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A Wildfire-relevant climatology of the convective environment of the United States

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Abstract. Convective instability can influence the behaviour of large wildfires. Because wildfires modify the temperature and moisture of air in their plumes, instability calculations using ambient conditions may not accurately represent convective potential for some fire plumes. This study used the North American Regional Reanalysis to develop a climatology of the convective environment specifically tied to large fire events. The climatology is based on the period 1979–2009 and includes ambient convective available potential energy (CAPE) as well as values when surface air is warmed by 0.5, 1.0 or 2.0 K or moistened by 0.5, 1.0 or 2.0 g kg^{-1}. Results for the 2.0 K and 2.0 g kg^{-1} modifications are presented. The results reveal spatial and seasonal patterns of convective sensitivity to added heat or moisture. The patterns suggest that use of ambient CAPE to estimate the potential plume growth of a large wildfire may underestimate that potential in heat- or moisture-sensitive regions.

Additional keywords: fire behaviour, instability, plume.

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Introduction

Crosby (1949) observed that 'an up-draft [sic] in a favorable atmosphere has the effect of pulling on the rising smoke column, thus increasing the air feeding the fire' What he called a 'favorable atmosphere' is an unstable atmosphere, where vertical stratification of temperature and moisture allow air from a fire to rise freely. The general association of instability with fire behaviour lies at the heart of subsequent works such as Byram and Nelson (1951), Brotak and Reifsnyder (1977), Haines (1988), Potter (2002), Nelson (2003) and Jenkins (2004). Instability fosters transport of drier upper level air to the surface, increased gustiness or turbulence in surface winds, and Crosby's increased air feeding the fire (generally stronger winds) – all of which modify the fire's behaviour.

Byram and Nelson (1951) cited instability and surface heating as drivers of turbulence and subsequently erratic fire behaviour. Brotak and Reifsnyder (1977) and Haines (1988) empirically associated atmospheric lapse rate (stability or instability) with fire size, finding unstable lapse rates more often near large fires, than near smaller ones. Both studies considered lapse rate over one or more layers of air elevated above the ground. Potter (2002) and Nelson (2003) incorporated lapse rate in theoretical calculations addressing plume strength as one component of a fire's circulation. Jenkins (2004) used a computer model and parcel theory to examine the role of instability in fire convection.

One common measure of instability and the energy it can contribute to a circulation is convective available potential energy (CAPE), the buoyant potential energy of a parcel of air starting at a given height, based on the temperature of the parcel and the temperature profile of its environment. Potter (2002) explicitly included CAPE in a simple fire circulation model and Jenkins (2004) examined updraft behaviour across a range of CAPE values. Haines (1988) pointed out that the role of moisture in determining CAPE (i.e. if the parcel of air is buoyant enough to rise to its lifted condensation level then greater moisture in the parcel increases CAPE) is inconsistent with the fact that drier surface air is more conducive to vigorous fire. As Potter (2005) discusses, moisture plays a dual role in fire dynamics and neither extremely dry nor extremely moist surface air produces the most intense fire behaviour. Jenkins' (2004) results support this concept of water's dual role.

Although theory and models indicate CAPE can influence fire circulations and dynamics, no empirical studies have clearly demonstrated a causal relationship or correlation between CAPE and fire behaviour. The most relevant published study is that of Fromm *et al.* (2010), which found no correlation between CAPE and pyrocumulonimbus events in the US and Canada. However, the authors had to use soundings from the nearest standard radiosonde stations, which can be over 100 km from a fire. They were also comparing CAPE with properties of the pyrocumulonimbus clouds rather than with direct fire behaviour data (such as intensity or rate of spread). These limitations typify the obstacles to any empirical analysis – neither the fire behaviour data nor the proximate and timely stability data exist to perform a robust study. Notwithstanding these challenges, CAPE is a reasonable and theoretically sound measure of instability to compare to fire behaviour.

Previous studies (e.g. Brooks *et al.* 2003, 2007; Riemann-Campe *et al.* 2009; Gensini and Ashley 2011) presented climatological summaries of CAPE over the US. This paper describes a climatology specifically designed for considerations of fire behaviour. For wildland fire concerns, the pertinent value of CAPE depends not only on the ambient temperature conditions but also on heat or moisture added to the convective column by combustion. The present study uses the North American Regional Reanalysis (NARR, Mesinger *et al.* 2006) and has a higher spatial resolution than Brooks *et al.* (2003, 2007) and Riemann-Campe *et al.* (2009). It has the same resolution as Gensini and Ashley (2011) but is more appropriate for wildland fire because it considers CAPE's sensitivity to heat or moisture added to the rising air by the fire.

Theory

It is important to clarify precisely what kind of fire-related convection this analysis addresses. Potter (2002) discussed the development of a wildland fire and its convective column, relating the depth of convection to the near-ground layers of the atmosphere. Within that three-stage framework (i.e. surface, deepening and penetrating fires) the basic CAPE computations in this paper are relevant to the first two stages – they rely on the stability or instability inherent in the ambient atmosphere for the convective potential. The heat- and moisture-modified CAPE calculations are more representative of penetrating fires, where the convective energy helps to loft the smoke plume above the height attainable by ambient, mixed layer air. The comparison between the base and modified CAPE values can indicate the relative vigour of a fire if it moves from the deepening to the penetrating stage.

The equation for calculating CAPE can take several forms. Here we use:

$$\text{CAPE} = g \int_{z_0}^{z_{eq}} \frac{\theta'_v(z) - \theta_v(z)}{\theta_v(z)} dz \qquad (1)$$

where g is gravitational acceleration (9.8 m s^{-2}); z_0 is the starting height of the parcel (m); z_{eq} is the equilibrium height of the parcel (m); $\theta'_v(z)$ is the air parcel's virtual potential temperature (K) at height z; and $\theta_v(z)$ is the environmental virtual potential temperature (K) at height z. For the present purposes, z_0 is the surface (ground) elevation at the location of interest. Equilibrium height, z_{eq}, is defined as the lowest height at which the parcel and the environmental air have the same virtual potential temperature. (The thermodynamics of convection are described in detail in textbooks such as Houze (1993).)

Our application of Eqn (1) has one key difference from the form commonly used for convective storm applications. In the latter context, integration begins at the level of free convection, rather than at the ground. A complementary measure, convective inhibition (CIN), indicates the energy required to lift a unit mass of air from the ground to the level of free convection. For a storm, some type of convergence or mechanical lifting must do the work to overcome CIN for CAPE to be realised. In the context of wildland fires, the energy needed to overcome CIN would come from combustion heating and moistening the air entering the base of the plume. This is precisely what we examine through our heat and moisture perturbations, which are simply specific forms of energy increase that might overcome CIN.

Bunkers *et al.* (2002) discuss three common methods for determining the parcel virtual potential temperature: using the surface air properties directly; using air properties averaged over a layer of some depth near the surface; or determining CAPE for successively higher layers of air below some maximum height, and using the highest of these CAPE values. In the US' operational forecasting community these are known as surface-based CAPE (SBCAPE), mixed-layer CAPE (MLCAPE) and most unstable CAPE (MUCAPE). Bunkers *et al.* (2002) discuss situations wherein one or another of these variants is more appropriate, and their respective strengths and weaknesses. SBCAPE gives the best indication of surface-based convective potential, which would be most suited to wildland fire situations. It is typically the highest of the three variations during daytime, the lowest of the three at night time, and is most variable spatially due to the fact that temperature and humidity both vary more at the earth's surface than they do aloft. Henceforth in this study, CAPE will refer to SBCAPE.

In order to examine the potential for wildland fire to modify the convective environment (i.e. CAPE) it was necessary to represent the fire's effect on surface air properties. The most direct way to do this is to modify surface air temperature or moisture to reflect the heat or moisture produced by combustion. In reality, the near-surface air entering the plume would be both heated and moistened (in terms of absolute moisture content). For this study we modified either temperature or moisture, but not both simultaneously, to get a sense of the individual contributions.

The existing literature contains observations that indicate the magnitude of the perturbations in temperature and moisture (Table 1). Taylor *et al.* (1968) flew aircraft through fire plumes

Table 1. Temperature and moisture perturbations due to fire, as reported in previous studies

Source study	Temperature perturbation (K)	Moisture perturbation (g kg^{-1})	Measurement height (m AGL)
Taylor *et al.* (1968)	0.6–1.3	n/a	0–1500
Jenkins (2002)	2–3	1 to 3	15
Trentmann *et al.* (2006)	5–50	n/a	0–3000
Clements *et al.* (2007)	30–40	2	25

to construct soundings upwind and downwind of three fires in Australia. They reported height-independent column temperatures 0.6, 1.3 and 2.3 K above ambient conditions. They did not measure moisture. Jenkins (2002) used a coupled fire–atmosphere model to examine fire behaviour and reported temperature perturbations of 2–3 K and moisture perturbations of 1–3 g kg^{-1} at a height of 15 m above the modelled fire. Trentmann *et al.* (2006) used an atmospheric model with parameterised combustion to study the Chisholm Fire from 2001 in Alberta, Canada. Their model showed temperature excesses just above the fire of 50 K, decreasing to ~5 K at 3000 m above the fire. Clements *et al.* (2007) measured temperatures and moistures over a prescribed grass fire in Texas. They report 1-min average moisture perturbations on the order of 2 g kg^{-1}. A visual estimate from their figures suggests 1-min average temperature perturbations as high as 30–40 K, at a height of 25 m above ground level.

The vertical resolution of the present analysis must also be considered. A physically appropriate perturbation must be comparable to what would be expected when the air reaches the first data level above the ground. The data used in this study (see next section) are given at specific pressure levels, at 25 mb intervals for pressures exceeding 700 mb. These correspond to ~250–300-m intervals, depending on the actual pressure and temperature. This suggests that the values reported in Clements *et al.* (2007) and Trentmann *et al.* (2006) are too close to the ground to be suitable in this study. We chose three values for temperature perturbation in this study: 0.5, 1.0 and 2.0 K. Though the evidence suggests the moisture perturbations may be smaller, we felt the range was similar enough to the temperature perturbation range and we use 0.5, 1.0 and 2.0 g kg^{-1}. We feel these perturbations are reasonable for air from fires of moderate to large size; though clearly higher values are possible, especially if a plume has sufficient spatial extent to prevent mixing of air in the middle of the updraft with air from the surrounding environment. As stated previously, the focus of this study is to obtain some indication of the relative vigour of fires in the deepening and penetrating stages, and the ease of a fire making that transition. Only the results for the 2.0 K and 2.0 g kg^{-1} are presented here.

Data

This study used NARR data from the years 1979–2009, at 0000 UTC and 1800 UTC, to produce the climatology. We selected these times because CAPE tends to attain its maximum value, and fires their greatest intensity, during mid- to late afternoon, and these two times span that period for locations in the western and eastern US. NARR data cover all of North America at a horizontal resolution of 32 km, with 29 pressure levels in the vertical, as well as at 2, 10 and 30 m above ground level (AGL). We used the data for the 29 pressure levels for our profiles, and the 10-m AGL temperature, pressure and moisture data as the parcel air in our CAPE calculations.

The NARR has several noteworthy issues. These include omission of 2-m observations; spurious precipitation in the reanalysis; a cross-hatching pattern that appears in some calculations; and estimation of the uncertainty in CAPE values calculated from it (see Appendix for a discussion of this uncertainty.) At the time the NARR project began, the system to assimilate 2-m AGL temperature observations produced unacceptable errors in the aboveground temperature and wind fields when these observations were included. Mesinger *et al.* (2006) show that the magnitude of the bias in NARR 2-m AGL temperatures is <1 K. For comparison, the US Automated Surface Observing System's (ASOS) root mean square error is 0.5 K (http://www.nws.noaa.gov/asos/aum-toc.pdf, accessed 4 December 2013). The cross-hatching appears to stem from small spatial variations in potential temperature near the ground, and was smoothed with a three-point boxcar filter in the maps presented here.

West *et al.* (2007) discovered that the assimilation of precipitation observations into the NARR produced what they called 'spurious grid-scale precipitation' (SGSP). It arises when there is a mismatch between the modelled and observed precipitation, and produces anomalous changes in the moisture and temperature profiles. They demonstrate how these anomalies affect calculations of SBCAPE, usually lowering it by producing surface cooling and latent heating aloft. These SGSP events cannot be removed, but the authors conclude that SGSP 'will probably have little or no effect on long-term hydrological averages prior to 2003.' Our analysis is not hydrological, but based on their magnitude, as well as their limited spatial extent and brief duration the effect of SGSP events on our analysis should be negligible.

Methods

Calculation of CAPE and statistics

CAPE was computed from the vertical profiles at each horizontal NARR grid point. Output CAPE values were written to new files for subsequent analysis using GNU Scientific Library's statistical routines (http://www.gnu.org/software/gsl/, verified 10 November 2014) to obtain mean, 50th, 75th, 90th and 95th percentile values as well as standard deviations for base and perturbed properties. In addition to these statistics for the individual perturbations, we computed several statistics comparing base and perturbed CAPE values at the stated times: (1) the mean of the maximum value among the base, temperature perturbed, and moisture perturbed CAPE values, for a given magnitude perturbation; (2) the average change in CAPE for given temperature perturbations; (3) the average change in CAPE for given moisture perturbations; and (4) the average difference in temperature-perturbed and moisture-perturbed CAPE values for a given magnitude perturbation. For the first and fourth of these, 'a given magnitude perturbation' means that 0.5 K and 0.5 g kg^{-1} perturbations were compared, 1 K and 1 g kg^{-1} were compared with each other and 2 K and 2 g kg^{-1} were compared with each other. (Again, only the 2 K and 2 g kg^{-1} results are presented here.) There is no physical justification for pairing these specific values; we chose these comparisons solely to gain some sense of how the temperature and moisture perturbations change CAPE relative to one another, rather than making all possible perturbation comparisons.

Each statistic was computed over monthly, seasonal and annual periods. Winter comprised January–March; Spring comprised April–June; Summer comprised July–September; and Autumn comprised October–December. These differ from the traditional seasons used in many meteorological studies

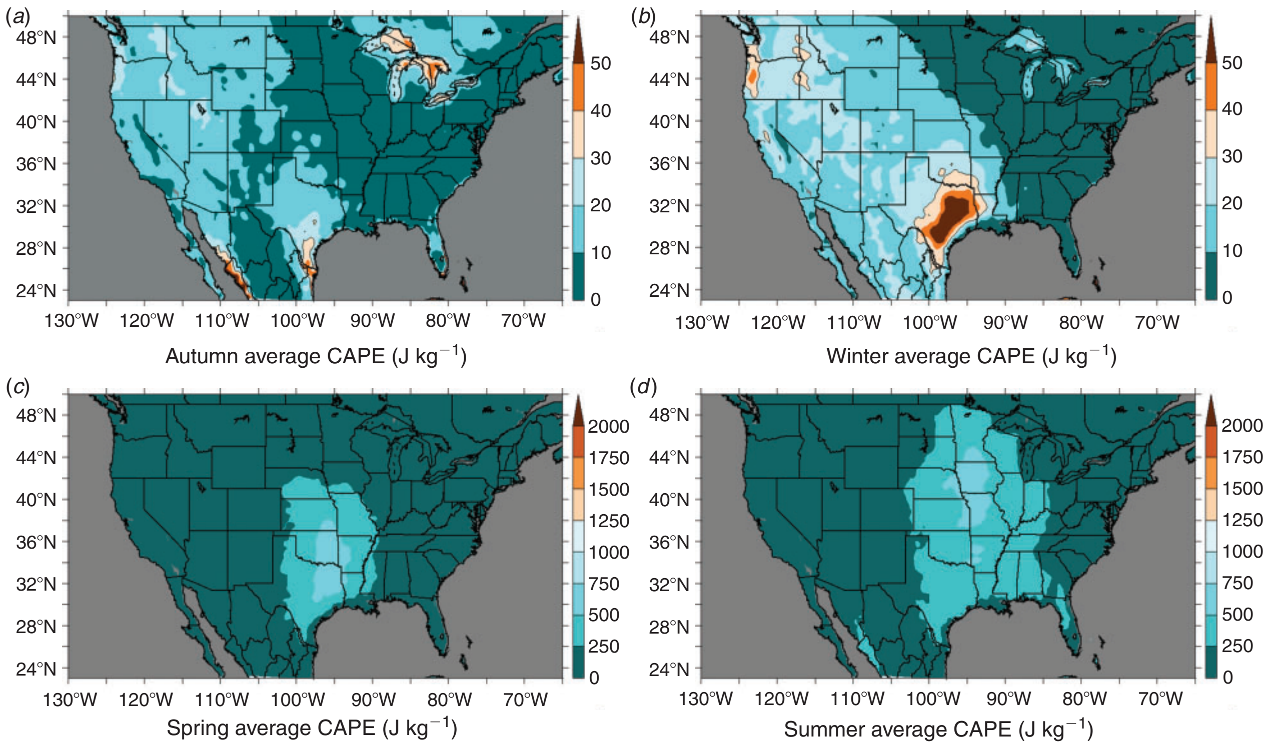

Fig. 1. Mean CAPE values for (*a*) fall, (*b*) winter, (*c*) spring, and (*d*) summer.

(wherein each season is one month earlier). We chose these seasons because they more closely correspond to the wildfire seasons in many parts of the US. Maps for the various quantities were produced using FERRET software (http://ferret.pmel.noaa.gov/Ferret/home, verified 10 November 2014).

Results

Ambient CAPE

Most seasonal mean CAPE values are below the NARR uncertainty. Fall and winter mean CAPE values (Fig. 1*a*, *b*) are in the 10–30 J kg^{-1} range, with the highest values during the fall months concentrated in southern Texas, along the Washington and Oregon coast, the Washington and Oregon borders with Idaho, and in northern Utah. Winter's high values are similar but slightly expanded to cover southern and eastern Texas, most of the region from Washington east to Montana, and south into northern Arizona and New Mexico. The highest values are those in Texas, where the mean exceeds 50 J kg^{-1}.

The highest mean CAPE values for spring and summer (Fig. 1*c*, *d*) are around 1000 J kg^{-1} and occur in the central states, just west of the Mississippi River. These high values are in Texas, Oklahoma, Kansas and Arkansas in the spring and extend farther north, into southern Minnesota in the summer. One consequence of this shift is that Louisiana, Texas, Oklahoma and Arkansas experience decreasing mean CAPE values from spring to summer.

+2 K CAPE

Increasing surface air temperature by 2 K yields mean CAPE values over much of the US that exceed the NARR uncertainties. Fall and winter spatial maxima (Fig. 2*a*, *b*) are ~200 J kg^{-1} and occur in Texas and Florida. Spring maxima (Fig. 2*c*), ~1200 J kg^{-1}, extend northward from the Texas–Louisiana Gulf Coast towards the Kansas City area. Summer maximum values (Fig. 2*d*) are slightly higher and are concentrated primarily in the states along the Gulf Coast, reaching up into the Mississippi River Valley.

The patterns in CAPE increases from ambient to +2 K values largely echo the +2 K CAPE patterns (Fig. 3). Both the actual +2 K CAPE values and the differences between +2 K and ambient CAPE values exceed the NARR uncertainties over substantial portions of the US. The addition of 2 K to surface air temperatures increases mean CAPE the most over Florida and southern Louisiana in the summer, by more than 1500 J kg^{-1}.

+2 g kg^{-1} CAPE

Seasonal mean CAPE values with 2 g kg^{-1}of water added exceed NARR uncertainties over much of the continental US. In fall and winter (Fig. 4*a*, *b*), southern Texas CAPE averages more than 200 J kg^{-1}. Values over the north-west (Washington, Oregon and Idaho) are ~100 J kg^{-1} in the fall and ~150 J kg^{-1} in the winter. Over the eastern half of the US, average +2 g kg^{-1} CAPE values are <50 J kg^{-1}. Almost all of the +2 g kg^{-1} CAPE in autumn and winter is the result of the added moisture (Fig. 5*a*, *b*).

In spring and summer (Fig. 4*c*, *d*), the highest average +2 g kg^{-1} CAPE values occur over the south-central region (eastern Texas, Oklahoma, and south-east Nebraska) in spring, and reach as far north as southern Minnesota in summer. Values in this swath average 1000–1500 J kg^{-1}, of which 600–1000 J kg^{-1} stems from the added moisture (Fig. 5*c*, *d*).

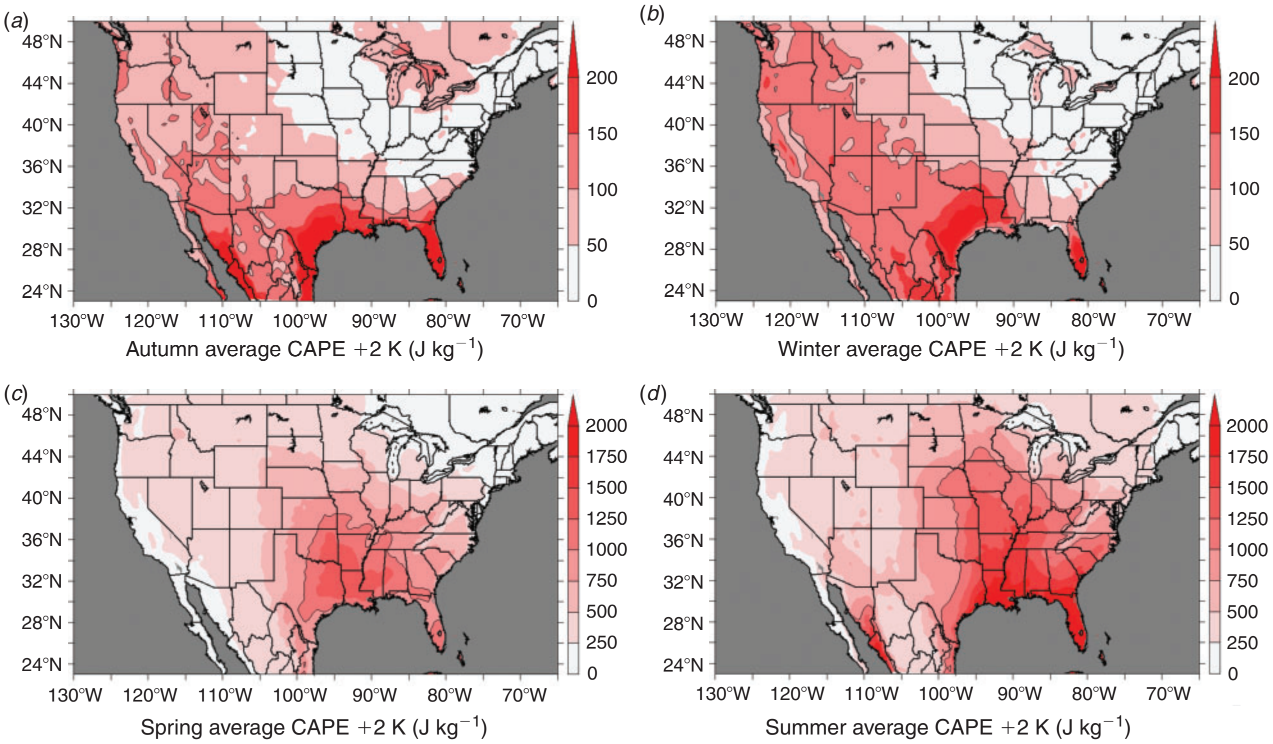

Fig. 2. As Fig. 1, but showing +2 K average CAPE values.

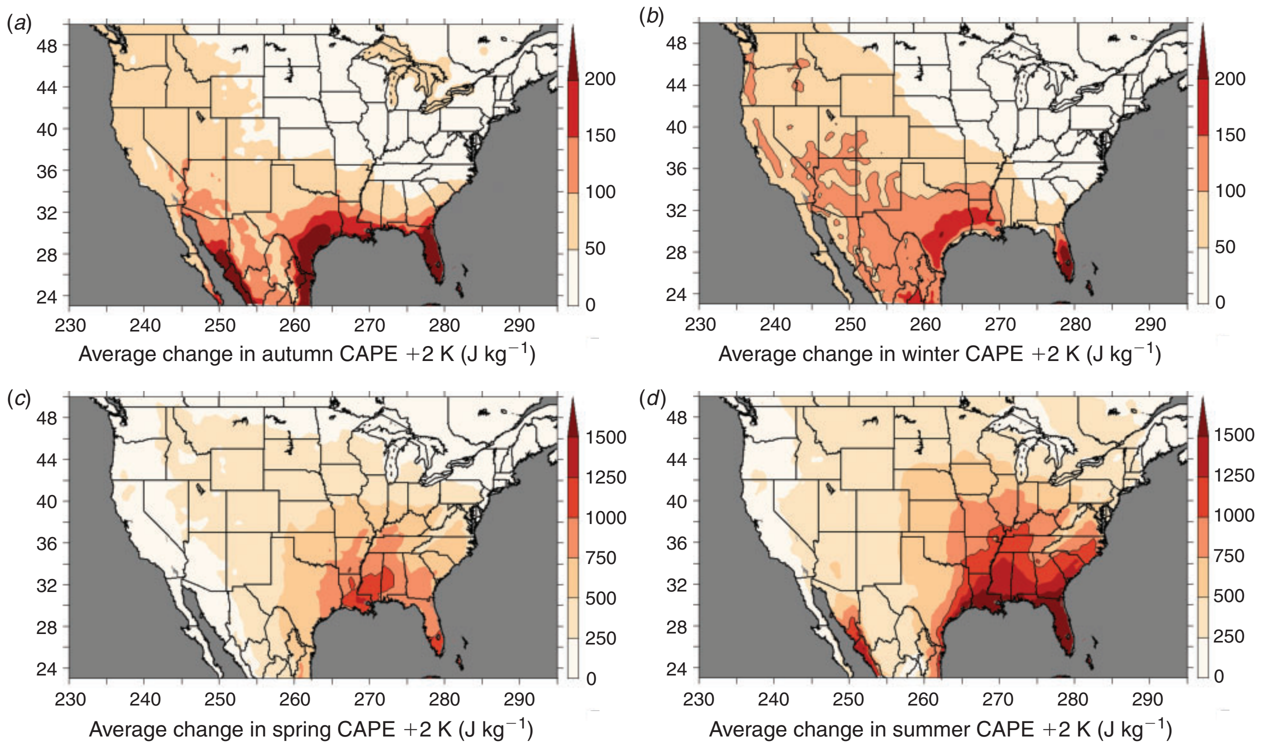

Fig. 3. As Fig. 1, but showing average change in CAPE from base to +2 K.

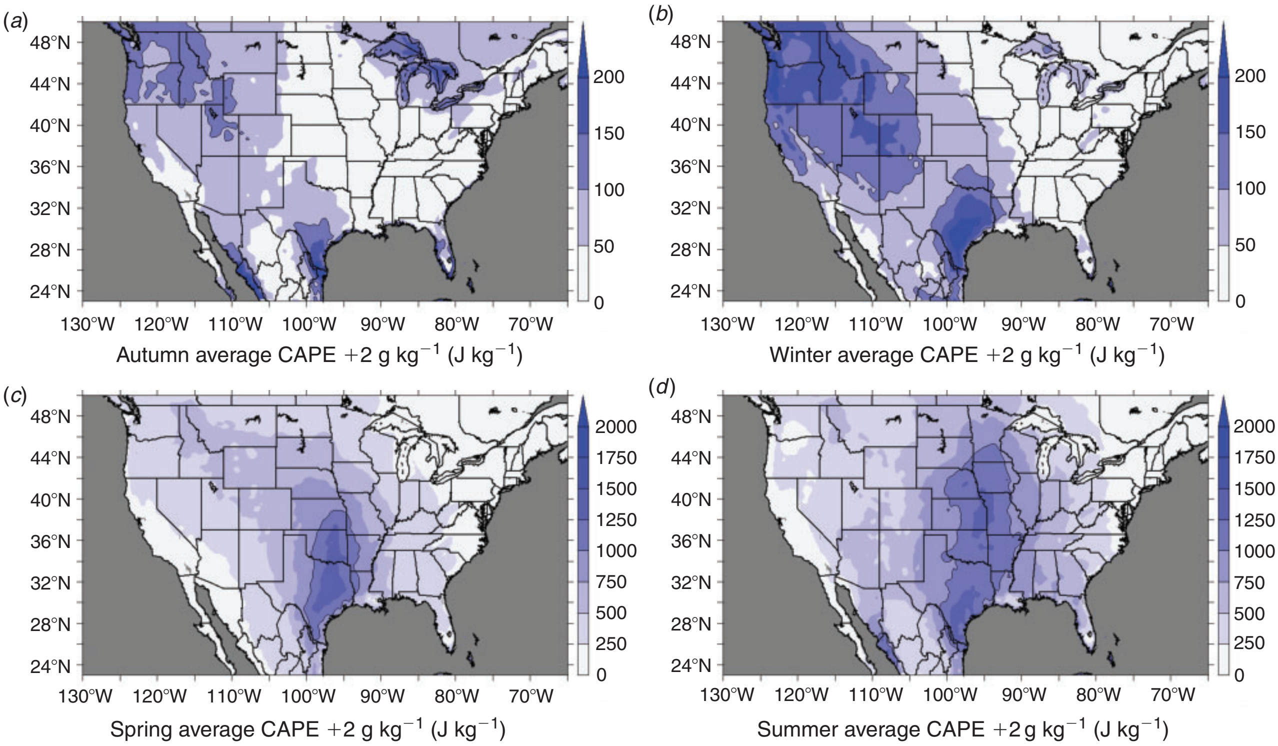

Fig. 4. As Fig. 1, but showing +2 g kg^{-1} average CAPE values.

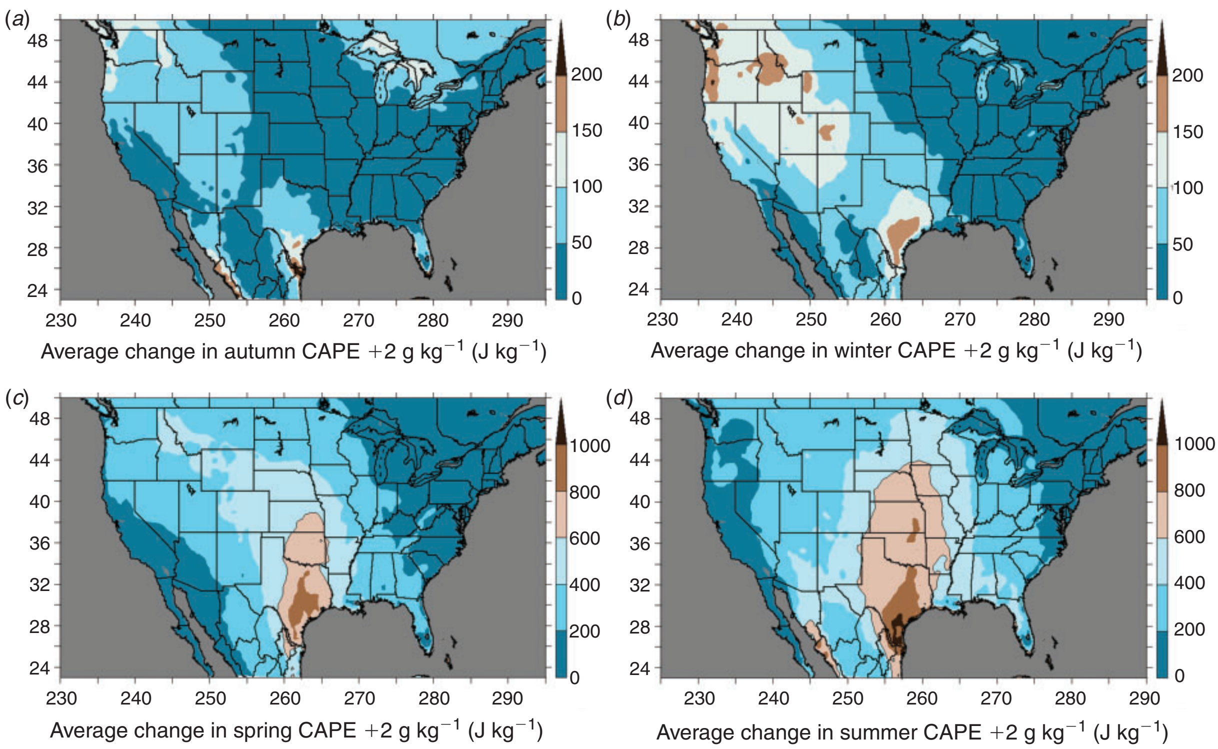

Fig. 5. As Fig. 1, but showing average change in CAPE from base to +2 g kg^{-1}.

The greatest increase in CAPE due to the addition of 2 g kg^{-1}, $>$1000 J kg^{-1}, occurs over southern Texas in summer. This is approximately two-thirds the maximum increase in mean CAPE when 2 K is added to surface air, noted above.

Discussion

Sensitivity to added combustion heat or moisture

Our study indicates that over parts of the US, primarily in the spring and summer, surface-based CAPE is sensitive to the addition of heat or moisture from a fire. Sensitivity is greatest east of the Rocky Mountains during spring and summer. This sensitivity reflects the strength and nature of stability, as well as the potential for a fire to loft its plume beyond the mixed layer, at these times and locations. In some cases, the sensitivity stems from surface stability wherein the applied temperature perturbations would overcome that stability. In other cases, there may be positive, weak CAPE at the ground and the added heat or moisture may allow the air to reach the lifted condensation level and then rise further. These situations have different implications for the circulation feeding the fire, and thus fire behaviour and smoke transport, but cannot be distinguished in the present framework.

The regions that are most sensitive to heat differ from those most sensitive to moisture. The magnitude of the effect from heat and moisture perturbations is comparable in some areas and seasons, slightly greater from heat than moisture in others. East Texas and Oklahoma, along with Louisiana and Arkansas, are regions where heat and moisture perturbations both affect the spring and summer convective environment strongly (heat somewhat more than moisture). Of these regions, only southern Texas shows sensitivity to added moisture in fall or winter, and only coastal Texas and Louisiana are sensitive to added heat in these seasons. The convective environment in southern Florida stands out as one area where added heat has a large effect, but added moisture does not.

Coastal Washington and Oregon in fall and winter appears to be the only area and season more affected by moisture perturbations than by heat perturbations. The convective environment in this area, as well as in California, appears unaffected by heat or moisture perturbations in summer.

Implications of using surface-based CAPE

The choice to use SBCAPE clearly affected the results, though it does represent the atmosphere as a developing fire on the ground would experience it. Locations and times with non-zero CIN produced zero values for CAPE in the present analysis, lowering the average and percentile values. It is possible that mean CAPE computed from the level of free convection would exceed the estimated uncertainty in the NARR more often. Using SBCAPE underestimates the potential for convection during fires because it ignores the possibility that local convergence or mechanical forcing could allow a fire's plume to reach great heights by boosting it above a layer of CIN to the level of free convection. Determining the extent of these effects would require extensive research into how fire plumes behave in stable surface-layer environments, and many assumptions. Observational research in stable atmospheres is a difficult prospect in the real world due to the smoke and air quality issues it would cause.

Conclusions

We created a climatological summary of the convective environment over North America for the period 1979–2009. The methods used in creating the climatology maximise its relevance to the convection associated with large wildland fires with plumes reaching above the ambient mixed layer. The results may not be ideal for other applications or smaller or less intense wildland fires. Comparison with uncertainty in the NARR temperature data indicates that mean and median environmental surface-based CAPE are typically below the likely level of that uncertainty. Higher percentile values, specifically 90th and 95th percentiles, and CAPE values when surface air is heated by 2 K or moistened by 2 g kg^{-1}, exceed the NARR uncertainty and reveal seasonal and spatial patterns relevant to wildfire research and operations.

The North American Regional Reanalysis dataset proved less than ideal for study of the convective environment. The estimated error or uncertainty of the NARR-derived CAPE and equilibrium heights is comparable to the climatological mean or median values of these quantities over much of the US, and much of the year. Since the initiation of this project, the National Centers for Environmental Prediction Climate Forecast System Reanalysis (Saha *et al.* 2010) has been released. This dataset improves on several limitations and weaknesses in the NARR. For example, the CFSR includes surface temperature observations whereas NARR did not. It is reasonable to believe that using the CFSR data for a project similar to this one would yield more reliable information regarding the convective environment.

This work could be refined with better data on the perturbations of heat and moisture from fires, or expanded with CAPE calculations using combined heat and moisture perturbations. However, as noted in the introduction, the critical missing link is work directly tying convective energy to fire behaviour – or clearly demonstrating a lack of such a link. The spatial and temporal scales, and the resolution necessary to accurately capture the relevant data on those scales, remain great challenges, but the potential insight into fire behaviour is considerable.

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Appendix 1. North American Regional Reanalysis (NARR) Uncertainty

Because the goal of this project is to examine sensitivity of CAPE to variations in surface air moisture and temperature, it is critical to know how errors inherent in the NARR influence CAPE calculations. How do the changes in CAPE produced by surface air heating and moistening compare to the variability of CAPE calculations due to any error or uncertainty in the NARR profiles? Mesinger *et al.* (2006) show the pressure-varying RMS temperature errors in the NARR analysis for January and July (their fig. 6a, b). There is no information in the peer-reviewed literature regarding NARR uncertainty or errors in atmospheric moisture. The temperature RMS errors decrease with height up to ~500 mb, then increase again up to 200 mb, where the figures stop. Errors are greater in January than in July.

To estimate NARR-based CAPE uncertainty, we randomly sampled dates from our study range, and locations from over the continental US. (Fig. A1 shows the region sampled). We then created piece-wise linear equations for RMS error as a function of pressure from the Mesinger *et al.* (2006) figures. For each location, we calculated CAPE using the original NARR data, then re-calculated it after adding random Gaussian, zero mean, and pressure-dependent RMS temperature errors using the piece-wise linear equations derived from Mesinger *et al.* (2006). These random perturbations, when negative, were not permitted to lower the temperature below the dew point temperature at that point in the profile. With no information available beyond Mesinger *et al.*'s (2006) fig. 6, we felt that the random perturbation distributions requiring the fewest assumptions were uniform or Gaussian. There are sound physical and numerical modelling arguments that neither of these is the true distribution, but absent further information we felt that using a Gaussian distribution would most closely reflect the actual error distribution as well as provide a reasonable estimate of the uncertainty that temperature errors create in CAPE. (For brevity, temperature-based NARR uncertainties are hereafter referred to as simply 'NARR uncertainties').

It is also the case that while we generated independent, random perturbations at each height of any given profile, NARR profile errors are the result of the NARR assimilation system's efforts to create a dynamically balanced atmosphere from observations. That assimilation will yield some amount of dependence and correlation throughout the profile, as well as across nearby points. For our purposes, we deemed the random time and place locations, and the random errors added to soundings sufficient for the purpose of estimating these NARR uncertainties.

We selected 10^4 January location–dates and 10^4 July location–dates separately. To help illuminate the significance of the error distribution, we then repeated the process using a uniform error distribution that yields the same pressure-dependent RMS errors as the Gaussian distribution. Table A1 shows the results of these tests for January and July. The nature of the distribution makes little difference to the final uncertainty values. We use the January uncertainties as a reference for fall and winter CAPE values, and the July uncertainties as a reference for spring and summer values.

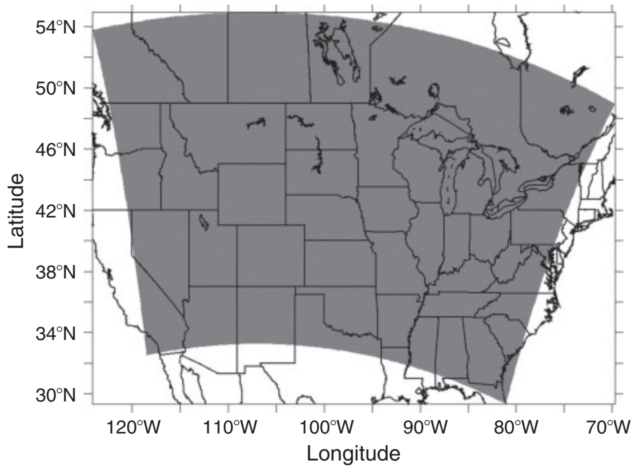

Fig. A1. Sampling domain used for calculation of NARR uncertainty (shaded in grey).

Table A1. Results of NARR uncertainty CAPE sensitivity tests
'Gaussian' refers to tests using a Gaussian distribution of errors; 'uniform' refers to tests using a uniform distribution of errors

	January		July	
	Gaussian	Uniform	Gaussian	Uniform
CAPE (J kg^{-1})	28	28	640	640