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Sensitivity of prescribed burn weather windows to atmospheric dispersion parameters over southeastern USA

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Abstract. Prescribed burning is an essential tool for forest and rangeland management that requires specific weather conditions to enable the efficient and safe application of fire. Prescribed burning is often limited by the ability to find suitable burn-days that fit within the identified weather parameters that balance good smoke dispersion and erratic fire behaviour. We analysed the sensitivity of the occurrence of widely used weather windows in the southeastern USA to modest changes in how they are defined. This analysis identified the most limiting prescription components and assessed where small changes in the prescription window can yield the greatest gains in additional burn-days. In the growing season (April–September), adjustments to mixing height offered the greatest such opportunity: a 12.5% increase in the upper-limit yields ~25% more burn-days during this period. During the dormant season (November–January), a 12.5% change in the upper-limit of transport wind yields ~20% more burn-days. Performing this analysis on the ventilation index revealed that comparable increases in burn-days were available by changing its upper limits. These results help inform ongoing discussions on potential changes to regional prescribed burn weather parameters that might help meet smoke management and treatment objectives in the southeastern USA and more broadly.

Additional keywords: fire behaviour, fire planning, mixing height, prescribed fire, smoke, transport winds, ventilation, wildland fire management.

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Introduction

Prescribed burning is an essential land management tool used to meet a wide range of objectives in forests and rangelands (Ryan *et al.* 2013), including the maintenance and restoration of endangered species and wildlife habitat, the reduction of hazardous levels of wildland fuels and controlling woody competition in stands managed for timber (Wade and Lunsford 1989; Waldrop and Goodrick 2012). To accomplish these objectives, prescribed burns are conducted under specific wind, atmospheric and fuel moisture conditions conducive to the effective and controlled application of fire. Nearly 70% of United States of America (USA) prescribed burning takes place within the southeastern USA (Melvin 2015; hereafter 'Southeast'). Notwithstanding this concentrated prescribed fire activity, limited availability of the preferred fire weather conditions – especially those safeguarding breathable air quality (smoke dispersion) – have been reported as a primary barrier to reaching the desired levels and timings of prescribed burn activity (Haines *et al.* 2001; Kobziar *et al.* 2015).

Previously, Chiodi *et al.* (2018) analysed the spatial and temporal distribution of mean seasonal prescribed burn weather windows across the Southeast based on the preferred atmospheric mixing height and transport wind range suggested by Wade and Lunsford (1989) and implemented widely using meteorological data from a pair of numerical weather model reanalyses. Each preferred range is defined by a lower limit (1700 ft/520 m agl for mixing height and 9 mph/4 m s^{-1} for transport wind), which safeguards against insufficient near-surface smoke dispersion, as well as an upper limit (6500 ft/1980 m, 20 mph/9 m s^{-1}) in place to mitigate the dangers of erratic fire behaviour. Prohibitively heavy precipitation (> 0.25 inches/6.35 mm day^{-1}), high 20-ft wind speeds (> 20 mph/~9 m s^{-1}) and low relative humidity (< 20%) day-of-burn conditions were also screened for, because of their adverse effects on the effectiveness and controllability of applied fire. These weather requirements for prescribed burning, although not comprehensive (e.g. severe widespread drought as measured by high values of the Keetch-Byram Drought Index (Waldrop and Goodrick

2012) or local burn bans would further narrow opportunity), were chosen for their general applicability across different subregions and treatment objectives and ability to quantify seasonal fire weather variability in a manner generally consistent with regional field staff experience.

Amid wide discussion over the preferred season-of-burn (Knapp *et al.* 2009; Hiers *et al.* 2000; Ryan *et al.* 2013; Kobziar *et al.* 2015; Platt *et al.* 2015), a major shift throughout the Southeast has been to increasingly focus burning during the growing season, in part to mimic putative prehistoric ignition timing (e.g. as discussed by Stambaugh *et al.* 2011 and Stambaugh *et al.* 2017). Based on the Wade and Lunsford (1989) mixing height and transport wind limits, however, the growing season is when the preferred fire weather conditions occur least frequently (Chiodi *et al.* 2018) and emissions from smoke coincide with poor ambient air quality (Wiedinmyer *et al.* 2006; Odman *et al.* 2009).

In addition to mixing height and transport wind conditions, calculated indices based on them are also used to estimate near-surface smoke dispersion conditions in the region (Goodrick *et al.* 2013). The product of mixing height and transport wind – often referred to as the ventilation index (VI) (Hardy *et al.* 2001; Goodrick *et al.* 2013) – offers an estimate of the volume into which smoke disperses upon mixing. The VI also partly determines the value of the atmospheric dispersion index (Lavdas 1986), which rates the dispersion potential of smoke within a 50-km rectangular volume (Waldrop and Goodrick 2012), based on the assumption that half of the smoke emitted from burning rises such that it affects breathable air quality by mixing into the volume described by the VI and the other half is initially ground-based (vertical scale 30 m a.g.l.). The ground-based portion is evaluated according to the method of estimating vertical diffusion suggested by Pasquill (1961; see also Taylor 1922) based on observations of vertical wind fluctuations aloft (500–5000 ft/ ~150–1500 m) made by Smith (1961). The heuristic approach of Pasquill (1961) was later codified by Gifford (1961) and Turner (1961, 1964) to depend on variables routinely made available by National Weather Service stations: cloud cover in tenths, cloud ceiling height and solar elevation. These variables, along with 10-m wind speed, mixing height and transport wind, make up the list of variables needed to calculate the Lavdas (1986) atmospheric dispersion index, which determines legal authorisation criteria for burning in some states.

Although prescription parameters can represent legal constraints for prescribed fire managers, the selection of preferred conditions is often arbitrary and based on recommendations of traditionally used parameters, rules of thumb or personal experience (Wade and Lunsford 1989; Robbins and Myers 1992; Waldrop and Goodrick 2012). These imprecise selection criteria, combined with increasing constraints on burning, motivates analyses of the consequences of marginally expanding some of the fire weather parameters under which prescribed burning is conducted. The objective of this study was to analyse the sensitivity of the climatological fire weather window to changes in the parameters used to define it. We present analysis of this sensitivity based on recalculating the burn-day climatology of Chiodi *et al.* (2018) after systematically widening the limits on the mixing height or transport wind speeds. We also examine the effects of including (for improved accuracy) or neglecting (often done in practice) the effects of humidity when estimating mixing height. Finally, we offer an evaluation of the climatological variation of prescribed burn-days based on upper and lower VI parameters. Although this analysis is focused on the Southeast, it has relevance to prescribed fire permitting and planning more broadly.

Data and methods

The salient mixing height and transport wind calculation procedures used in this study follow the methods of Chiodi *et al.* (2018), which contain additional detailed descriptions. The atmospheric variables needed to calculate mixing height and transport wind (vertical profiles of temperature, specific humidity, wind speed and geopotential height, along with surface temperature and elevation) were obtained from two numerical weather models run in data assimilation mode (a.k.a. reanalyses): the North American Regional Reanalysis (NARR; Mesinger *et al.* 2006, available at http://www.esrl.noaa.gov/psd/, accessed 1 April 2017) and the NCEP Climate Forecast System Reanalysis product (CFSR; Saha *et al.* 2010, available at https://rda.ucar.edu/datasets/ds093.0/, accessed 1 April 2017). NARR data has $\sim 1/3°$ latitude $\times$ $1/3°$ longitude and 3 h resolution, with 29 pressure levels spaced by 25 hPa from 1000 to 700 hPa and 50 hPa thereafter. The CFSR data over the study period (1979–2010) has similar vertical resolution as NARR, but lower spatial ($0.5°$ longitude $\times$ $0.5°$ latitude) and temporal (6 h) resolution. We based our analysis on the available mid-morning to afternoon analysis product time steps, namely 15:00, 18:00 and 21:00 Coordinated Universal Time (UTC) from NARR (10:00, 13:00 and 16:00 Eastern Standard Time) and 18:00 UTC from CFSR.

We used the equilibrium height approach to estimate mixing height, calculated as the height above ground to which an air parcel heated to the surface temperature would rise, if buoyant, before it becomes neutrally buoyant at some higher altitude. The equilibrium height method is commonly used by US National Weather Service Forecast Offices when issuing mixing height forecasts and has been found to provide an effective estimate for the mixing height when virtual potential temperature (as used by Stull 1991) is used as a proxy for air density (Fearon *et al.* 2015). A more traditional mixing height estimation approach (e.g. Holzworth 1967), which does not account for humidity effects on air density, however, has commonly been used in practical application over the Southeast (Brown and Hall 2010). We therefore repeated our calculations (which included humidity effects in the base case) after neglecting humidity (i.e. using potential temperature rather than virtual potential temperature to estimate mixing height) to better understand the consequences that this choice has on the resulting prescribed burn weather window.

Profiles of zonal and meridional wind were also acquired from the NARR and CFSR reanalyses to calculate transport wind, defined as the vertically averaged wind speed from the ground to the mixing height. We also acquired 2-m humidity and 10-m wind speed from the NARR and CFSR reanalyses in order to apply the additional low relative humidity ($<20\%$) and high-wind (20 ft/6.1 m winds > 20 mph/~ 9 m s^{-1}) screens, with 20-ft wind speed estimated as the 10-m wind speed divided by 1.15 (c.f. Turner and Lawson 1978). To screen for 24-h precipitation accumulations greater than 0.25 inch (6.35 mm), we acquired precipitation information from the National Oceanic and Atmospheric Administration (NOAA) CPC Daily USA Unified Precipitation dataset (Higgins *et al.* 2000) available at http://www.esrl.noaa.gov/psd, (accessed 15 January 2016). This gauge-based precipitation dataset is available on a 0.25° latitude × 0.25° longitude grid and was re-gridded to the respective NARR and CFSR horizontal grids before analysis. All reanalysis time steps within the daily accumulation period (starting 12:00 UTC) were flagged as unavailable for prescribed burning when the 0.25 inch day^{-1} (6.35 mm day^{-1}) precipitation threshold was met or exceeded (c.f. Chiodi *et al.* 2016).

We also calculated, for comparison purposes, the climatological variation of prescribed burn-days based on VI, rather than mixing height and transport wind parameters. In the VI case we use a lower bound of 25 800 ft^2 s^{-1}, or ~2400 m^2 s^{-1}, which is the value suggested for distinguishing fair from poor ventilation by Waldrop and Goodrick (2012) and an upper bound of 8360 m^2 s^{-1}. This upper limit corresponds to VI values at which the atmospheric dispersion index reaches a value of 80 in moderately unstable conditions (c.f. Waldrop and Goodrick 2012). Dispersion index values > 80 are often red-flag criteria used to mitigate the risk of erratic fire behaviour in burn prescriptions that consider this index. We did not examine the climatological variation of the atmospheric dispersion index in this study, but return to its derivation in the Discussion section, where we offer some comments on issues encountered when contemplating best-practices for doing so based on currently available reanalysis or numerical weather forecast data. For consistency, the same precipitation, extreme relative humidity and 10-m wind speed screens as used in the mixing height and transport wind case were also applied in the VI case.

The sensitivity of the mixing height and transport wind burn-day climatology to change in the parameters used to define it is examined by recalculating the climatology after separately relaxing the respective upper and lower bounds by 12.5%; for example, using 3.5 m s^{-1} rather than 4 m s^{-1} as lowest acceptable and then 10.125 m s^{-1} rather than 9 m s^{-1} as highest acceptable transport wind. Similar 12.5% relaxations were also applied to examine sensitivity in the VI case. The results offer two metrics for gauging climatological annual mean sensitivity at each grid point; one is the fractional increase in prescribed-burn-available times contributed by a given bound-relaxation relative to the total number of possible daytime time steps (in the NARR case, $n = 3$ daytime time steps per day × days in the 1979–2010 period). The other is the fractional increase relative to the original base case result. Maps of annual mean sensitivity (discussed below) reveal spatial gradients across the Southeast. Parameter sensitivity was also tabulated on a monthly climatological basis and then spatially averaged over the Southeast study region to reveal how sensitivity changes with season in a climatological and regionally averaged sense.

Results

Daytime mixing height and transport wind frequency distributions

We began with examination of the regional distribution of mixing height and transport wind over the 1979–2010 study period. In the case of the NARR results (Fig. 1; left panels), the preferred range for each variable included the most frequently occurring value (~1350 m and 4.4 m s^{-1}, respectively). The transport wind peak of 4.4 m s^{-1}, however, is relatively close to the lower bound of the preferred range, which is 4.0 m s^{-1}. The mixing height distribution, based on NARR, exhibited a much broader peak relative to the preferred range than did transport wind. For example, the mixing height distribution varied by only 11% of its mean within the preferred range, whereas the transport wind distribution varied by 58%. For both variables, however, the fall-off in frequency in the bins that are below the lower bound is steeper than the drop-off above the upper bound (c.f. Fig. 1). The distributions of the subsets of times and locations that satisfied the other preferred fire weather criteria (e.g. the portion of the mixing height distribution that met preferred transport wind, precipitation, relative humidity and 20-ft wind speed parameters) are shown by darker shading (blue or green) in each panel. The otherwise-available portion of the mixing height distribution constituted 44% of the total. In the transport wind case, the otherwise-available portion constituted 38% of the total. For each weather variable (mixing height and transport wind), the otherwise-available distribution was comparable in shape to the total distribution. In the transport wind case, however, there was a shift in the position of the peak from 4.4 to 5.2 m s^{-1}, meaning that a larger fraction of the times with low-end-preferable transport wind values (~4 m s^{-1}) failed to meet the other criteria than was the case for the mid-range-preferable (e.g. 5 m s^{-1}) transport wind conditions.

Comparison of the CFSR and NARR distributions revealed both similarities and differences (Fig. 1). For example, there was good qualitative agreement between the NARR and CFSR results for the shape of the transport wind distribution. In this case, the basic characteristics of the NARR results (e.g. the relationship between below and above-threshold rates of change, position of peak values, and the shift towards higher-winds for the available blue- or green-shaded subset) held in the CFSR case as well. The mixing height distributions, however, were clearly different in character, with the CFSR case exhibiting a much sharper peak (90% increase within the preferred range) at lower heights (~850 m) than was observed in the NARR case (20% increase within the preferred range).

Chiodi *et al.* (2018) previously noted that the surface temperatures required to estimate the mixing height by the equilibrium height method differ substantially depending on the choice of reanalysis, thereby revealing a source of uncertainty in mixing height estimated by this method. Surface temperature differences between NARR and CFSR remain a primary cause of the mixing height differences revealed here between the NARR and CFSR results. Despite this difference between the NARR and CFSR mixing height results, further examination revealed basic agreement between the reanalyses in terms of the spatial and temporal distribution of sensitivity – as is described in the following sections.

Spatial distribution of climatological mean sensitivity

Relaxing the lower transport wind threshold by 12.5% contributed only a modest +2% annual mean increase in availability

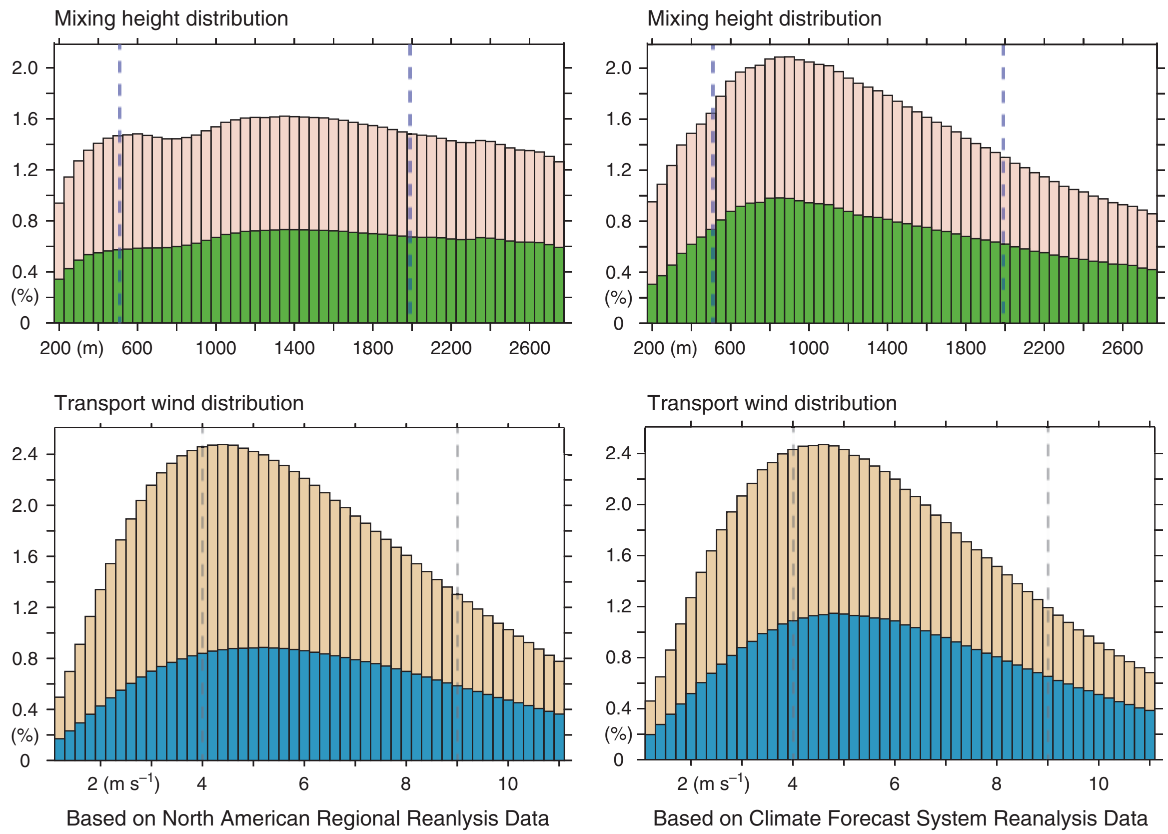

Fig. 1. Distribution of mixing height (upper left) and transport wind (lower left) binned from each study-region grid cell and daytime time-step (15:00, 18:00 and 21:00 Coordinated Universal Time [UTC]) based on North American Regional Reanalysis data, period 1979–2010. The *y*-axis values represent the percentage of total possible (n = daytime time-steps × land grid points) values that fall into the given bin, which have widths of 50 m and 0.2 m s^{-1}, respectively. The vertical dashed lines in each panel denote the base case prescribed-burn parameters and colours (green and blue) show the portion of each bin that meets the other burn-day criteria (e.g. green bars in upper panel show the portion within the preferable transport wind, precipitation, relative humidity and 20-ft wind speed parameters). Panels on the right are the same as those on the left, except for being based on Climate Forecast System Reanalysis Data, in which case only the local daytime time-step at 18:00 UTC is considered.

over the Southeast, with values given as the percentage increase relative to the total number of possible daytime time steps (Fig. 2*a*). The effect of making a commensurate 12.5% change to the upper-bound parameters resulted in greater burn-day availability (Fig. 2*b*, *d*). Specifically, increasing the upper transport wind bound from 9 m s^{-1} to 10.125 m s^{-1} and the upper mixing height bound from 1980 m to 2230 m resulted in area-averaged increases of 2.9% and 3.3%, respectively. Across the region, enhancements were evident to the south-eastern portion of the study area in the upper-bound mixing height case. The north-western portion of our study area showed a greater response to the transport wind case, while peak sensitivity to raising the mixing height upper bound was observed over the Florida Peninsula. Relaxing the lower mixing height threshold, however, produced the smallest overall change (area-average increase of only +0.7%) of the four cases considered.

The CFSR-based results (Fig. 3) were qualitatively similar to the NARR-based results (Fig. 2) in many respects. For example, the reanalyses agreed that the upper bounds offered more sensitivity to change than the lower bounds based on the percent-wise relaxations considered. Also, by each reanalysis, relaxing the lower mixing height bound resulted in the fewest additional times available for prescribed burning. Some differences, however, were evident between the NARR and CFSR results. For example, the transport wind upper bound was the most sensitive to change, in a time- and area-averaged sense, based on the CFSR data (especially in the more northern and northwestern parts of the study region), whereas the mixing height upper bound was most sensitive based on NARR. There was, however, basic agreement between the two reanalysis products that the upper-bound mixing height sensitivity was larger in the southeast than northwest portion of the study region, whereas the opposite (northwest peak in sensitivity) held in the transport wind case.

Although they may seem relatively modest in amplitude by the absolute metrics presented in Figs 2 and 3, it is useful to recall that, based on our calculations, the overall availability of burn-preferable times accounted for a relatively modest fraction of the total possible (19.7% and 24.6% based on NARR and CFSR time–space averages, respectively). Consequently, the increases discussed above account for substantial fractions of

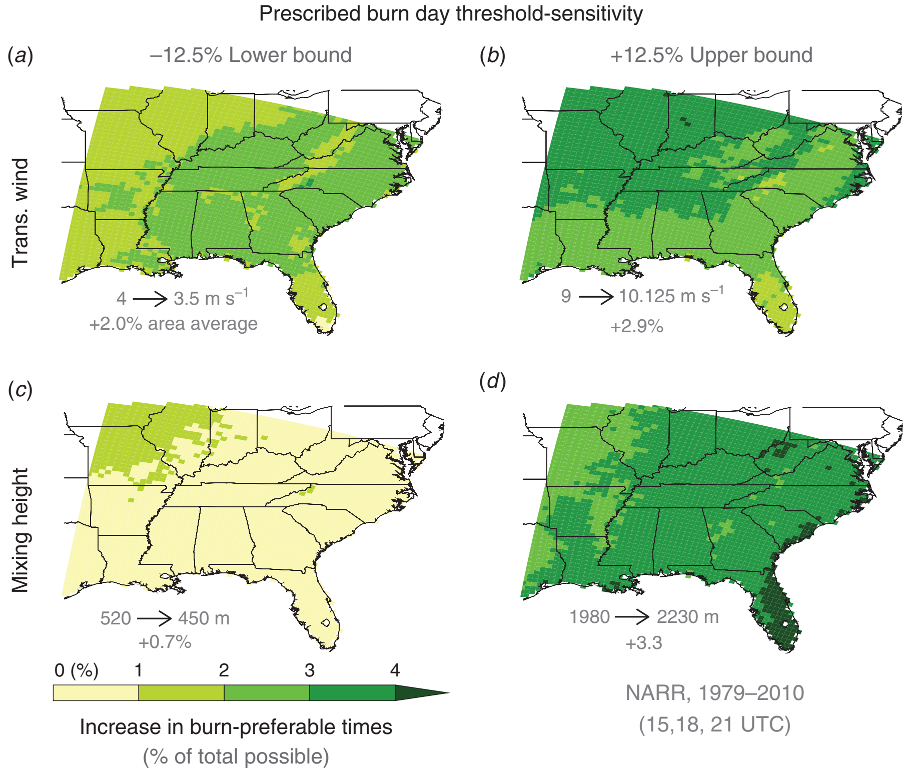

Fig. 2. Increased availability of burn-preferable mid-morning to afternoon reanalysis time steps caused by separately relaxing the upper and lower mixing height and transport wind bounds. Based on North American Regional Reanalysis (NARR) data, with results averaged over the 1979–2010 period and given as a percentage of the number of total possible mid-morning to afternoon time steps over this period. UTC, Coordinated Universal Time.

the prescribed burn-days identified by our base case calculation. The percentage increase, relative to the base case value, associated with the upper-bound mixing height and transport wind sensitivities are shown in Fig. 4, which shows that our candidate 12.5% relaxations resulted in area-averaged relative increases of more than 12.5% (up to 17.3% in the NARR mixing height case) in three of the four cases shown, with the CFSR mixing height being the one just below this level, at 12.1%. The discrepancies evident in Fig. 4 between the CFSR results highlight the same sources of uncertainty discussed above and in Chiodi *et al.* (2018). For example, there are some more highly defined extremes evident along the Appalachian Mountains in the NARR than in the CFSR case, which were associated with transport wind differences between the reanalyses and may be associated with NARR being run at higher spatial resolution. Also, the aforementioned mixing height differences have proximate cause largely in the associated surface temperature differences.

Seasonality of threshold-sensitivity

Comparison of the seasonality of the four sensitivities presented in Fig. 5 reveals two main features: (1) the upper bounds are associated with stronger seasonal variations in sensitivity than the lower bounds and (2) of the four considered, only the upper mixing height threshold offered near-peak sensitivity in the growing season (April–September), with the other three cases having relatively larger effects in autumn or winter (e.g. October–February). These features were consistent with the identification of the main seasonal fire weather constraints offered in Chiodi *et al.* (2018), who, for example, found that above-threshold mixing height was a primary reason for time steps to fall out of the preferred weather range in summer (June–August). Further, the transport wind thresholds were more likely to be exceeded in autumn and winter (October–February), in which case both above and below threshold cases were frequently observed.

Although the magnitudes of the effects shown in Fig. 5 accounted for only a modest fraction of the total possible times (days), they nonetheless equated to substantial increases over the base case availability. For example, the spring-to-summer (April–September) peaks seen in the upper-bound mixing height result would contribute ~25% more prescribed burn-days than are available at that time of year without these relaxations. An increase over the base case of 20% more prescribed burn-days would also be contributed by the upper-bound transport wind relaxation of 12.5% during the dormant season.

The corresponding result based on CFSR data is shown in Fig. 6. Comparison with the NARR case (Fig. 5) shows that the two reanalyses are in close agreement in terms of the climatological sensitivity aspects described above.

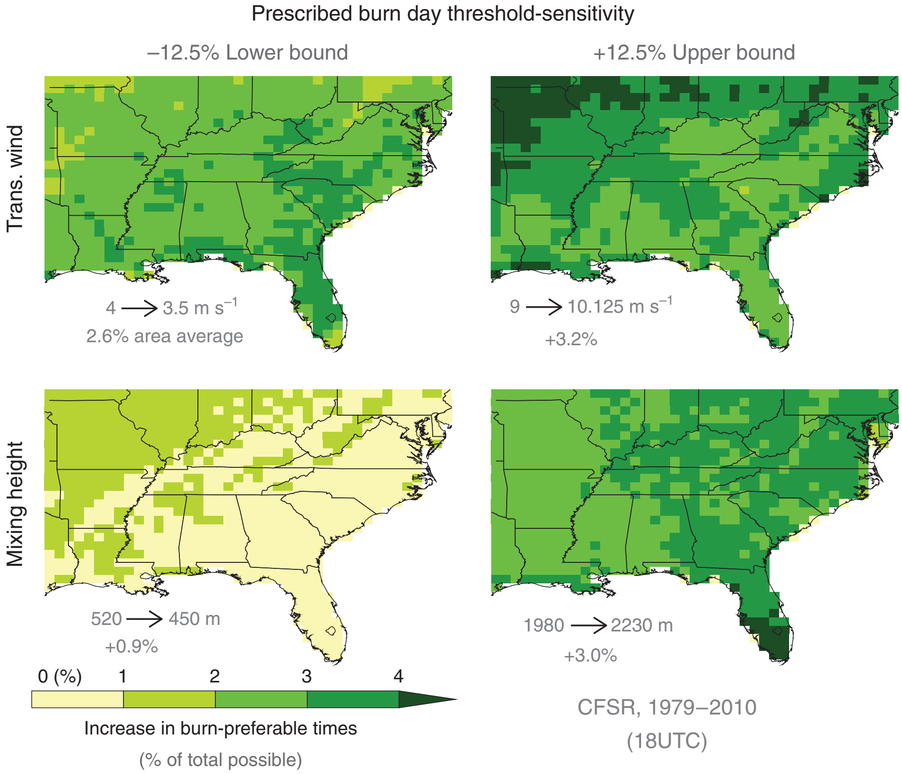

Fig. 3. Increased availability of burn-preferable mid-morning to afternoon reanalysis time steps caused by separately relaxing the upper and lower mixing height and transport wind bounds using Climate Forecast System Reanalysis (CFSR) data. Trans. wind, transport wind; UTC, Coordinated Universal Time.

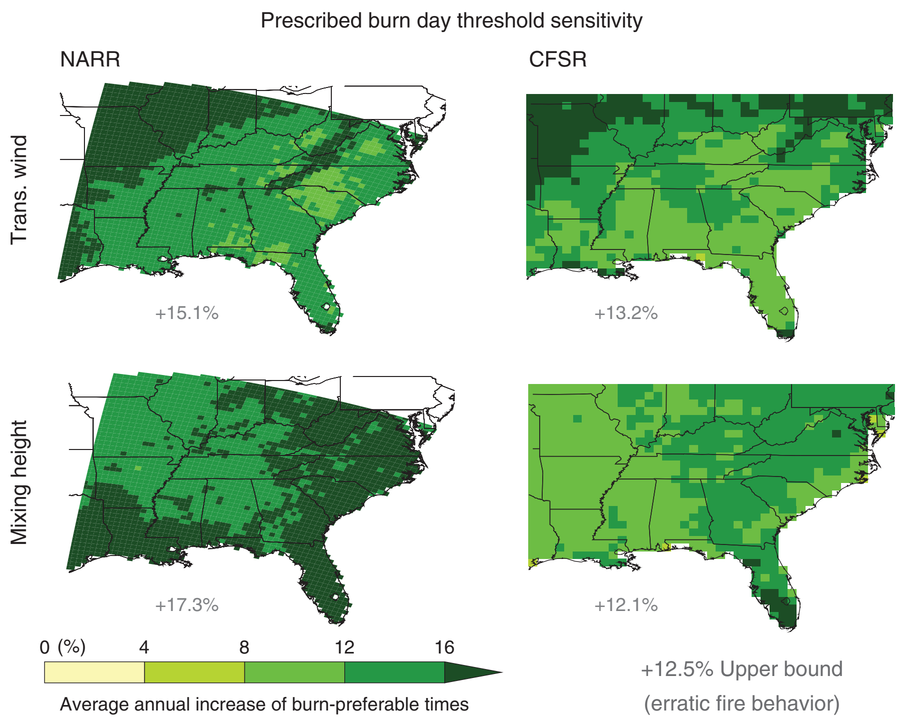

Fig. 4. The upper-bound sensitivity results shown in Figs 2 and 3 are repeated here, given as percentage increase over the base case availability. CFSR, Climate Forecast System Reanalysis; NARR, North American Regional Reanalysis; Trans. wind, transport wind.

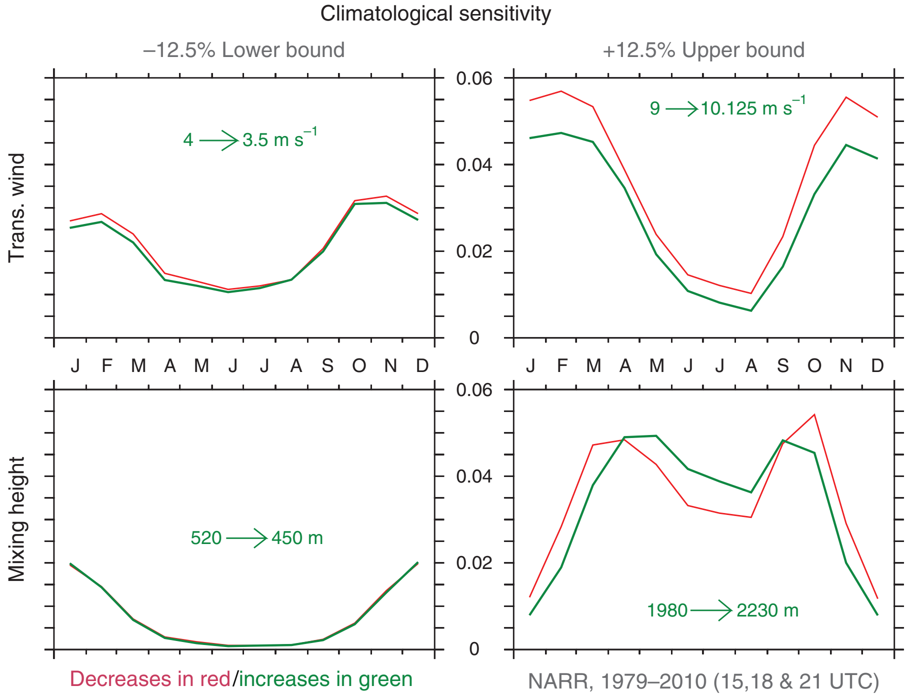

Fig. 5. Regionally averaged monthly climatological increases (green curves) in prescribed burn-preferable time step availability based on 12.5% relaxations of the upper and lower mixing height and transport wind bounds. Based on North American Regional Reanalysis (NARR) data. Values given in similar units as in Figs 2 and 3: fractional change relative to the total possible number of mid-morning to afternoon time steps, period 1979–2010. Red curves show the decreases that result from tightening the bounds by 12.5%. Trans. wind, transport wind; UTC, Coordinated Universal Time.

Humidity effects on equilibrium-level mixing height estimation

We offer a set of results in this section based on recalculating the prescribed burn-day climatology after neglecting the effects of humidity on air density when estimating the mixing height; in other words, using the potential temperature profiles, rather than virtual potential temperature profiles.

Area-averaged results based on NARR data (Fig. 7, upper left panel) revealed that the primary effect of neglecting humidity was to increase the availability of prescribed-burn-preferable times in the warm season, with peak effects reaching ~8% of potentially available times in June and July. During this peak season, increases were evident, in the climatological-average sense, at all locations in the study region (Fig. 7, upper right panel), with a maximum over the Ohio River Valley. In the winter, however, there were decreases seen over most of the study region, but they were smaller in amplitude than the increases seen in summer and offset in the regional average by wintertime increases over the Florida Peninsula (Fig. 7, upper middle panel).

The corresponding CFSR-based results (Fig. 7 lower panels) were somewhat different in detail to the NARR-based results. For example, the magnitudes of the humidity effects were, in an area-averaged sense, smaller according to CFSR than NARR. For example, the maximum increase seen in June based on CFSR (~4% of potentially available times) was only half as large as the NARR result. Nonetheless, the basic character of the humidity effect remained the same regardless of which dataset was used: summertime availability is increased if humidity is neglected. Thus, from the manager's point of view, making a more thermodynamically consistent calculation (accounting for humidity) narrows the growing season window of opportunity because the estimated mixing heights are thereby increased, the upper mixing height threshold then provides a main constraint and many formerly borderline, high-preferable mixing heights would then exceed the upper limit.

VI results

The fraction of mid-morning to afternoon times available for prescribed burning based on the NARR data and VI values being $> 2400\ m^2\ s^{-1}$ and $< 8360\ m^2\ s^{-1}$ is shown in a region-averaged sense in Fig. 8 (blue curve). The previously discussed climatology based on application of Wade and Lunsford (1989) mixing height and transport wind parameters is also shown in Fig. 8 (green curve).

Based on these applied sets of weather parameters, preferable conditions for prescribed burning occur more frequently in the VI case than in the mixing height and transport wind case. Averaged over all months, the VI climatology (27% of total possible times available) exceeded the base case mixing height and transport wind climatology (20% available) by a factor of ~1.4 (27/20 = 1.4), with a peak difference in August (factor 2.7) and minimum difference in April (factor 1.0).

The VI and mixing height and transport wind climatologies were in agreement that preferable conditions for prescribed

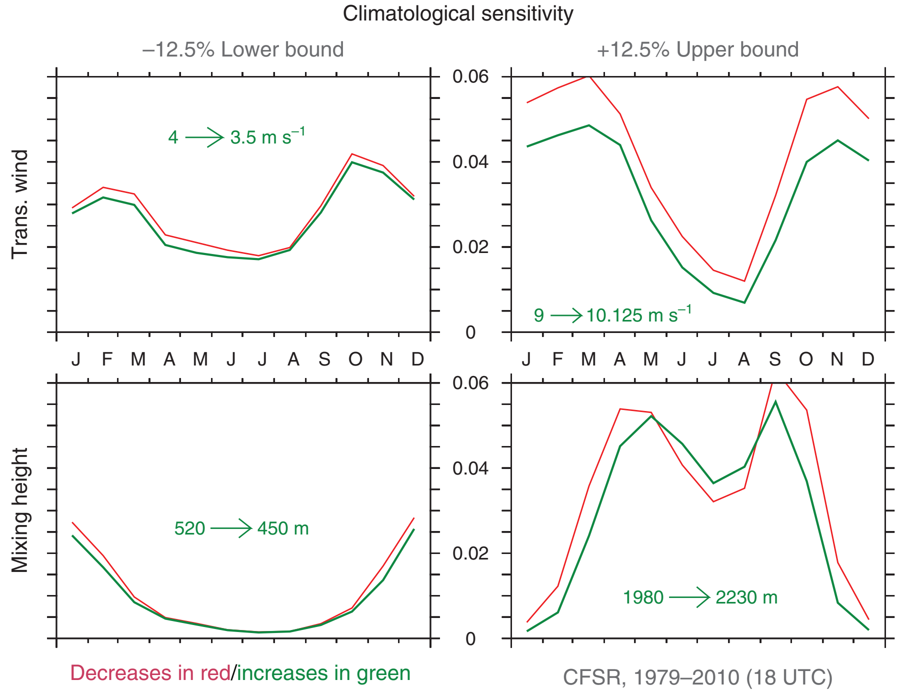

Fig. 6. Regionally averaged monthly climatological increases (green curves) in prescribed burn-preferable time step availability based on 12.5% relaxations of the upper and lower mixing height and transport wind bounds, based on Climate Forecast System Reanalysis (CFSR) data. Values given in fractional change relative to total possible mid-morning to afternoon time steps. Red curves show the decreases that result from tightening the bounds by 12.5%. Trans. wind, transport wind; UTC, Coordinated Universal Time.

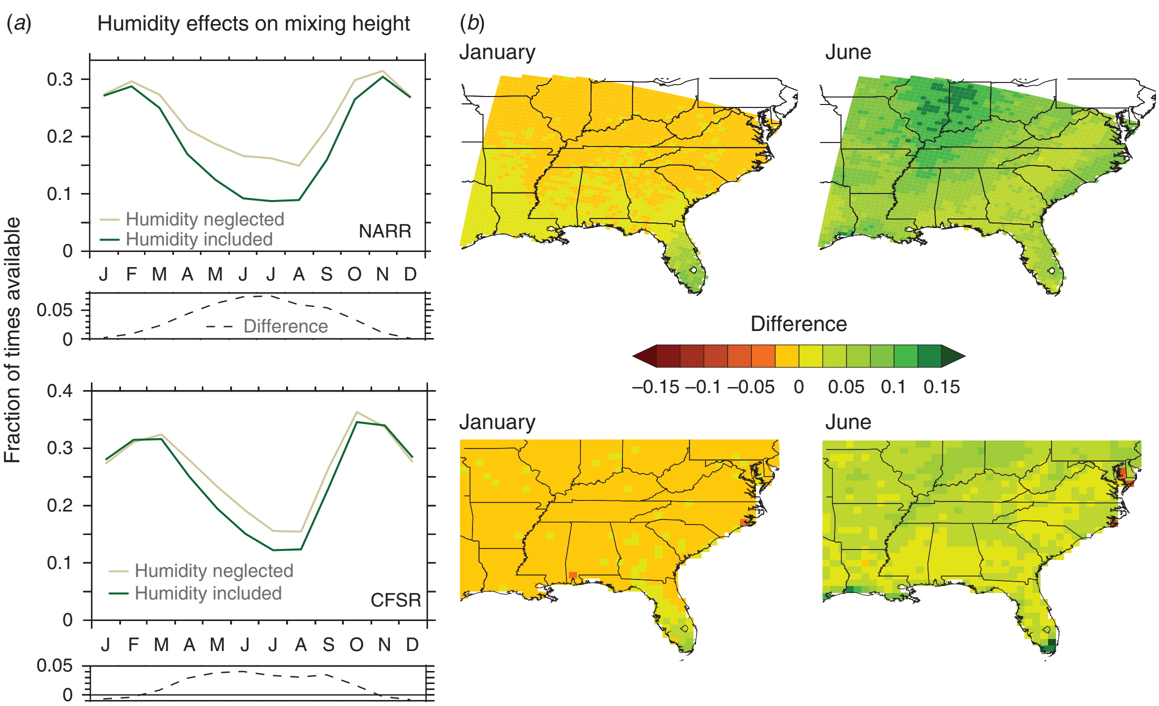

Fig. 7. (*a*) Regionally averaged monthly climatological availability of burn-preferable time steps based on accounting for (green curve) and neglecting (tan curve) humidity effects in the mixing height estimation procedure. (*b*) Maps show the climatological mean difference for January and June (humidity neglected results minus humidity included). Upper panels are based on North American Regional Reanalysis data (NARR) and lower panels based on Climate Forecast System Reanalysis (CFSR) data, period 1979–2010.

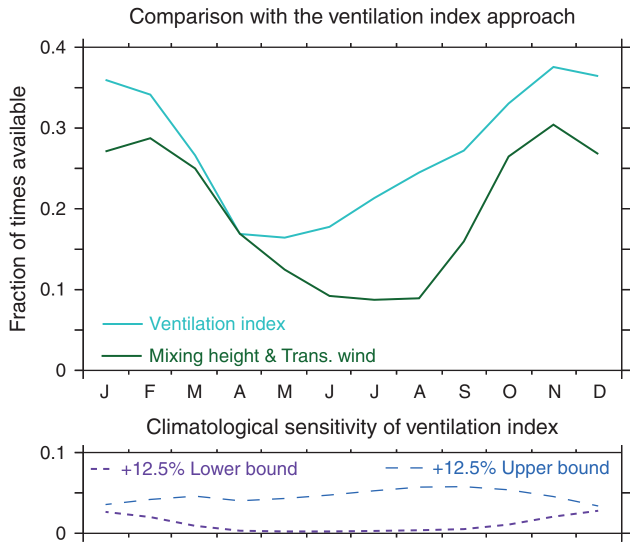

Fig. 8. (*a*) Climatological variation of the fraction of 15:00, 18:00 and 21:00 UTC times available for prescribed burning based on screening for the preferred Wade and Lunsford (1989) mixing height and transport wind conditions (green curve) and, alternatively, ventilation index values >2400 m^2 s^{-1} and <8360 m^2 s^{-1} (blue curve). (*b*) Regionally averaged monthly climatological increases in prescribed burn-preferable time step availability based on 12.5% relaxations of the upper and lower ventilation index bounds. These results are based on North American Regional Reanalysis (NARR) data. UTC, Coordinated Universal Time.

burning are more frequently available in autumn and winter (October–February) than in spring and summer (April–September). The timing of the minimum, however, depends on the approach considered, with minimum availability occurring in the mixing height and transport wind case in August (when the regionally averaged mixing height peaks), whereas in the VI case, the minimum occurs in April when the transport winds reach their peak.

We also calculated the change in availability produced by relaxing the upper and lower VI bounds by 12.5% (c.f. lower panels of Figs 8 and 5). In the VI case (Fig. 8, lower panel), the upper-bound relaxation yielded more prescribed burn-days than the lower bound-relaxation in each month, but was especially dominant during the spring and summer when the lower bound sensitivity was quite small (< 2% increase, relative to the base case, in June–August). This lack of lower-bound-summertime sensitivity can be at least partially understood by the fact that most days from March through September (63% of 15:00, 18:00 and 21:00 times averaged over these months and the region) exhibit VI conditions already above the applied lower bound of 2400 m^2 s^{-1}. In winter, however, the lower bound VI sensitivity is much larger than in summer (7–8% increase, relative to the base case in December and January) and in fact approaches that of the upper bound at that time of year.

Relaxing the upper bound by 12.5% increased the amount of burn-preferable times by 9–27%, relative to the original monthly averages, depending on month, with the relative maximum in May–June and minimum in December–January. Tabulating the increases alternatively in an absolute sense (out of all possible times), the minimum sensitivity remained in December–January (3–4%), but the maximum (~6%) shifts to August–September. Although substantial, the seasonal variability of upper-bound VI sensitivity is not as dramatic as in the mixing height upper bound and transport wind upper bound cases (c.f. Fig. 5). Evidently, the seasonally out-of-phase nature of the mixing height and transport wind sensitivities acts to buffer the VI upper bound sensitivity from undergoing comparably dramatic change with season.

Companion results based on CFSR data were calculated (not shown) and found to be qualitatively consistent with the NARR-based results described above.

Summary and Discussion

The southeastern USA prescribed burn-day climatology of Chiodi *et al.* (2018) was calculated with a focus on the preferred mixing height (1700 ft/520 m – 6500 ft/1980 m) and transport wind (9 mph/4 m s^{-1} – 20 mph/9 m s^{-1}) parameters suggested by Wade and Lunsford (1989) and implemented in practice in the Southeast. Results based on a pair of reanalysis products (NARR and CFSR) agreed that the availability of preferred fire weather windows was narrowest in the growing season, wherein the majority of days fell outside the preferred range (e.g. regional average availability of 10–15% in August). If minor changes in one parameter's range could result in a sizable expansion of opportunity, then reconsidering these limits may enable substantial increases in burning activity.

Our sensitivity analysis found that relaxing the upper mixing height threshold offered the most efficient way of increasing the number of days available for prescribed burning in April through September. In this case, each percentage increase in height threshold would contribute approximately double that percentage increase in times available for prescribed burns (e.g. 12.5% height increase causes 20–25% more burn-days). This is consistent with the Chiodi *et al.* (2018) finding that the upper mixing height limit provided the primary weather hurdle to summertime prescribed burning over most of the study region. In practice, some managers and permitting authorities have already relaxed this upper bound. Research on how fire behaviour is affected and the degree to which these high mixing height days are related to erratic fire behaviour is warranted.

We also analysed the climatology for its sensitivity to changes in how the mixing height was estimated; specifically, whether or not humidity is (as in the Stull (1991) method) or is not (as in the Holzworth (1967) method) accounted for when estimating surface air parcel buoyancy in the equilibrium height approach to mixing height estimation. Previously, Fearon *et al.* (2015) found that there was an average increase in estimated mixing height of ~500 m associated with a switch from potential temperature to virtual potential temperature over the USA; water vapour is less dense than dry air and switching from neglecting to accounting for humidity generally raises the mixing height. This has the effect of marginally increasing the number of days available for prescribed burning over most of the study region in the dormant season (the Florida Peninsula being an exception), but has a more constraining effect in the summer months. Our base case calculations accounted for humidity because it should be included from a thermodynamic perspective; moreover, it has been demonstrated that the equilibrium height estimation approach produces more accurate results when humidity is accounted for (Fearon *et al.* 2015). Across the Southeast, however, it has been reported that humidity has not been accounted for in operational forecasts (Brown and Hall 2010). The magnitude of the summertime humidity effect differs depending on which reanalysis product is used, with NARR suggesting larger (regional average near 8% of potentially available times) effects than CFSR (near 4%). This 4–8% range brackets the summertime region-averaged effect of raising the mixing height threshold by 250 m (12.5% increase over 1980 m), meaning that the effects of changing the mixing height estimation method could be largely offset by changing the upper mixing height bound for prescribed burning.

Although the availability of prescribed burn-days is smaller in the growing than in the dormant season, the dormant season itself remains more closed than open under the criteria used here (October through March monthly and regionally averaged availability ranges from 25% to 35%). In the dormant season, it is percentage-wise changes to the upper transport wind bound that most effectively alter the burn-day availability, with a 12.5% increase to the upper transport wind bound of 9 m s^{-1} contributing ~5% more days available for prescribed burning (out of the total possible). This represents an increase of ~20% over the dormant season availability calculated originally using a 9 m s^{-1} upper bound. The winter and early spring months (December–April) are shown to already represent most of burned area in the region (Nowell *et al.* 2018).

The upper mixing height and transport wind limits are in place to guard against the risk of erratic fire behaviour. This motivates the question of whether these bounds might be beneficially relaxed to meet extensive regional management objectives. Consideration of the concerted use of other approaches available to mitigate the potential for erratic fire behaviour, such as increasing resources, antecedent fuel treatments and altered ignition patterns, along with efforts to better understand fire behaviour at or near the upper limits, may prove fertile ground for future study.

The issue of whether humidity is, or is not, accounted for when estimating mixing height via the equilibrium height method motivates a similar consideration; in cases where the equilibrium height method is being used without accounting for humidity, switching to doing so will cause more days to exceed both the lower and upper mixing height bounds. Under the prescription definition applied here, this mainly decreases the number of burn-days available during the growing season over the Southeast. In this situation, a compensating upper bound change – with amplitude comparable to the 12.5% relaxation considered in our analysis above – may be reasonable to consider, especially if the upper bounds formerly in place have proven to be adequate from the fire behaviour perspective.

Because the product of the mixing height and transport wind (a.k.a. the VI) is also used regionally to assess the prevailing capacity for smoke dispersion, we calculated the prescribed burn-day climatology based on daytime VI values calculated from NARR data falling between a lower limit of 2400 m^2 s^{-1} and an upper limit of 8360 m^2 s^{-1}. The resulting VI-based climatology was consistent with the mixing height and transport wind case in that each found that the availability of the preferred weather conditions was better in the fall and winter (September through February regional and monthly averaged availability ranges from 27% to 38%) than spring or summer (March through August range of 16–25%). These two approaches differ, however, in regards to the season in which burn-days are least likely in a region-averaged sense; in the VI case, the preferred conditions are least likely to occur in spring (April or May have regionally averaged availability of 17% and 16%, respectively) when the transport winds reach their climatological peak and upper bound exceedance contributes the strongest constraint. In the mixing height and transport wind case, preferred weather conditions are least likely to occur in August, when mixing heights reach their climatological peak in a region-averaged sense. In both cases, however, we found it was the applied upper, rather than lower, bounds that most efficiently offered more prescribed burn-days when relaxed.

Although the atmospheric dispersion index suggested by Lavdas (1986) is a common estimate of dispersion used in regional smoke management applications, successful consideration of its climatological variation over the full study region will require addressing several complicating factors. First, it is unclear how best to calculate the dispersion index based on reanalysis and numerical weather forecast data. Possible pathways to doing this include: (1) estimating cloud cover in tenths and cloud ceiling height from the available reanalysis data; (2) using the surface solar radiation data provided by the reanalyses to estimate surface heating (which is the goal of tabulating solar elevation and cloud conditions); or (3) using vertical temperature profiles to evaluate stability (which is the goal of tabulating surface heating). Advantages and disadvantages are apparent with each choice: case (1) has the advantage that no modification of the dispersion index algorithm is needed; however, the relationship between the cloud information provided by reanalyses (e.g. low, mid and high cloud area fractions are available from NARR) and the surface radiation budget is ambiguous and choosing this pathway may introduce unnecessary uncertainties when ground heating knowledge is the goal. Alternatively, using the surface solar radiation or temperature profiles routinely provided by the reanalyses offers a more direct pathway for introducing stability information into the dispersion index algorithm, but would require transposing Turner's (1961, 1964) cloud cover-based tables (who, incidentally, recommended that stability be calculated from temperature profiles when that information was available) to depend on these variables.

A second major issue with calculating the Lavdas dispersion index emerges from literature that reveals that the vertical wind fluctuation measurements made by Smith (1961) – the data upon which the Pasquill (1961) approach at distances greater than 1 km from the emission source were based – were intended to improve understanding of turbulence characteristics at various heights above ground, rather than describe turbulence near the ground. The Smith (1961) finding that turbulence intensity aloft decreases 'with increasing wind speed, a result peculiar to these heights' continues to inform how turbulence is predicted to vary based on wind speed in the Lavdas (1986) algorithm. This assumption motivates the question of whether it is appropriate in the scenario imagined, in which it is the dispersion of near-ground smoke that is being modelled and thus, mechanical contributions to turbulence are likely to play an important role in controlling the effects on breathable air quality. We suggest that the role of wind speed in this context may deserve further consideration.

Reaching consensus on the best-practice for quantifying atmospheric dispersion potential caused by turbulence in a manner that remains consistent across the use of operational forecast and reanalysis data would facilitate further study. It also remains to examine the extent to which the results described here, based on the basic agreement found between two reanalysis products, might differ from the operational case wherein the numerical weather model, after being initialised based on observational information, must run in forecast rather than data assimilation mode. Thus, collecting and analysing archives of the weather forecasts issued operationally across the study region, or forecasts provided retrospectively by newly implemented weather models, will provide a useful basis for further study.

Conclusions

Prescribed fire remains one of the most critical natural resource management tools available to meet a variety of conservation objectives and ecosystem services (Ryan *et al.* 2013). The southeastern USA is an epicentre for its application in North America. Relating information about prevailing weather, moisture and fuel conditions to prescription parameters for burn-days, however, has historically been based on experience and rules of thumb that conservatively balance the need for fire application to be both safe and effective (Wade and Lunsford 1989). Urbanisation and changing demographics across the Southeast and other fire-prone areas across the USA have largely increased the need for prescribed burning (especially from the wildfire smoke and hazardous fuel level perspectives) while presenting hurdles to its application (Quinn-Davidson and Varner 2012; Brown *et al.* 2014; Garfin *et al.* 2014; Joyce *et al.* 2014; Kobziar *et al.* 2015). This situation calls into question whether regional managers can continue to achieve extensive area-treated objectives in a sustainable manner under current prescription parameters. It also motivates consideration of whether some of these parameters might be moderately relaxed such that the opportunity for effective prescribed burning significantly increases while the associated risks are either reduced or remain within our ability to adequately mitigate them.

This study is therefore a useful retrospective analysis of the opportunity costs associated with commonly recommended prescribed burn weather parameters, as well as approaches used to calculate and define them. The expansion or contraction of these parameters was shown to substantially effect the number of burn-days available with greater sensitivity for upper-bound mixing height during the growing season and upper-bound transport wind during the dormant season; in each case, the burn season was expanded percentage-wise by roughly double the parameter relaxation (i.e. 12.5% relaxation contributed 20–25% more days). Sensitivity also varied geographically, exhibiting three-fold change between the local minimum and maximum in the time-averaged upper-bound transport wind case, and up to five-fold change across the region in the time-averaged upper-bound mixing height case. Given this sensitivity and increasing burn complexity, future work must be done to more mechanistically link prescription ranges, recommendations and risks to sustain necessary prescribed fire activity in the region. Investigations in other regions within the USA and globally that face narrow prescription windows because of smoke dispersion hurdles could utilise our methodology to identify similar opportunities to optimise burning opportunities.

Conflicts of interest

The authors declare no conflicts of interest.

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