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Climate change and associated fire potential for the south-eastern United States in the 21st century

Anthony P. Bedel[A,D], *Thomas L. Mote*[B] *and Scott L. Goodrick*[C]

[A]Kentucky Division for Air Quality, 200 Fair Oaks Lane, 1st Floor, Frankfort, KY 40601, USA.
[B]University of Georgia, 210 Field Street, Room 204, Athens, GA 30602, USA.
[C]United States Department of Agriculture's Forest Service, Southern Research Station, Center for Forest Disturbance Science, 320 Green Street, Athens, GA 30602, USA.
[D]Corresponding author. Email: anthony.bedel@ky.gov

Abstract. Climate models indicate that the climate of the south-eastern US will experience increasing temperatures and associated evapotranspiration in the 21st century. The current study found that conditions in the south-eastern US will likely become drier overall, given a warmer environment during future winter and spring seasons. This study examined the potential effects of a warmer climate in the 21st century on relevant meteorological fire parameters (e.g. total and convective precipitation, 500-hPa geopotential heights, near-surface relative humidity) and popular fire indices (e.g. Haines and Keetch–Byram Drought Indices) in the south-eastern US. Although the results offered conflicting implications in portions of the study domain, the southern half of the south-eastern US (including the Deep South, the southern Piedmont and Florida) exhibited the highest potential for increasing fire activity in the mid-21st century, given maximum warming and drying in these areas, especially in the spring season.

Additional keywords: forest fires, Haines Index, KBDI.

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Introduction

Meteorology plays a central role in the onset, spatial extent and duration of forest fires. Such weather phenomena as high temperatures, low humidity and strong horizontal winds are ingredients conducive to forest fire development and spread (e.g. Martín *et al.* 1997; Hostetler *et al.* 2005). Such conditions are typical of the boreal winter and spring months in the south-eastern US, contributing to the peak annual fire season in this region. Droughts represent prolonged dry periods, typically associated with higher maximum temperatures and lower relative humidity (RH), conditions that promote periods of frequent and extensive forest fires. The threat of climate change will likely have a direct effect on forest fires in the future. Recent warming trends and periodic anomalous drought conditions have already influenced wildfire characteristics considerably in the early part of the 21st century (Bernstein *et al.* 2007). Climate projections for the 21st century suggest increasing temperatures and prolonged periods of droughts across the south-eastern US (e.g. Bernstein *et al.* 2007; Meehl *et al.* 2007; Flannigan *et al.* 2009; Liu *et al.* 2013).

One potential focus of climate change that has been largely overlooked is the regional influence of projected climate change on prominent meteorological and climatological conditions shown to be correlated with wildfire onset and expansion. This study aims to address the potential (i.e. the likelihood of an increase relative to present-day) of forest fire activity (i.e. forest fires ignited and spread naturally) in the south-eastern US during the 21st century. In a warmer and generally drier climate, it is hypothesised that conditions conducive to wildfire development will be more widespread than at present. Given its abundance of forested landscape, such a scenario implies a possible upward trend in forest land burnt in the south-eastern US, likely placing additional strain on fire management agencies that must allocate already limited resources to mitigate a growing threat to human and environmental health.

Background

In general, forest fires are a vital component to the landscape of the south-eastern US, where prescribed fires in this region comprise 75% of all intentional burns in the US overall and occur on a year-round basis (Krock 2011). Research suggests that naturally caused forest fires in the US are responsible for diversifying tree species in relatively new forests that arise from the remains of previously scorched forested land (Krock 2011). Prescribed fires, in contrast, are often initiated to reduce accumulated forest fuel loads for the protection of human health and property. In this study, the south-eastern US and study domain approximately encompasses the states of Kentucky, Virginia, North and South Carolina, Georgia, Florida, Alabama, Tennessee, Mississippi, Arkansas, Louisiana and eastern Texas. Currently, the dominant fire season in this region occurs during the transition period from winter to spring, when climate conditions are generally dry following the winter months, and when the trees are leafless, allowing the surface layer to become a heat sink (Gagnon 2009; Krock 2011). Fire activity typically shifts north from Florida and the Gulf Coast as the winter season transitions into spring (Krock 2011). There is also considerable year-to-year variability in overall fire activity in the south-eastern US, partially due to teleconnection influences such as the El Niño–Southern Oscillation (ENSO), which has been shown to contribute to extreme fire activity in Florida during cold ENSO phases (Goodrick and Hanley 2009).

An abundance of recent and current scientific literature has concluded that Earth will warm significantly over the next century (e.g. Füssel 2009). Such events as the heat waves of Russia (in 2010) and Texas (in 2011) demonstrate the types of extreme events that are expected to become more common and require further human adaptation in the 21st century. A projected warmer environment in the 21st century – especially in the higher latitudes of the northern hemisphere (e.g. Francis and Vavrus 2012) – suggests that future storm tracks will weaken given an associated reduction in the meridional temperature gradient. In this study, storm tracks are considered to be the typical climatological paths taken by mid-latitude cyclones (MLCs), which are simply individual synoptic-scale storm systems that are often associated with transitioning thermal and atmospheric moisture characteristics before and after a MLC affects a given area. Analyses by Francis and Vavrus (2012) implied both a northward displacement in, and the enhanced amplification of storm tracks over, the northern hemisphere in the early 21st century relative to the late-20th century, especially in the winter season when MLCs are typically most prominent in the south-eastern US.

In general, forest fires occur in environments where conditions are both warm and dry. With a potential doubling of current CO_2 concentrations in the near future, an additional increase of 1.8 to 4.0°C is expected globally over the next century (Bernstein *et al.* 2007). Thus, it is reasonable to conclude that the potential for forest fires will also increase on a global scale in the future, despite regional variations in precipitation forecasts (Bernstein *et al.* 2007). Such increasing forest fire activity would release higher rates of stored carbon into the atmosphere, accelerating overall carbon emissions and contributing to a positive feedback of warming and drying conditions under additional greenhouse gas (GHG) emissions (Kurz *et al.* 1995; Flannigan *et al.* 2006). These global warming projections include the south-eastern US, where temperatures are projected to continue to warm over the next century, especially inland from the Gulf of Mexico and the Atlantic Ocean.

Several wildfire indices are based on the input of meteorological and climatological variables developed for forest fire prognoses. The Haines Index (HI) quantifies the potential for large, plume-driven wildfires to continue to grow and exhibit unpredictable behaviour (Haines 1988; Winkler *et al.* 2007). Another fire index used extensively in the south-eastern US is the Keetch–Byram Drought Index (KBDI), developed by John Keetch and George Byram to calculate drought conditions in an area based on daily soil moisture depletion (Keetch and Byram 1968; Janis *et al.* 2002). Projected higher near-surface temperatures in the 21st century may increase low-level lapse rates and near-surface soil drying in the south-eastern US, leading to increases in future KBDI and HI, and associated potential for fires respectively to ignite and spread. With higher temperatures and associated drying surface conditions predicted for the south-eastern US, the literature appears to converge on the theory that the potential for forest fires in this region will increase, given more readily available fuels from enhanced vegetative growth, due to generally warmer and longer growing seasons.

Materials and methods

Daily and 3-h timestep data from two pairs of global (GCM) and regional (RCM) climate model simulations (i.e. Canadian Regional Climate Model (CRCM) and Community Climate System Model (CCSM); Weather Research & Forecasting Model (WRFG) and Community Climate System Model (CCSM)) were used for the purposes of this study during both the late-20th (1981–1999) and mid-21st (2051–2069) centuries. Modelled data were made available by the North American Regional Climate Change Assessment Program (NARCCAP), and the model pairings and time periods were chosen based on data availability. The CCSM boasts the finest spatial resolution of any of the four coupled Atmosphere-Ocean GCMs utilised by NARCCAP ($1.4 \times 1.4°$ latitude and longitude) along with 26 atmospheric layers and the inclusion of a full vegetation canopy in the land surface model (UCAR 2012). The NARCCAP project team simulates all GCM–RCM combinations at a 50-km spatial resolution with the A2 emissions scenario, the most aggressive scenario in terms of GHG emissions and potential warming in the next century.

The CRCM–CCSM pairing was utilised for all data fields with the exception of the precipitation analyses because CRCM–CCSM temperature data were available on a 15-min time interval, whereas WRFG–CCSM temperature data were simply hourly values. WRFG–CCSM total and convective precipitation data were substituted for the precipitation analyses in this study given the improved cumulus parameterisation scheme (i.e. Grell *et al.* 1995; *v.* mass flux, i.e. mass transport caused by turbulent flow) and timestep temporal resolution (15 *v.* 2.5 min) of the WRFG RCM over the CRCM, both of which are necessary components for accurate convective resolution in atmospheric simulations (UCAR 2012). Moving forward, however, it would be naïve to expect any model simulation at 50-km spatial resolution to accurately portray the true convective environment for Florida, given its peninsular geography and the sea- and land–breeze mechanisms that dominate much of the state (e.g. Byers and Rodebush 1948; Simpson *et al.* 1980; Wilson and Megenhardt 1997). Recent analyses of NARCCAP data have suggested relatively strong correlations between modelled NARCCAP data using different model pairings with observed datasets over the final two decades of the 20th century (Shem *et al.* 2012). Such analyses have also exposed a general 'cold' bias in the data. However, this perceived bias did not present a significant complication for the analyses conducted in this study given that these analyses focussed on the comparison of future and recent historical modelled data.

The study area included the south-eastern US, consisting of the region defined previously plus eastern Oklahoma (Fig. 1), to reflect the Southern Region of the United States Forest Service

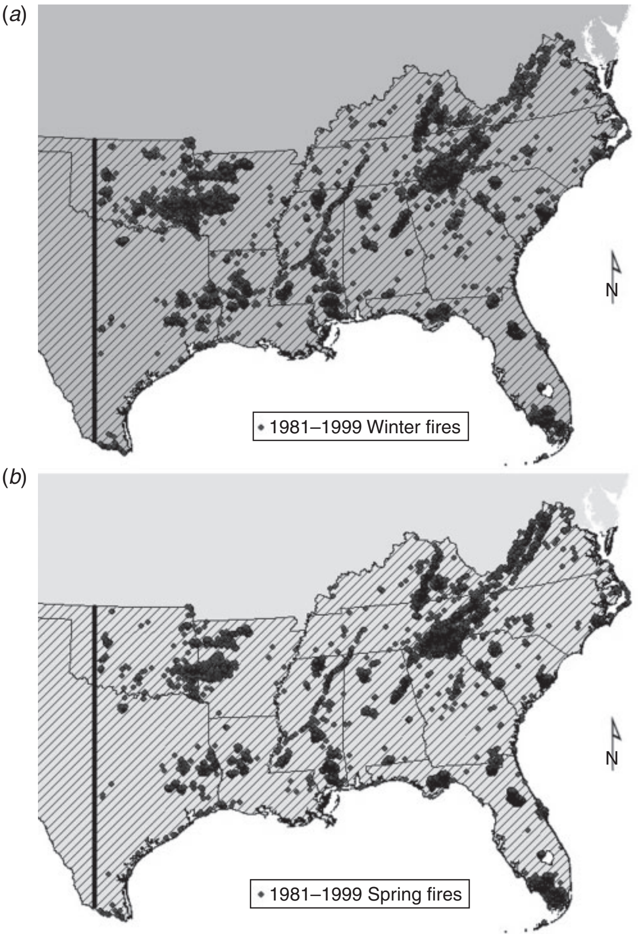

Fig. 1. Forest fire locations from 1981 to 1999 in the study domain during the (*a*) winter and (*b*) spring seasons. Thick black lines designate the western extent of the study domain.

(USFS 2013). Analyses were conducted during two annual seasons: boreal winter and boreal spring. Seasonal totals of total and convective precipitation over the south-eastern US were analysed to determine if either parameter would change significantly in the 21st century. The 500-hPa geopotential height fields provided both a metric for atmospheric stability and a method for storm track identification using an elevated constant pressure level in the atmosphere. Paralleling the work of Salathé (2006), areas of maximum variances in the 500-hPa geopotential height fields were determined to be the likely locations for storm tracks in the region during recent historical and future periods. Frequent MLCs over a particular area cause significant variability in the 500-hPa geopotential heights, because of raised (lowered) heights out ahead (in the wake) of MLCs as they progress.

Additionally, mean monthly values of HI were calculated using recent historical and future monthly NARCCAP temperature data at 950 and 850 hPa as well as specific humidity data at 850 hPa (needed to calculate 850-hPa dew point depression data). Initially referred to as the 'Lower Atmospheric Severity Index', HI was developed by Donald Haines in 1988 to assess the potential for existing forest fires to become extensive and exhibit irregular behaviour (Winkler *et al.* 2007). Three variants of the HI are used for low-, mid- and high-elevation locations. The south-eastern US, with the exceptions of the Appalachian Mountains and the Ozarks Region in Arkansas and Missouri, lies within the low-variant region. Stability and moisture component values at each grid point in the south-eastern US were calculated and simply summed to generate a comprehensive HI value that ranges from 2 (stable and moist environment; very low 'large' fire risk to human health and property) through 6 (unstable and dry environment; high 'large' fire risk). Additional information on the calculation of HI may be found in Winkler *et al.* (2007).

Monthly average values of KBDI were also calculated for the recent historical and future study periods because of its relevance to south-eastern US soil conditions and its ability to reflect near-surface temperature and moisture conditions collectively. KBDI is calculated using mean annual rainfall, daily maximum temperature and daily rainfall throughout the study domain. Originally developed by John Keetch and George Byram in 1968, KBDI quantifies drought conditions and associated fire potential on a daily basis (Keetch and Byram 1968; Janis *et al.* 2002). Essentially, this index was intended to measure the potential flammability of surface organic materials with respect to the combined effects of evapotranspiration and precipitation on soil moisture deficiency (Keetch and Byram 1968). Additional information on KBDI may be found in Janis *et al.* (2002).

Because KBDI is computed daily, one of its principal drawbacks involves initialising the index on a period when the upper-layer soils are sufficiently saturated (i.e. when KBDI is assumed to be 0). Fujioka (1991) calculated KBDI over a period using selected initial values (i.e. 0, 200 and 400) and concluded that the error associated with arbitrarily initialising KBDI diminishes over time until it is eventually eliminated altogether. KBDI initialisation errors were tested and shown in this study to disappear by 1 May in year 1 for both the recent historical (1981) and future (2051) periods at each of the four soil moisture deficit cooperative station locations. Thus, KBDI was initialised at 0 for both the recent historical (1 January 1981) and future (1 January 2051) periods across the domain, and the analyses were conducted over the final 18 years of each period (i.e. 1982–1999 and 2052–2069).

Based on the work of Flannigan and Harrington (1988), this study also examined consecutive days with daily RH values less than statistically derived critical thresholds for the late-20th and mid-21st century periods. For the south-eastern US, a critical threshold for RH in anomalously active fire months was attained using average monthly mean daily RH data calculated with daily average ambient and dew point temperature data from the National Climatic Data Center (see Global Summary of the Day, http://www7.ncdc.noaa.gov/CDO/cdogetsubquery.cmd, accessed 14 February 2012). This procedure was conducted by computing the mean fire frequency and mean total area burnt on a monthly basis for the recent historical period. For this study, an anomalously active fire month consisted of either fire frequency or total area burnt that was at least one standard deviation higher than its respective mean.

Although other variables (e.g. temperature anomalies, soil moisture) and fire-weather-related indices (e.g. Fosberg Fire Weather Index (Fosberg FWI)) may also be relevant for this type

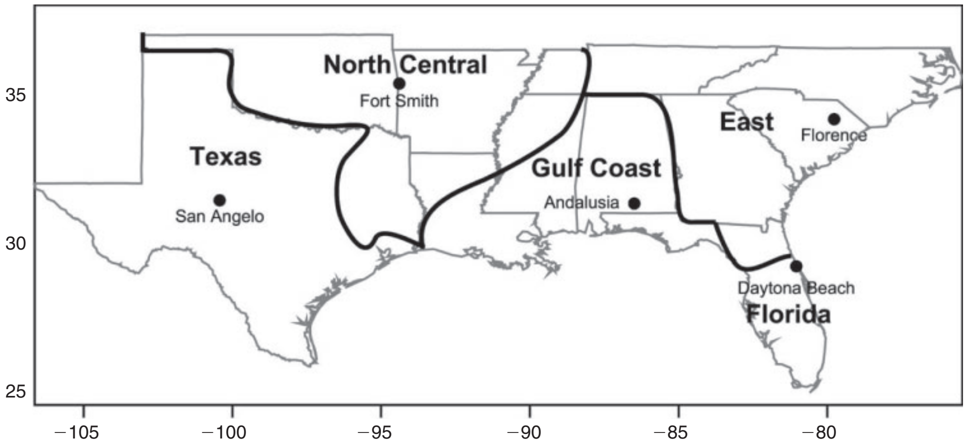

Fig. 2. Five soil moisture deficit regions and representative point locations utilised in this study (Doublin and Grundstein 2008).

of study, only the variables and indices discussed in this section were considered here. Collectively, these variables and indices appropriately addressed the combined interests of this study to analyse atmospheric and near-surface thermal and moisture characteristics throughout the study domain.

Inspired by the work of Flannigan and Harrington (1988), the final section of results presented here focussed on the probability of days with 'low' RH and the mean number of consecutive low-RH days throughout the study domain, to determine possible changes in fire potential with respect to atmospheric moisture content. Using derived RH thresholds for the study domain, the frequency of days in which the RH value at 1500Z, 1800Z, 2100Z or 0000Z on a given day fell below the respective threshold of either category (i.e. fire frequency and area burnt) was computed at each grid point in the study domain over the entire study period for that particular season.

Using fire statistics (e.g. counts, locations, area burnt, onset dates) from the Fire Program Analysis System (http://www.forestsandrangelands.gov/FPA/index.shtml, accessed 28 June 2013) of the National Interagency Fire Center, the results for the historical period (1981–1999) were tested for correlation with relevant fire statistics (i.e. fire frequency, total area burnt and mean fire size with respect to area burnt, using Pearson's correlation coefficient and the coefficient of determination (R^2) burnt). Only federal fire data (i.e. fires that occurred on federal land, which encompasses approximately one-third of all land in the study domain (USFS 2013)) were utilised in this study, to eliminate any potential redundancies that may arise from the inclusion of various state fire datasets offered in the south-eastern US. Also, matched-pairs difference of means Student *t*-tests at a significance level of $\alpha = 0.05$ offered measures of statistical strength in changes of such variables in the future period. This procedure was carried out by breaking the study domain down into the five soil moisture deficit regions produced in Doublin and Grundstein (2008) for each of the variables under analysis (Fig. 2). For this study, Virginia and all but extreme western Kentucky were added to the East Region, whereas extreme western Kentucky was added to the North Central Region. Each of these soil moisture deficit regions, defined based on distinct soil moisture deficit magnitudes and patterns, contains representative cooperative observing stations that may be used for data collection and analysis. The Texas Region variables, with the exception of the RH threshold calculations, were subsequently removed from this study because of insufficient fire data. For an entire domain correlation analysis, the results from the four participating cooperative stations were averaged to produce one comprehensive set of values that are representative of the south-eastern US.

The rationale behind this approach was chosen so that fire data would be analysed in a more appropriate fashion by separating forest fires during the recent historical period into divisions of similar soil moisture deficit characteristics. Although there is some bias here considering the fact that the results at a single point location have been deemed appropriate for statistical correlation with fire data over an entire area, these cooperative stations were considered representative for their respective regions in terms of precipitation amount and intensity, making them suitable for this type of statistical analysis. (For more information on the soil moisture deficit regions utilised in this study, see Doublin and Grundstein (2008).)

Results

Analyses of 500-hPa geopotential heights and variances

In the future period, 500-hPa geopotential heights rise by ~40–50 geopotential metres (gpm) (0.7–0.8% of the recent historical mean heights) throughout the study domain (Fig. 3*a*). 500-hPa geopotential height variances indicated that during the winter, MLCs were more likely to be found with increasing latitude, given relatively low (high) 500-hPa geopotential height variance values found over the Deep South (Mid-Atlantic–Northeast). Fig. 4*a* reveals that the Appalachian Mountains' region east to the Atlantic Ocean exhibited a decrease in mean winter 500-hPa geopotential height variances in the future period (up to ~7%) relative to the final two decades of the 20th century. This overall reduction in 500-hPa geopotential height variances leads to the conclusion that winter storm tracks identified by the highest variance values east of the Mississippi River in the recent historical period will migrate north by ~0.4–0.8° latitude by the mid-21st century, resulting in fewer MLC occurrences in this area of the south-eastern US.

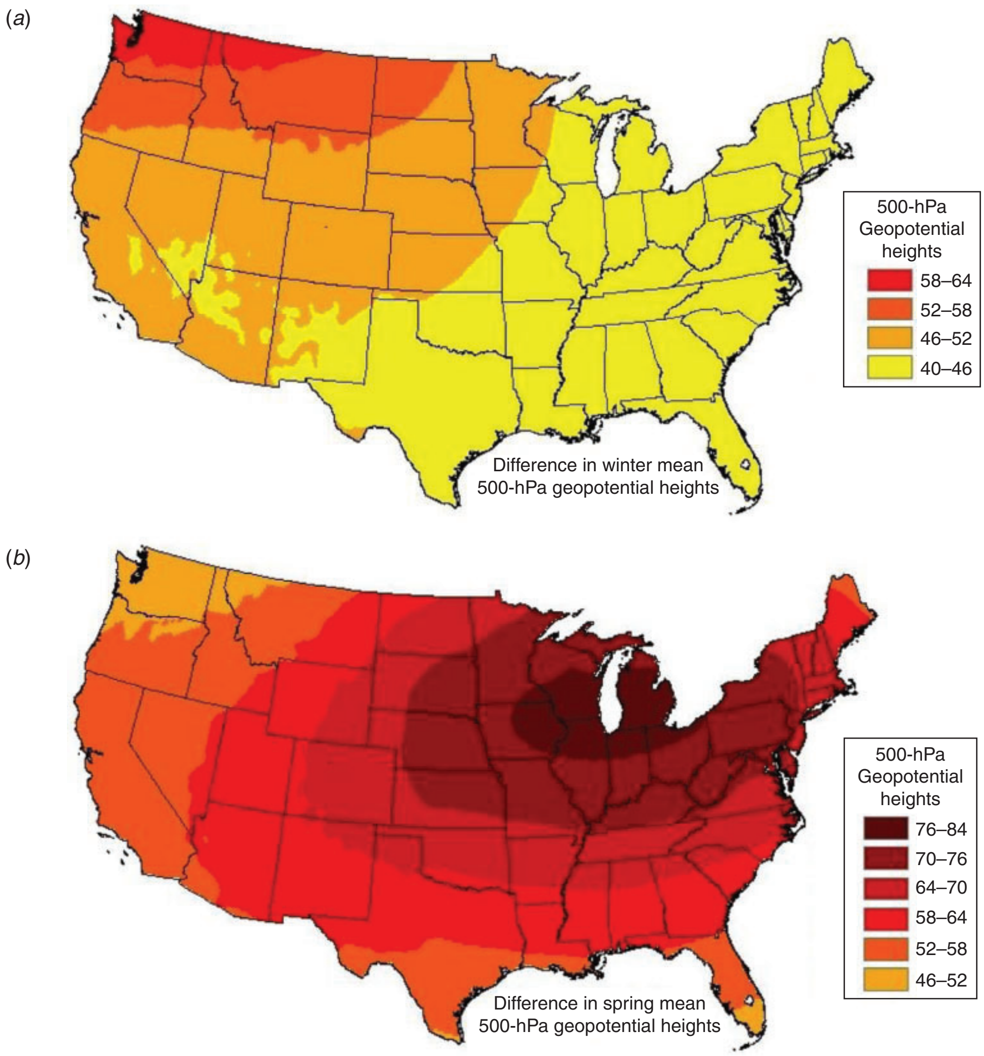

Fig. 3. Differences in mean 500-hPa geopotential heights (gpm) for the (*a*) winter and (*b*) spring seasons. Differences are calculated by subtracting recent historical (1981–1999) heights from future (2051–2069) heights.

During the spring, 500-hPa geopotential heights will rise even further by ~50–77 gpm (0.8–1.3% of the recent historical mean heights) (Fig. 3*b*). Differences in all four soil moisture deficit regions along with the domain were statistically strong in the future spring period relative to the recent historical period with *t* values ranging from −11.02 to −12.72. For the spring analysis, much of the study domain showed little to no change in either direction of 500-hPa geopotential height variances (Fig. 4*b*).

Convective and total precipitation analyses

There was generally little change overall in mean daily convective precipitation in the future winter period, with maximum increases (decreases) of ~0.2–0.3 mm over much of the domain east of the Mississippi River (central and southern Florida and Arkansas). Changes in mean daily total precipitation reflected a similar distribution to convective precipitation during the winter season, with the only notable difference being a decrease in total precipitation in the Arkansas–Louisiana–Texas (ArkLaTex) region. Increases of ~0.8–0.9 mm were found over the Appalachians and the Piedmont, whereas ArkLaTex and much of Florida showed very slight decreases of ~0.2–0.4 mm. Differences in mean daily convective and total precipitation were insufficient to be considered statistically strong anywhere in the south-eastern US.

Spring convective precipitation appeared to decrease in the 21st century over much of the study domain and especially so along the Atlantic coast of South Carolina, Georgia and Florida where convective precipitation decreased by ~0.7 mm daily. Pockets of slight increases (~0.4–0.5 mm) were found over the southern Appalachian Mountains in North Carolina and along the Gulf Coast west of New Orleans, LA. Differences in mean daily total precipitation during the spring closely resembled that of convective precipitation in distribution and relative magnitudes. The portion of the lower Mississippi River Valley located

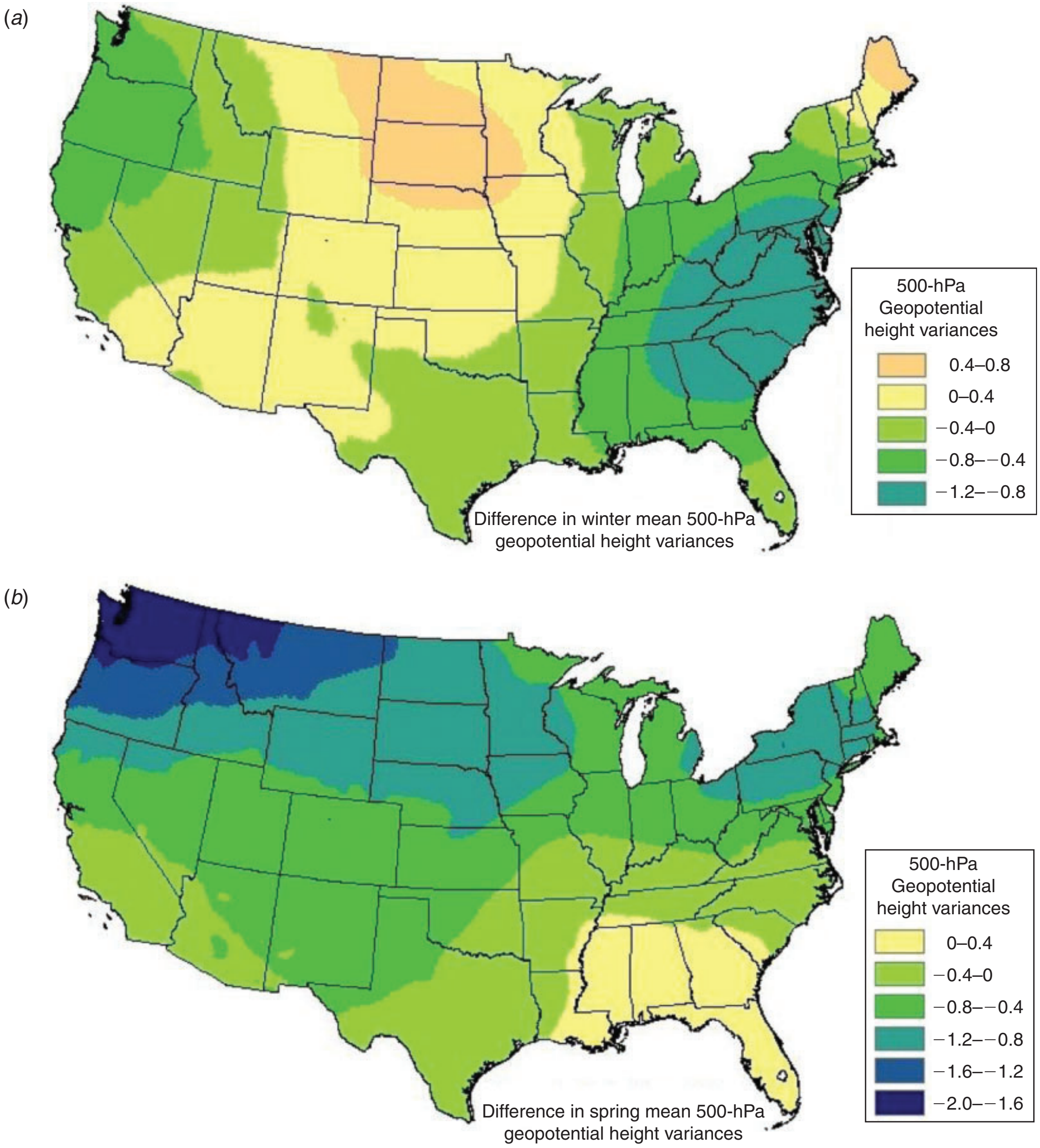

Fig. 4. Differences in mean 500-hPa geopotential height variances for the (*a*) winter and (*b*) spring seasons. Differences are calculated by subtracting recent historical (1981–1999) variances from future (2051–2069) variances.

in eastern Arkansas, northern Mississippi and western Tennessee, along with the Atlantic coast of South Carolina, Georgia and Florida, revealed decreases in mean daily total precipitation of ~1.0–1.1 mm. The southern Appalachian Mountains and the Texas and Louisiana Gulf Coast showed increases in total precipitation of up to ~0.8–0.9 mm daily. Differences in mean daily convective and total precipitation were found to be statistically strong in Florida during the spring season.

Haines index

HI was not shown to significantly change in the future winter or spring periods in any soil moisture deficit region, with only pockets of incremental differences observed during the months of January through May. The month of June displayed the most apparent changes in average HI values, with nearly the entire domain outside of the Appalachian Mountains and the Gulf Coast of Texas and Louisiana indicating an average HI value of at least 5 in the future period. Furthermore, maximum average HI values of 6 were found over much of Oklahoma, the Ozarks and central Tennessee in the vicinity of Chattanooga in the month of June, up from 4 in the recent historical period.

Keetch–Byram drought index

Much like HI, KBDI did not indicate notable changes until late in the spring season (Fig. 5). The trend with respect to future changes in KBDI during the spring begins in the month of May, where increases in KBDI initially were found over the Deep South and Piedmont regions. By June, the entire domain displayed higher

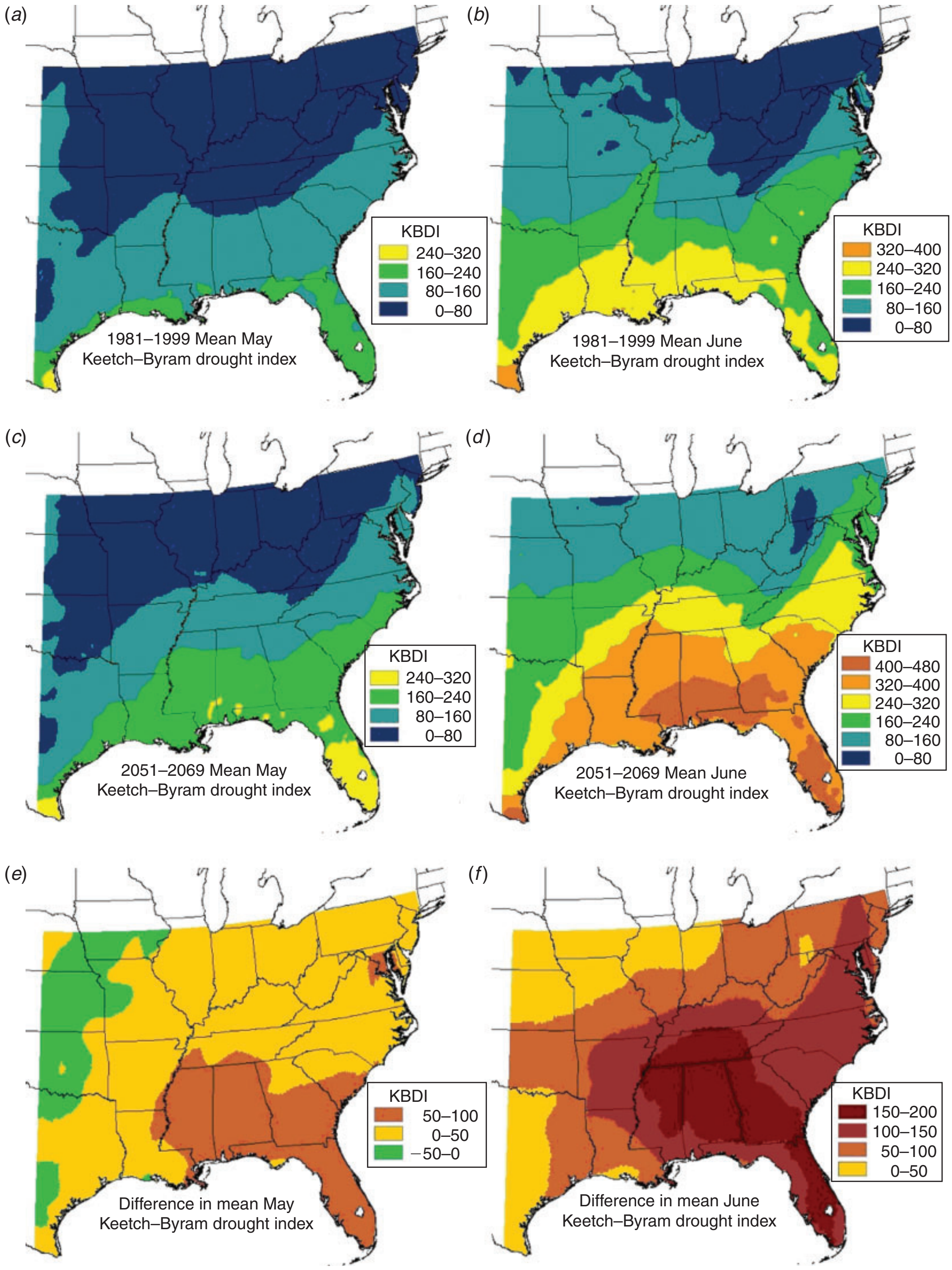

Fig. 5. Mean KBDI for May (left) and June (right), where (*a*) and (*b*) reflect recent historical values and (*c*) and (*d*) show future values. (*e*) and (*f*) display the difference maps for both months, where recent historical values are subtracted from future values.

KBDI values in the future, whereas the Deep South and Florida offered evidence of increasing KBDI by over 200 in some areas. These increases contributed to mean June KBDI values of over 450 in southern Mississippi, southern Alabama, south-western Georgia and Florida. According to the USDA Forest Service, these values are presently typical of late summer and early autumn (ASO), when ground and near-surface soil layer organic materials contribute to fire intensity and burn actively (USFS 2012). Significant increasing temperatures were observed to be the principle factor behind these increases in KBDI in the future spring, especially given the relative disagreement in changing precipitation totals spatially across the region (Fig. 6).

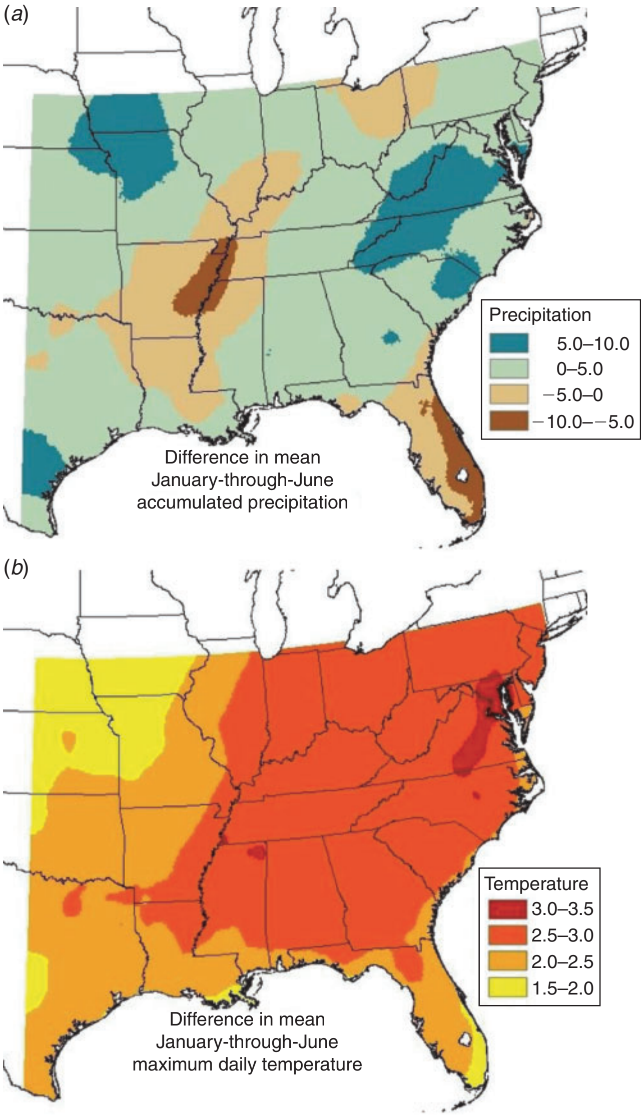

Fig. 6. Differences in (*a*) mean accumulated precipitation (cm) and (*b*) mean daily maximum temperature (°C) from January through June. Differences are calculated by subtracting recent historical (1981–1999) values from future (2051–2069) values.

Relative humidity analyses

Although the winter season revealed no statistically strong changes in low-RH probabilities or mean low-RH sequence lengths anywhere in south-eastern US, low-RH day probabilities appeared to increase slightly throughout the domain in the future spring period, with very marginal decreases found only over the Appalachian Mountains and in the western portion of the domain. Furthermore, increases of nearly 17% were seen in southern Texas and southern Florida, indicating a generally higher likelihood that a given spring day in the future period exhibited low-RH conditions. As for the mean low-RH day sequence lengths, virtually the entire domain outside of southern Missouri offered evidence of increasing mean sequence lengths in the future period under more consistent dry conditions. In the Deep South near the Mississippi River and in southern Florida, mean sequence lengths increased by nearly 6 days.

Summary

Many of the significant findings in this study were closely tied to the apparent increase in mid-21st century temperatures relative to the late-20th century (Fig. 6*b*). The 500-hPa geopotential heights were found to be generally higher across the domain in the future, leading to generally more stable conditions. Increases in HI, KBDI and low-RH day sequence lengths were pronounced in the month of June as the warm season approached, again indicating the importance of the effects of higher temperatures on fire indices such as these. Furthermore, HI and KBDI as well as sequences of low-RH days were positively correlated with fire activity. These results indicated that fire potential in the 21st century will likely increase, especially in the southern half of the domain.

Discussion

Results presented in this study pertaining to convective precipitation should be interpreted with caution, as the WRFG–CCSM convective precipitation was simulated based on larger-scale atmospheric 'triggers' that essentially determine an area to be suitable for deep convection (Rogers and Fritsch 1996). Seasonal low-RH day probabilities and sequence lengths in the state of Florida should also be examined carefully given the 50-km spatial resolution of the NARCCAP data. Coastal sea breezes promote a fairly consistent on-shore transport of atmospheric moisture over Florida during periods lacking significant synoptic activity.

Results presented in this study indicate that the fundamental calculation of HI in the 21st century may require some alterations with respect to the atmospheric levels utilised in the three variant calculations. In a generally warmer and drier future environment, the surface boundary layer would likely deepen given additional sensible heat influx (Pielke *et al.* 1998). A deeper boundary layer in general would likely introduce a lower stability and a higher moisture bias in the future HI results.

The entire study domain exhibited an environment characteristic of a generally warmer climate annually in the future period (i.e. 2051–2069) given significantly higher 500-hPa geopotential heights throughout the south-eastern US. Furthermore, significantly lower 500-hPa geopotential height variances in the future winter period, especially in the eastern half of the domain, offered evidence of poleward shifting wintertime storm tracks across the south-eastern US, and fewer MLC occurrences across the domain in general (Fig. 4*a*). A shifting – and potentially weaker, given the results in Fig. 3*a* – wintertime storm track may strain the presently characteristic on-shore transport of moisture from the Gulf of Mexico into the south-eastern US during this season. Such a scenario suggests the possible entrainment of relatively drier air from continental sources (i.e. southern Plains), contributing to a generally drier air mass during the winter over the south-eastern US than at present.

The results for the fire indices presented here suggested that the southern half of the domain exhibited increasing fire potential in the future spring season. Higher HI values late in the spring implied greater 'large' fire risk given the positive correlation between HI and both total area burnt and mean fire size in the domain. The most significant results in this study appeared to be associated with KBDI and RH analyses for the spring season. Increases in KBDI suggested enhanced drought and associated fire potential throughout the south-eastern US in the future spring period as KBDI explained over 40% of the variances in both total area burnt and mean fire size in the domain. In agreement with the projected warming temperatures over the Deep South and Florida in the future spring, low-RH day probabilities and mean sequence lengths were found to be respectively higher and longer during this period.

Increasing wildfire potential in areas like the Deep South and Florida poses considerable threats to both humans and the biological landscape in the south-eastern US. It appeared that the spring season presented the most significant potential for increasing wildfire risk in the future given warmer and drier conditions during this season relative to the future winter period. This increased springtime threat was important because it alluded to the possibility that even greater fire risk may occur during the future summer months when precipitation across the south-eastern US at present is almost exclusively convective in nature.

Although it has been linked to the potential for fire activity, temperature has also been projected to contribute to considerable landscape and tree species changes in the 21st century. For example, winter and temperate deciduous forests that may be at present found as far south as northern Georgia, Alabama and Mississippi may retreat to the Kentucky–Tennessee border by 2095 (Bachelet *et al.* 2003). Further, Bachelet *et al.* (2001) noted that increasing annual temperatures may shift and extend the growing season in the US. This phenomenon may shift the peak fire season in regions such as the south-eastern US either earlier or later in the year, and also potentially extending wildfire activity over longer periods on an annual basis.

Conclusions

In this study, analyses of climatic parameters relevant to forest fire activity (e.g. temperature, precipitation, humidity) were examined to assess the potential for enhanced wildfire activity in the south-eastern US in the mid-21st century under projected climate change. In the Deep South, the Gulf Coast and the southern portion of the Piedmont (e.g. Georgia and South Carolina), fire activity is expected to increase – especially in the spring season – given inconsistent changes in precipitation (Fig. 6*a*), higher HI and KBDI values, and more frequent and longer periods of days on which RH will fall below the thresholds derived in this study for wildfire potential. After reviewing the results, it became apparent that only in areas where precipitation increases – especially in the spring season – would increasing fire potential be mitigated in the mid-21st century. Advanced adaptation methods to address such changing forest characteristics, as well as significant fire suppression schemes (e.g. implementation of additional prescription fires on an annual basis to suppress extreme fire fuel accumulations), will likely be called into play in the 21st century to counteract this projected increase in fire potential that threatens humans as well as the biological landscape in portions of the south-eastern US.

A majority of the significant findings in this study were associated with the spring season (especially June) when higher temperatures were found relative to the winter season. Thus, an extension of this study may involve the boreal summer months to determine if forest fire activity, which at present typically peaks during the late winter and spring months in the south-eastern US, will increase into the summer months in the 21st century. Also, other variables (e.g. temperature anomalies, modelled soil moisture, surface wind components) that have exhibited relevancy with respect to fire activity along with other fire indices (e.g. Fosberg FWI) may be analysed in the future to determine if they are better correlated with fire activity than are the variables and indices studied here. Caution should be taken when generating conclusions from the results of analyses on a limited number of model pairings in a study such as this. Thus, additional model pairings from the NARCCAP project as well as modelled data from sources that incorporate other emissions scenarios would be beneficial for comparisons with the data and results investigated in this study.

Acknowledgements

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