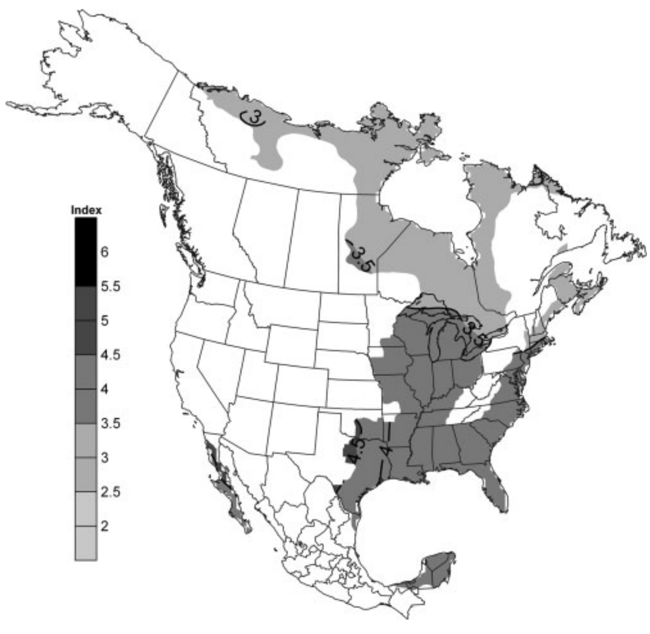

Fig. 3. Annual mean Haines Index (low variant) for 1961–2000. Locations outside the low variant region are shown in white.

(*a*) (*b*)

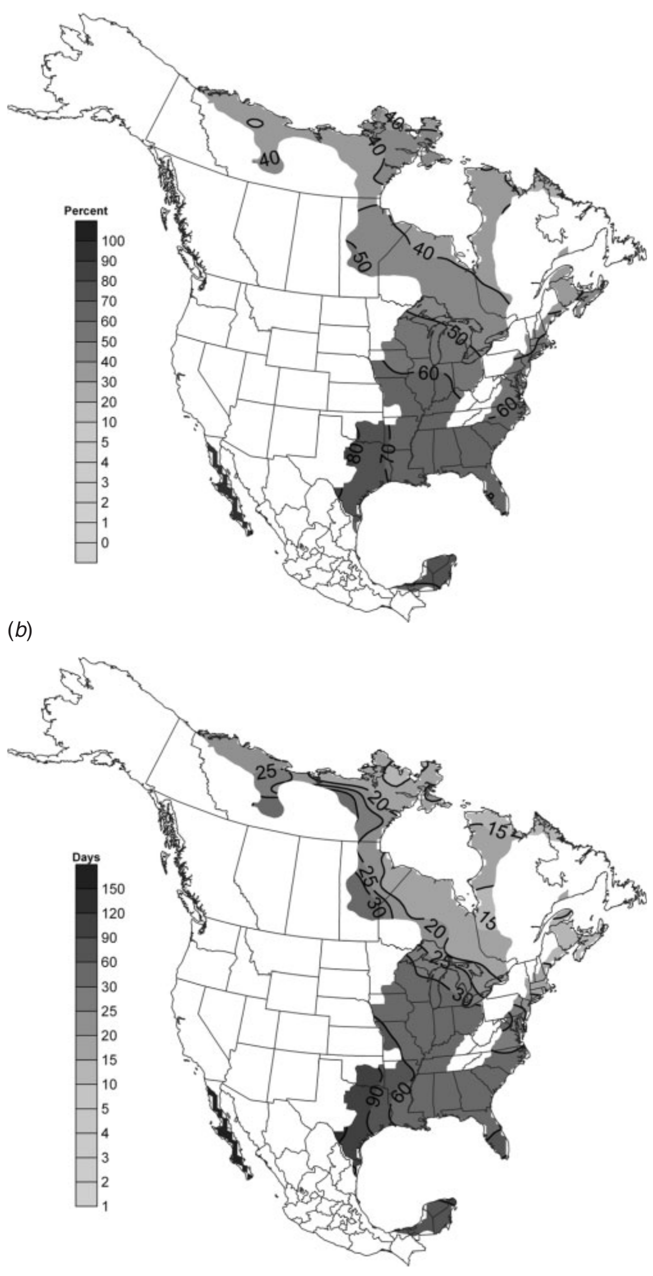

Fig. 4. Haines Index low variant: (*a*) frequency (as percentage of days per year) that the index is ≥4, and (*b*) the maximum consecutive number of days during 1961–2000 with index values ≥4 at 0000 UTC. Locations outside the low variant region are shown in white.

Basin along the border between Utah and Colorado. Here, the average environmental lapse rate is ≥22°C, which corresponds to an A component value of 3. The largest dewpoint depressions are located over northern and central California where the average 700 hPa dewpoint depression exceeds 20°C (equivalent to a B component of 3). These large dewpoint depressions reflect the influence of summertime subtropical high-pressure systems over the eastern Pacific Ocean (Klein 1957). Average dewpoint depressions during summer are relatively small (<14°C; B component of 1) over western Canada, the Northern Rockies, the Front Ranges of the Rocky Mountains, and central Mexico. Larger average values (15 to 18°C; B component of 2) are found over much of the Great Basin, especially south-western Utah and Nevada.

Summertime average Haines Index values fall within the 'very low' or 'low' categories for much of western North America (Fig. 12). Average values are lowest in western Canada, the Pacific North-west, the Northern Rockies, and central Mexico, primarily because of high relative humidity at 700 hPa in these areas. Average Haines Index values in excess of 4 are found

(*a*) (*b*)

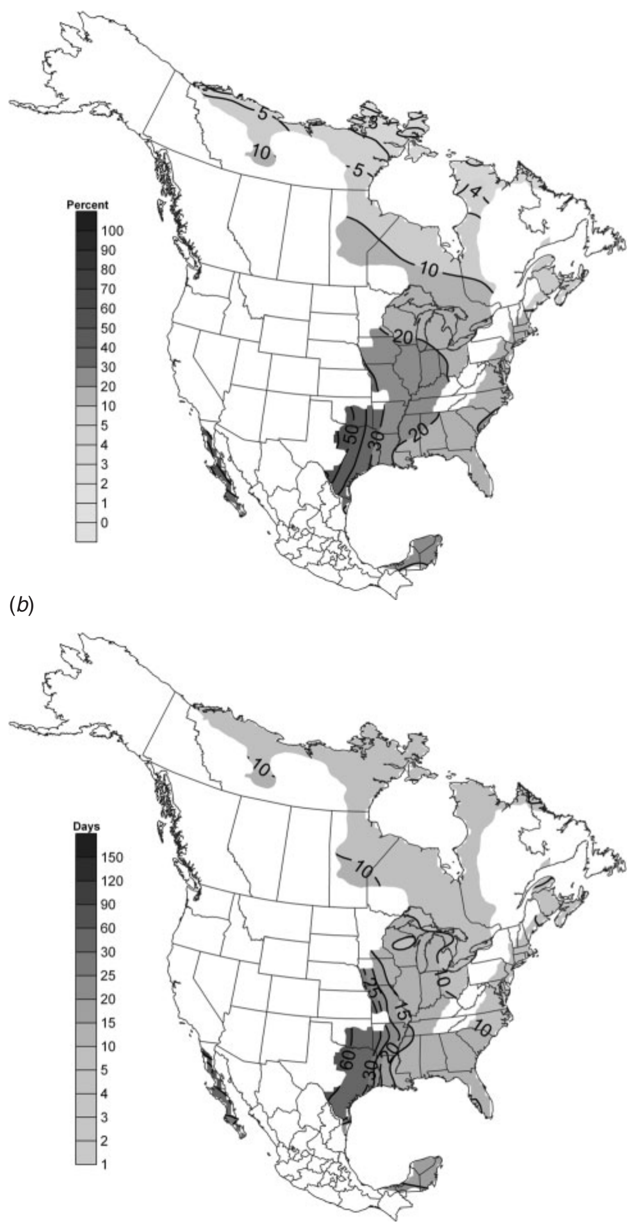

Fig. 5. As in Fig. 3 except for values of the Haines Index low variant ≥5.

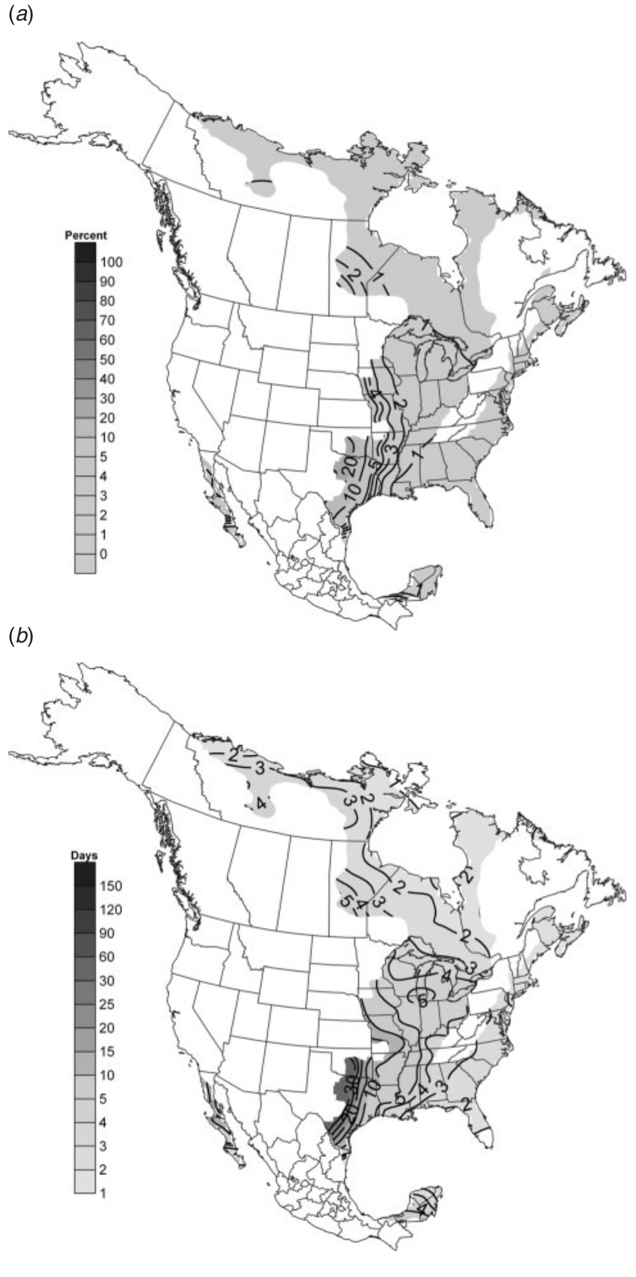

Fig. 6. As in Fig. 3 except for values of the Haines Index low variant equal to 6.

in the Great Basin, specifically Utah, where both the environmental lapse rate and the dewpoint depression tend to be relatively large.

In western Canada and southern Mexico, index values of ≥4 occur on less than 20% of all summer days. In some areas, the frequency is less than 5%, which suggests that index values ≥4 represent relatively unique stability and humidity conditions for these locations (Fig. 13). On the other hand, in California and the Great Basin, index values of ≥4 are frequent, occurring on 50 to 60% of summer days. Maximum run lengths for 1961–2000 were also larger in this region with index values ≥4 persisting at times for close to 30 days. Haines Index values of ≥5 are most frequent in central California and the Great Basin, where they occur on 30 to 40% of summer days (Fig. 14). In these areas, high or very high fire potential has persisted for as long as 30 days. In contrast, maximum run lengths during 1961–2000 were less than three days for western Canada and ∼5 to 10 days in central Mexico.

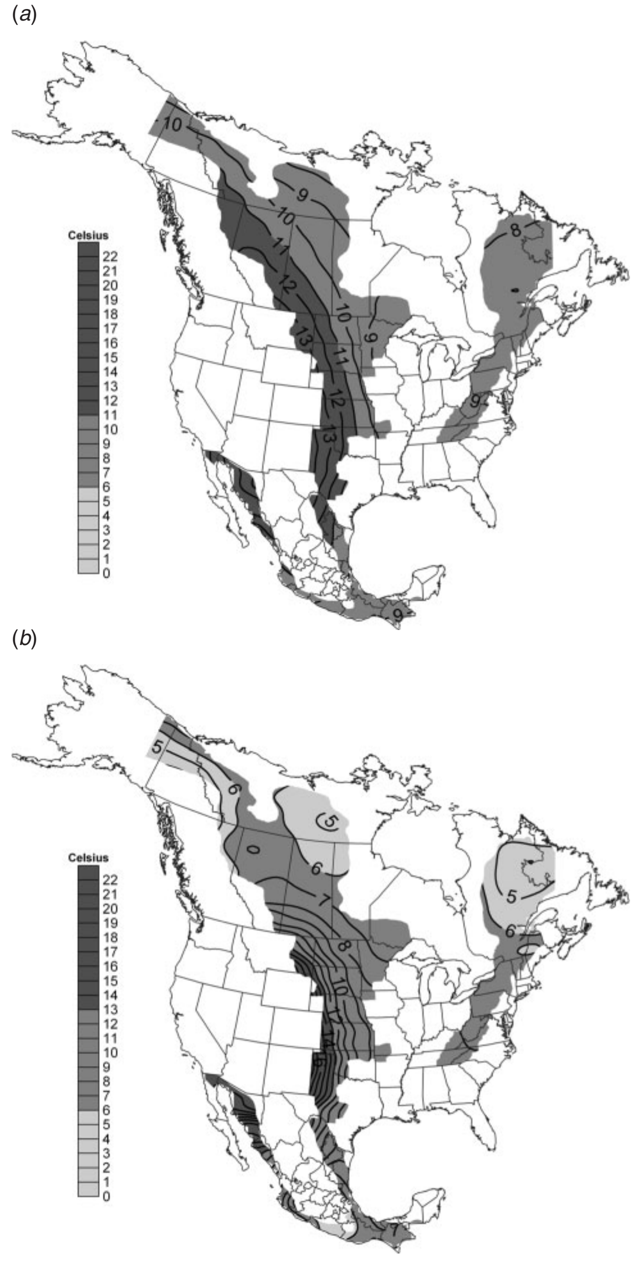

Fig. 7. Summer (June, July, August) (*a*) mean environmental lapse rate (850-hPa temperature minus 700-hPa temperature) in °C, (*b*) 850-hPa dewpoint depression (°C) during 1961–2000 for the mid variant of the Haines Index. Shading refers to the categorical values for the stability (A) and humidity (B) components, with light shading, medium shading, and dark shading representing categorical values of 1, 2, and 3, respectively. Locations outside the mid variant region are in white.

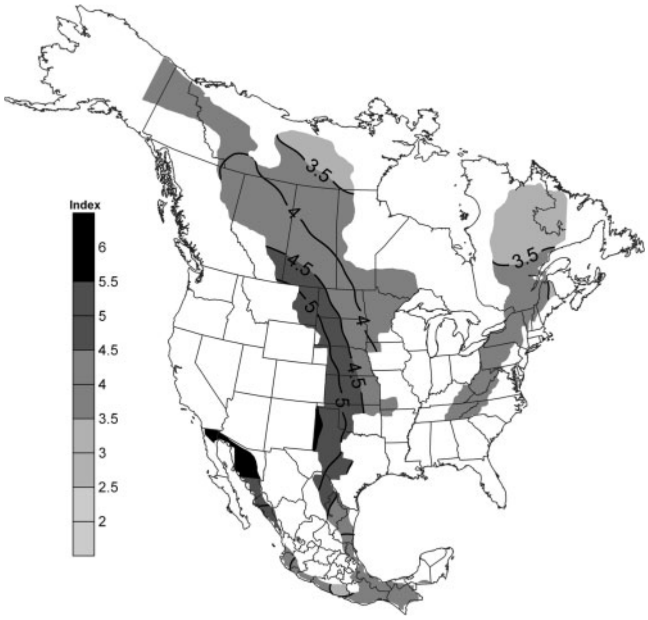

Fig. 8. Summer mean Haines Index (mid variant) for 1961–2000. Locations outside the mid variant region are shown in white.

The frequency of very high potential for plume-dominated wildfires is largest over the Great Basin and the central and southern Rocky Mountains, where index values equal to 6 are present on more than 10% of summer days (Fig. 15). In western Colorado, southern Utah, and eastern Nevada, over 20% of summer days have Haines Index values equal to 6. In contrast, Haines Index values of 6 occur on fewer than 5% of summer days over much of California, even though index values of 4 and 5 are very frequent in this area. Less than 1% of all summer days in western Canada, the north-western United States, and central and southern Mexico report Haines Index values of 6 at 0000 UTC. The spatial pattern of the maximum run length of Haines Index values equal to 6 is almost identical to that for the frequency of very high potential index values (Fig. 16). Maximum run lengths during 1961–2000 were largest in the Great Basin where they approached 20 days. On the other hand, a day with a very high potential for plume-dominated fires in western Canada was rarely, if ever, followed by a second day of elevated potential.

Discussion

Original design of the Haines Index

Reading 'in-between the lines' of Haines' original paper, it appears that he considered a desirable index to be one that (1) can be easily calculated from routinely available observations, (2) has a strong association with actual fire occurrence, and (3) is structured so that the high categories are climatologically infrequent. The use of mandatory pressure levels meets the first of these criteria, and Haines selected the thresholds for the A and B components based on 74 large fires that occurred in the United States during a 20-year period such that the index values are large for wildfire events. Haines' analysis of one year of index values for two locations suggested that the third criterion was also met. However, the climatological analyses presented here demonstrate that for large portions of North America the highest categories (5 and 6) of the Haines Index occur frequently, with some places experiencing large index values on well over half of all days. Furthermore, the two stations (Salem and Winslow) that Haines selected to validate his index lie close to large gradients in the frequency of high index values. Selection of locations either farther north (in the case of Winslow) or farther west (in the case of Salem) may have led to a quite different formulation of the index.

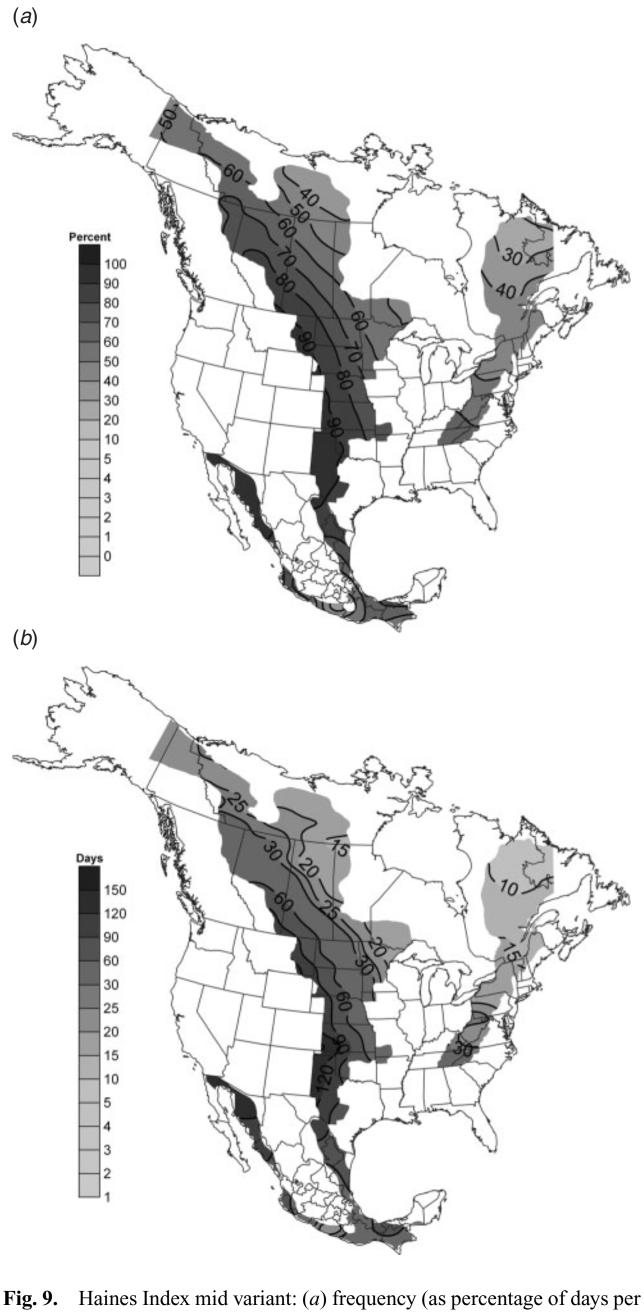

Fig. 9. Haines Index mid variant: (*a*) frequency (as percentage of days per summer season) that the index is ≥4, and (*b*) the maximum consecutive number of days in summer during 1961–2000 with index values ≥4 at 0000 UTC. Locations outside the mid variant region are shown in white.

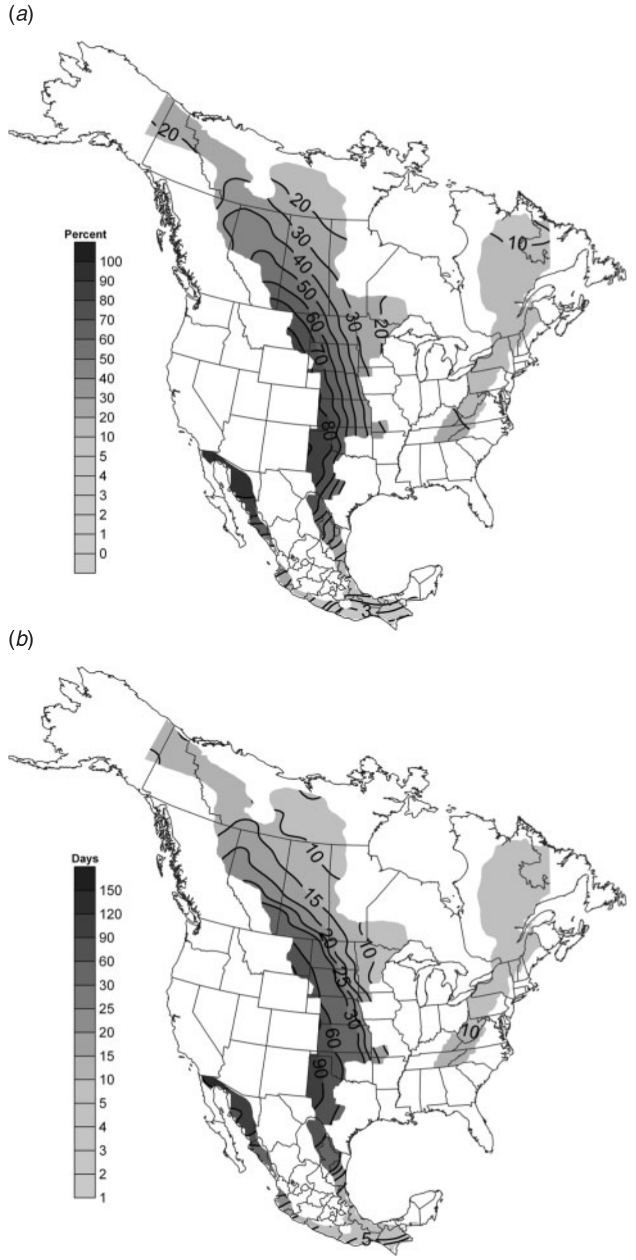

Fig. 10. As in Fig. 8 except for values of the Haines Index mid variant ≥5.

Comparison with previous climatologies

The most extensive prior climatology is that of Werth and Werth (1998) who used 6 years of observations at 20 radiosonde stations in the western United States to analyse the monthly and seasonal frequencies of Haines Index values for the warm season (defined as June through October). There is considerable agreement between their results and ours. For example, the spatial pattern of summertime high variant Haines Index values equal to 6 shown here is strikingly similar to the distribution provided by Werth and Werth (1998) for the warm season (their fig. 3), with the highest frequencies (>20% for both studies) observed over the Great Basin and lowest frequencies (<2%) over the Pacific North-west. Both studies also identified large dewpoint depressions over California, and noted that Haines Index values of 4 and 5, but not 6, are as frequent over central California as over the Great Basin and central Rocky Mountains.

Three other studies focused on the frequency of the Haines Index at only one or two radiosonde stations, and the climatological analyses presented here also agree reasonably well with the findings from those analyses. Jones and Maxwell (1998) found for Albuquerque, New Mexico that the average monthly frequency of Haines Index values equal to 6 is ~21% during June through August; the estimated summertime frequency over central New Mexico from the NCEP/NCAR climatology

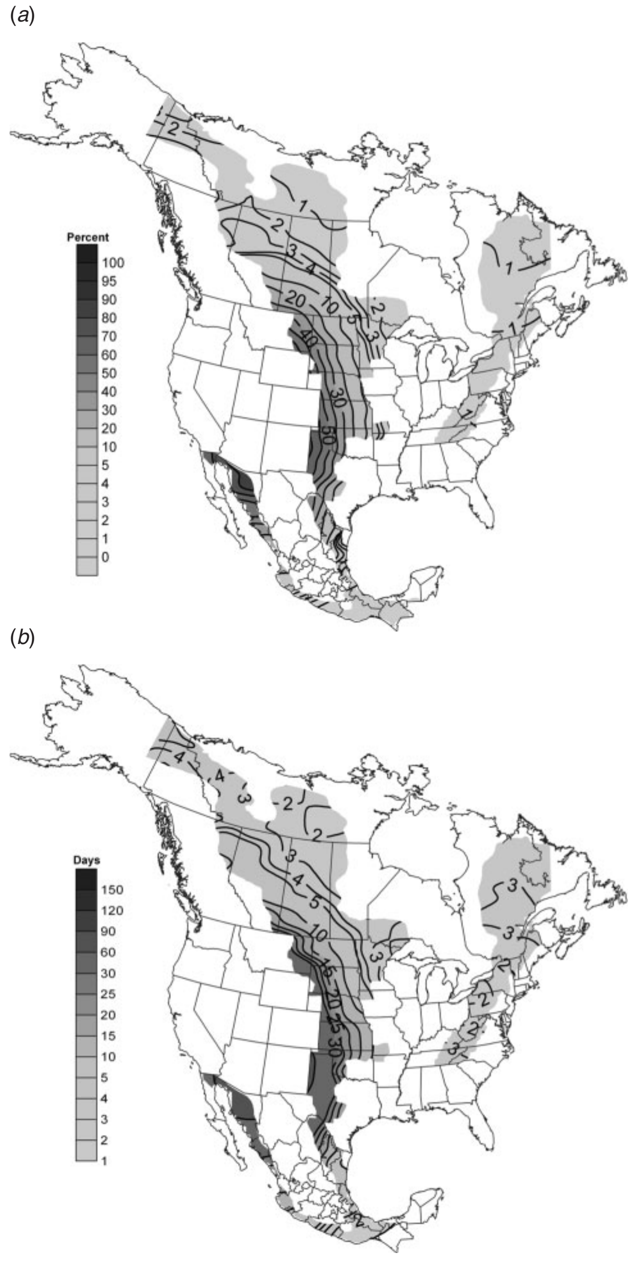

Fig. 11. As in Fig. 8 except for values of the Haines Index mid variant equal to 6.

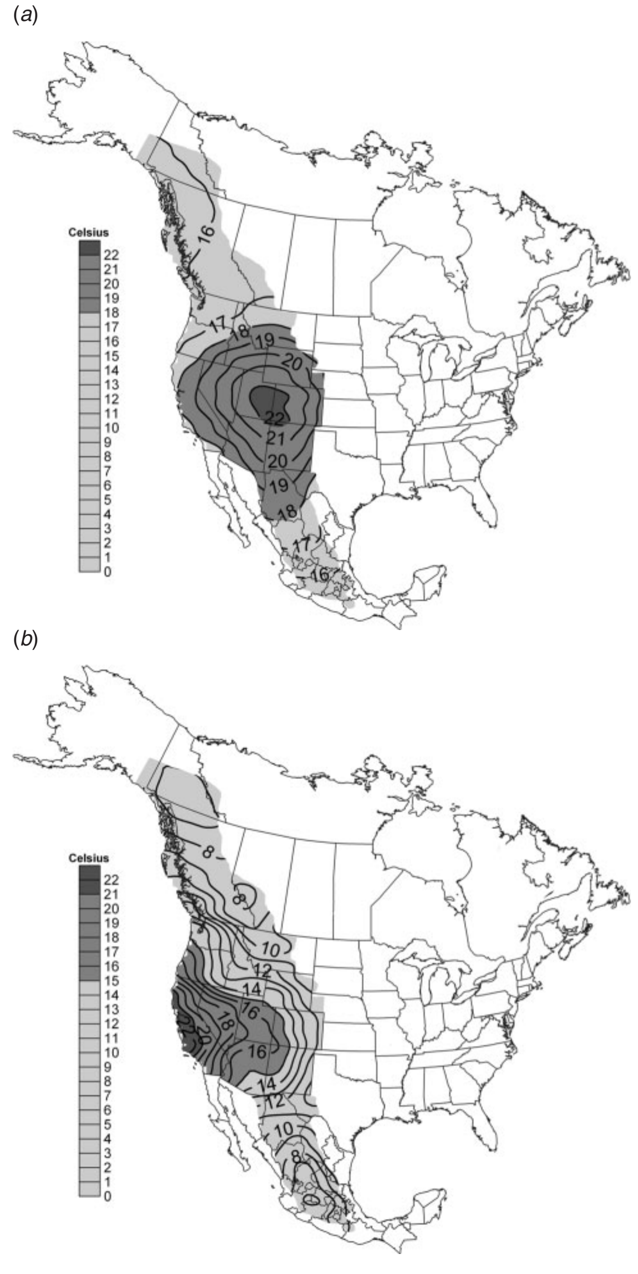

Fig. 12. Summer (June, July, August) (*a*) summer mean environmental lapse rate (700-hPa temperature minus 500-hPa temperature) in °C, and (*b*) summer mean 700-hPa dewpoint depression (°C) during 1961–2000 for the high variant of the Haines Index. Shading refers to the categorical values for the stability (A) and humidity (B) components, with light shading, medium shading, and dark shading representing categorical values of 1, 2, and 3, respectively. Locations outside the high variant region are shown in white.

is ~15%. The results presented here also agree generally with the rudimentary climatologies that Haines used to develop his index. Using radiosonde observations for one year (1981) at two radiosonde locations (Salem, Illinois and Winslow, Arizona), Haines found that the median index value fell in the 'low potential' category, which corresponds well with the average Haines Index values shown here of around 3.5 in the vicinity of both Winslow and Salem. Haines also concluded, based on the analysis for these two stations, that for the low elevation variant about 5% of all fire season days had index values of 6, and that for the high elevation variant about 6% of all fire seasons days had index values of 6. The frequencies for north central Arizona obtained from the NCEP/NCAR climatology are somewhat higher at ~10–12%, although these values are for the shorter summer period rather than the longer fire season. The NCEP/NCAR climatology frequencies for western Illinois fall only within the 1–2% range, but in this case, the frequencies refer to the entire year rather than only the fire season. The only study for which the results presented here are not in good agreement is the analysis by Croft *et al*. (2001) of summertime Haines Index values for Bismarck, North Dakota using one year of radiosonde observations. Their analyses suggest that index values of 6 occur 52% of the time during summer, whereas the NCEP/NCAR climatology suggests a 10–15% frequency.

Reanalysis data and radiosondes

The comparisons above suggest that the NCEP/NCAR climatology captures the major spatial patterns and the relative frequency of the different index categories and is an appropriate climatological baseline to which observed and forecasted values of the Haines Index can be compared. Even though the Haines Index was originally developed from radiosonde observations, a radiosonde-based climatology may not necessarily be a 'better' or more appropriate climatological baseline compared to one developed from reanalysis fields. Many forecast and land management offices now calculate the 'observed' Haines Index values from the initialisation fields of numerical weather prediction models rather than from radiosonde observations, and forecasted values of the index are, of course, calculated from model fields. This suggests that model initialisation fields may be a more appropriate dataset for a baseline analysis. A difficulty

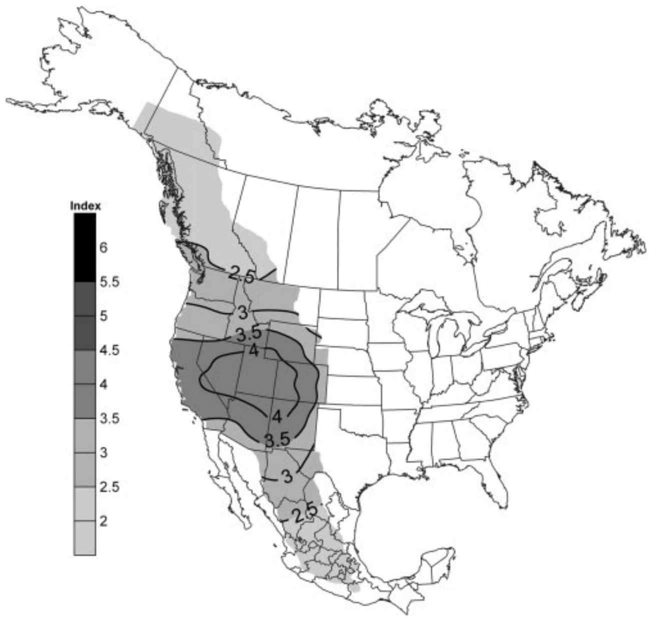

Fig. 13. Summer mean Haines Index (high variant) for 1961–2000. Locations outside the high variant region are shown in white.

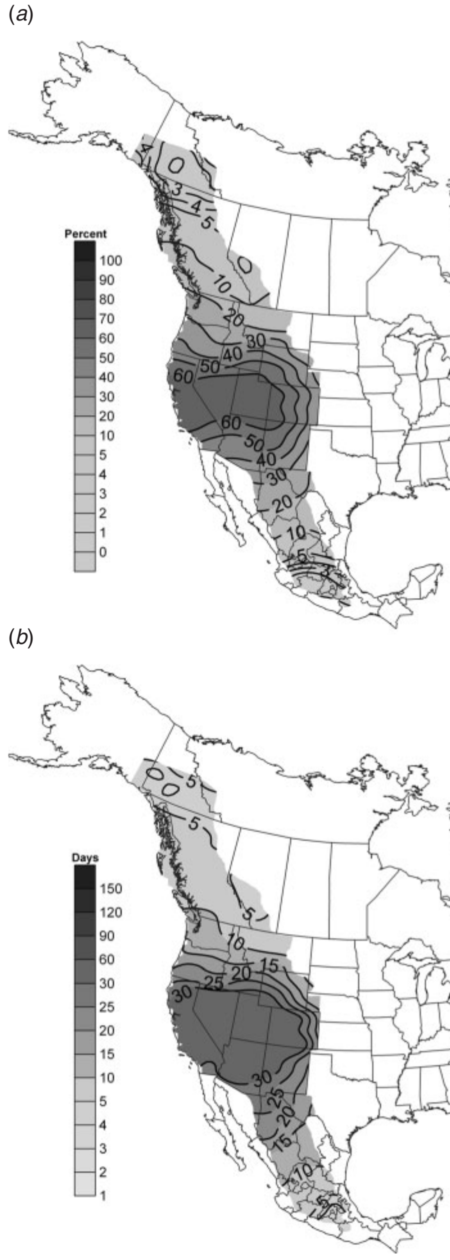

Fig. 14. Haines Index high variant: (*a*) frequency (as percentage of days per summer season) that the index is ≥4, and (*b*) the maximum consecutive number of days in summer during 1961–2000 with index values ≥4 at 0000 UTC. Locations outside the high variant region are shown in white.

is that frequent changes to model structure prohibit the accrual of a sufficiently long database for climatological analysis. The NCEP/NCAR reanalysis fields, which have characteristics of both observations and model fields, are perhaps currently the best available long-term database for climatological analysis of the Haines Index.

Influence of elevation

Ideally, a climatological analysis of the Haines Index would point out those areas where stability and humidity are more favourable for development of large or erratic plume-dominated wildfires as a result of the larger-scale atmospheric circulation. The analyses shown here suggest that it is often difficult to isolate the influence of atmospheric circulation on fire potential because of the strong association of high index values with elevation. For many locations with elevated topography, the lower portion of the layer used in the index calculation appears to fall within the mixing layer rather than above it. While others have focused on the relation between high index values and elevation in the mountainous areas of the western United States (e.g. Werth and Werth 1998), the analyses provided here suggest that elevation has an even larger impact on index values in the western portions

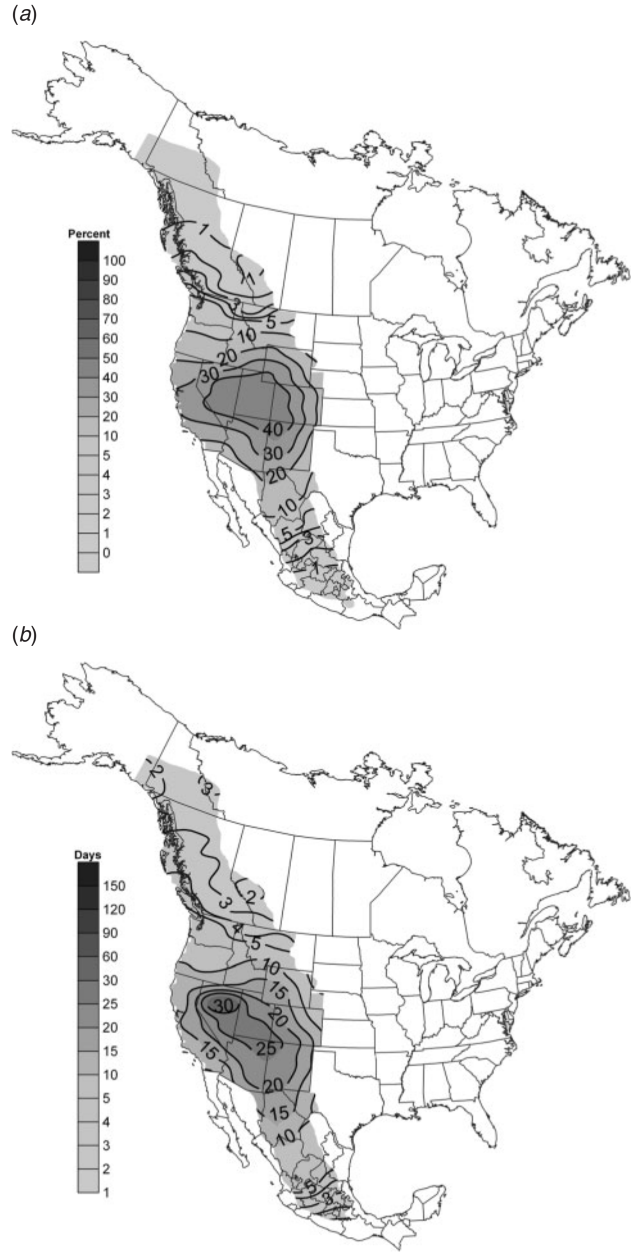

Fig. 15. As for Fig. 13 except for values of the Haines Index high variant ≥5.

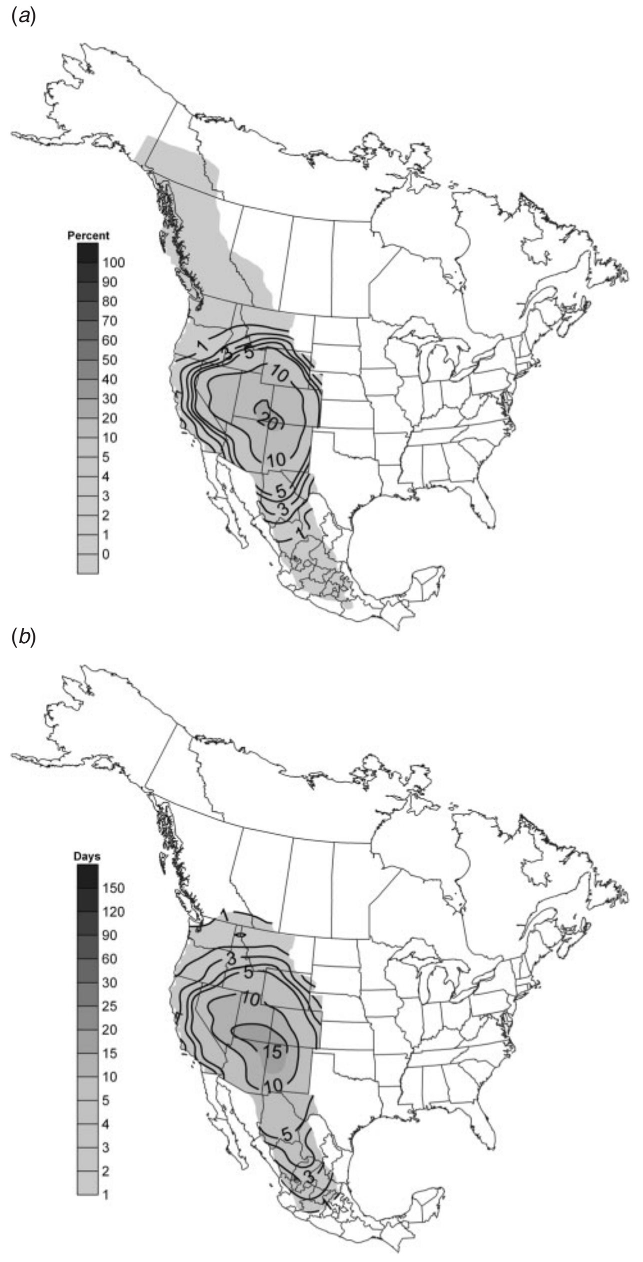

Fig. 16. As for Fig. 13 except for values of the Haines Index high variant equal to 6.

of the mid variant region, an area of sloping topography with elevations approaching 1000 m above sea level. Here index values of 5 or 6 are not able to distinguish days with typical stability and humidity conditions from those with unusual conditions. In fact, in parts of north-west Texas, the average Haines Index value is a 6! These findings are in line with the contention of Kochtubajda *et al*. (2001) that the mid variant of the Haines Index is not sensitive enough to identify the potential for extreme fire behaviour, and the concern of Potter *et al*. (2002) that large instability values, caused by the mixing layer extending through the Haines layer, are particularly frequent in the mid variant region. On the other hand, in some high elevation areas, most noticeably the northern Rocky Mountains, large values of the Haines Index occur infrequently, and the index appears to be able to identify those days with unusual stability and humidity conditions.

Operational issues

Numerous authors have suggested modifications to the Haines Index (e.g. Jenkins 2002, 2004). Underlying these proposals is a still unresolved operational and philosophical issue regarding the Haines Index and indices in general. Some users prefer a 'universal method', where the Haines Index is calculated the same everywhere, and a value of 6 indicates similar environmental lapse rates and dewpoint depressions regardless of location. For these users, the thresholds for a particular variant of the Haines Index would be kept constant, similar to what is done today. But as illustrated by the results herein, the use of constant thresholds for the A and B components leads to wide variations in the frequency of Haines Index values of 6 from place to place.

Other users prefer a 'universal meaning', in the sense that Haines Index values of 6 indicate the same percentile of extreme instability and humidity conditions at all locations. This goal is only possible if every location uses unique thresholds for the A and B components. Setting these thresholds would require a major research undertaking, which would include the measurement of temperature and dewpoint temperature a kilometre or more above the surface for an extended period. Furthermore, there is no guarantee that the thresholds determined for a site would remain stable over time.

These same concerns lie behind the National Fire Danger Rating System pocket cards used in the United States. Pocket cards developed for individual forests or parts of the country allow an individual to see what constitute 'normal' values of various indices for that place and at various times of the year. The climate atlas of the Haines Index serves much the same purpose. It provides a context for the fire fighter, manager, or forecaster to understand what today or tomorrow's Haines Index means for their situation.

In summary, many of the concerns others have voiced in the past, and the results of this climatology, show the limitations of the Haines Index. It was not the purpose of this study to remove these limitations, or to modify the Haines Index. These are topics for other experiments and studies. However, in the meantime, the climatology provides the most thorough context presently available for understanding the meaning of a particular measurement or prediction of the Haines Index. Addressing the limitations of the Haines Index is scientifically possible; however, such efforts are more likely to serve the needs of the operational user community if members of that community participate in these efforts, as well as reaching some consensus regarding questions of universal methods *v.* meaning.

Conclusions

A detailed, long-term climatology of the Haines Index for North America was developed from 0000 UTC temperature and humidity fields from the NCEP/NCAR reanalysis. A unique aspect of the climatology is the explicit inclusion of persistence measures that indicate how often days of high potential for plume-dominated fires are followed by another day of elevated potential. The climatology provides fire managers with useful information for interpreting and evaluating Haines Index observations and forecasts, and is available in the form of an electronic atlas (http://www.haines.geo.msu.edu, verified March 2007), allowing for easy access by fire weather forecasters and fire managers.

The climatology points to important considerations for the operational use of the Haines Index, in particular the substantial spatial variations in the characteristics of the Haines Index between and within the three elevation variants. For the most part these spatial variations correspond to differences in elevation. While the climatology presented here reveals some of the limitations of the Haines Index, it also provides a context for interpreting particular observations or predictions of the Haines Index.

Acknowledgements

This project was funded by Joint Fire Science Program agreement 03-1-1-37. In-kind support was provided by Michigan State University and the United States Forest Service North Central Research Station. We thank the anonymous reviewers and the editor for their helpful suggestions.

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Appendix 1. Calculating the Haines Index

The Haines Index was first proposed in 1988 as an indicator of dry, unstable air. The concept behind the index formulation, based on earlier work by Brotak (1976), is that dry, unstable air increases the likelihood of large and/or erratic wildfires. The index includes a stability (A) component and a humidity (B) component. The A component is the environmental temperature difference between two fixed pressure surfaces, and measures the potential buoyancy of air parcels or, in other words, the potential for atmospheric mixing. The B component is the dewpoint depression at a fixed pressure level.

The major consideration in the selection of the pressure levels used to compute the index is that they be high enough in the atmosphere to not be overly influenced by diurnal variations of surface temperature or by surface inversions. Haines divided the United States into three regions based on surface elevation and developed separate variants of the index, referred to as the 'low', 'mid' and 'high' Haines Index, each calculated from a different pair of fixed pressure levels (Table 1). Haines did not use specific elevations as the boundaries between the three regions but rather placed USA climatological divisions into the three regions based on the general elevation above sea level. As a result, the elevation of the boundaries between the low and mid regions and between the mid and high regions is not constant and varies unsystematically. An important consideration when using and interpreting the Haines Index is that the index regions, particularly the high region, encompass complex physiography and a range of surface elevations. For example, coastal California with elevations near sea level falls within the high variant region.

For the mid and high variants, the index uses temperature and humidity measurements from mandatory pressure levels (the 850 and 700-hPa levels for the mid variant and the 700 and 500-hPa levels for the high variant), required by the World Meteorological Organization in all upper-air observations. On the other hand, the low variant uses observations from a mandatory level (850 hPa) and a non-mandatory pressure level (950 hPa). When the index was originally formulated, measurements at 950 hPa, although not mandatory, were often reported. However, in the 1990s a new mandatory level at the 925 hPa level was established, and since then observations at the 950 hPa level are uncommon. No standardised adjustment to the calculation of the low variant of the Haines Index has been made to account for this change in data availability. However, Potter *et al.* (2005, 2007) showed, for 18 rawinsonde locations in the low Haines region, that estimating the 950-hPa temperature using a log–pressure interpolation of the values for the surrounding 1000 and 925-hPa mandatory levels replicates the original Haines Index value on over 90% of all observations times. The one exception is during autumn at locations that experience frequent inversions. In contrast, directly substituting the 925-hPa temperature for that of 950 hPa, which is a method for calculating the low variant index that is frequently used operationally, underestimates the original Haines Index value between 20 and 70% of the time, depending on location.

To ensure that the stability and humidity components are weighted equally in the index, the temperature and humidity differences are converted into ordinal values (1, 2 or 3). To select threshold values demarcating the ordinal values for the A and B categories, Haines subjectively compared lapse rates and dewpoint depressions at one to three radiosonde stations closest in location to 74 wildland fires that occurred over a 20-year period. The ordinal values for the A and B components are then summed, and the resulting Haines Index ranges from 2 (very low potential of large or erratic plume-dominated behaviour) to 6 (very high potential).